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The effect of elbow position and grip span on isometric grip strength and force distribution of fingers.

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THE EFFECT OF ELBOW POSITION AND GRIP SPAN ON ISOMETRIC GRIP STRENGTH AND FORCE DISTRIBUTION OF FINGERS

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ABSTRACT

Injuries to the hand, lower arm, and shoulder are often attributed to inappropriate use or poor design of hand tools. Also, work requiring high force has been identified as a risk factor for hand-wrist cumulative trauma disorders. Cross-action tools, such as pliers and cutters, can be described as first class because work with such tools often requires a substantial amount of force. Isometric grip, performed with the angled handles of pliers was investigated in this study.

For this thesis, three factors were studied. They were grip type (traditional and reversed grip), elbow position (0°, 30°, 60°, 90°, and 120°), and grip span (50, 60, and 70 mm). Based on this arrangement, a 2x4x5 full factorial design was employed. Seven male and seven female subjects participated in this study. The resultant forces between the jaws of the pliers and finger forces were measured under each condition.

The purpose of this study was to evaluate the effect of elbow position and grip span on grip strength and force distribution across the fingers. The results showed that elbow position, grip span and grip type have significant effects on resultant force and finger force. The forces were statistically higher at the fully extended elbow position than at the 30°, 90° and 120° elbow positions, and the resultant force was higher at the 60°, 30°, and 90° positions than at the 120° position. Regardless of elbow positions and grip type the optimal grip span was found to be 50 mm and forces decreased as grip span increased. The resultant force obtained in a traditional grip exceeded the force obtained in a reversed grip. Also, the finger force varied according to elbow position, grip span and grip type. The influences of these factors also varied according to fingers. Interactions between grip span and grip type were found in index and ring fingers.

DEDICATION

To My Parents, Qifang Chen and Chang'e Wu

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CHAPTER 1

INTRODUCTION

1.1 Scope

Many industrial tasks require workers to exert force with the hands and fingers to grip or manipulate objects. At the same time, it is increasingly recognized that forceful hand exertions and awkward postures are a potential cause of chronic musculoskeletal disorders [1]. The magnitude of the risk to the American workforce is at least partially revealed by data collected during the National Occupational Exposure Survey (NOES) of 1981-1983. Hand/wrist manipulations were among the ergonomic hazards most frequently identified by the NOES survey [2]. It has become obvious that successful prevention requires a better understanding of the causes of these disorders.

Hand tools are special types of objects with the principal aim of enhancing hand function and making the task easier to accomplish [3]. Because some of the major causes of work-related hand injuries and diseases are suggested to be linked to inappropriate use or poor design of hand tools, they are of special interest to study in occupational tasks. Among hand tools, cross-action tools, such as pliers and cutters, can be described as first class [4]. This type of tool is operated by a one handed squeezing action and produces a mechanical advantage for users [3]. However, work with such tools often requires a substantial amount of force which has been identified as one risk factor for cumulative trauma disorders.

It is important to measure hand strength applied during actual manual work. Since the recent advent of a small, thin force sensor which can be attached to each finger, it has become possible to measure the external forces which are applied to each finger during a gripping task.

Grip strength can be affected by numerous factors. The distance between the handles is one important factor directly influencing grip strength for cross-action tool [4]. This has been investigated by numerous authors, including Fransson and Winkel [4], Pheasant and Scriven [5] and the Eastman Kodak Company [6].

Working with hand tools requires versatility of the hand, wrist and elbow in grasping and manipulating objects. Various studies have shown that gender, hand size , wrist position and body posture also affect grip force. These factors have been organized and arranged in different ways, depending on the aims of the study. However, there are few reports on whether elbow position is also a significant variable.

Usually, a cross-action tool is held in a power grip with the index finger closest to the head of the tool. This is known as a traditional grip. In a reversed grip, the tool is held with the smallest finger closest to the head of tool. Reversed grip offers the longest lever arms to the strongest part of hand, and may thus increase the total torque produced by the hand. Spontaneous use of the reversed grip has been observed among workers who are accustomed to using various tools within their daily work [7]. Both types of grip will be investigated in this study.

Maximal muscle tension varies with the speed of contraction and whether it is isotonic or isometric or whether the contraction occurs during lengthening of the muscle by opposing force. Isometric grip, performed with angled handles, is of great interest to work with cross-action tools, since many tasks are performed with such a grip [4].

To our knowledge, the effects of elbow position, grip span, and grip type on grip strength and individual finger force for an isometric contraction using a cross-action tool have not been studied. The results of such studies would be useful for developing functional biomechanical models and for designing tools, work equipment and manual activities. A better understanding of grip strength should lead to successful prevention of cumulative trauma disorders.

1.2 Objective of the Study

The objective of this research is to investigate the effect of elbow position, grip span, and grip type, as well as their interactions on the resultant force between the jaws of the tool and finger force for an isometric contraction using a pair of pliers with angled handles.

Resultant force (RF) and finger force (FF) will be measured during grip tasks consisting of 5 elbow positions, 3 grip spans, and 2 grip types. The RF and FF were studied according to: (1) grip type (traditional and reversed grip); (2) grip span (50, 60, 70 mm); (3) elbow position (0°, 30°, 60° , 90° , 120°).

CHAPTER 2

LITERATURE REVIEW

2.1 Cumulative Trauma Disorders

Cumulative trauma disorders (CTDs) refer to a category of physical signs and symptoms due to chronic musculoskeletal injuries where the causes appear to be related to some aspect of repetitive work [1]. Putz-Anderson defines CTDs as "a disorder of the muscular and/or osseous and /or nervous system(s) caused, precipitated or aggravated by repeated exertions or movements of the body" [1].

Occupational causes of CTDs include repetitive and forceful activities resulting in prolonged exertions, static muscle load, awkward body postures, direct pressure from work equipment, vibration from machinery, and exposure to cold temperature or airflow.

The force required to perform various occupational activities is a critical factor in contributing to the set of CTDs [1]. As the muscle effect increases in response to high task load, blood circulation to the muscle decreases causing more rapid muscle fatigue. Recovery time can exceed actual work time for jobs where force requirements are high. Deprived of sufficient recovery time, soft tissue injuries will occur.

2.2 The Anatomy of the Human Hand

The human hand is a complex structure composed of bones, arteries, nerves, ligaments, and tendons, as shown in Figure 2.1. The fingers are flexed by muscles in the forearm. The muscles are connected to the fingers by tendons which pass through a channel in the wrist. This channel is formed by the bones of the back of the hand on one side and transverse carpal ligament (flexor retinaculum) on the other. The resulting channel is called the carpal tunnel. Through this tunnel passes a many vulnerable anatomic structures including the radial artery and median nerve. Running over the outside of the transverse carpal ligament are the ulna artery and ulna nerve. This artery and this nerve pass beside a small bone in the wrist called the pisiform bone.

The bones of the wrist connect to the two long bones of the forearm - the ulna and the radius. The radius connects to the thumb side of the wrist, and the ulna connects to the little-finger side of the wrist. The configuration of the wrist joint permits movements in only two planes, each one at an approximately 90° angle to the other. The first plane allows palmar flexion or, when it is performed in the opposite direction, dorsiflexion. The second movement plane, consists of either ulnar deviation or radial deviation of the hand.

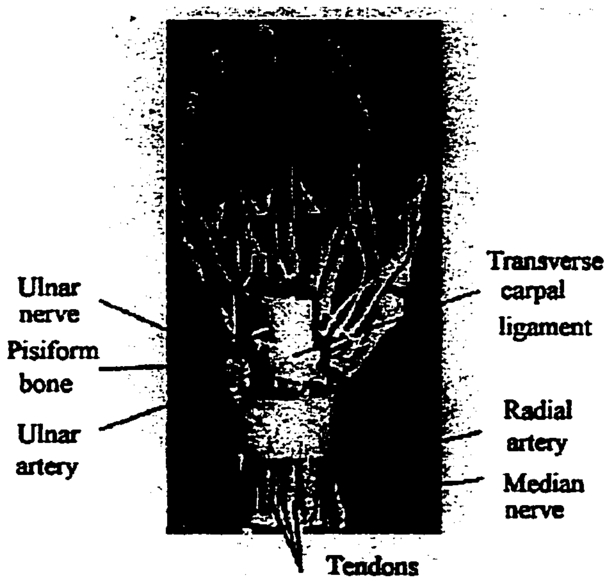

Figure 2.1 Anatomy of the hand as seen from
the palm side.(Source: Tichauer, 1978, Fig. 50 [39]).

The ulna and radius of the forearm connect to the humerus of the upper arm, as shown in Figure 2.2. The biceps muscle connects to the radius. When the arm is extended, the biceps muscles will pull the radius strongly against the humerus. This can cause friction and heat in the joint. The biceps muscle is both a flexor of the forearm and an outward rotator of the wrist. This can be seen by bending the arm 90 degree at the elbow and rotating the wrist outward, causing the biceps muscle to contract and bulge. Thus, any movement that requires a strong pull and simultaneous inward rotation of the hand should be avoided [8].

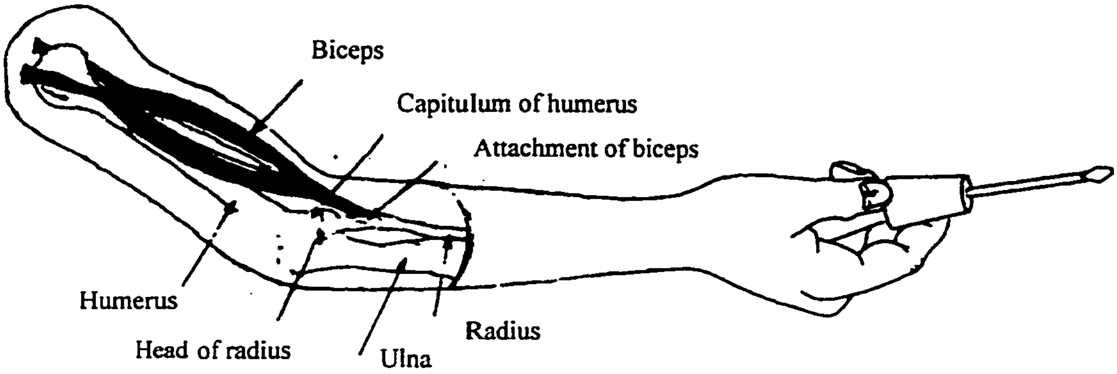

Figure 2.2 The elbow joint showing the connection of the biceps to the radius. (Source: Tichauer,1978 [39])

2.3 Injuries due to hand tool use

Injuries, disabilities and disfigurations to workers occur while using hand tools. In 1973, the National Safety Council estimated that 6% of all compensable work injuries caused by hand tools and 24.85% of all the injuries surveyed are the result of over-exertion. Repetitive, sustained or forceful motions occurring over time may compromise the integrity or functioning of the soft tissues, producing inflammation of the tendons or compression of the peripheral nerves leading to a group of cumulative trauma disorders (CTDs), such as carpal tunnel syndrome, tenosynovitis, “trigger finger”, ischemia, vibration-induced white finger, and even tennis elbow.

Improperly designed tools have several undesirable consequences, including accidents and injuries [8]. Aghazadeh and Mital [9] surveyed various state agencies in the United

States regarding hand tool industrial injuries. Hand tool-related injuries comprised about 9% of all work-related compensable injuries. Aghazadeh and Mital estimated that there were over 260,000 hand tool-related injuries in the United States each year and that the associated medical costs alone come to some $400 million. Incidence rates of cumulative-trauma disorders can be quite high in industries and jobs requiring repetitive use of hand tools. The department of labor reports that in 1988 cumulative trauma accounted for 48% of all industrial illnesses in the United States. In many cases, cumulative-trauma disorders do not show up on accident injury reports but often lead to reduced work output, poorer-quality work, increased absenteeism, and single-incident traumatic injuries. Hand tool injuries are costly, severe, and occur frequently [9].

2.4 Grip type

Several writers have suggested that hand function may be divided into power and precision functions. Napier [10] classified any gripping posture into three types:

(1) A hook grip in which the fingers are flexed around the object and the thumb isn't used for gripping.

(2) A power grip in which the object is clamped between the partly flexed fingers and palm with the thumb opposing the grip and lying along the plane of the palm

(3) A precision grip in which the object is pinched between the flexor aspects of the fingers and opposing thumb [11].

The power grip is the type of grip most frequently used. Cross-action tools like pliers are held in a power grip. Usually the tool is held with the index finger closest to the head of the tool. In a reversed grip, a tool is held with the smallest finger closest to the head of the tool.

Grip strength can be exerted statically or dynamically. Kroemer [12] defined static strength as the maximal force muscles can exert isometrically in a single voluntary effort. As defined, strength is exerted "isometrically" or "statically", indicating that during the contraction period the length of the muscles involved is kept constant and, therefore, attached body segments remain motionless. Without motion, all acting forces must be in balance. Neither of the terms "isometric" nor "static" provide information about the magnitude or steadiness of muscle tension. Muscles are not strained isotonially when moving a body segment against a constant resistance during the motion, the tension of the involved muscles changes with their changing lengths and with the changing mechanical advantages. "Dynamic" is really the appropriate term [7].

2.5 Factors Influencing Grip Strength

2.5.1 Wrist Position

A neutral wrist position is preferable to palmar flexion or dorsiflexion position because higher force can be exerted and it is less likely to contribute to the development of a

CTDs [1]. While in a 45 degree extended position, forces of approximately 75-82% of the neutral position are possible, while forces of only 60-72% can be exerted when the hand is in a 45 degree flexed position [13,14,1].

Imrhan [15] examined the effects of different wrist positions on maximum voluntary pinch strength. The results showed that all deviated wrist positions degraded pinch strength, with palmar flexion having the greatest effect and radial deviation the least. Strength degradation ranged from 14% to 43%, depending on wrist position and type of pinch. A lateral pinch was less affected than the others.

2.5.2 Hand Dominant

The percentage of strength of the non-dominant hand as compared to the dominant hand has been cited in several studies. The non-dominant hand has been found to generate forces of approximately 93% (Swanson, Matev, & de Groot [16] and Hunter, Schneider, Mackin, & Bell [17]), 94% (Hallbeck and McMullin [13]) and 97% (McMullin and Hallbeck [14]) that of the dominant hand in grasp.

2..5.3 Gender

Gender has been shown to have a significant effect on grip strength. Various studies concluded that females possess 51% (Hunter, et al.[17]), 66% (McMullin and Hallbeck

[14] and Putz-Anderson [1]), 68% (Williamson and Rice [18]), and 74% (Hallbeck and McMullin [13]) the grip strength of males.

