HHS Public Access
Author manuscript
J Biomech. Author manuscript; available in PMC 2024 March 25.

Published in final edited form as:
J Biomech. 2018 October 05; 79: 164–172. doi:10.1016/j.jbiomech.2018.08.002.

An Investigation on Normal Force Distribution and Posture of a Hand Pressing on a Flat Surface

R. Figueroa-Jacinto[1,2,*], **T. Armstrong**[2], **W. Zhou**[2]

[1]Explico Engineering Co., Novi, MI

[2]Department of Industrial and Operations Engineering, University of Michigan, Ann Arbor, MI

Abstract

Hand strength data are needed to understand and predict hand postures and finger loads while placing the hand on an object or surface. This study aims to analyze the effect of hand posture and surface orientation on hand force while pressing a flat surface. Twelve participants, 6 females and 6 males ages 19–25, performed three exertions (100%, 30% and 10% MVC- Maximum Voluntary Contraction) perpendicular to a plate in 4 angles (−45°, 0°, 45° and 90° with respect to horizontal plane) at elbow height. Exertions involved pushing in two postures: 1) whole hand and 2) constrained to only using the fingertips. Inter-digit joint angles were recorded to map hand and finger motions and estimate joint moments for each condition. Participants exerted twice the force when pushing with whole hand vs. fingertips. 72–75% of the total force was exerted over the base of the palm, while only 11–13% with the thumb for exertions at 90°, 45° or 0° plate angles. Males maximum force for pushing at 0°, 45° and 90° plates averaged 49% higher than females for the whole hand and 62% for the fingertips ($p<0.01$). There was no significant sex difference ($p>0.05$) for the −45° plate. Thumb joint loads were generally higher than the other individual fingers ($p<0.05$) in all %MVC and accounted for 12% of total force during whole hand exertions. On average, joint moments were 30% higher during fingertip conditions vs. whole hand. Thumb and finger joint moment magnitudes when pushing the plate at 100%MVC indicated that Metacarpophalangeal (MCP) joint moments were higher ($p<0.05$) than Distal Interphalangeal joints (DIP) and Proximal Interphalangeal joints (PIP) under whole hand and fingertips conditions.

Keywords

hand posture; push; hand-force distribution; finger force; one-hand push

---

*Corresponding author: Rosemarie Figueroa Jacinto, 40028 Grand River Ave. Suite 300, Novi, MI, 48375, (248) 595-9025, rosemfig@umich.edu.

All authors were fully involved in the study and made substantial contributions to all of the following: (1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, (3) final approval of the version to be submitted. The preparation of the manuscript and the material within has not been and will not be submitted for publication elsewhere.

Conflict of Interest Statement

The manuscript is the original work of the authors and has not been published or accepted for publication elsewhere except as an abstract and is not under consideration at this or another journal.

Introduction

Hand strength data are needed to understand and predict hand postures and finger loads while placing the hand on an object or surface. Most available strength data are based on forces exerted between the fingers and the thumb or palm while gripping an object (Kargov et al., 2009; Zhou et al., 2011; Rosenbaum et al., 2009; Mathiowetz et al., 1985). However, in several cases the fingers' force is exerted against an external surface instead of another part of the hand. These exertions could include only the fingertips or the whole hand, and are common in everyday activities, including when a person supports their body on a table, plays sports (e.g. football, sprinting and gymnastics), and many work activities (e.g. installing interior panels in automobiles; laying hardwood floors).

However, prior studies have focused on pushing while grabbing a handle or while grasping objects. Force exertion during pushing tasks had been evaluated while grabbing handles in different sizes (Seo et al., 2007), on fixed or variable heights (Chaffin et al. 1983; Hoffman et al., 2007) and different angles (Das & Wang, 2004). Additionally, previous studies have shown that hand placement is related to object and task factors. For instance, Rosenbaum et al. (1990) and Zhou et al. (2011) demonstrated that grip selection depends on prior specifications of object orientation. These studies suggest that relative joint loads and force distribution are related to hand placement when grasping objects. In this study, during exertions using either just fingertips or whole hand, the forces involve muscles that produce moments and loads about inter phalangeal joints making the hand and fingers flex against the surface. Those joint positions and loads determine hand strength capabilities and hand posture (Chaffin, 2008; Hara et al., 1992; Daams, 1993; Rancourt & Hogan, 2001; Di Dominizio & Keir, 2010).

Prior studies also show that maximum grip force capability occurs when there is a larger amount of area to distribute the force around the object, where finger and thumb forces work together against the palm region while grasping an object (Seo et al., 2007; Szychlinska et al. 2017). Seo et al. (2007) showed this by analyzing hand force distributions and resultant forces on different diameter cylinders. However, force distribution has not being analyzed while pushing a flat surface.

This study aims to examine how hand force exerted against a flat surface is affected by hand posture and surface orientation. Towards this end, this study investigates 1) the effect of orientation of a flat surface on finger force distribution and upper extremity posture, 2) force distribution between the fingers, and 3) hand-joint moment magnitudes while pressing the flat surface. Such hand strength data is necessary for hand posture and force predictions, which are used in several fields ranging from computer graphics to biomechanical and ergonomic assessments. It is hypothesized that 1) plate orientation will affect the magnitude of hand push forces, 2) whole hand push forces will he significantly higher than fingertip forces, 3) finger moments will be significantly higher for fingertip exertions vs. whole hand exertions, and 4) the larger the area to distribute the force, higher the grip forces similarly to results from Seo et al. (2007).

Methods

To achieve the stated aim, a laboratory study was conducted on contact force distribution while pressing a flat surface using a whole hand vs. fingertips under −45°, 0°, 45° and 90° orientations and at 100%, 30% and 10% Maximum Voluntary Contraction (MVC).

Apparatus

Grip strength was measured with a Jamar® grip dynamometer at 49mm span, and thumb-index finger pinch strength was measured with a B&L® pinch gauge (Mathiowetz et al., 1985; Hamilton et al., 1992). Hand length was measured with a caliper (Gordon et al., 1989) with a caliper over their hand on a table with the fingers together.

An aluminum plate of 230 by 230 mm was attached to a force transducer with rotation about a single axis (Figure 1a). LabVIEW (National Instruments, Inc., Austin TX) at 60Hz was used to determine total normal force (F) and to ensure participants exert normal forces, discarding any friction forces. Data were averaged over 3s during maximum force exertions. A video display was placed in front of the participants to provide feedback by showing their normal force at 200ms intervals.

Normal contact forces and force distribution were evaluated using an I-Scan™ (Tekscan Inc., Boston, MA) at 60 Hz. Each pressure-mapping sensor has an effective sensing area of 111.8 mm by 111.8 mm, which consists of an array of sensors that have the size of 2.5 mm by 2.5 mm. Two sensors were placed side by side to cover a large area of the aluminum plate. The sensors were calibrated at pressures of 34.5kPa and 206kPa (5PSI and 30PSI) with weights and a rubber sheet in between to ensure the weight is evenly distribute on all pixels. Forces for palm, and digits proximal (PP), middle (MP) and distal (DP) were determined by segmenting force data in selected regions (Nicholas et al. 2012).

Four cameras and MaxTRAQ software (Innovision Systems, Inc.) were used to track markers on right hand, arm and shoulder joints (Innovision Systems, 2012; Figueroa et al., 2014; Yu, 2014; Zhou, 2013) to analyze joint locations and moments.

Participants

Twelve right-handed participants (6 males and 6 females), free of known movement disorders, gave written informed consent in accordance with IRB regulations to participate in this study.