2.5.4 Anthropometric Dimensions

Several attempts have been made to derive empirical equations for grip strength, associating with it the subjects' anthropometric dimensions. Schmidt and Toews [19] found grip strength to be proportional to height and weight, up to a maximum of 75 inches and 215 pounds. Lunde, Brewer, and Garcia [20] derived equations to predict both dominant and non-dominant hand grip strength using height and weight, but these equations had relatively low coefficients of determination. Wang [21] correlated grip strength to anthropometric data of the hand for males and females, separately. He found thumb circumference to be a good correlate (R^2=0.5) of grip strength for males, and hand breadth and finger crotch length to be a good correlate (R^2=0.8) for females.

2.5.5 Grip Span

Most studies on the strength of the hand have concentrated on hand grip. Fransson and Winkel [4] stated that one important factor, directly influencing the grip strength for cross-action tools, is the distance between the handles.

The distance spanned by the dynamometer handle was studied by Wang [21]. The dynamometer used in his study was set at spans of 3.5, 4.7, and 6.0 cm. Paired t-tests that were performed on this data showed the 3.5 and 4.7 cm handles to be in one grouping, and the 4.7 and 6.0 cm handles to be in another grouping.

Pheasant and Scriven [5] investigated this using an adjustable strain gauge dynamometer. Twenty two males and twenty two females, matched for age (from 20 to 44 years) acted as subjects. They exerted their maximum steady squeeze grip with handle separations on the dynamometer ranging from 35 to 95 mm. Subjects used their preferred hands throughout the experiment. The order of presentation was randomized and rest pauses were given. The result showed that a handle separation of 45 - 55 mm was optimal for both male and female subjects. Grip situation wasn't indicated in his study.

Petrofsky et al. [22] measured 8 females' and 14 males' isometric grip strength using strain gauge hand grip. In this study the grip span is distance separating the outside limits of the two grip poles of the dynamometer, and six pre-set distances from 32 mm to 80 mm were designed. The results showed that large hands have greater optimal grip span than small but that no significant correlation between hand size and strength had been found.

An isometric grip, performed with parallel handles, has been studied in numerous investigations. Bechtol [23] used the Jamar dynamometer in the experiment. He examined 220 females' and 215 males' grip force when grip spans, considered as the distance between handles, were 25, 38, 51, 64, 76 mm. The result showed that the optimum force occurs with a span of 38 mm for females and 51 mm for males. Hertzberg [24] studied males' grip force by using a Smedley hand dynamometer when the distances between palm and inner surface of fingers were 38, 64, 102 and 127 mm, and found the optimal grip span was 64 mm. Montoye and Faulkner [25] investigated the grip force by using the same equipment. Sixty four females and one hundred and thirty eight males including adults and children acted as subjects. They measured the grip force at grip span (between grip surface) of ten settings of 2.5 mm from 42.5 mm to 65 mm and discovered only small differences in performance at the various settings. Cotten and Bonnell [26] studied female's grip force at spans of five settings ('smallest' to 'largest') and found that "Medium small was one of the best settings for a high strength reading". Cotten and Johnson [27] used an adjustable cable tensimeter to measure 30 males' grip forces when the distances between gripping surfaces were 40, 52, 65, 78 and 90 mm and found optimum force occurred when the span was 48 mm for small hands and 58 mm for large hands.

A dynamic grip, performed with angled handles, was studied by Fitzhugh [28] and Greenberg and Chaffin [29]. Fitzhugh investigated the dynamic grip with angled handles at grip spans of 58, 69, 70, 86, 96, 107, and 117 mm in the first test and 69, 79, 86, 102 mm in the later test. The grip span refers to initial displacement between grip surface at the center of grip. Five females and five males in the first test and 25 females and 25 males in the later test acted as subjects using the hand tool Simulator Dynamometer as equipment. Fitzhugh found the correlation between maximum force and hand measurements that were given and found the strongest relationship between grip strength and middle finger length and forearm girth in later experiment. At a closing speed of 29 mm/s, the highest force was developed when using an initial handle separation of 83-89 mm. Still, the optimal handle separation, where the highest force was obtained, was approximately 52 mm. No more details of the experiment have been found.

Greenberg and Chaffin [29] considered the grip span as the initial displacement between gripping surface at the center of grip and set displacement from 25 mm to 114 mm. Fifty males and fifty females acted as subjects and results showed that optimum force occurred at 64-89 mm initial handle displacement. Equipment was not indicated in the study.

An isometric grip, performed with angled handles, was studied by Fransson and Winkel [4]. The maximal force from each of the fingers 2-5 (FF) and the resultant force between the jaw of the tool (RF), due to contribution from all fingers, were measured using a pair of modified slip joint pliers. Eight females and eight males acted as subjects and all of them used their right hands throughout the experiment. The RF was measured at 21 handle separations and FF was measured at seven handle separations for each finger. A traditional grip type was compared with a 'reversed' grip where the little finger was closest to the head of the tool. The result showed that both the RF and FF varied according to the distance between the handles. For both grip types, the highest RF was obtained at a handle separation of 50-60 mm for females and 55-65 mm for males. For wide handle separations, the RF was reduced by 10% (cm increase in handle separation). The force-producing ability of the hand was influenced by the grip type and the highest RF was obtained when using a traditional grip. An interaction was found between the fingers, i.e., the maximal force of one finger depended not only on its own grip span, but also on the grip spans of the other fingers. About 35% of the gender difference in hand strength was due to hand size difference.

2.5.6 Body position

Teraoka [30] investigated the peculiarity in isometric strength of both hands in three positions (upright, sitting, and supine). Subjects were 9,543 healthy males and females from 15 to 55 years of age. Maximum isometric strength was recorded by grip dynamometer (Smedley type). The results showed that grip strength depended upon body positions in all age groups and in both sexes. Grip strength was stronger in an upright position than in a sitting position. Likewise grip strength was stronger in a sitting position than in a supine position. The differences in grip strength in relation to three kinds of body positions observed in the experiments were demonstrated by E.M.G. of muscle flexor of digitorum superficialis.

2.6 Finger Forces and Measurement During Grip Exertions

Measurement and prediction of individual finger forces during grip exertions are important for developing functional biomechanical models and for designing tools, work equipment, and manual activities.

Individual finger forces have been studied in numerous investigations involving maximal grip exertion levels or strength (Swanson et al. [16], Dickson et al. [31], Ohtsuki [32], An et al. [33], and Amis [34]).

Since force sensors needed for measuring individual finger forces applied during grasping activities have been available, Radwin & Oh [35] conducted a study concerning submaximal grip exertion. They used small conductive polymer force sensors to measure individual finger forces exerted during submaximal static pinch. They state that the two strongest fingers, the index and middle fingers, exerted the greatest average submaximal finger forces. Although individual finger force contributions were equivalent to individual finger relative strength on the average for total pinch force exertion levels between 10% and 30% MVC (maximum voluntary contraction) or force loads between 1.0 kg and 2.0 kg, individual finger force contributions were not constant for increasing force requirements. As the exertion level increased from 10% to 30% MVC the middle finger contribution increased from 25% to 38%. Similarly, as load weight increased from 1.0 kg to 2.0 kg, the index finger contribution decreased from

38% to 30%. These observed recruitment interactions are not included in biomechanical analysis that assumes external finger forces are exerted in proportion to relative finger size or muscle physiological cross-sectional areas.

2.7 The Need For Studies

An isometric grip, performed with angled handles, is of great interest to cross-action tool work because many tasks are performed with such a grip. It has been investigated by numerous authors cited in the previous literature review.

Fransson and Winkel [4] studied this kind of grip using small thin load cells. The maximal individual finger force and resultant force between the jaws of the tool, due to contributions from all fingers, were measured using a pair of modified pliers. Four load cells were attached to one handle of the pliers to measure each finger force. Both the RF and FF varied according to the distance between the handles (grip span). The force-producing ability of the hand was influenced by the grip type, hand size and gender. In Fransson and Winkel's study, however, the effects of elbow and wrist position were not strictly controlled.

The elbow, like the wrist, plays an important function in hand use, but there are few reports on whether elbow position is also a variable. In some previous studies elbow position has been standardized in extension or 90° of flexion, while other studies did not control elbow position. Mathiowetz et al.[36] examined elbow position in extension or 90° flexion and revealed that grip strength was significantly higher when the elbow was in a 90° flexed position than in the fully extended position. However, many questions still remain regarding the effect of elbow position on hand strength. Would other elbow positions such as 120° or 60° flexion cause even higher hand strength? Clearly, the effect of elbow position on grip strength needs further study. Since grip span is one important factor influencing grip strength we will consider it as a variable in our study.

This research will solve the questions regarding the elbow position, such as: Would the RF and FF change with the elbow in different positions? What are the interactions among elbow position, grip span, and grip type?

CHAPTER 3

METHODOLOGY

3.1 Subjects

Seven females and seven males participated in this study. The randomly selected subjects were all healthy young students with no previous history of neuromuscular orthopedic dysfunction that would significantly affect hand strength. Palmar hand length (hl), metacarpal breadth (hb) and finger length (fl), forearm and upper arm length, stature and body weight were measured in pre-experiment. Name, sex and age were recorded for every subject. Tables 3.1 and 3.2 show anthropometric summary data of subjects.

Measurement	Mean	Std Dev	Range
Age(years)	25.71	6.58	21 - 40
Stature(mm)	175.86	5.21	169 -184
Body Weight(kg)	79.63	9.87	65 - 95
Finger Length(mm)	71.61	3.30	63 - 76
Hand Breadth(mm)	87.14	5.67	80 - 95
Hand Length(mm)	184.14	7.24	175 - 196
Forearm length(mm)	260.00	17.18	240 - 280
Upper Arm Length(mm)	288.57	14.14	270 - 310

Table 3.1 Anthropometric summary data of male subjects

Measurement	Mean	Std Dev	Range
Age(years)	23.43	4.28	20 - 30
Stature(mm)	163.93	4.46	155 - 168
Body Weight(kg)	67.14	13.41	52 - 87
Finger Length(mm)	64.68	2.71	63 - 70
Hand Breadth(mm)	77.00	5.48	70 - 85
Hand Length(mm)	166.86	6.39	160 - 175
Forearm length(mm)	241.43	17.00	210 - 265
Upper Arm Length(mm)	270.71	23.53	240 - 300

Table 3.2 Anthropometric summary data of female subjects

3.2 Equipment

The equipment for the experiment consisted of a pair of pliers as a gripping device, the devices to measure RF and FF, and a IBM PC to acquire, record, and analyze data. The modified multiple slip joint pliers with angled handles (model 10" Groove Joint Pliers) was used for gripping in this study, keeping the slip joint at a constant position throughout the study. The measuring devices consisted of four small load cells, one force monitor and four amplifiers. A fixture was designed to allow the resultant force between the jaws of the tool to be measured by the sensor of a force monitor. Because only the perpendicular force can be measured by the force sensor, the fixture was designed not only to change the opening of the pliers but also to make the output force perpendicular to the force sensor. Finger force was measured by a small load cell enclosed in a custom-designed fixture. Four fixtures were designed to apply four small commercial load cells (Sensotec; Subminiature Load cell, model 13) to the lower leg of the pliers and were freely movable along the handle of the pliers. The load cells were connected to amplifiers and then to an IBM PC where an analog-to-digital converter (Das-16G) had been installed. The IBM PC equipped with software (Keithley ASIST, 1992) controlled all data acquisition, display, and storage. A VIEWDAC sequence was set to capture the data collected using an analog-to-digital conversion program. One hundred readings of FF signals were captured per second from four channels. FF signals were collected in a period of 3 seconds at each trial. Statistical analysis was performed by VIEWDAC showing the maximal and means of data. The maximal value under each condition was used in subsequent analysis. Figure 3.1 is a flow chart of devices for measuring the FF and RF.

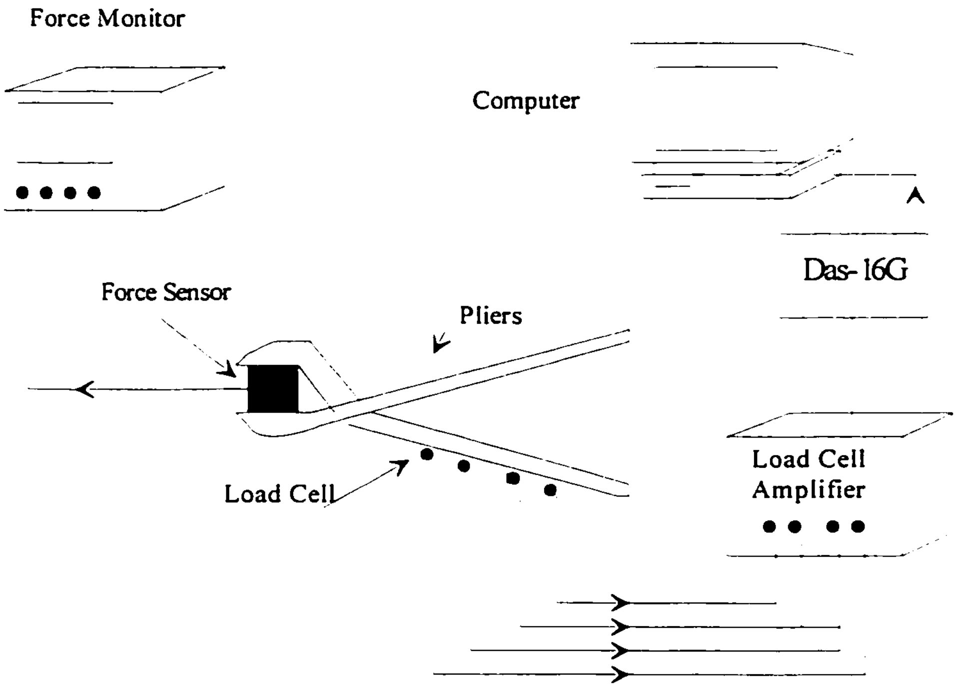

Figure 3.1 Flow chart of devices to measure RF and FF

The RF and FF from four fingers at a time were measured simultaneously. The FF-signals were very small so they needed to be amplified before connecting to the DAS-16G Board. Figure 3.2 shows the illustration of how grip span, finger force and resultant force were measured.

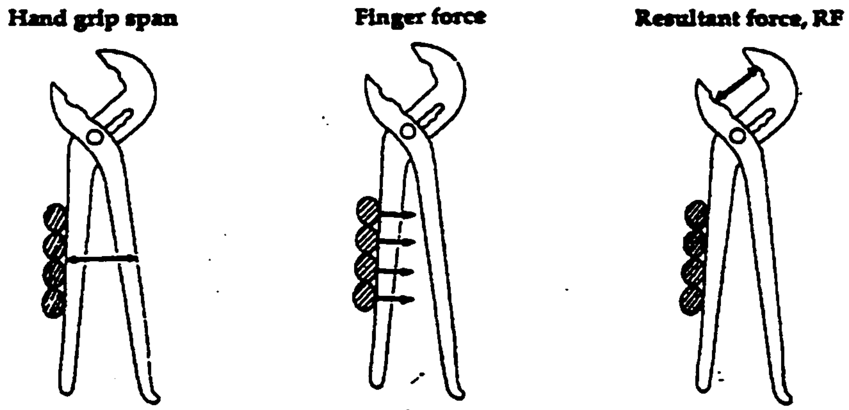

Figure 3.2 Illustration of how grip spans, finger force(FF) and resultant force between the jaws of the tool(RF) were measured

Figure 3.3 shows the device for measuring finger force. The calculation of the actual finger force was needed because only the perpendicular component of the finger force could be measured by load cells. The followings are the equations to calculate the actual finger force.