Experimental Design and Procedure

Participants were instructed to perform three exertions (100%, 30% and 10%MVC) perpendicular to an aluminum plate in −45°, 0°, 45° and 90° pitch at elbow height (Figure 1b). Exertions were performed for 3 seconds using 1) whole hand and 2) fingertips (Figure 2). Fingertips exertions were constrained to the area of one pressure-mapping sensor. There were two replicates for each condition. Trials were blocked on plate orientation, with randomized selections between participants. Participants were allowed to become familiar with the tasks through practice sessions for each condition. Participants were instructed to try different postures and select the posture they felt more comfortable to obtain maximum exertions, with the plate constraint at elbow height and to keep the hand within the area of pressure maps. Elbow height was measured with participant standing straight, with both arms straight down on the sides. First, participants were asked to perform maximum exertions (100%MVC). An average of the 100%MVC was used to record 30%MVC and 10%MVC conditions. The order of force exertions was randomized within the block for 30%MVC and 10%MVC. There was a minimum of two minutes of rest between exertions.

Reflective markers were attached to anatomical landmarks found by palpation. Specifically, they were placed on the lateral epicondyle, on the acromion process, on the ulna styloid process and radial styloid process, on the Metacarpophalangeal (MCP), Proximal Interphalangeal (PIP), Distal Interphalangeal (DIP) and Interphalangeal (IP) joints, and on the tip of each finger.

Vectors were defined between markers to compare postures among participants. Shoulder-Elbow, Elbow-Wrist vectors were used to compute elbow angle (Figure 1b). Elbow angle was defined on the anterior side of the arm (Knudson, D. 2007) and the global angle of the segment was defined as negative θ (−θ) when facing downwards related to global Y-axis and positive θ (+θ) when facing upwards related to global Y-axis (Figure 1b). Linear distance from shoulder to tip of middle finger (Shoulder-to-D3) was used as a measure of arm straightness (Zhou, 2013). The linear distance between shoulder and wrist joints (SW) was used to measure the angle (α) between the resultant force ($\boldsymbol{F}_Y$) (Figure 1b) and shoulder-to-wrist vector ($\mathbf{r}_{Sw}$). Where,

$$\cos\alpha = \frac{\overline{\boldsymbol{r}}_{SW} \cdot \overrightarrow{\boldsymbol{F}_Y}}{|\boldsymbol{r}_{SW}|\left|\overrightarrow{\boldsymbol{F}_Y}\right|} \tag{1}$$

Moments ($\mathbf{M}$) at each joint k (k=1, 2 3 or 4 for DIP, PIP, MCP, and Wrist, respectively) were computed as the product of the force $\overrightarrow{F}^n$ (n= DP, MP, PP and palm region) measured by the pressure-mapping sensor and the perpendicular distance $\boldsymbol{r}_k^n$ of force ($\overrightarrow{F}^n$) to joint k (Seo et al., 2007; Zhou, 2013)

Where,

$$\mathbf{M} = \begin{bmatrix} M_{DIP} & M_{PIP} & M_{MCP} & M_{Wrist} \end{bmatrix}$$

$$\mathbf{M} = \begin{bmatrix} M_{DIP}^{DP} & M_{PIP}^{DP} & M_{MCP}^{DP} & M_{Wrist}^{DP} \\ 0 & M_{PIP}^{MP} & M_{MCP}^{MP} & M_{Wrist}^{MP} \\ 0 & 0 & M_{MCP}^{PP} & M_{Wrist}^{PP} \\ 0 & 0 & 0 & M_{Wrist}^{Palm} \end{bmatrix}$$

$$\mathbf{M} = \begin{bmatrix} \overrightarrow{F}^{DP}\left(r_{DIP}^{DP}\right) & \overrightarrow{F}^{DP}\left(r_{PIP}^{DP}\right) & \overrightarrow{F}^{DP}\left(r_{MCP}^{DP}\right) & \overrightarrow{F}^{DP}\left(r_{Wrist}^{DP}\right) \\ 0 & \overrightarrow{F}^{PP}\left(r_{PIP}^{PP}\right) & \overrightarrow{F}^{PP}\left(r_{MCP}^{PP}\right) & \overrightarrow{F}^{PP}\left(r_{Wrist}^{PP}\right) \\ 0 & 0 & \overrightarrow{F}^{MP}\left(r_{MCP}^{MP}\right) & \overrightarrow{F}^{MP}\left(r_{Wrist}^{MP}\right) \\ 0 & 0 & 0 & \overrightarrow{F}^{Palm}\left(r_{Wrist}^{Palm}\right) \end{bmatrix}$$

(2)

for whole hand condition and can be simplified to

$$\mathbf{M}=\begin{bmatrix}\vec{F}^{DP}\left(r_{DIP}^{DP}\right) & \vec{F}^{DP}\left(r_{PIP}^{DP}\right) & \vec{F}^{DP}\left(r_{MCP}^{DP}\right) & \vec{F}^{DP}\left(r_{Wrist}^{DP}\right)\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}$$

(3)

for fingertips condition. Figure 2 shows a 2D-Body Diagram for moment at the MCP joint (M_{MCP}).

Statistical Analysis

The independent variables in this experiment were sex, hand posture (fingertips/whole hand) and plate orientation. The dependent variables were grip/pinch/push force, hand force distribution, joint locations, and joint moments. Sex (female, male) data was aggregated for joint and force distribution.

ANOVA was used (MINITAB®) to compare the effect of force required (%MVC) on hand force distribution, finger placements and joint moments in fingertips and whole hand conditions. This analysis was also used to determine how resultant force was affected by plate orientation (−45°, 0°, 45° and 90°) by hand posture (whole hand vs. fingertips). The mean values for each main effect and simple interaction were computed and significant factors were determined. A paired t-test (MINITAB®) was used to find the mean of the differences conditions, and subsequently the standard error of their mean. The analysis was performed within and between blocks conditions. Bonferroni correction was used as a post-hoc test. Significance was set at $p<0.05$. The Bonferroni correction was alpha level (α) divided by the number of tests based on each condition testes.

Results

Force Exertions

Descriptive statistics of the participants are summarized in Table 1. Males consistently exerted more force than the females (except for the −45° pitch conditions). Average maximum force for pushing with whole hand at 0°, 45° and 90° plates was 49% higher than for female (p<0.01); average maximum for pushing with the fingertips was 62% greater for males than females (p<0.01) (Table 2).

Grip strength was 6.6 times greater than pinch strength (p<0.01). Grip strength (Table 1) was 4.6 and 7 times greater than flat hand and fingertips average maximums, respectively, while pushing in a downward and inward direction (−45°- Table 2). Grip strength was 2–3 times and 4.2– 5.3 times higher than the average maximum push with the whole hand and fingertips, respectively, while pushing downward (0°- Table 2) and away from the body (45° and 90°- Table 2). Maximum thumb-index finger pinch strength (Table 1) was 0.7 and 1.1

times the average maximum force exerted down and inward at −45° (Table 2) with the whole hand and fingertips, respectively. Thumb-index finger pinch strength was about 0.4 times and about 0.7 times the average maximum force exerted with the whole hand and fingertips, respectively, at 0° 45° and 90° (Table 2).

Force Distribution per Hand Segment

Normal forces per segment for each orientation and each hand posture are shown in Table 3. Thumb force was 12% of the total force when pushing with whole hand ($p<0.05$) and 38% of the total force for pushing with the fingertips ($p<0.01$). The sum of finger forces (excluding thumb) corresponded to 62% of the total force for pushing with the fingertips, but only 15% of the total force for pushing with the whole hand. Seventy-three percent of the total force was exerted with the palm. When constrained to fingertips, the force exerted by the thumb increased by 37% and the sum of the force exerted by the fingers increased by 50% (Figure 3) for all conditions ($p<0.01$).

Posture Analysis

Shoulder-D3 distances, while pressing a flat surface under whole hand posture per sex, are shown in Figure 4. The angle (α) between the resultant hand force (F_Y) and the vector corresponding to the linear distance between the shoulder and wrist joints (R_{SW}) for 0°and 90° orientations by sex, and hand posture are shown in Table 4. Angle (α) between resultant force (F_Y) and shoulder-to-wrist vector (RSW) was different in low %MVC vs. 100 %MVC ($p<0.05$) when pushing in both fingertips and whole hand conditions.

For the 0° condition, Females acquired a posture with shoulder abduction and negative elbow angle (Figure 1b, Figure 5) during fingertip posture at 100% MVC conditions, and a positive value for the rest of the conditions (Figure 1b, Figure 5). Males elbow angle involved shoulder abduction without significant change between force levels ($p>0.05$) ((Figure 1b, Figure 5) during all conditions.

Joint Moments

Moments of the wrist, thumb and finger joints were calculated when pushing the plate in 4 orientations (−45°, 0°, 45° and 90°) with fingertips and whole hand postures for 100%MVC exertions (Table 5).

On average, finger joint moment magnitudes were 30% higher when pressing with fingertips vs. whole hand postures ($p<0.01$). Wrist moments were 36% higher under 0°, 45° and 90° orientations and 50% lower under −45° orientation when pressing with fingertips vs. whole hand ($p<0.05$).

Thumb MCP moments were 65% and 63% higher than its IP joint during whole hand and fingertips, respectively ($p<0.01$). Wrist moment was 49% higher than MCP3 ($p<0.01$) and 11% higher (but not significant) than MCP1 joints during fingertip exertions. For the rest of the fingers (index to little fingers), MCP moments were 70% higher than DIP and 34% higher than PIP during whole hand posture and 67% and 37%, respectively during fingertips posture ($p<0.05$).

Discussion

This study was primarily concerned with exertions of the thumb, fingers and palm, which are in the same direction pushing on a flat surface. Hand strength measurements are typically based on maximum finger flexion against an object supported by the palm and thumb (Zhou, 2013; Salimi et al. 2003; Hamilton et al., 1992), a cylinder (Wu et al., 2012), or during push/pull tasks while holding a handle (Szychlinska et al., 2017; Nicholas et al., 2012; Di & Keir, 2010; Seo et al., 2007; Das & Wang, 2004; Chaffin et al., 1983).

In power grip the fingers are flexed against an object supported in the palm (Szychlinska et al., 2017; Seo et al., 2007; Napier, 1956) so that the fingers forces act in opposition to the thumb and palm. When pushing with a flat hand, the fingers, thumb and palm all exert force in the same direction. In pinch grip the thumb acts in opposition with one or more fingers, where the thumb or opposing fingers limits strength (Budgeon et al., 2008). Pinch strength and pressing on a flat external surface with fingertips are biomechanically similar; in both cases forces are exerted with the distal portion of the fingers. When pressing a flat surface with the fingers and thumb, all are exerted in the same direction so that the average maximum force is related to the sum of individual fingers and the thumb. However, results from Tables 1 and 2 show that grip strength was considerably greater than both whole hand and fingertips average maximum push exertions.

This study shows that greater normal contact force can be exerted with the base of the palm than with the fingertips (Table 3, Figure 3) when pushing away from the body at 45° and 90° or downward at 0° (Table 2). It also shows that more force can be exerted horizontally at 0° than downward at 90° (Tables 2 and 3), although horizontal forces are limited by shoe-floor traction (Fischer et al., 2013), hand-handle friction (Seo et al., 2010), anthropometry (Chaffin et al., 1983), balance (Rancourt & Hogan, 2001) and strength of the legs, trunk and upper limbs (Hoffman et al., 2007). Finger joints are the weakest links in the kinematic chain; unable to counteract the load moments produced by the DP segments maximum exertions away from the body. This explains the differences among forces for pushing with fingertips versus whole hand (Table 2). The ability of the body to exert force with the base of the palm is not limited by hand strength when pushing with the whole hand.

This study found that substantially more force is exerted away from the body at elbow height. It appears that participants were unable to use their body weight when they reached over the plate to push down in an inward direction (−45° Table 2). As a result, finger strength was not limiting and there were no significant sex differences between the maximum forces exerted during −45°. Per observations, the lack of sex difference was likely do to the awkward posture acquired when reaching over the plate to push in an inward direction- similar to a pulling task.

It is not possible to determine which finger joint is limiting, but it is reasonable to assume that participants position their hands to equalize the relative moments (%MVC) about each joint (An et al. 1984; Bean et al. 1988). This is consistent with previous findings related to finger force distribution while grasping a flat plate (Zhou, 2013; Salimi et al. 2003) or cylinder (Wu et al., 2012), and in push/pull tasks (Nicholas et al., 2012) where participants modified digit positions and scaled fingertips forces to obtain higher comfort and balance based on external torque created by changes in weight amount and location. It follows that all of inter-digit joints are at or near maximum during average maximum push exertions (Table 4).

It was observed that under all %MVC conditions, males maintained an arm posture involving shoulder abduction with inward rotation having the anterior side of the elbow facing down when pushing downwards (0°) with the whole hand (Figure 1b, Figure 5). Females only acquired the same posture while pushing downward (0°) with the fingertips during 100%MVC and while pushing forward (90°) with the whole hand during 100%MVC (Figure 4). This posture included shoulder abduction, and high wrist extension with radial deviation (Figure 1b). While this is one of the poorest upper body positions, which contributes to upper extremity MSDs (Garg & Kapellusch 2011), it suggests that the elbow joint didn’t limit their strength and all efforts were focused on minimizing the moment arm between the resultant force and the shoulder joint. This was also shown with the large results for Shoulder-to-D3 distances (Figure 4), indicating that the arm was straight. It is hypothesized that shoulder moment arms for these scenarios where the arms were straight would likely be smaller, dependent on orientation of the push force and the angle of the arm in respect to the torso.

Thumb and finger forces are consistently 40–50% less when pushing with the whole hand than with the fingertips (Table 3). A similar trend exists for finger moments (Table 5), but the moment differences between whole hand and fingertips are closer to 30%. Maximum finger moments might be expected in both cases, but it is likely that the exertions with a flat hand on the 90°, 45° and 0° push plates are more limited by traction, leg, torso and shoulder strength. Work by Elkus and Basmajian (1973) demonstrated that finger flexor muscles relax when ligaments can support hand loads. In these cases, the fingers are partially relaxed when the loads are transmitted directly into the long axis of the upper limb. Given the resultant push force vector is aligned with the shoulder joint, it can be assumed that trunk, lower limbs or traction limit the force.

Forces are not distributed equally over the surface of the hand. Thumb and finger forces during whole hand posture were concentrated primarily on distal segments vs. middle and proximal segments (Figure 3). This is consistent with previous studies that analyzed the ratio of the contact forces applied on the distal, middle, and proximal segments during grip exertions (Chao et al., 1989; Wu et al., 2012; Amis, 1987). The base of the palm exerted 72–75% of total force, followed by the thumb with 11–13% for exertions at 90°, 45° or 0° push plate angles (Table 3). While pushing at −45° plate angles, the force over the palm was reduced to 32% of the total force while the thumb force was increased to 31%.