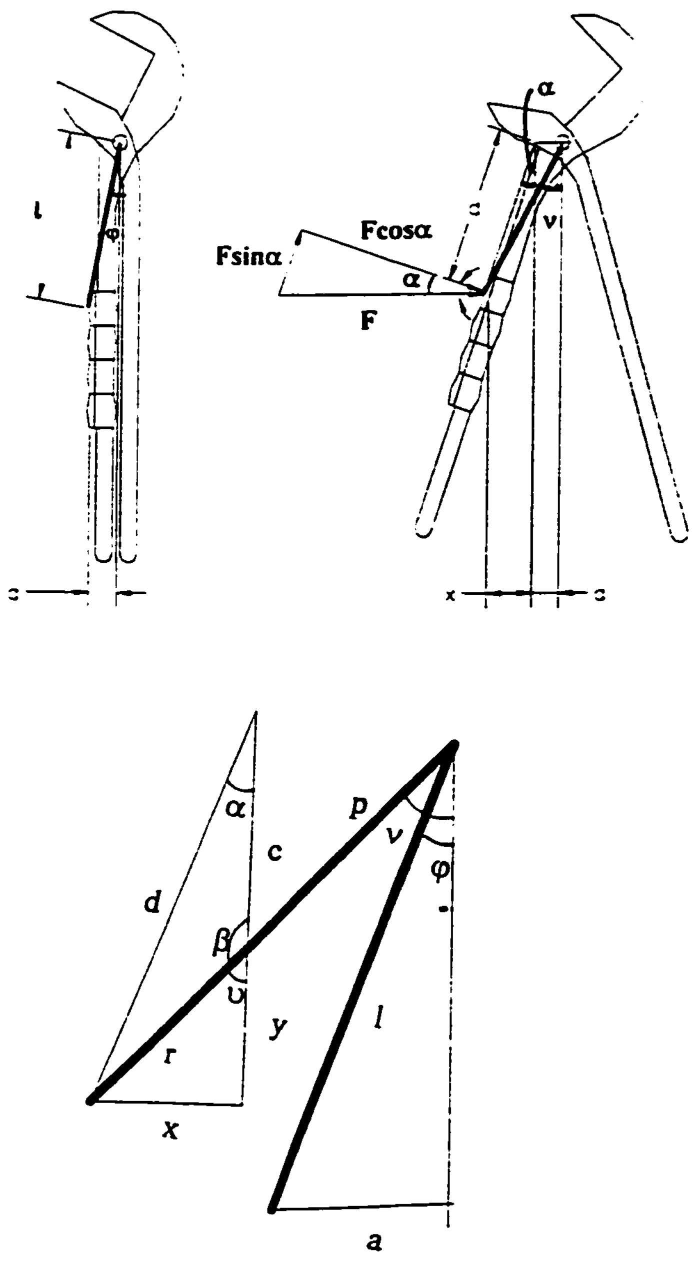

Figure 3.3 The device for measuring finger force

$$\sin\varphi = a / l \qquad \ldots(3.1)$$

$$\sin\upsilon = (a + x) / l \qquad \ldots(3.2)$$

$$\beta = 180^0 - \upsilon \qquad \ldots(3.3)$$

$$y = x / \tan\upsilon \qquad \ldots(3.4)$$

$$r = (x^2 + y^2)^{1/2} \qquad \ldots(3.5)$$

$$p = l - r \qquad \ldots(3.6)$$

$$c = (p^2 - a^2)^{1/2} \qquad \ldots(3.7)$$

$$d = (c^2 + r^2 - 2 \cdot c \cdot r \cdot \cos\beta)^{1/2} \qquad \ldots(3.8)$$

$$\sin\alpha / r = \sin\beta / d \qquad \ldots(3.9)$$

$$\alpha = \arcsin(r \cdot \sin\beta / d) \qquad \ldots(3.10)$$

$$FF = FF_{\perp} / \cos\alpha \qquad \ldots(3.11)$$

where, a = distance between finger and the center line of the tool when the pliers are closed

x = opening distance

l = distance between finger and rotation axis of the tool

d = distance between finger and the intercept between center line+a and its perpendicular line at the level of the rotation axis

α = angle between finger force and perpendicular line of the handle of the pliers

φ = angle between l and the center line of tool when the pliers are closed

υ = angle between l and the center line of tool when the pliers are opened

β, r, p, c are introduced variables, used for description and calculation only.

Taking a = 21.0 mm for the entire experiment, l varied according to load cell position, and x varied according to load cell position and grip span. These variables, l and x, can be measured accordingly (see Appendix F). When these parameters are given, α can be determined from the above equations. The force $FF_{\perp}$ measured by load cells divided by cos α was actual finger force FF. A program was developed for calculation.

3.3 Procedure

Before the beginning of the first experimental session, the procedure was thoroughly explained and each subject was asked to sign a consent form. Then, demographic (age and sex) and anthropometric (height, weight and hand dominance) characteristics were obtained and recorded. Palm hand length, metacarpal breadth as well as fingers and arm length were measured. At the same time, each subject was asked if he/she had ever previously suffered any hand pain or discomfort or had any hand disease, including neuromuscular or orthopedic dysfunction.

There were 30 conditions in total that needed to be tested. Prior to the experiment, the test order was arranged by randomly selecting 30 conditions. Once a condition was selected, it was removed to avoid repetition. In this way, the order of postures performed by subjects was randomized so that practice efforts or fatigue didn't influence any significant findings. The positions of the four load cells were adjusted according to each subject's hand size before the experiment.

During the experiment, the subject stood in a standard position and was encouraged to exert his/her maximal force using the dominant hand. Each subject was also required to keep the wrist neutral during exertion, and squeezed the pliers with the elbow positioned at 0°, 30°, 60°, 90°, and 120° angles, and grip span at 50, 60, and 70mm in both traditional and reversed grip. The hand and arm was to be free of the body, not touching anything. The test involved an all-out effort for 4 to 5 seconds. No swinging or pumping of the arm was allowed. Each condition was repeated once and RF and FF were measured at each trial. Only the maximal force of each condition was used. Each subject had 2 (grip types) x 3 (grip spans) x 5 (elbow positions) x 2 (repetition) = 60 measurements. The whole experiment process was divided into three test sessions, each test session consisting of 20 trials with a 2 minute rest between each trial. The rest time between each session was at least one hour.

Voltage readings from four sensors were collected in each trial and the resultant force between the jaws of the pliers was read and recorded from a force monitor at each trial. Only the maximum values were used as the results for each condition. Each voltage value was converted to force by timing a constant after the offset was subtracted. The constants were obtained from the calibration and varied according to channels (See Appendix E).

3.4 Experimental Design

For this thesis, the experimental design can be described as a "Factorial Design", meaning that in each complete trial or replication of the experiment all possible combinations of the levels of the factors are investigated [37]. In general, factorial designs are most efficient for this type of experiment. This experiment is also called repeated measures experimental design, since during the study each subject performed the experiment for each combination of factors and a number of measurements or results are obtained from an individual performing an experiment [38].

The three factors are grip type, grip span, and elbow position. These terms should be defined before proceeding. The hand grip span is defined as the shortest distance between the handles at the position between the middle finger and ring finger (Figure 3.2). A traditional grip is defined as a power grip with the index finger closest to the head of the tool. A power grip with the small finger closest to the head of tool is defined as a reversed grip. Elbow position refers to the degree of elbow flexion.

After obtaining data, mean values and standard deviations were calculated by standard methods. Linear correlation analysis was applied to study the relationship between the RF and the anthropometric data. Multiple factors analysis of variance (ANOVA) tests were performed on RF and FF to find which factor would be significant at 5 percent. If the analysis of variance indicated that row or column means differed, Duncan's Multiple Range Test was used to make comparisons between the individual row or column means to discover the specific differences.

The ANOVA was calculated with three factors: grip type, elbow position and grip span. In the ANOVA table, elbow position, grip span and grip type are independent variables. The response variables (FF and RF) are dependent variables. The effect of gender will be considered in the analysis of variance. In that way, subjects will be nested within each gender. The following is a list of variables and their levels.

Independent variables are:

1. The types of grip: traditional and reversed grip.

2. Grip span:

   Three grip span levels are used, 50, 60, 70 mm. The spans are controlled by a fixture whose width can be changed by adjusting the screw.

3. Elbow positions:

   Five levels are used, 0° , 30° , 60° , 90° , 120°.

The dependent variables are the maximum force from each of the fingers (FF) and the resultant force between the jaws of the tool (RF). They are:

----Resultant force (RF)

----Index finger force (FF1)

----Middle finger force (FF2)

----Ring finger force (FF3)

----Small finger force (FF4).

CHAPTER 4

RESULTS & DISCUSSION

4.1 Resultant Force

The mean resultant forces (RF) and standard deviations of seven male subjects using the same postures are summarized in Tables 4.1 and 4.2. The data are all peak forces obtained under each condition.

Table 4.1: Traditional grip - mean RF and standard deviations (in parentheses) of male subjects at different elbow positions and spans

	0 °	30°	60 °	90°	120°
50 mm	378.14 N (87.04)	386.14 N (43.38)	420.00 N (32.63)	398.71 N (55.55)	389.43 N (65.31)
60 mm	372.71 (86.58)	339.86 N (32.62)	394.86 N (63.69)	378.43 N (93.90)	345.57 N (48.09)
70 mm	341.86 N (63.37)	338.86 N (44.26)	301.29 N (48.50)	308.43 N (29.97)	287.57 N (36.47)

Table 4.2: Reversed grip - mean RF and standard deviations (in parentheses) of male subjects at different elbow positions and spans

	0°	30°	60°	90°	120°
50 mm	395.70 N (44.99)	375.10 N (67.80)	343.00 N (48.52)	370.10 N (50.48)	285.00 N (50.34)
60 mm	375.60 N (87.72)	343.40 N (76.79)	339.40 N (53.60)	347.43 N (62.53)	330.60 N (48.52)
70 mm	340.90 N (84.56)	306.70N (55.95)	324.7 N (79.60)	288.57 N (55.11)	279.71N (71.67)

The mean resultant forces and standard deviations of seven female subjects using the same postures are summarized in Tables 4.3 and 4.4.

Table 4.3: Traditional grip - mean RF and standard deviations (in parentheses) of female subjects at different elbow positions and spans

	0 °	30°	60 °	90°	120°
50 mm	245.43 N (64.99)	224.71 N (50.78)	243.86 N (49.71)	225.00 N (48.23)	196.71 N (34.49)
60 mm	202.29 N (48.05)	185.86 N (27.66)	208.5 N (44.33)	179.71 N 29.61	195.71 N (34.80)
70 mm	190.71 N (43.44)	175.00 N (22.69)	189.14 N (49.27)	173.71 N (27.57)	161.00 N (29.41)

Table 4.4: Reversed grip - mean RF and standard deviations (in parentheses) of female subjects at different elbow positions and spans

	0°	30°	60°	90°	120°
50 mm	234.00 N (48.00)	218.71 N (46.86)	238.7 N (56.12)	206.14 N (32.46)	185.14 N (52.28)
60 mm	227.2 N (38.19)	187.29 N (52.35)	189.7 N (53.01)	185.29 N (32.76)	183.00 N (26.94)
70 mm	159.71 N (29.30)	184.2 N (30.62)	171.5 N (38.58)	171.00 N (35.52)	151.14 N (21.44)

Table 4.5: Summary of ANOVA table

Dependent Variable: RF

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F
Model	42	3157003.19	75166.74	42.04	0.0001
Gender	1	2395464.19	2395464.19	1339.85*	0.0001
Subject (within gender)	12	393662.35	32805.20	18.35*	0.0001
Elbow (A)	4	71134.32	17783.58	9.95*	0.0001
Span (B)	2	221872.43	110936.22	62.05*	0.0001
Type (C)	1	23430.40	23430.40	13.11*	0.0003
A*B	8	14243.92	1780.49	1.00	0.4387
A*C	4	12300.92	3075.23	1.72	0.1448
B*C	2	6972.75	3486.37	1.95	0.1437
A*B*C	8	17921.90	2240.24	1.25	0.2670
Error	377	674025.52	1787.87		
Corrected Total	419	3831028.71			

* Significant at the level of 0.05

The RF varied according to elbow position (F = 9.95), according to grip span (F = 62.05) and according to grip type (F = 13.11). Table 4.5 shows SAS results of analysis of variance.

The elbow position variable was significant at 0.0001, indicating that changing the elbow position resulted in significantly different RF. Duncan's test was used to compare the RF at different elbow positions and confirmed that the mean force at five elbow positions formed three groups according to force magnitude (Group 1: 0°, 60°; Group 2: 60°, 30°, and 90°; Group 3: 120°, in decreasing order of magnitude). Means in the same group are not significantly different. The 0° elbow position was found to yield the greatest grip force. In Figure 4.1 the RF values for all subjects, males and females, were plotted against five elbow positions. Duncan's test further compared the RF means for each gender. The results indicated that the mean RF at five elbow positions formed two groups (0°, 60°, 30°, and 90°; 120°) for males and another four groups (0° and 60°; 60° and 30°; 30° and 90°; 90° and 120° in decreasing order of magnitude) for females according to force magnitude.

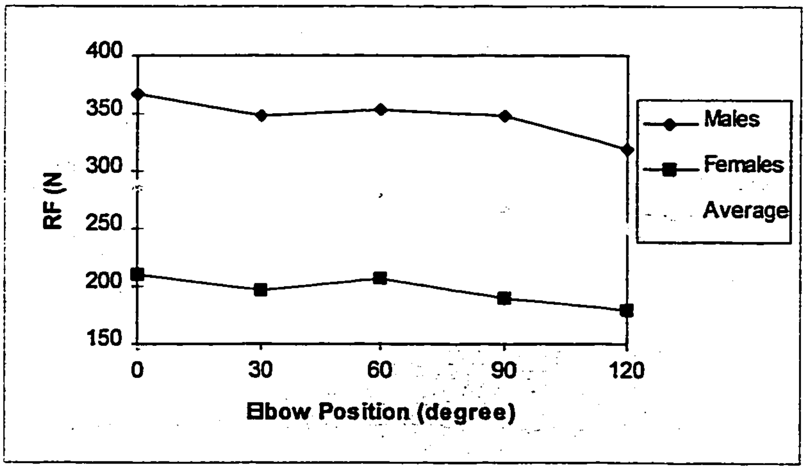

Figure 4.1 Comparison of five levels of elbow position

The effect of grip span was statistically significant on RF at the level of 0.0001, indicating that changing the grip span resulted in significantly different RF. When grip span increased from 50 mm to 70 mm, the grip force declined gradually, in both traditional and reversed grip. The optimal hand grip span, defined as the hand grip span where the highest RF was obtained, was 50 mm for both traditional and reversed grip. Regardless of elbow position and grip type, subjects generated the greatest force at a 50 mm grip span and the weakest force at a 70 mm span. According to Duncan's test, the mean force formed three groups according to force magnitude (50 mm; 60 mm; and 70 mm, in decreasing order of magnitude).