In all studies that examined relative finger strength for grip and pinch exertions (Barter et al. 1958; Fransson and Winkel 1991; Swanson et al. 1970; Hazelton et al. 1975; Seo et al., 2007), the middle finger was the strongest- accounting for approximately 33% of the sum of all fingers. The index finger accounted for 21–31% as compared to the sum of all fingers, the ring finger for 22–26% and the little finger for 13–18%. For comparison purposes, in this study the relative finger forces (excluding thumb) for pushing away from the body or downward with the whole hand (90°, 45°, 0° - Table 3) were 12–13%, 22–24%, 25–33% and 17–36% for index, middle, ring and little fingers, respectively. For pushing inward and down (−45° - Table 3) the relative forces were 30%, 28%, 25% and 17% for index, middle, ring and little fingers, respectively. The relative finger forces (excluding thumb) for pushing away from the body or downward with the fingertips (90°, 45°, 0° - Table 3) were 27–31%, 23–28%, 23–27% and 19–23% for index, middle, ring and little fingers, respectively. For pushing inward and down (−45° - Table 3) the relative forces were 30%, 28%, 25% and 17% for index, middle, ring and little fingers, respectively. There were no significant changes between relative finger loads during different % MVCs.

Conclusion

An experiment was performed in which participants were asked to push with a single arm on a flat surface at elbow height. Results obtained in this study can help to understand and predict hand postures and finger loads based on object orientation and force required.

Object location, space for hand placement, and physical space should be considered when designing workplaces or household spaces. Results from this study (Tables 2 and 3) suggest that when a person is expected to press or support their body, spaces should be designed to provide enough space to fit the palm, especially if maximum exertions are required. If a person can use the whole hand to press on a surface, they will do so.

Although the advantages for pressing a surface with the whole hand are clear, some tasks require only the fingertips (i.e. setting the volleyball and starting position of race, positioning items against a surface when cooking or writing). Studies have shown that using the fingertips adds a higher level of control and precision (Napier, 1956) over an object when lower exertions are required. Thus, it is important to understand the strength capabilities when pressing a surface with them.

This work can be used to prevent awkward postures and increase comfort for all users through improved design. A workspace should include enough clearance to accommodate the whole population so that the worker can stretch their arms if needed, to exert force and reach maximum force capability without the need of acquiring awkward postures. If the task could involve a person supporting their body on a surface or object (e.g. getting up from a chair, pressing on panels), enough surface space should be provided for them to have a straight arm.

Joint moment calculations, finger force distributions, and joint moment ratios can be used to compare strength capabilities from one position to another and for further biomechanical analyses. These parameters can be used when designing work tasks to ensure a balance between safety, comfort and productivity.

Limitations and future work

This study considered only the normal force component due to the limitation of the pressure mapping system. Object orientation could result in significant friction forces and affect the magnitude of the resultant force. Future studies should examine the effect of friction on hand force distribution and hand placement. Average maximum whole hand forces exerted perpendicular to a flat surface may be limited by whole body strength and traction. This idea could be tested by providing external support for the body so that foot friction is not limiting and subjects can assume a position of average maximum force.

Hand placement was constrained by the pressure sensor area. However, it is likely that participants would demonstrate a similar behavior with larger pressure sensor area (Zhou, 2013; Duemmler et al., 2008).

Calculations for hand kinematics can be rather complex, moments created on the fingers by push exertion on DP segments are not counteracted solely by finger flexor muscle exertions. There are also moments generated by ligaments and bone-on bone contact. This study was limited to simple kinematics, show joint moment magnitudes mainly based on flexion/extension.

Acknowledgements

This research was supported by General Motors and by the partners of the Human Motion Simulation Laboratory at the University of Michigan (http://www.humosim.org/) and with funds from the NIOSH Pilot Project Research Training Program (PPRTP) and the NIH grant 2T42OH008455-09.

References

Amis AA (1987). Variation of finger forces in maximal isometric grasp tests on a range of cylinder diameters. Journal of biomedical engineering, 9(4), 313–320. [PubMed: 3682795]

Budgeon MK; Latash ML; Zatsiorsky VM (2008). Digit force adjustments during finger addition/removal in multi-digit prehension. Exp. Brain. Res. 189, 345–359. [PubMed: 18553076]

Buchholz B, Armstrong TJ, & Goldstein S. a. (1992). Anthropometric data for describing the kinematics of the human hand. Ergonomics, 35(3), 261–73. [PubMed: 1572336]

Chaffin DB (2008). Digital Human Modeling for Workspace Design. Reviews of Human Factors and Ergonomics, 4(1), 41–74.

Chaffin D, Andres R, & Garg A (1983). Volitional postures during maximal push/pull exertions in the sagittal plane. Human Factors: The Journal of the Human Factors and Ergonomics Society.

Das B, & Wang Y (2004). Isometric pull-push strengths in workspace: 1. Strength profiles. International Journal of Occupational Safety and Ergonomics, 10(1), 43–58. [PubMed: 15028193]

Di Domizio J, & Keir PJ (2010). Forearm posture and grip effects during push and pull tasks. Ergonomics, 53(3), 336–43. [PubMed: 20191408]

Dickerson CR, Martin BJ & Chaffin DB, 2007. Predictors of perceived effort in the shoulder during load transfer tasks. Ergonomics, 50 (7), 1004 – 1016. [PubMed: 17510819]

Dijkerman H, Mcintosh R, Schindler I, Nijboer T & Milner A, 2009. Choosing between alternative wrist postures: Action planning needs perception. Neuropsychologia, 47 (6), 1476–1482 [PubMed: 19114051]

Drillis R, Contini R, & Maurice Bluestein MME (1966). Body Segment Parameters.

Elkus R, & Basmajian JV (1973). Endurance in hanging by the hands. Why do people hanging by their hands let go?. American journal of physical medicine, 52(3), 124–127. [PubMed: 4707974]

Figueroa R, Das S, Armstrong T, Woolley C, & Chung K (2014). Enhanced Hand Function Assessment Using Pressure Mapping and Low Cost Motion Capture. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 58, No. 1, pp. 1290–1294). SAGE Publications.

Fischer SL, Picco BR, Wells RP, & Dickerson CR (2013). The roles of whole body balance, shoe-floor friction, and joint strength during maximum exertions: Searching for the “weakest link.” Journal of Applied Biomechanics, 29(1), 1–11. [PubMed: 22813535]

Fransson C, Winkel J (1991). Hand strength: the influence of grip span and grip type. Ergonomics, 34(7), 881–892. [PubMed: 1915253]

Frontera WR, Hughes V.a, Lutz KJ., & Evans WJ. (1991). A cross-sectional study of muscle strength and mass in 45- to 78-yr-old men and women. Journal of Applied Physiology (Bethesda, Md. : 1985), 71(2), 644–650. [PubMed: 1938738]

Garg a., & Kapellusch JM. (2011). Job Analysis Techniques for Distal Upper Extremity Disorders. Reviews of Human Factors and Ergonomics, 7(1), 149–196.

Gordon CC, Churchill T, Clauser CE, Bradtmiller B, McConville JT, Tebbetts I, and Walker RA (1989). 1988 Anthropometric Survey of U.S. Army Personnel: Methods and Summary Statistics. (Final Report. (NATICK/TR-89/027).

Hamilton GF, McDonald C, & Chenier TC (1992). Measurement of grip strength: validity and reliability of the sphygmomanometer and jamar grip dynamometer. Journal of Orthopaedic & Sports Physical Therapy, 16(5), 215–219.

Hazelton FT, Smidt GL, Flatt AE and Stephens RI (1975). “The influence of wrist position on the force produced by the finger flexors.” J Biomech 8(5): 301–6. [PubMed: 1184601]

Hoffman SG, Reed MP, & Chaffin DB (2007). The Relationship between Hand Force Direction and Posture during Two-Handed Pushing Tasks. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 51(15), 928–932.