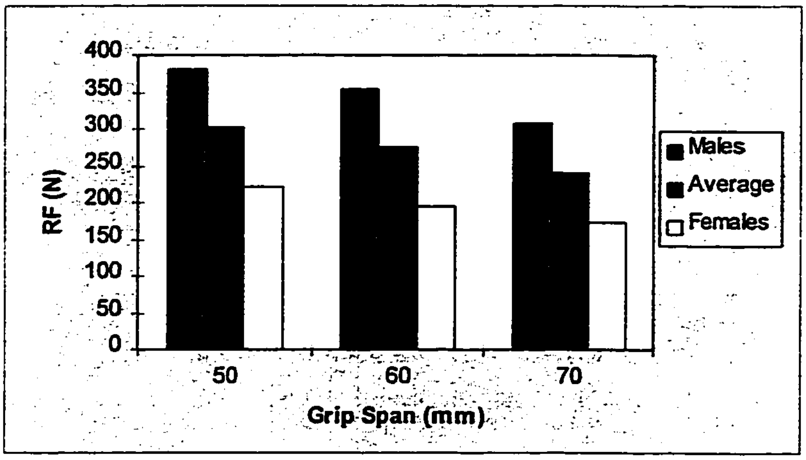

Figure 4.2 Comparison of three levels of grip span

The F ratio of 13.11 for grip type (factor C) was significant at the 0.0003 level, indicating that changing the grip type resulted in significantly different RF. The highest RF was obtained when using the traditional grip type. Regardless of elbow position, for the spans from 50 mm to 70 mm, the mean RF obtained in a traditional grip exceeded the RF obtained in a reversed grip. From Figure 4.3 , for male subjects, the RF in a traditional grip was significantly higher than RF in a reversed grip, however, for female subjects, there was no significant difference in RF between a traditional grip and a reversed grip.

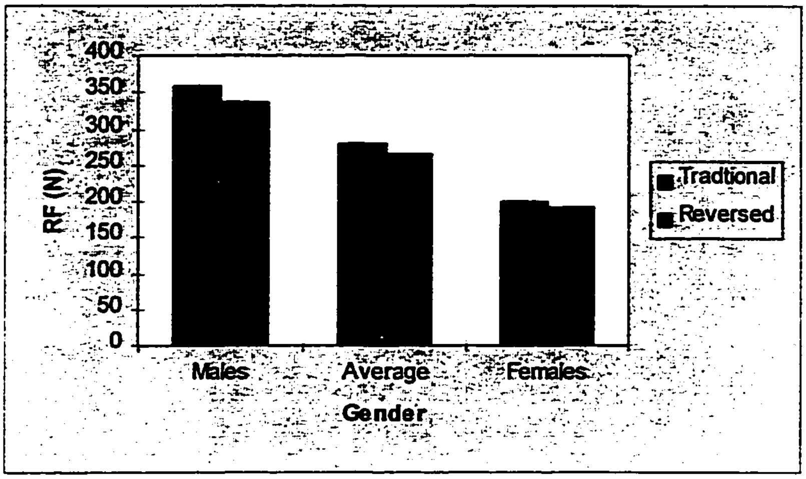

Figure 4.3 Comparison of two levels of grip type

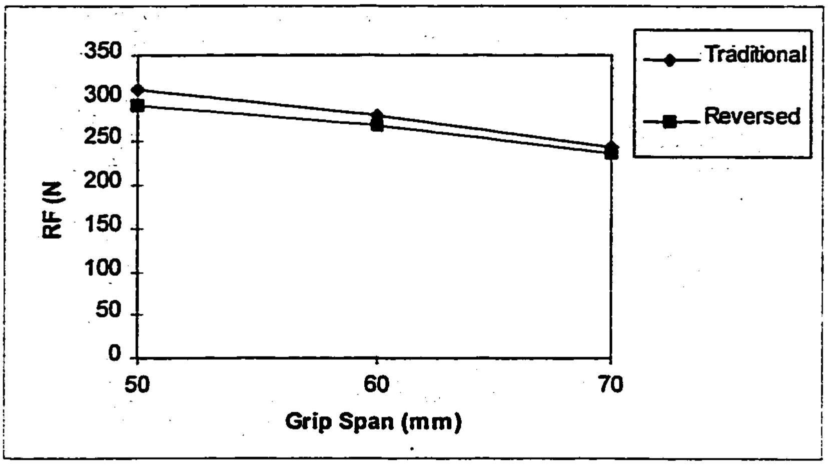

Figure 4.4 Average RF in two grip types was plotted against grip span

No significant interactions were found between the three factors. It can be observed from Figure 4.4 that the difference between the RF in a traditional grip and a reversed grip is only 5.6 N (18.7 N at 50 mm and 11.7 N at 60 mm) at a grip span of 70 mm. There was a trend that the lines of the traditional grip and the reversed grip would be crossed at some span over 70 mm.

Gender has a significant effect on the RF ($F=1339.85$, $P < 0.0001$) and made the greatest contribution to the total sum of squares. Also, the difference between the subjects within gender was statistically significant ($F=18.35$, $P < 0.0001$).

Table 4.6: Overall mean resultant forces of subjects (in N)

Subject	Male	Female
1	363.4	247.8
2	358.0	168.7
3	329.6	170.9
4	327.8	199.9
5	409.6	221.8
6	350.0	169.2
7	294.6	196.0
Mean	347.6	196.3

On average, female RF comprised 56.5 % of male RF, while average female hand size corresponded to 89.8 % of male hand size (fl: 90.3%, hl: 90.6%, and hb: 88.4%). Therefore, correlation analysis was performed to determine the association of RF with subjects' anthropometric data. Since it is known that the maximal force of a muscle is proportional to the square of body length [5], hand size measurements were squared when correlated to the RF. The correlation coefficients between the RF and the square of average length of fingers, the square of hand length, and the square of metacarpal hand breadth were 0.7314 ($P=0.0029$), 0.7875 ($P=0.0008$) and 0.7573 ($P=0.0017$) respectively. When the anthropometric data of males and females was separated to correlate to their RF, low correlation coefficients were found.

4.2 Finger force

Finger forces were measured by load cells. The actual finger forces were calculated and summarized in Tables 4.7, 4.8, 4.9 and 4.10.

Table 4.7: Mean individual finger peak force of males in traditional grip (in N)

		FF1	FF2	FF3	FF4
Span 50 mm	Elbow 0°	15.81	47.86	45.72	21.66
	30°	36.13	58.72	57.25	28.63
	60°	31.96	64.43	54.34	31.34
	90°	29.10	56.83	58.83	19.74
	120°	20.80	38.89	47.26	10.52
Span 60 mm	Elbow 0°	35.77	65.12	51.70	20.63
	30°	31.59	79.51	52.55	26.25
	60°	32.14	53.38	64.57	23.22
	90°	38.89	80.59	54.25	22.74
	120°	21.01	53.01	57.32	13.11
Span 70 mm	Elbow 0°	39.83	46.81	58.29	11.63
	30°	22.46	40.47	52.03	22.66
	60°	26.96	44.31	55.15	24.91
	90°	36.55	59.67	59.23	15.99
	120°	20.09	55.56	56.69	12.17

Table 4.8: Mean individual finger peak force of males in reversed grip (in N)

		FF1	FF2	FF3	FF4
Span 50 mm	Elbow 0°	12.37	82.44	78.55	10.72
	30°	33.48	64.64	71.33	24.54
	60°	37.60	59.97	59.98	20.25
	90°	36.54	87.15	69.25	22.19
	120°	9.87	90.87	53.41	16.31
Span 60 mm	Elbow 0°	26.39	78.94	68.31	15.52
	30°	26.39	92.98	74.52	20.99
	60°	27.60	89.54	79.45	13.83
	90°	29.78	69.29	67.28	19.96
	120°	38.42	71.41	62.50	15.78
Span 70 mm	Elbow 0°	33.62	97.41	53.49	12.85
	30°	33.62	80.06	62.89	19.54
	60°	18.61	87.98	72.15	14.48
	90°	22.82	68.71	59.39	17.33
	120°	15.71	65.77	52.27	14.69

Table 4.9: Mean individual finger peak force of females in traditional grip (in N)

		FF1	FF2	FF3	FF4
Span 50 mm	Elbow 0°	17.77	42.18	25.98	10.73
	30°	33.58	35.67	26.52	10.20
	60°	40.19	55.50	34.21	13.63
	90°	31.98	32.49	27.13	18.12
	120°	41.62	25.75	19.65	19.63
Span 60 mm	Elbow 0°	28.69	51.19	42.27	19.34
	30°	29.07	47.28	40.34	13.54
	60°	33.82	48.27	38.09	10.69
	90°	35.94	35.11	27.01	11.95
	120°	31.62	38.47	30.24	17.20
Span 70 mm	Elbow 0°	21.01	34.22	28.99	10.97
	30°	30.12	34.22	28.51	15.65
	60°	28.31	23.45	22.65	13.87
	90°	34.07	35.48	18.89	10.51
	120°	27.27	34.98	17.23	12.39

Table 4.10: Mean individual finger peak force of females in reversed grip (in N).

		FF1	FF2	FF3	FF4
Span 50 mm	Elbow 0°	15.25	47.36	32.43	11.60
	30°	27.03	32.90	33.13	14.01
	60°	19.16	57.72	54.77	7.11
	90°	31.35	28.32	28.36	9.84
	120°	12.40	36.34	23.57	13.18
Span 60 mm	Elbow 0°	27.49	55.51	24.99	13.86
	30°	27.91	57.14	37.09	14.92
	60°	22.00	47.68	37.45	14.08
	90°	30.09	55.85	28.81	10.76
	120°	28.34	49.15	26.09	9.76
Span 70 mm	Elbow 0°	25.36	47.34	23.86	10.92
	30°	25.62	48.56	25.78	10.49
	60°	23.00	46.37	20.60	9.55
	90°	14.95	56.04	21.70	9.84
	120°	12.13	49.52	27.91	7.29

Table 4.11: Summary of ANOVA table

Dependent variable: Index Finger Force

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	42	14808.4	352.50	20.48	0.0001
Subj (Gender)	12	1947.72	162.31	9.43*	0.0001
Gender	1	10943.4	10943.4	635.80*	0.0001
Elbow (A)	4	604.48	151.12	8.78*	0.0001
Span (B)	2	648.9	324.45	18.85*	0.0001
Type (C)	1	72.12	72.12	4.19*	0.0425
A*B	8	141.84	17.73	1.03	0.4153
B*C	2	273.68	136.84	7.95*	0.0005
A*C	4	38.56	9.64	0.56	0.6952
A*B*C	8	137.7	17.21	1.00	0.4387
Error	377	9488.92	17.21		
Corrected Total	419	21297.32			

Table 4.12: Summary of ANOVA table

Dependent variable: Middle Finger Force

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	42	27823.8	662.45	8.38	0.0001
Subj (Gender)	12	9594.97	799.58	10.12*	0.0001
Gender	1	12972.02	12972.02	164.18*	0.0001
Elbow (A)	4	955.01	238.75	3.02*	0.0189
Span (B)	2	1459.25	729.63	9.23*	0.0001
Type (C)	1	1308.67	1308.67	16.56*	0.0001
A*B	8	628.91	78.61	0.99	0.4411
B*C	2	333.42	166.71	2.11	0.089
A*C	4	154.90	38.72	0.49	0.7430
A*B*C	8	415.93	51.99	0.66	0.7280
Error	377	17495.48	79.01		
Corrected Total	419	45319.28			

Table 4.13: Summary of ANOVA Table

Dependent variable: Ring Finger Force

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	42	15272.64	361.99	10.60	0.0001
Subj (Gender)	12	3763.08	313.59	9.18*	0.0001
Gender	1	8761.36	8761.36	256.48*	0.0001
Elbow (A)	4	1072.64	268.16	7.85*	0.0001
Span (B)	2	630.6	315.30	9.23*	0.0001
Type (C)	1	140.40	140.40	4.11*	0.0187
A*B	8	202.23	25.28	0.74	0.5677
B*C	2	228.19	114.09	3.34*	0.0377
A*C	4	140.74	35.18	1.03	0.4153
A*B*C	8	333.40	41.68	1.22	0.2982
Error	377	12878.32	34.16		
Corrected Total	419	28150.96			

* Significant at the level of 0.05.

The individual finger force was different from finger to finger. The average force distribution among the index, middle, ring, and small fingers of males was 16.06 %, 38.77 %, 34.53 %, and 10.64 %, respectively. The average force distribution for females was 24.10 %, 38.56 %, 26.12 % , and 11.23 %. Among four fingers the middle finger is the strongest finger and exerted the greatest force during the gripping task.

Finger force varied according to elbow position ($F = 8.78$, $P<.0001$ for index finger, $F =3.02$, $P < 0.0189$ for middle finger, $F = 7.85$, $P < 0.0001$ for ring finger). Figures 4.5 and 4.6 illustrate how each finger force varied according to elbow position for both males and females. It was observed that there was a significant difference between the finger force at the 120° elbow position and the finger force at the other elbow positions. All fingers exerted the weakest force at the 120° elbow position.

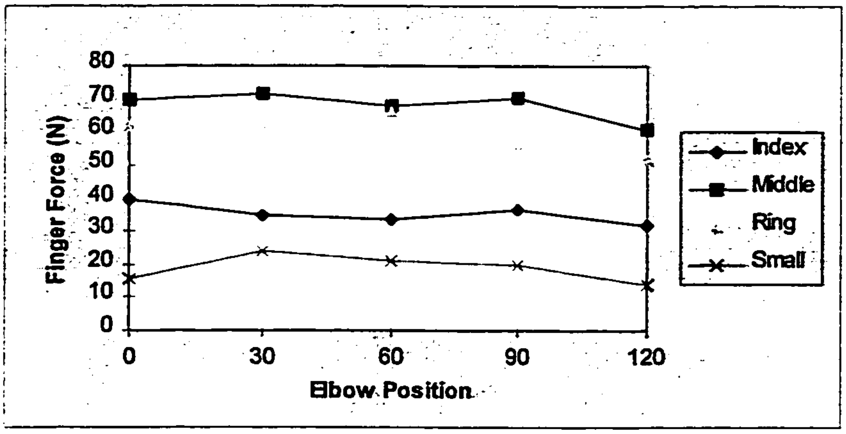

Figure 4.5. Average force of index, middle, ring and small fingers at all levels of exertion as a function of elbow position for males

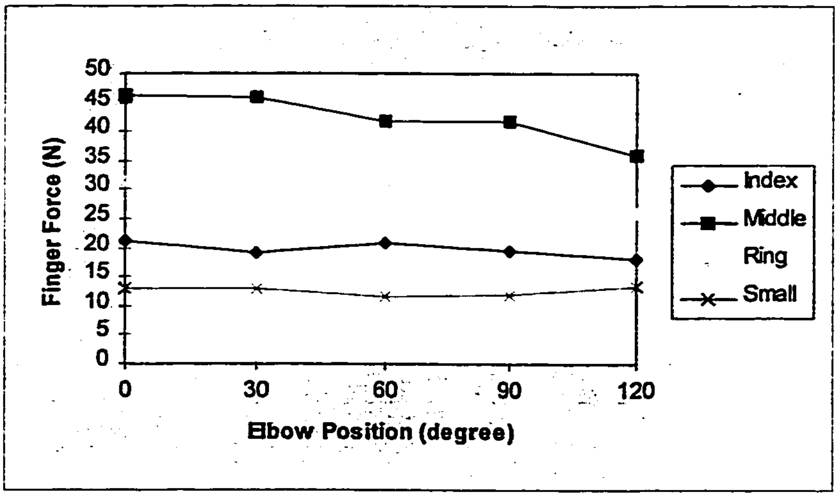

Figure 4.6 Average force of index, middle, ring and small fingers at all levels of exertion as a function of elbow position for females.

Finger force was also found to vary according to grip span ($F = 18.85$ for index finger, $F = 9.23$ for middle finger, $F = 9.58$ for ring finger, $P<0.05$). Duncan's test confirmed that the mean forces according to force magnitude can be formed in two groups (Group 1: 60 mm and 50 mm; Group 2: 70 mm in decreasing order of magnitude).

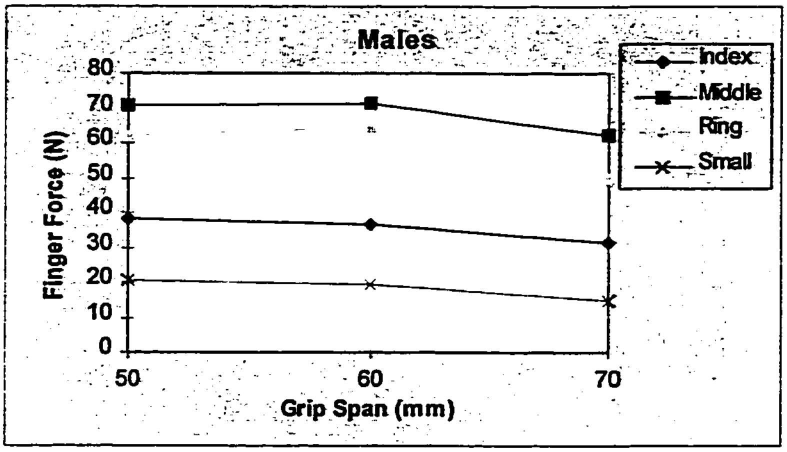

Figure 4.7 Average force of index, middle, ring and small fingers at all levels of exertion as a function of grip span for males

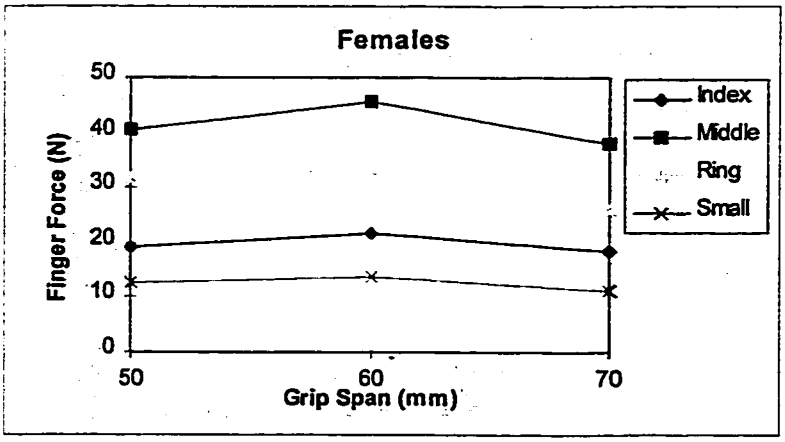

Figure 4.8 Average force of index, middle, ring and small fingers at all levels of exertion as a function of grip span for females

Average individual finger force was plotted against three levels of span in Figures 4.6 and 4.7. The results of comparing the RF at three spans varied according to fingers.

Grip type had a significant effect on finger force ($F = 4.19$ for index finger, $F = 16.56$ for middle finger, $F = 4.11$ for ring finger, $Pr < 0.05$). The influence of grip type on finger force also varied according to finger . Figure 4.6 shows this relationship between grip type and finger. This result indicates an interaction between the fingers and the grip types. For the grip span from 50 mm to 70 mm, the mean force of a specific finger differed between the traditional and the reversed grip type. The middle finger force in a reversed grip was higher than that in a traditional grip. For index and ring finger, the forces varied according to grip span x grip type ($F = 7.95$ for index finger, $F = 3.34$ for ring finger, $Pr < 0.05$). Figures 4.10 and 4.11 illustrate the interaction between grip span and type.

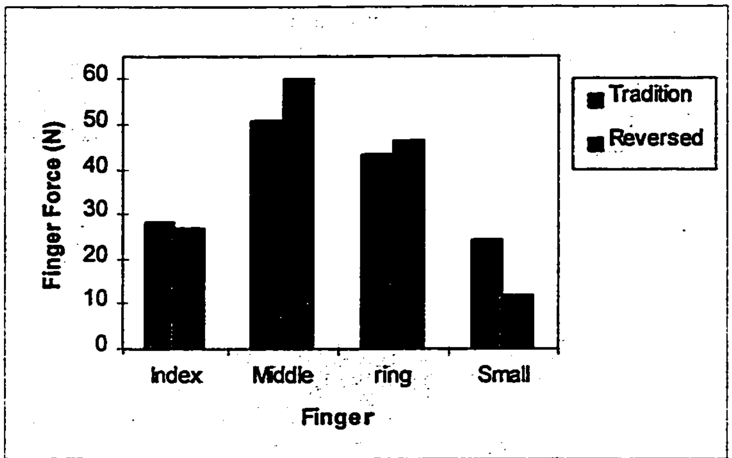

Figure 4.9 Average finger force in two grip types

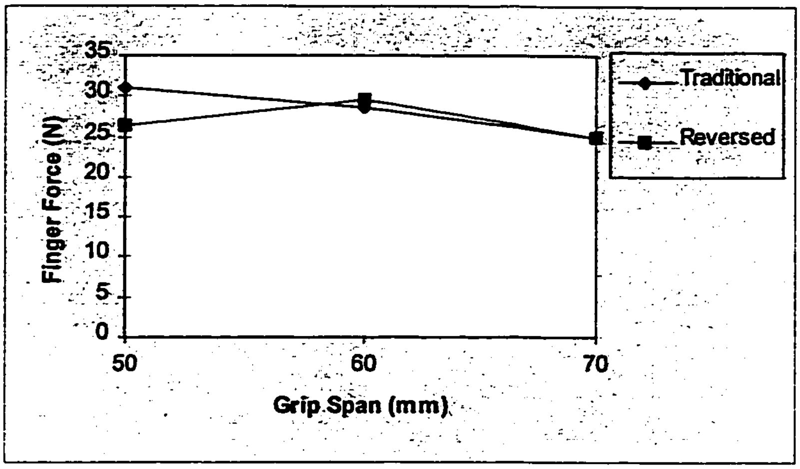

Figure 4.10 An interaction between grip span and type for index finger force

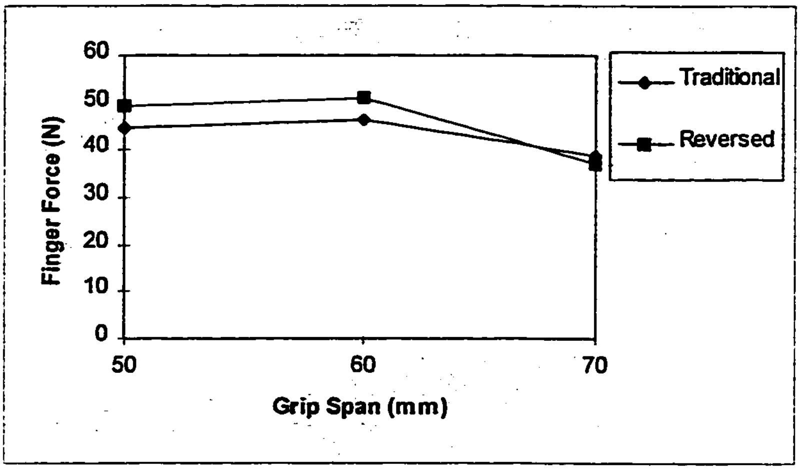

Figure 4.11 An interaction between grip span and type for ring finger force

Gender had a significant effect on the FF (F=635.80 for index finger, Pr<0.05) and made the greatest contribution to the total sum of squares. The difference between the subjects within gender was statistically significant, but the F radio was much lower than the F ratio of gender. Average female FF comprised 59.11 % of the corresponding male FF.

4.3 Discussion

4.31 Elbow Position

The results show that elbow position has a significant effect on grip force and finger force. The results support the recommendation of the American Society of Hand Therapists that arm positioning should be standardized for hand strength testing. However, the results of comparison of the RF at 0° and 90° elbow positions contrast with the results of Mathiowetz et al. [36] who stated that grip force at a 90° elbow position is stronger than at a 0° position. The results of this study indicated that the RF was significantly higher when the elbow was fully extended than the RF at the other positions. The inconsistency of the results might be due to experimental device and method. Also, there are gender differences between the findings for males and females according to Duncan's test. This is probably due to arm size difference. The average female arm length corresponded to 93.4% of average male arm length (Lower arm length 92.9% and upper arm length 93.8%). Females generally have shorter lower and upper arms and are more likely to be affected by elbow positions.

The effect of elbow positions on finger force corresponded to the effect on RF. Both resultant force and finger force were weakest at the 120° elbow position. These results indicated that over flexion of elbow position should be avoided in manual gripping tasks.

4.32 Grip Span

Both resultant force and finger force vary according to handle separation. This may be due to several factors:

(1) The finger/hand grip span affects the pre-contractile length in the finger flexor muscles of the forearm. Accordingly, the number of cross-bridges that can be formed differs, which affects the muscle force correspondingly.

(2) The force loss at wide hand grip spans may be due to a change in lever arms: as the hand grip span increases, the handle moves from the proximal to the distal part of the fingers. Thus, the lever arm of the extension movement, which opposes the finger flexion, increases correspondingly. As a consequence, the force output of a wide hand grip span is lower than that of a narrow hand grip span.

(3) For wide hand grip spans, all fingers cannot grip properly around the handle of the tool, implying a corresponding loss of force [4].

The optimal span was found to be 50 mm for both genders. This result is comparable to that of Fransson and Winkel [4], who found the optimal grip span was 50 - 60 mm for females and 55 - 65 mm for males. The difference is probably due to hand size. Subjects' hand size in the present study corresponded to 97.7% of the subjects' hand size in Fransson and Winkel 's study [4].

4.33 Grip Type

The data showed that the two grip types were significantly different. In fact, subjects obtained the highest grip force when using the traditional grip. The results coincide with Fransson and Winkel's results that the subjects obtained the highest RF when using the traditional grip [5]. It is found that the average RF in a reversed grip comprised 95% RF in a traditional grip and 93% in Fransson and Winkel's study for a grip span from 50 mm to 70 mm. The results showed that the average RF for male subjects obtained was 356.9 N in a traditional grip and 339.8 N in a reversed grip. The RF difference between the two results was 45.4% for male subjects and 46.8% for female subjects. The probable reasons for this are that different types of pliers were used and the slip joint was kept at different positions. Another reason is different samples used in experiments. The average age of subjects in this study is 43.7% younger than the age of subjects in Fransson and Winkel's study.

The reversed grip does not imply an increased RF compared to the traditional grip. The results coincide with Fransson and Winkel's results [4]. One likely explanation for this is that the advantage of the reversed grip (longer level arms for the strongest part of the hand) is opposed by more disadvantage of finger grip span. Another factor contributing

The influence of grip type on finger force varies according to fingers. For the index finger and ring finger, the influence of grip type also varies according to grip span. However, interaction between grip span and type was not found in the middle finger force as well as the resultant force. We can speculate that there is a possibility of interaction because the F ratios are found to be relatively higher than the other interactions ($F=1.95$ for RF, $F=2.11$ for middle finger). The trend of interaction could be observed in Figure 4.4. This finding is consistent with Hall's results [3] which stated that there was an interaction between grip span and type. The interaction occurs in the index and ring finger while it does not occur in other fingers. The reason for this is that there is an interaction between the fingers. The finger force and the resultant force do not vary in the same way. The fingers have different optimal grip spans. This is probably because some of the finger flexors, e.g., m. flexor digitorum profundis and m. flexor digitorum superficialis, are united at the origin. Also, the fingers are, to some extent, linked together via the juncture tendon. Therefore, the fingers should not be considered as separate units, but as intimately cooperative parts of the hand.

After comparison the force distribution across the fingers with Hall's study, it was found that the figures in the present study (20.2%, 36.4%, 28.1% and 15.3%) correspond to the figures in Hall's study (21.2%, 33.6%, 26.5% and 18.1%).

4.34 Implications

4.34 Implications

This study measured grip strength and finger force by squeezing handles of pliers. This grip type is perhaps the most commonly used grip for cross-action tools. The traditional grip and reversed grip used for this investigation may be observed during numerous common industrial activities. The practical implications of the results are for hand tool use and job design. An elbow fully extended or flexed at a 60° angle is preferred to other positions. It is best to exert force when the elbow is at a 0° position and grip span at 50 mm in a traditional grip. An elbow flexed at 120° with wide span over 70 mm in a reversed grip should be avoided during the application of hand tools.

The results of this study support the American Society of Hand Therapists' recommendation of standardized positioning for grip-strength measurements. The results confirm that it is essential to use the same elbow position in grip strength testing. Any further research correlating factors with power grip strength should control the subject's elbow positioning to ensure that the factor is indeed the only variable acting in the study.