Systems Innovision (2012). MaxTRAQ 3-D, Innovision Systems, Inc.

Kargov A, Pylatiuk C, Martin J, Schulz S, Kargov A, Pylatiuk C, … Do L (2009). A comparison of the grip force distribution in natural hands and in prosthetic hands A comparison of the grip force distribution in natural hands and in prosthetic hands, 8288(May).

Knudson D (2007). Fundamentals of biomechanics. Springer Science & Business Media.

Kong YK, Kim DM, Lee KS, & Jung MC (2012). Comparison of comfort, discomfort, and continuum ratings of force levels and hand regions during gripping exertions. Applied Ergonomics, 43(2), 283–289. [PubMed: 21696703]

Lee JW, Rim K, 1991. Measurement of finger joint angles and maximum finger forces during cylinder grip activity. Journal of Biomedical Engineering 13, 152–162. [PubMed: 2033951]

Mathiowetz V, Kashman N, Volland G, Weber K, Dowe M, & Rogers S (1985). Grip and pinch strength: normative data for adults. Archives of Physical Medicine and Rehabilitation, 66(2), 69–74. [PubMed: 3970660]

Napier JR The prehensile movements of the human hand. J. Bone Jt. Surg. Br. 1956, 38-B, 902–913. 8

Nicholas JW, Corvese RJ, Woolley C, and Armstrong TJ (2012). Quantification of hand grasp force using a pressure mapping system. Work Journal of Prevention, Assessment and Rehabilitation, 41:605–612.

Pataky TC, Slota GP, Latash ML & Zatsiorsky VM, 2011. Radial force distribution changes associated with tangential force production in cylindrical grasping, and the importance of anatomical registration. Journal of Biomechanics.

Rosenbaum D, Cohen R, Dawson A, Jax S, Meulenbroek R, Wel R & Vaughan J, 2009. The posture-based motion planning framework: New findings related to object manipulation, moving around obstacles, moving in three spatial dimensions, and haptic tracking. Progress in Motor Control, 485–497.

Rancourt D, & Hogan N (2001). Dynamics of pushing. Journal of Motor Behavior, 33(4), 351–62. [PubMed: 11734410]

Rosenbaum DA, Cohen RG, Meulenbroek RG & Vaughan J, 2006. Plans for grasping objects. In Latash M. & Lestienne F. eds. Motor control and learning over the lifespan. New York: Springer, 9–25.

Salimi I, Frazier W, Reilmann R & Gordon AM, 2003. Selective use of visual information signaling objects’ center of mass for anticipatory control of manipulative fingertip forces. Exp Brain Res, 150 (1), 9–18. [PubMed: 12698211]

Seo NJ, Armstrong TJ, Ashton-Miller J a, & Chaffin DB. (2007). The effect of torque direction and cylindrical handle diameter on the coupling between the hand and a cylindrical handle. Journal of Biomechanics, 40(14), 3236–43. [PubMed: 17570375]

Shim JK, Latash ML & Zatsiorsky VM, 2005. Prehension synergies: Trial-to- trial variability and principle of superposition during static prehension in three dimensions. Journal of Neurophysiology, 93 (6), 3649–3658. [PubMed: 15728759]

Swanson AB, Matev IB, de Groot G (1970). The Strength of the Hand. Bulletin of Prosthetics Research pp. 145–153. [PubMed: 5522244]

Szychlinska M, Dullaert K, Beumer A, Nsir H, Guglielmino C, Mazzone V, & Giunta S (2017). Ergonomics of Prehensility in Pushing and Pulling Motions: An Anatomical and Biomechanical Overview. Journal of Functional Morphology and Kinesiology, 2(1), 6. 10.3390/jfmk2010006

Waters TR, Dick RB, Davis-Barkley J, Krieg EF, 2007. A cross- sectional study of risk factors for musculoskeletal symptoms in the workplace using data from the General Social Survey (GSS). Journal of Occupational and Environmental Medicine.

Wiker SF, Chaffin DB & Langolf GD, 1990. Shoulder postural fatigue and discomfort: A preliminary finding of no relationship with isometric strength capability in a lightweight manual assembly task. International Journal of Industrial Ergonomics, 5 (2), 133–146.

Wu J, Dong R, & Warren C (2012). A Hybrid Model Simulating Hand Gripping on a Cylindrical Handle. W.asbweb.org, 1–2.

Yu D (2014). Application of Human Factors in Surgery: Studies on Technique, Displays, and Performance (Doctoral dissertation).

Zatsiorsky VM, Gao F & Latash ML, 2003. Finger force vectors in multi-finger prehension. Journal of Biomechanics, 36 (11), 1745–1749. [PubMed: 14522218]

Zhou W, Armstrong T, Wegner DM & Reed MP, 2011a. Influence of object weight and terminal orientation on upper limb postures during grasping, holding, and placing cylindrical object. Proceedings of Human Factors and Ergonomics Society Annual Meeting.

Zhou W (2013). Development of Biomechanical Models for Describing Hand and Finger Placements in Handling Work Objects (Doctoral dissertation).