The study also indicates some gender differences beyond the difference of force magnitude. This will enable a better understanding of the difference between female workers and male workers' hand exertion. A better understanding of hand strength will lead to the successful prevention of trauma disorders. The data of finger force will be useful for designing tools, work equipment and manual activities.

CHAPTER 5

CONCLUSIONS

The elbow position, grip span, as well as grip type, have significant effects on resultant force. The RF is significantly higher at the 0° elbow position than at the 30°, 90° and 120° elbow positions, and the RF is significantly higher at the 60°, 30°, and 90° elbow positions than at the 120° position. Regardless of elbow position and grip type the optimal grip span was found to be 50 mm. In addition, force decreases while grip span increases. Subjects generated greater force in a traditional grip than in a reversed grip. The female subjects, considered separately, show a difference from male subjects in the results of a comparison between five levels of elbow position. Also, for spans ranging from 50 mm to 70 mm, the resultant force obtained in a traditional grip exceed the RF obtained in a reversed grip, but the difference between two grip types was not significant.

The middle and ring fingers, the two strongest fingers, exerted the greatest average maximal finger force. The average force distribution between index, middle, ring and small fingers is 16.06%, 38.77%, 34.53%, and 10.64% for males, and 24.10%, 38.56%, 26.12 %, and 11.23 % for females. Finger force varies according to elbow position and grip span and grip type. The influence of elbow, grip span, and grip type also varies according to fingers. The interaction between grip span and type was found in the index and ring fingers.

Although more and more manual work is being done by machines, hand exertion is still necessary in industrial tasks. Gradual and often cumulative overstrain to the hand by the repetitive application of maximal or submaximal forces of the grip has been documented. Therefore, it is important to study the working capacities of the hand during hand tool use.

In this study, the maximum output force between the jaws of the pliers as well as finger forces applied to the handle of the pliers were measured. The forces were investigated under five elbow positions, three grip spans and two grip types. Elbow position was shown to have a significant effect on the RF, but still needs further study. Because the elbow is a joint of muscles and bones of the forearm and upper arm, the finger extensor muscles attached to the elbow control the movement of the wrist and hand. One can speculate that there is an interaction between elbow position and wrist position. In this thesis, the wrist position was in a neutral position. It is not known if similar results would be found if the wrist position was considered as a variable.

To further this study, the elbow position and wrist position should be considered as two main factors to be investigated to determine whether there is an interaction between these two factors. The results will be of great interest in the study of hand exertion. Future

The results of the study have enhanced our understanding of hand strength, and are useful in the design of hand tools, tasks and workplaces. For using hand tools, it is best to exert force with the elbow fully extended or flexed at a 60° angle with a narrow span in a traditional grip because the greatest force can be exerted under this condition. Over flexion of the elbow and wide grip span, especially in a reversed grip should be avoided. Gender differences in grip strength emphasize the danger of not considering the differences of males and females. The result also indicates that for females it is best to exert the maximal force with a more narrow span with the elbow fully extended or flexed at a 60° angle in a traditional grip, because of the hand size difference between males and females.

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APPENDIX

PART A

THE EXPERIMENTAL SET-UP

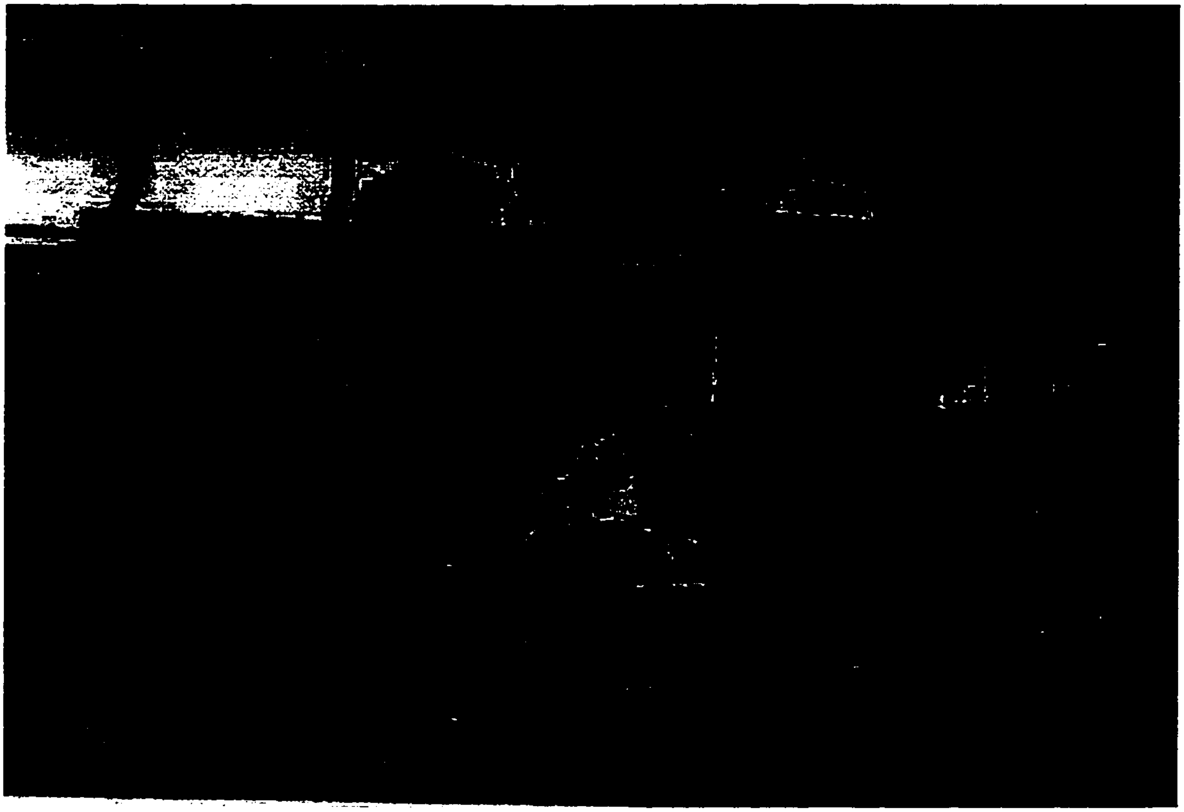

Figure 1A. Experiment display

PART B

CONSENT FORM

CONSENT FORM

I, ______________________________, am participating in this study of my own free will. The decision to participate is completely voluntary on my part. No one has coerced or intimidated me to participate.

The investigator has answered any and all questions I have asked about this study, my participation, and the procedures involved, which are described in the attachment to this consent form, which I have initialled.

I understand that the investigator or her Supervisor will be available to answer any questions concerning procedures throughout this study. I understand that if significant new findings develop during the course of this research which may relate to my decision to continue participation, I will be informed. I further understand that I may withdraw consent at any time and discontinue further participation at my discretion. I understand that the Investigator or the Supervisor or any medical consultant may terminate my participation in this study if it is felt to be in my best interest.

I do not have any pain or discomfort for my hands. I have not had any hand disease including no previous history of neuromuscular or orthopedic dysfunction that make it inadvisable for me to participate as a subject in this experiment.

I understand that the results of my efforts will be recorded but that no photographic record will be made of the experiment. I consent to the use of the recorded information for scientific or training purposes and understand that any records of my participation in this study may be disclosed only according to federal and provincial law and that no one will be able to identify me as a participant in this study from the reporting of any results or conclusions reached by the investigator. I also understand that personal information will not be released to an unauthorised third party without my permission.

I understand that I will be compensated at the minimum wage rate as set out by law. This money will be paid to me at the conclusion of my participation in this study. I understand that I will not be paid if I do not complete the study, unless I have a medical or other valid reason for not completing the study and documentation to support this fact.

I FULLY UNDERSTAND THAT I AM MAKING A DECISION WHETHER OR NOT TO PARTICIPATE IN THE STUDY. MY SIGNATURE INDICATES THAT I HAVE DECIDED TO PARTICIPATE UNDER THE CONDITIONS DESCRIBED ABOVE.

Volunteer Signature
Date

Signature of Witness
Date

This study has been cleared by the Ethics Committee of the University of Windsor. Any questions or comments concerning research ethics can be addressed to the office of Research Services at (519) 253-4232, Ext.3916. Any other questions or comments concerning study procedures may be addressed to the Department of Industrial and Manufacturing System engineering at (519) 253-4232, Ext. 2607.

ATTACHMENT TO CONSENT FROM

You are invited to participate as a subject in an experiment to measure grip and finger force during gripping a pair of pliers. The data gathered in this study will be used to study the effect of elbow position and grip span on grip strength.

The test encompasses approximately thirty conditions with three hours to complete the test. The time to conduct the experiment will be scheduled at mutually convenient times. In performing the task, you will be required to exert maximal voluntary contractions (MVC) in the standard way through all the tests.

The results of your participation will be recorded and analysed. Only overall results of all subjects who participate in this study will be reported. There will be no reporting of results in a manner that will allow anyone to specifically identify your specific results.

Before you act as a test subject, you must inform the Investigator or Supervisor of any change to your physical status. This information will include any medication taken or medical care or conditions that will directly or indirectly affect the experiment.

If you have any questions you can reach the Investigator(Sue Chen) or Supervisor (Dr. S. M. Taboun) via the Department of Industrial and Manufacturing Systems Engineering at the University of Windsor at (519) 253-4232, extension 2607, during normal business hours.

Subject's Initials:____

PART C

SUBJECTS' CHARACTERISTICS

SS #	SEX	AGE (YEARS)	WEIGHT (KG)	HEIGHT (M)	FL* (MM)	HB* (MM)	HL* (MM)	FOREARM (MM)	UPPERARM (MM)
1	M	23	78	1.69	67.5	90	180	250	280
2	M	27	65	1.80	73.8	80	190	280	300
3	M	24	75	1.75	67.5	85	185	250	290
4	M	21	87	1.74	73.8	90	178	250	270
5	M	22	83	1.84	76.3	95	196	240	290
6	M	23	95.4	1.78	71.8	90	175	280	310
7	M	40	70.8	171	70.8	80	185	270	280
8	F	20	87	1.64	63.5	75	170	240	270
9	F	21	64.5	1.68	66	75	175	265	300
10	F	21	65.5	1.68	70.3	82	175	255	300
11	F	20	84	1.66	62.8	85	164	240	270
12	F	29	61	1.62	64.3	80	162	240	270
13	F	23	52	1.55	62.5	72	162	240	245
14	F	30	56	1.64	63.5	70	160	210	240
MEAN		24.6	73.4	169.9	68.2	82.1	175.5	250.5	279.6
SD		5.4	11.6	4.8	3.0	5.6	6.8	17.09	18.8

*FL --- Average Finger Length
HB --- Hand Breadth
HL --- Hand Length

PART D

RF & FF DATE RECORD OF SUBJECTS

Table A1. Maximal RF of subject 1 in traditional and reversed grip (in N).

Traditional	Elbow 0°	30°	60°	90°	120°
Span 50 mm	312	338	387	490	436
60 mm	471	361	427	312	303
70 mm	387	312	307	307	304
Reversed	Elbow 0°	30°	60°	90°	120°
Span 50 mm	392	392	387	427	316
60 mm	413	352	338	325	352
70 mm	374	383	303	396	298

Table A2. Maximal RF of subject 2 in traditional and reversed grip

Traditional	Elbow 0°	30°	60°	90°	120°
Span 50 mm	329	445	392	432	387
60 mm	347	356	405	387	343
70 mm	418	347	347	325	303
Reversed	Elbow 0°	30°	60°	90°	120°
Span 50 mm	436	414	383	383	285
60 mm	405	356	320	369	387
70 mm	298	338	236	263	303

Table A3. Maximal RF of subject 3 in traditional and reversed grip

Traditional	Elbow 0°	30°	60°	90°	120°
Span 50 mm	481	345	427	378	312
60 mm	394	336	365	401	323
70 mm	325	356	245	294	240
Reversed	Elbow 0°	30°	60°	90°	120°
Span 50 mm	374	269	263	338	256
60 mm	381	332	296	443	298
70 mm	352	263	267	294	240

Table A4. Maximal RF of subject 4 in traditional and reversed grip

Traditional	Elbow 0°	30°	60°	90°	120°
Span 50 mm	285	378	387	312	289
60 mm	249	356	396	312	323
70 mm	240	374	378	303	280
Reversed	Elbow 0°	30°	60°	90°	120°
Span 50 mm	401	352	280	392	361
60 mm	374	298	316	383	285
70 mm	272	294	345	312	307

Table A5. Maximal RF of subject 5 in traditional and reversed grip

Traditional	Elbow 0°	30°	60°	90°	120°
Span 50 mm	476	356	472	396	463
60 mm	494	303	512	547	441
70 mm	374	386	289	329	356
Reversed	Elbow 0°	30°	60°	90°	120°
Span 50 mm	445	476	396	365	298
60 mm	471	490	458	329	409
70 mm	490	343	476	258	396

Table 6. Maximal RF of subject 6 in traditional and reversed grip

Traditional	Elbow 0°	30°	60°	90°	120°
Span 50 mm	452	436	443	414	412
60 mm	329	289	325	423	374
70 mm	369	254	249	347	254
Reversed	Elbow 0°	30°	60°	90°	120°
Span 50 mm	361	447	363	414	256
60 mm	394	340	354	369	343
70 mm	369	263	334	274	249

Table A7. Maximal RF of male subject 7 in traditional and reversed grip

Traditional	Elbow 0°	30°	60°	90°	120°
Span 50 mm	312	405	432	369	427
60 mm	325	378	334	267	312
70 mm	280	343	294	254	276
Reversed	Elbow 0°	30°	60°	90°	120°
Span 50 mm	361	276	329	272	223
60 mm	191	236	294	214	240
70 mm	231	263	312	223	165

Table A8. Maximal RF of female subject 1 in traditional and reversed grip

Traditional	Elbow 0°	30°	60°	90°	120°
Span 50 mm	352	325	320	289	258
60 mm	298	224	313	200	263
70 mm	263	191	294	227	223
Reversed	Elbow 0°	30°	60°	90°	120°
Span 50 mm	251	151	174	183	120
60 mm	276	129	129	214	183
70 mm	165	160	134	147	120

Table A9. Maximal RF of female subject 2 in traditional and reversed grip

Traditional	Elbow 0°	30°	60°	90°	120°
Span 50 mm	178	223	191	254	156
60 mm	157	214	186	183	218
70 mm	147	138	160	187	129
Reversed	Elbow 0°	30°	60°	90°	120°
Span 50 mm	205	151	174	183	120
60 mm	183	129	129	214	183
70 mm	107	160	134	147	120

Table A10. Maximal RF of female subject 3 in traditional and reversed grip

Traditional	Elbow 0°	30°	60°	90°	120°
Span 50 mm	198	160	209	187	178
60 mm	176	140	187	116	169
70 mm	142	169	156	156	160
Reversed	Elbow 0°	30°	60°	90°	120°
Span 50 mm	209	191	205	178	165
60 mm	214	196	174	160	165
70 mm	174	174	134	138	147

Table A11. Maximal RF of female subject 4 in traditional and reversed grip

Traditional	Elbow 0°	30°	60°	90°	120°
Span 50 mm	275	231	285	272	225
60 mm	187	187	218	183	185
70 mm	227	196	169	151	151
Reversed	Elbow 0°	30°	60°	90°	120°
Span 50 mm	196	223	294	200	174
60 mm	240	147	156	178	196
70 mm	151	178	165	169	187

Table A12. Maximal RF of female subject 5 in traditional and reversed grip

Traditional	Elbow 0°	30°	60°	90°	120°
Span 50 mm	294	218	267	165	189
60 mm	227	174	151	191	174
70 mm	196	200	200	174	156
Reversed	Elbow 0°	30°	60°	90°	120°
Span 50 mm	334	280	280	276	254
60 mm	254	263	263	240	209
70 mm	205	223	227	200	169

Table A13. Maximal RF of female subject 6 in traditional and reversed grip

Traditional	Elbow 0°	30°	60°	90°	120°
Span 50 mm	183	191	191	183	174
60 mm	169	176	196	205	165
70 mm	169	156	156	147	147
Reversed	Elbow 0°	30°	60°	90°	120°
Span 50 mm	209	191	214	200	142
60 mm	196	142	142	178	134
70 mm	156	147	138	138	142

Table A14. Maximal RF of female subject 7 in traditional and reversed grip

Traditional	Elbow 0°	30°	60°	90°	120°
Span 50 mm	238	225	244	225	197
60 mm	202	186	209	180	196
70 mm	191	175	189	174	161
Reversed	Elbow 0°	30°	60°	90°	120°
Span 50 mm	234	219	231	206	185
60 mm	221	187	195	185	183
70 mm	160	183	178	171	151

Table A15. Maximal Voltages of FF-signal for Male subject 1.