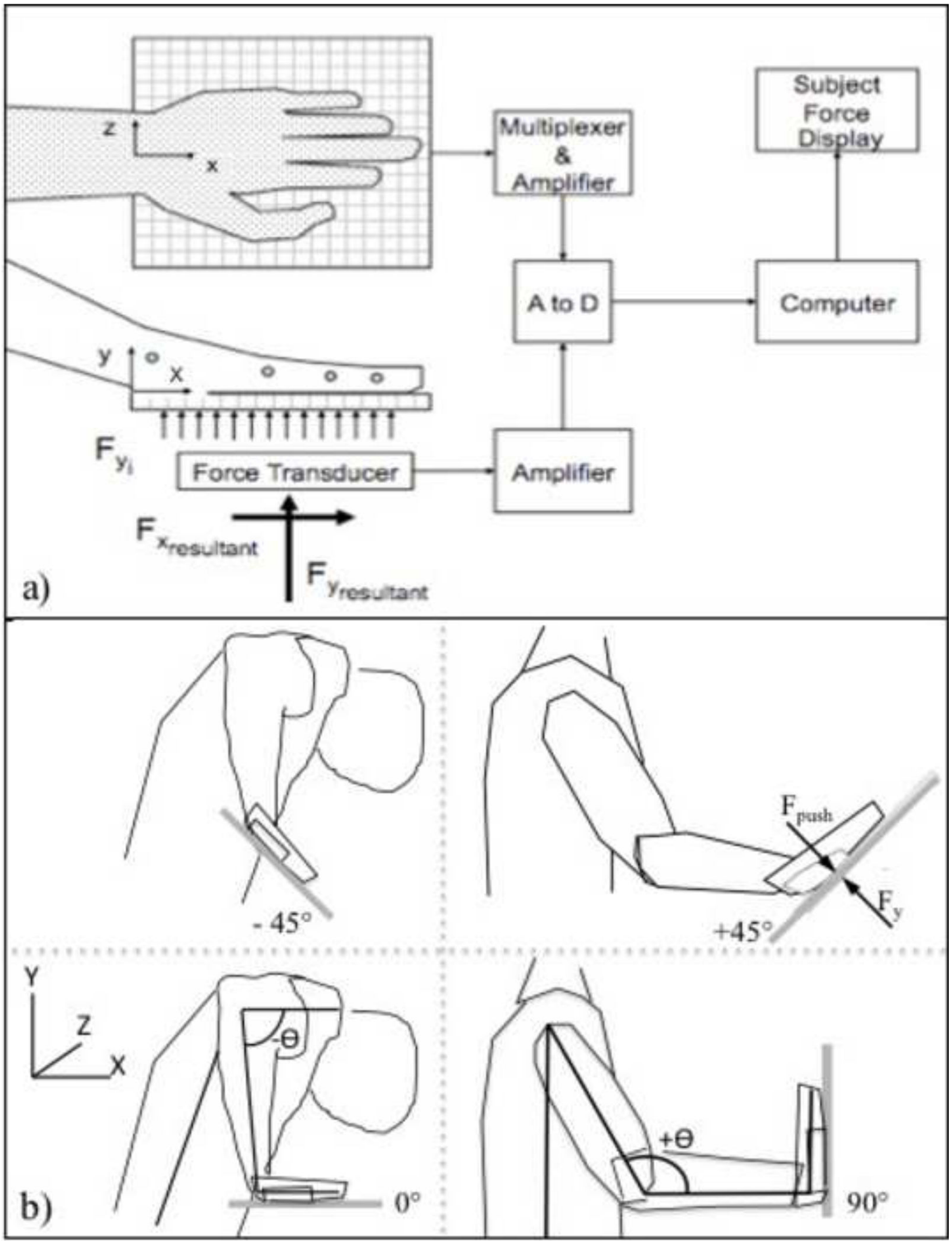

Figure 1.

a) Force transducer setup when pressing with whole hand posture at 0° angle. b) Forces were exerted perpendicular to a surface oriented −45°, 0°, +45°, 90°, and pitch with respect to horizontal. Friction force is represented as F_x and normal force as F_y. Bottom figures show elbow angle represented with a negative value (left) when facing downwards related to global Y-axis and positive (right) when facing upwards related to Y-axis.

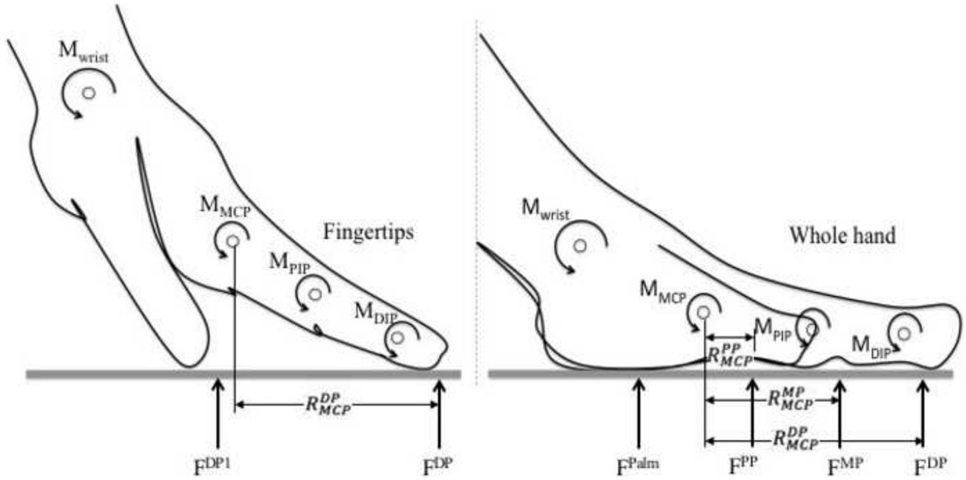

Figure 2.

Exertions at 0° angle with fingertips (left) and whole hand (right) postures. Sample Free Body Diagram for moment at the MCP joint (M_{MCP}) produced by force (F^n) at each segment (n).

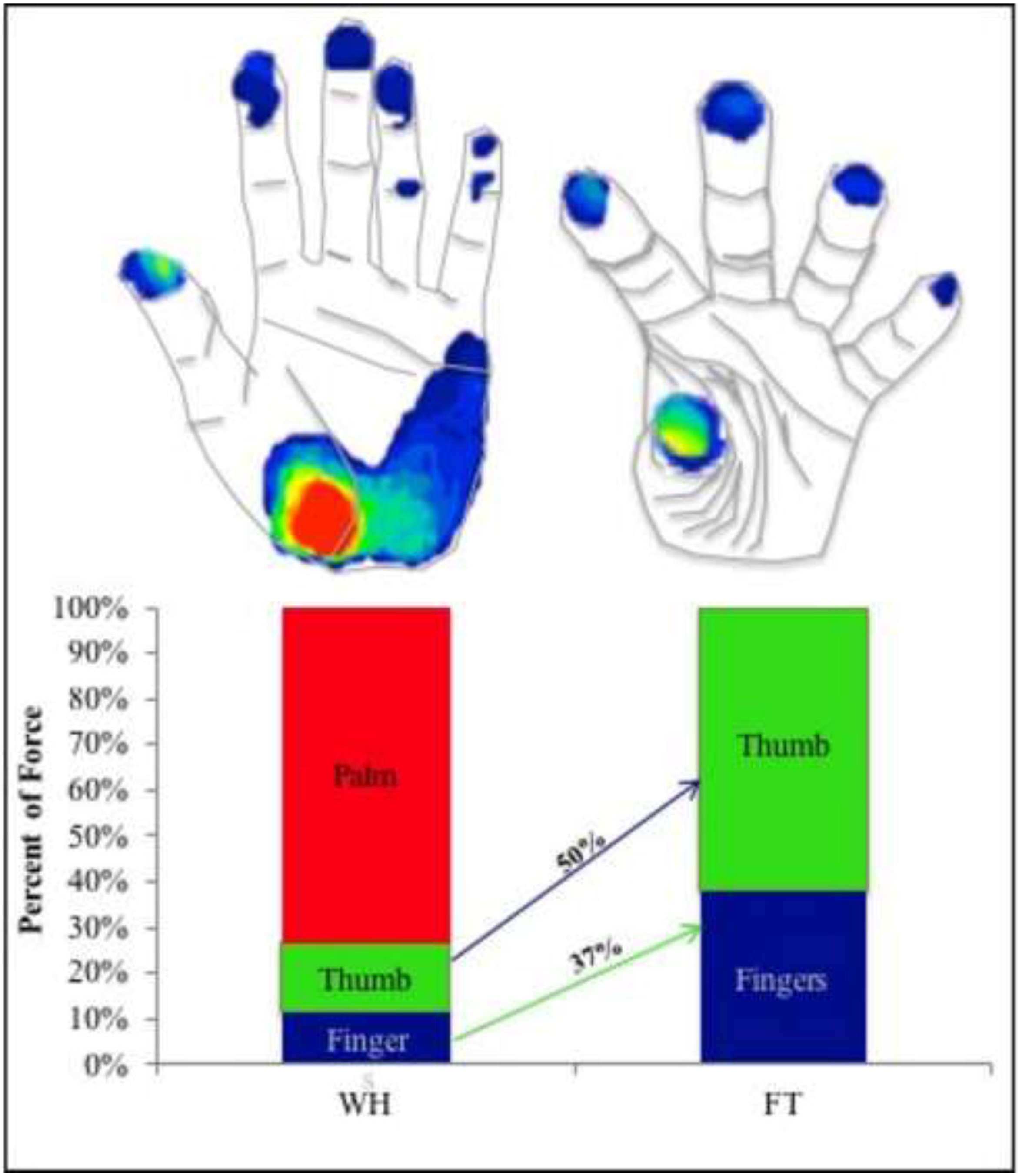

Figure 3.
Forces distribution per segment when pushing perpendicular to the flat surface at maximum force exertion (100 %MVC) in 2 hand postures, a) fingertip (FT) and b) whole hand (WH) (pooled for all participants) at 0° pitch. Red (highest) to Dark Blue (lowest) force values.