GRIP TYPE	SPAN (MM)	FINGER	ELBOW 0°	30°	60°	90°	120°
Traditional	50	FF1	0.2202	0.2095	0.3408	0.2588	0.2480
		FF2	0.5562	0.5845	0.8306	0.6182	0.5664
		FF3	0.1030	0.1519	0.2100	0.1147	0.1108
		FF4	0.1416	0.1465	0.1670	0.1885	0.1519
	60	FF1	0.3521	0.2559	0.3037	0.2944	0.2661
		FF2	0.6772	0.6694	0.5771	0.6885	0.5571
		FF3	0.1475	0.1167	0.1362	0.1279	0.1646
		FF4	0.2212	0.1108	0.1768	0.1758	0.1772
	70	FF1	0.2148	0.2866	0.2119	0.2974	0.2476
		FF2	0.6216	0.6489	0.5723	0.6455	0.6582
		FF3	0.1230	0.1704	01724	0.1016	0.1250
		FF4	0.1641	0.1143	0.1875	0.1675	0.1836
Reversed	50	FF4	0.2109	0.2197	0.2144	0.2124	0.2036
		FF3	0.7334	0.6978	0.7261	0.6221	0.7100
		FF2	0.2305	0.3394	0.2900	0.3633	0.2847
		FF1	0.1753	0.2998	0.2104	0.3193	0.1074
	60	FF4	0.2393	0.2358	0.2368	0.2075	0.1992
		FF3	0.7085	0.7510	0.7583	0.7256	0.6079
		FF2	0.3032	0.3237	0.3306	0.3022	0.3311
		FF1	0.2520	0.2568	0.2603	0.2773	0.3325
	70	FF4	0.2134	0.2241	0.2778	0.2900	0.2339
		FF3	0.6382	0.6040	0.7490	0.7187	0.7314
		FF2	0.2881	0.2690	0.2727	0.3706	0.3247
		FF1	0.2378	0.2710	0.2046	0.1177	0.1074

Table A16. Maximal Voltages of FF-signal for Male subject 2

GRIP TYPE	SPAN (MM)	FINGER	ELBOW 0°	30°	60°	90°	120°
Traditional	50	FF1	0.1265	0.2603	0.2114	0.1909	0.1763
		FF2	0.6260	0.7021	0.6426	0.6465	0.6123
		FF3	0.0952	0.1318	0.0840	0.1113	0.1284
		FF4	0.1055	0.1006	0.1025	0.1016	0.1006
	60	FF1	0.1923	0.1831	0.2510	0.1875	0.1636
		FF2	0.6899	0.7324	0.8389	0.5976	0.7417
		FF3	0.1040	0.1260	0.2891	0.0942	0.1294
		FF4	0.1045	0.1021	0.1040	0.1021	0.1030
	70	FF1	0.1880	0.1636	0.1938	0.1563	0.1431
		FF2	0.6465	0.7173	0.6123	0.6519	0.6265
		FF3	0.1035	0.1045	0.0889	0.1411	0.1016
		FF4	0.1069	0.1021	0.1030	0.1050	0.1035
Reversed	50	FF4	0.1289	0.2603	0.2114	0.1909	0.1763
		FF3	0.7412	0.7021	0.6426	0.6465	0.6123
		FF2	0.3271	0.1318	0.0840	0.1113	0.1284
		FF1	0.1001	0.1011	0.1025	0.1160	0.1060
	60	FF4	0.1924	0.1831	0.2510	0.1875	0.1997
		FF3	0.6899	0.7324	0.8389	0.5977	0.7339
		FF2	0.1040	0.1260	0.2891	0.0942	0.3369
		FF1	0.1045	0.1021	0.1040	0.1021	0.1006
	70	FF4	0.1274	0.1636	0.1455	0.1431	0.1484
		FF3	0.7007	0.7173	0.6724	0.6807	0.6763
		FF2	0.2793	0.1045	0.2485	0.2651	0.3569
		FF1	0.1040	0.1021	0.1045	0.0972	0.1016

Table A17. Maximal Voltages of FF-signal for Male subject 3.

GRIP TYPE	SPAN (MM)	FINGER	ELBOW 0°	30°	60°	90°	120°
Traditional	50	FF1	0.2414	0.2646	0.2822	0.3169	0.2783
		FF2	0.6880	0.5938	0.7261	0.7061	0.6362
		FF3	0.1489	0.1235	0.1953	0.1792	0.1372
		FF4	0.1929	0.1377	0.2134	0.2197	0.1572
	60	FF1	0.2325	0.2681	0.2554	0.2593	0.2358
		FF2	0.7141	0.6123	0.6138	0.5693	0.5737
		FF3	0.1939	0.1221	0.1230	0.1113	0.1270
		FF4	0.2148	0.1646	0.1797	0.1582	0.1631
	70	FF1	0.2617	0.3808	0.2461	0.2549	0.2759
		FF2	0.5256	0.6144	0.6387	0.6051	0.6349
		FF3	0.1531	0.1475	0.1128	0.1411	0.2017
		FF4	0.1558	0.2144	0.1733	0.1987	0.1885
Reversed	50	FF4	0.2015	0.2311	0.1905	0.1856	0.1866
		FF3	0.6860	0.6299	0.6899	0.6621	0.6323
		FF2	0.3193	0.2402	0.2569	0.25	0.1372
		FF1	0.2261	0.2310	0.2134	0.2427	0.2072
	60	FF4	0.2236	0.2389	0.2400	0.2263	0.1987
		FF3	0.6567	0.6616	0.6755	0.6532	0.6333
		FF2	0.2676	0.3103	0.2956	0.3044	0.2549
		FF1	0.1675	0.2200	0.2398	0.2301	0.2017
	70	FF4	0.2377	0.2461	0.2419	0.2412	0.1841
		FF3	0.6421	0.6387	0.6544	0.6133	0.5967
		FF2	0.2661	0.1128	0.2251	0.2368	0.2402
		FF1	0.1670	0.1733	0.1952	0.2163	0.2007

Table A18. Maximal Voltages of FF-signal for Male subject 4

GRIP TYPE	SPAN (MM)	FINGER	ELBOW 0°	30°	60°	90°	120°
Traditional	50	FF1	0.2954	0.2465	0.2914	0.2510	0.2197
		FF2	0.5760	0.6142	0.6494	0.6350	0.5676
		FF3	0.1040	0.1372	0.2890	0.1909	0.1747
		FF4	0.1189	0.1040	0.0996	0.1286	0.1030
	60	FF1	0.2465	0.2138	0.2363	0.3227	0.1885
		FF2	0.6386	0.5761	0.640	0.5979	0.5690
		FF3	0.0864	0.1293	01421	0.099	0.1821
		FF4	0.1152	0.1044	0.1159	0.1220	0.0956
	70	FF1	0.2470	0.2836	0.2036	0.1895	0.2089
		FF2	0.6796	0.6150	0.6045	0.6490	0.5996
		FF3	0.1142	0.1382	0.1552	0.1641	0.0770
		FF4	0.1064	0.1056	0.1125	0.1123	0.1015
Reversed	50	FF4	0.2217	0.1928	0.1953	0.2305	0.1884
		FF3	0.7114	0.6186	0.6142	0.6590	0.6474
		FF2	0.3716	0.2426	0.1982	0.2856	0.2338
		FF1	0.1089	0.1035	0.096	0.1022	0.1025
	60	FF4	0.2143	0.1914	0.1953	0.2426	0.2285
		FF3	0.7446	0.6494	0.6318	0.7412	0.7270
		FF2	0.4047	0.2890	0.2379	0.3930	0.3183
		FF1	0.1035	0.0996	0.1015	0.1044	0.1064
	70	FF4	0.2217	0.2344	0.2256	0.1938	0.2124
		FF3	0.6640	0.6690	0.6300	0.6162	0.6064
		FF2	0.2856	0.1899	0.1982	0.2167	0.2167
		FF1	0.1125	0.0958	0.1127	0.1030	0.1030

Table A19. Maximal Voltages of FF-signal for Male subject 5*

GRIP TYPE	SPAN (MM)	FINGER	ELBOW 0°	30°	60°	90°	120°
Traditional	50	FF1	0.1567	0.2041	0.1548	0.1943	0.1665
		FF2	0.2783	0.2231	0.2744	0.3213	0.2573
		FF3	0.2432	0.2793	0.2705	0.4053	0.1870
		FF4	---	---	---	---	---
	60	FF1	0.1616	0.1797	0.1479	0.2271	0.1689
		FF2	0.3407	0.3667	0.2017	0.4590	0.1416
		FF3	0.2017	0.2598	0.2676	0.3149	0.2310
		FF4	---	---	---	---	---
	70	FF1	0.1611	0.1577	0.1553	0.2427	0.1582
		FF2	0.3130	0.1147	0.2881	0.3652	0.2993
		FF3	0.2358	0.2236	0.2637	0.3604	0.2637
		FF4	---	---	---	---	---
Reversed	50	FF4	0.1514	0.1426	0.1377	0.1502	0.1302
		FF3	0.3099	0.2217	0.1846	0.3965	0.2210
		FF2	0.3232	0.1665	0.1987	0.1989	0.2623
		FF1	---	---	---	---	---
	60	FF4	0.1406	0.1689	0.1431	0.1675	0.1504
		FF3	0.2729	0.2275	0.1689	0.2574	0.2461
		FF2	0.2861	0.4385	0.3140	0.3228	0.2848
		FF1	---	---	---	---	---
	70	FF4	0.1665	0.1356	0.1767	0.1460	0.1460
		FF3	0.2163	0.2597	0.2539	0.2559	0.2457
		FF2	0.3062	0.3770	0.3384	0.2456	0.1929
		FF1	---	---	---	---	---

Table A20. Maximal Voltages of FF-signal for Male subject 6*

GRIP TYPE	SPAN (MM)	FINGER	ELBOW 0°	30°	60°	90°	120°
Traditional	50	FF1	0.1816	0.2402	0.1616	0.1943	0.1579
		FF2	0.3364	0.4209	0.3515	0.3213	0.2495
		FF3	0.3359	0.3267	0.2871	0.4053	0.3350
		FF4	---	---	---	---	---
	60	FF1	0.1968	0.2402	0.1616	0.2271	0.1479
		FF2	0.3389	0.4209	0.3515	0.4590	0.4204
		FF3	0.3647	0.3267	0.2871	0.3149	0.3647
		FF4	---	---	---	---	---
	70	FF1	0.1647	0.1440	0.2368	0.1987	0.1795
		FF2	0.2026	0.3218	0.2803	0.2344	0.3076
		FF3	0.2979	0.3208	0.3350	0.3511	0.2906
		FF4	---	---	---	---	---
Reversed	50	FF4	0.1489	0.1665	0.1792	0.1802	0.1602
		FF3	0.3906	0.4644	0.3921	0.3965	0.2710
		FF2	0.4409	0.3428	0.3701	0.3989	0.4546
		FF1	---	---	---	---	---
	60	FF4	0.1406	0.1587	0.1479	0.1675	0.1421
		FF3	0.3799	0.4155	0.4204	0.3574	0.3906
		FF2	0.4736	0.4595	0.3647	0.3228	0.3887
		FF1	---	---	---	---	---
	70	FF4	0.1465	0.1440	0.1553	0.1812	0.1450
		FF3	0.3101	0.3218	0.4209	0.2827	0.3208
		FF2	0.5239	0.3208	0.3072	0.3418	0.2360
		FF1	---	---	---	---	---

Table A21. Maximal Voltages of FF-signal for Male subject 7*

GRIP TYPE	SPAN (MM)	FINGER	ELBOW 0°	30°	60°	90°	120°
Traditional	50	FF1	0.3247	.2778	0.3174	0.2896	0.2895
		FF2	0.3615	0.3610	0.3425	0.3684	0.3806
		FF3	0.1895	0.2505	0.2241	0.2519	0.1772
		FF4	---	---	---	---	---
	60	FF1	0.2666	0.2661	0.2793	0.3394	0.2052
		FF2	0.3639	0.3091	0.3218	0.3859	0.2625
		FF3	0.2124	0.1855	0.1880	0.2773	0.1367
		FF4	---	---	---	---	---
	70	FF1	0.2720	0.2241	0.2354	0.2480	0.2271
		FF2	0.3698	0.3379	0.3135	0.3684	0.3320
		FF3	0.2095	0.1851	0.1890	0.2080	0.2002
		FF4	---	---	---	---	---
Reversed	50	FF4	0.1992	0.2085	0.1728	0.1978	0.1655
		FF3	0.3708	0.3674	0.3669	0.3732	0.2451
		FF2	0.2466	.2585	0.2862	0.2867	0.2578
		FF1	---	---	---	---	---
	60	FF4	0.1987	0.1938	0.1938	0.2085	0.1812
		FF3	0.3649	0.3708	0.3708	0.3684	0.3208
		FF2	0.3053	0.3398	0.3398	0.3721	0.3164
		FF1	---	---	---	---	---
	70	FF4	0.2021	0.1802	0.2136	0.1758	0.1841
		FF3	0.2679	0.2778	0.2708	0.2847	0.2690
		FF2	0.2766	0.2495	0.2667	0.3276	0.2066
		FF1	---	---	---	---	---