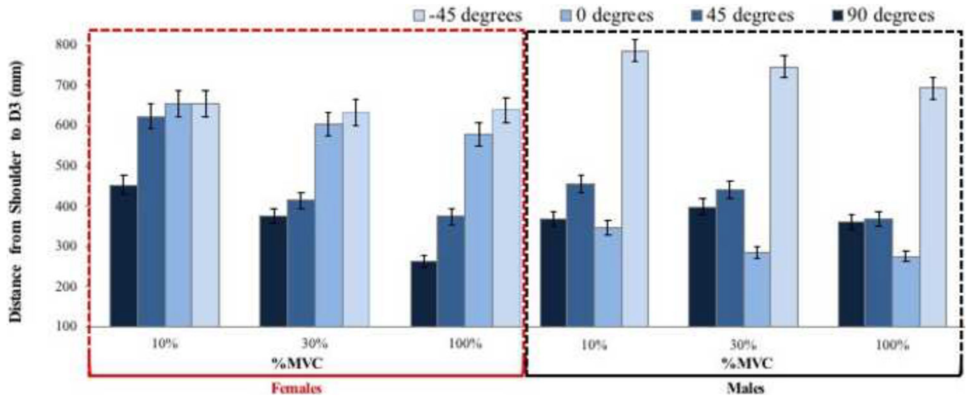

Figure 4.

Comparison of linear distance of shoulder to tip of middle finger (Shoulder-to-D3) for females and males pressing the plate with whole hand posture in 4 orientations (90°, 45°, 0° and −45°) under 3 conditions (100, 30 and 10 %MVC).

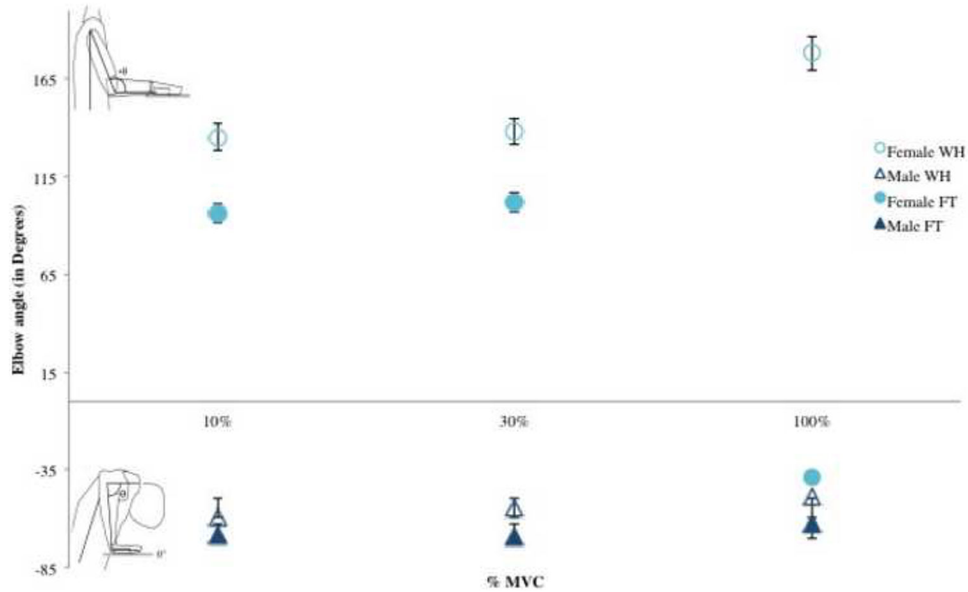

Figure 5.

Comparison of elbow angles for female group (light blue) and male group (dark blue) pressing the plate in fingertip (FT) and whole hand (WH) postures at 0° pitch under 3 conditions (100, 30 and 10 %MVC).

Author Manuscript

Author Manuscript

Author Manuscript

Table 1.

Basic information about participants (mean ± SD)

Item	Male Group	Female Group
Age (years)	22.0 ± 2.6	21.5 ± 2.9
Stature (cm)	180.1± 5.5	166.4± 5.6
Hand Length (cm)	19.8 ± 1.1	16.7 ± 0.4
[a] Range of Hand Length Percentiles	21st - 96th	3rd - 81st
[b] Grip Strength (N)	483.0 ± 56.2	305.2 ± 15.2
[c] Thumb-index Finger Pinch Strength (N)	73.4 ± 5.3	45.4 ± 5.2

[a]Percentiles based on the 1988 ANSUR army male and female data (Gordon et al., 1989)

[b]Grip strength was measured with a Jamar® grip dynamometer with a grip span of 49mm

[c]Thumb-index Finger Pinch was measured with a B&L® pinch gauge

Table 2.

Total maximum exertions (N) per orientation for male and female groups while pushing with the whole hand (WH) and fingertips (FT) (mean ± SD)

Orientation (°)	Male Group Maximum Exertions (N)		Female Group Maximum Exertions (N)		Total Maximum Exertions (subjects pooled) (N)	
	WH	FT	WH	FT	WH	FT
−45	84.3 ± 7.0	58.4 ± 8.6	86.4 ± 21.5	51.5 ± 12.8	85.6 ± 9.0	55.3 ± 4.4
0	198.8 ± 3.3	91.1 ± 16.4	128.5 ± 29.4	62.9 ± 8.7	164.0 ± 44.5	82.0 ± 9.5
45	154.4 ± 21.1	84.8 ± 30.5	132.2 ± 11.6	56.2 ± 12.6	142.2 ± 38.7	74.4 ± 7.6
90	252.1 ± 38.7	114.1 ± 25.8	142.5 ± 42.7	76.1 ± 15.9	198.3 ± 54.8	94.9 ± 10.6

Table 3.

Finger force distribution (normal force) pushing the plate with 4 orientations (−45 °, 0 °, 45 ° and 90 °) and 2 hand postures (whole hand-WH and fingertips- FT) (mean ± SD) (pooled for all participants)

% MVC	Object Orientation (°)	Hand Posture	Forces (subjects pooled) (N) Thumb	Index	Middle	Ring	Little	Palm Region	Total
100	−45	WH	13.5 ± 4.0	4.8 ± 1.9	4.5 ± 1.7	3.9 ± 1.6	2.7 ± 1.2	14.1 ± 12.5	85.6 ± 9.0
		FT	18.0 ± 8.0	10.8 ± 4.3	8.9 ± 3.0	8.4 ± 3.2	7.1 ± 3.9		55.3 ± 4.4
	0	WH	19.8 ± 6.7	2.8 ± 1.6	5.7 ± 3.1	7.9 ± 4.5	7.3 ± 3.2	110.6 ± 31.2	164.0 ± 44.5
		FT	29.7 ± 12.9	14.5 ± 4.0	12.4 ± 5.8	11.5 ± 6.3	9.0 ± 5.5		82.0 ± 9.5
	45	WH	16.4 ± 5.5	2.5 ± 0.9	4.7 ± 1.8	6.3 ± 2.7	7.0 ± 2.8	102.3 ± 19.7	142.2 ± 38.7
		FT	28.3 ± 12.4	12.1 ±.0	10.4 ± 5.0	12.2 ± 7.7	10.3 ± 5.7		74.4 ± 7.6
	90	WH	20.2 ± 8.6	3.5 ± 1.5	5.9 ± 2.8	8.0 ± 3.4	9.9 ± 4.1	139.9 ± 47.8	198.3 ± 54.8
		FT	31.8 ± 14.0	14.3 ± 5.2	14.4 ± 6.8	11.5 ± 6.6	10.8 ± 5.8		94.9 ± 10.6
30	−45	WH	4.2 ± 1.6	1.5 ± 0.6	1.2 ± 0.5	1.1 ± 0.6	0.8 ± 0.3	3.8 ± 3.9	12.5 ± 1.5
		FT	5.0 ± 3.0	2.6 ± 0.9	2.7 ± 1.2	2.3 ± 0.9	2.0 ± 1.0		14.7 ± 1.2
	0	WH	5.5 ± 2.0	1.0 ± 0.3	1.7 ± 1.0	2.3 ± 1.0	2.0 ± 0.7	33.8 ± 10.7	46.3 ± 12.9
		FT	8.6 ± 3.8	4.7 ± 2.2	3.4 ± 1.3	3.3 ± 1.3	3.2 ± 2.4		23.2 ± 2.3
	45	WH	4.9 ± 2.4	0.8 ± 0.3	1.2 ± 0.7	1.9 ± 0.9	1.9 ± 0.6	29.7 ± 5.1	40.5 ± 11.4
		FT	9.1±6.2	4.0 ± 1.2	3.1 ± 1.4	2.9 ± 1.5	3.0 ± 1.7		22.1 ± 2.7
	90	WH	6.9 ± 4.0	0.8 ± 0.5	2.0 ± 1.0	2.6 ± 1.4	2.5 ± 1.0	42.7 ± 16.3	57.5 ± 16.4
		FT	7.2 ± 2.9	5.2 ± 2.1	4.2 ± 2.3	3.8 ± 2.3	3.6 ± 3.4		24.1 ± 1.5
10	−45	WH	1.6 ± 0.5	0.6 ± 0.2	0.5 ± 0.2	0.5 ± 0.2	0.3 ± 0.1	1.5 ± 1.5	5.0 ± 0.6
		FT	1.7 ± 0.9	0.8 ± 0.5	0.9 ± 0.7	0.9 ± 0.4	0.8 ± 0.3		5.1 ± 0.4
	0	WH	1.2 ± 1.7	0.9 ± 0.1	0.9 ± 0.9	0.1 ± 0.1	0.7 ± 0.6	14.4 ± 8.3	17.8 ± 14.2
		FT	2.6 ± 1.3	1.7 ± 0.6	1.2 ± 0.6	1.1 ± 0.7	1.4 ± 1.1		8.1 ± 0.6
	45	WH	1.4 ± 0.9	0.2 ± 0.2	0.5 ± 0.3	0.6 ± 0.4	0.7 ± 0.4	11.1 ± 3.3	14.6 ± 4.3
		FT	3.7 ± 4.9	1.0 ± 0.6	0.8 ± 0.5	0.9 ± 0.6	0.9 ± 0.6		7.3 ± 1.2
	90	WH	2.3 ± 1.2	0.4 ± 0.3	0.7 ± 0.4	1.0 ± 0.7	1.1 ± 0.5	13.8 ± 4.7	19.2 ± 5.3
		FT	3.4 ± 2.7	2.6 ± 1.9	1.9 ± 2.1	1.7 ± 1.8	1.4 ± 2.3		11.0 ± 0.8

Table 4.

Angle (α) between resultant force (F_Y) and shoulder-to-wrist vector (R_{SW}) while pressing perpendicular to a flat surface under 0 ° and 90 ° orientations and 2 hand postures (whole hand-WH and fingertips- FT).

Object Orientation (°)	% MVC	Hand Posture	α (Degrees)	
			Males	Females
0	100	WH	12.3	6.41
		FT	15.4	9.74
	30	WH	59.9	44.1
		FT	66.9	38.3
	10	WH	36.7	41.4
		FT	43.2	42.7
90	100	WH	8.04	6.52
		FT	7.88	8.31
	30	WH	48.4	37.9
		FT	51.6	43.7
	10	WH	52.7	26.0
		FT	63.8	47.8

Table 5.

Joint moment magnitudes when pushing perpendicular to a flat surface with 4 orientations (−45 °, 0 °, 45 ° and 90 °) and 2 hand postures (whole hand-WH and fingertips- FT) during 100%MVC condition for females (upper) and males (bottom).

			Females Finger Joint Moment Magnitudes (N*m)														
	Object Orientation (°)	**Hand Posture**	**Thumb**		**Index**			**Middle**			**Ring**			**Little**			**Wrist**
			IP	**MCP**	**DIP**	**PIP**	**MCP**	**DIP**	**PIP**	**MCP**	**DIP**	**PIP**	**MCP**	**DIP**	**PIP**	**MCP**	
Females	−45°	WH	0.29	0.75	0.14	0.26	0.61	0.20	0.42	0.77	0.18	0.36	0.69	0.12	0.30	0.65	1.89
		FT	0.41	0.86	0.26	0.54	0.74	0.32	0.64	0.86	0.28	0.52	0.79	0.24	0.49	0.70	1.24
	0°	WH	0.57	1.71	0.32	0.77	1.09	0.54	0.82	1.31	0.35	0.83	1.17	0.29	0.79	0.95	1.88
		FT	0.83	2.62	0.43	0.91	1.52	0.76	1.37	1.99	0.64	1.01	1.73	0.41	0.85	1.56	2.99
	45°	WH	0.34	1.12	0.20	0.39	0.88	0.38	0.63	0.95	0.33	0.67	1.01	0.15	0.42	0.37	1.43
		FT	0.46	1.39	0.34	0.63	1.16	0.48	0.99	1.33	0.38	0.71	0.87	0.28	0.66	1.25	1.85
	90°	WH	0.56	1.53	0.24	0.68	0.95	0.45	0.75	1.22	0.42	0.76	1.04	0.21	0.71	0.88	1.74
		FT	0.77	2.20	0.39	0.88	1.40	0.63	1.12	1.68	0.53	0.93	1.61	0.46	0.80	1.42	3.20
			Males Finger Joint Moment Magnitudes (N*m)														
	Object Orientation (°)	**Hand Posture**	**Thumb**		**Index**			**Middle**			**Ring**			**Little**			**Wrist**
			IP	**MCP**	**DIP**	**PIP**	**MCP**	**DIP**	**PIP**	**MCP**	**DIP**	**PIP**	**MCP**	**DIP**	**PIP**	**MCP**	
Males	−45°	WH	0.34	0.88	0.17	0.36	0.75	0.28	0.5	0.95	0.25	0.44	0.99	0.16	0.4	0.81	2.85
		FT	0.53	1.12	0.35	0.65	1.04	0.45	0.92	1.08	0.39	0.65	1.05	0.31	0.63	0.83	1.93
	0°	WH	0.67	2.32	0.44	0.97	1.54	0.65	1.13	1.77	0.41	1.2	1.54	0.41	1.05	1.15	2.68
		FT	1.15	3.76	0.5	1.09	1.96	1.08	1.68	2.48	0.9	1.19	2.5	0.51	1.05	1.84	3.68
	45°	WH	0.42	1.36	0.26	0.47	1.01	0.51	0.73	1.09	0.41	0.78	1.46	0.17	0.55	0.43	1.86
		FT	0.6	1.81	0.44	0.83	1.69	0.69	1.21	1.75	0.47	0.94	1.03	0.36	0.8	1.62	3.01
	90°	WH	0.77	2.07	0.31	0.88	1.26	0.54	1.08	1.71	0.48	0.98	1.32	0.24	0.83	1.14	2.27
		FT	0.99	3.09	0.48	1.01	1.98	0.73	1.53	2.33	0.75	1.32	2.21	0.66	1.07	1.73	3.66