Table A22. Maximal Voltages of FF-signal for Female Subject 1*

GRIP TYPE	SPAN (MM)	FINGER	ELBOW 0°	30°	60°	90°	120°
Traditional	50	FF1	0.2251	0.2446	0.2007	0.2192	0.2358
		FF2	0.2762	0.2723	0.2815	0.2688	0.2815
		FF3	0.0610	0.0635	0.0796	0.0700	0.0400
		FF4	---	---	---	---	---
	60	FF1	0.1870	0.2031	0.2085	0.2217	0.1943
		FF2	0.2770	0.2732	0.2781	0.2840	0.1273
		FF3	0.070	0.0732	0.0781	0.0840	0.0723
		FF4	---	---	---	---	---
	70	FF1	0.1738	0.2046	0.2045	0.1851	0.1650
		FF2	0.2424	0.2356	0.2678	0.2688	0.2262
		FF3	0.0776	0.5630	0.0786	0.0601	0.5070
		FF4	---	---	---	---	---
Reversed	50	FF4	0.2080	0.1787	0.2207	0.2007	0.2251
		FF3	0.1723	0.1606	0.1708	0.1713	0.1752
		FF2	0.2588	0.2163	0.2622	0.0095	0.1387
		FF1	---	---	---	---	---
	60	FF4	0.1992	0.1650	0.1694	0.2012	0.2207
		FF3	0.1742	0.1732	0.1723	0.1790	0.1718
		FF2	0.1855	0.2558	0.2622	0.2417	0.1514
		FF1	---	---	---	---	---
	70	FF4	0.2168	0.1567	0.1728	0.2178	0.1792
		FF3	0.0894	0.0725	0.0718	0.0728	0.0830
		FF2	0.1631	0.2305	0.2407	0.2061	0.2319
		FF1	---	---	---	---	---

Table A23. Maximal Voltages of FF-signal for Female Subject 2*

GRIP TYPE	SPAN (MM)	FINGER	ELBOW 0°	30°	60°	90°	120°
Traditional	50	FF1	0.1328	0.1958	0.1260	0.1646	0.1245
		FF2	0.1318	0.1045	0.1387	0.0996	0.1230
		FF3	0.1157	0.0991	0.1096	0.0732	0.1191
		FF4	---	---	---	---	---
	60	FF1	0.1387	0.1953	0.1450	0.2056	0.2124
		FF2	0.1860	0.2319	0.1406	0.0947	0.1416
		FF3	0.1187	0.0552	0.1440	0.0669	0.0845
		FF4	---	---	---	---	---
	70	FF1	0.2129	0.1357	0.1587	0.1934	0.1304
		FF2	0.2627	0.1470	0.1475	0.2144	0.1240
		FF3	0.0879	0.1167	0.1259	0.1152	0.1153
		FF4	---	---	---	---	---
Reversed	50	FF4	0.1221	0.1265	.1528	0.1655	0.1216
		FF3	0.1890	0.1274	0.3042	0.1157	0.1763
		FF2	0.1875	0.0630	0.2949	0.2380	0.1669
		FF1	---	---	---	---	---
	60	FF4	0.1426	0.1230	0.1240	0.1577	0.1382
		FF3	0.1494	0.1631	0.1924	0.1987	0.1719
		FF2	0.2544	0.1724	0.2304	0.2651	0.2300
		FF1	---	---	---	---	--
	70	FF4	0.1274	0.1240	0.1274	0.1509	0.1304
		FF3	0.1421	0.1880	0.1758	0.1782	0.1885
		FF2	0.2061	0.1216	0.1929	0.2422	0.2368
		FF1	---	---	---	---	---

Table A24. Maximal Voltages of FF-signal for Female Subject 3*.

GRIP TYPE	SPAN (MM)	FINGER	ELBOW 0°	30°	60°	90°	120°
Traditional	50	FF1	0.1694	0.1484	0.1943	0.1826	0.1934
		FF2	0.3599	0.1519	0.1982	0.1308	0.1221
		FF3	0.2148	0.0991	0.1797	0.1333	0.1123
		FF4	---	---	---	---	---
	60	FF1	0.1304	0.2114	0.2075	0.1523	0.1904
		FF2	0.1909	0.1738	0.2227	0.1304	0.1440
		FF3	0.1372	0.1357	0.1587	0.1333	0.0884
		FF4	---	---	---	---	---
	70	FF1	0.2378	0.2197	0.1846	0.1563	0.2095
		FF2	0.2798	0.1997	0.1889	0.1333	0.1641
		FF3	0.1025	0.1304	0.1264	0.0801	0.0908
		FF4	---	---	---	---	---
Reversed	50	FF4	0.1401	0.1323	0.1484	0.1284	0.1445
		FF3	0.1973	0.2539	0.2646	0.2300	0.2070
		FF2	0.2749	0.2051	0.2227	0.1929	0.1802
		FF1	---	---	---	---	---
	60	FF4	0.1484	0.1421	0.1455	0.1284	0.1382
		FF3	0.2129	0.2153	0.2305	0.2319	0.2192
		FF2	0.2910	0.2861	0.2324	0.1929	0.2197
		FF1	---	---	---	---	---
	70	FF4	0.1416	0.1665	0.1299	0.1289	0.1445
		FF3	0.1777	.1919	0.1509	0.1641	0.1070
		FF2	0.1998	0.2427	0.1123	0.2388	0.1802
		FF1	---	---	---	---	---

Table A25. Maximal Voltages of FF-signal for Female Subject 4*

GRIP TYPE	SPAN (MM)	FINGER	ELBOW 0°	30°	60°	90°	120°
Traditional	50	FF1	0.1587	0.1553	0.1621	0.2563	0.1499
		FF2	0.1753	0.1772	0.2300	0.1226	0.1606
		FF3	0.1772	0.1362	0.2388	0.1475	0.1484
		FF4	---	---	---	---	---
	60	FF1	0.1851	0.1733	.1450	0.1694	0.1349
		FF2	0.1211	0.1128	0.1406	0.1196	0.1191
		FF3	0.0635	0.1123	0.1444	0.1537	0.1143
		FF4	---	---	---	---	---
	70	FF1	0.2378	0.1602	0.2017	0.1714	0.2510
		FF2	0.1128	0.1484	0.1294	0.1191	0.1270
		FF3	0.0560	0.1387	0.0557	0.1370	0.0463
		FF4	---	---	---	---	--
Reversed	50	FF4	0.2075	0.1528	.1528	0.1909	0.1484
		FF3	0.1323	0.1377	0.3042	0.1206	0.1206
		FF2	0.0425	0.1797	0.2949	0.0942	0.1046
		FF1	---	---	---	---	---
	60	FF4	0.1646	0.1450	0.1470	0.1968	0.1777
		FF3	0.1318	0.2563	0.2573	0.1504	0.1304
		FF2	0.2061	0.3047	0.1914	0.2227	0.1738
		FF1	---	---	---	---	---
	70	FF4	0.1362	0.1479	0.2070	0.1929	0.1567
		FF3	0.2095	0.1348	0.1499	0.1479	0.1309
		FF2	0.2056	0.2212	0.2305	0.1797	0.1724
		FF1	---	---	---	---	---

Table A26. Maximal Voltages of FF-signal for Female Subject 5.

GRIP TYPE	SPAN (MM)	FINGER	ELBOW 0°	30°	60°	90°	120°
Traditional	50	FF1	0.1720	0.1865	0.1572	0.1934	0.1948
		FF2	0.6577	0.5347	.5303	0.5269	0.5273
		FF3	0.1582	0.078	0.0605	0.0464	0.0508
		FF4	0.1518	0.1470	0.1558	0.1758	0.1704
	60	FF1	0.2300	0.1763	0.1792	0.1880	0.1663
		FF2	0.6723	0.5273	0.5269	0.5303	0.5488
		FF3	0.1640	0.0596	0.0454	0.0493	0.1025
		FF4	0.1513	0.1206	0.1177	0.1572	0.1234
	70	FF1	0.2227	0.1636	0.1943	0.1899	0.1788
		FF2	0.5400	0.7173	0.5244	0.5220	.5110
		FF3	0.0625	0.1045	0.0625	0.0459	0.0464
		FF4	0.1294	0.1021	0.1362	0.1240	0.1265
Reversed	50	FF4	0.1738	.1592	0.1528	0.1460	0.1372
		FF3	0.6938	0.6108	0.6177	0.5718	0.5996
		FF2	0.2588	0.2192	0.2168	.1919	0.1909
		FF1	0.1987	0.261	0.2061	0.2090	0.1937
	60	FF4	0.2212	0.1587	0.1445	0.1558	0.1470
		FF3	0.6274	0.6372	0.5967	0.5884	0.6138
		FF2	0.2476	0.2568	0.2143	0.1943	0.1655
		FF1	0.2563	0.2588	0.1865	0.2632	0.1895
	70	FF4	0.1533	0.1558	0.1523	0.1523	0.1491
		FF3	0.5781	0.6162	0.5903	0.5657	0.5841
		FF2	0.1523	0.1929	0.2139	0.2138	0.2012
		FF1	0.1860	0.2178	0.2520	0.2520	0.2295

Table A27. Maximal Voltages of FF-signal for Female Subject 6.

GRIP TYPE	SPAN (MM)	FINGER	ELBOW 0°	30°	60°	90°	120°
Traditional	50	FF1	0.1772	0.1622	0.1844	0.1641	0.1355
		FF2	0.6577	0.6855	0.6742	0.6533	0.6241
		FF3	0.1582	0.0840	0.0741	0.0752	0.0770
		FF4	0.1518	0.1628	0.1422	0.1452	0.1644
	60	FF1	0.2300	0.2133	0.2455	0.2122	0.2300
		FF2	0.6723	0.6587	0.6060	0.6223	0.6221
		FF3	0.1640	0.1755	0.1855	0.1847	0.1633
		FF4	0.1513	0.2258	0.2383	0.2160	0.2247
	70	FF1	0.1786	0.1831	0.1752	0.1832	0.1710
		FF2	0.6396	0.5947	0.6102	0.6245	0.5863
		FF3	0.1142	0.1177	0.1256	0.1478	0.1130
		FF4	0.1523	0.1626	0.1644	0.1455	0.1366
Reversed	50	FF4	0.2456	0.2856	0.2710	0.2630	0.2214
		FF3	0.6542	0.6410	0.6323	0.6741	0.5987
		FF2	0.2456	0.3012	0.2854	0.2412	0.2300
		FF1	0.2488	0.2844	0.2546	0.2711	0.2416
	60	FF4	0.2212	0.2165	0.2410	0.2010	0.2077
		FF3	0.6274	0.6223	0.6005	0.6589	0.5966
		FF2	0.2476	0.2569	0.2477	0.2600	0.2379
		FF1	0.2563	.2576	0.2576	0.2144	0.2000
	70	FF4	0.1400	0.1875	0.1955	0.2056	0.1765
		FF3	0.5874	0.6012	0.5941	0.5602	0.5720
		FF2	0.1416	0.1651	0.1325	0.1231	0.1541
		FF1	0.2651	0.2844	0.2311	0.2412	0.2100

Table A28. Maximal Voltages of FF-signal for Female Subject 7*.

GRIP TYPE	SPAN (MM)	FINGER	ELBOW 0°	30°	60°	90°	120°
Traditional	50	FF1	0.1820	0.2248	0.2427	0.2204	0.2457
		FF2	0.2359	0.2157	0.2774	0.2066	0.2371
		FF3	0.1238	0.1256	0.1507	0.1275	0.1032
		FF4	---	---	---	---	---
	60	FF1	0.2254	0.2301	0.2456	0.2612	0.2284
		FF2	0.2510	0.2614	0.2374	0.2410	0.2253
		FF3	0.1302	0.1411	0.1570	0.1332	0.1240
		FF4	---	---	---	---	---
	70	FF1	0.1785	0.2145	0.2310	0.2014	0.2002
		FF2	0.2251	0.2410	0.2388	0.2175	0.2011
		FF3	0.1302	.1322	0.1440	0.1120	0.1130
		FF4	---	---	---	---	---
Reversed	50	FF4	0.1653	0.1718	0.1531	0.1605	0.1695
		FF3	0.2056	0.2102	0.2751	0.1930	0.1781
		FF2	0.1930	0.1462	0.2202	0.1281	0.1573
		FF1	---	---	---	---	---
	60	FF4	0.1707	0.1735	0.1713	0.1625	0.1599
		FF3	0.1825	0.2203	0.2314	0.1987	0.1788
		FF2	0.2193	0.2230	0.1939	0.2204	0.2040
		FF1	---	---	---	---	---
	70	FF4	0.1617	0.1606	0.1582	0.1589	0.1525
		FF3	0.1790	0.1849	0.1689	0.1724	0.1986
		FF2	0.1923	0.1978	0.1910	0.2181	0.1941
		FF1	---	---	---	---	---

*Channel 4 load cell was used to measure the middle finger in traditional grip and the ring finger in reversed grip

PART E

CONVERSION CONSTANTS AND OFFSET

CHANNEL	CH #1	CH #2	CH #3	CH #4
Offset (V)	0.1339	0.4982	0.0395	0.1048
Constant (LB/V)	82.88	74.90	69.18	71.79

PART F

DATA FOR CALCULATING ACTUAL FINGER FORCE

Table A29: Average x values measured at different load cells and grip spans (in mm)

	LOAD CELL #1	LOAD CELL #2	LOAD CELL #3	LOAD CELL #4
Span 50 mm	5.5	6.0	6.0	6.0
60 mm	10.1	13.0	14.5	16.2
70 mm	12.4	16.0	19.1	20.1

Table A30: Average l values measured at different load cells

	LOAD CELL #1	LOAD CELL #2	LOAD CELL #3	LOAD CELL #4
L (mm)	88	112	134	157

VITA AUCTORIS

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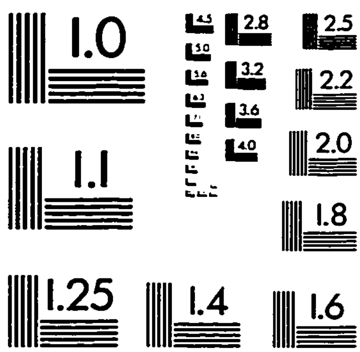
IMAGE EVALUATION
TEST TARGET (QA-3)



150mm

6"

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