



Developing predictive models for hand strength in dynamic grasping tasks based on static grip strength and anthropometric measures
by Robert S Howell

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science In
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Abstract:

Despite various efforts to reduce the risk of musculoskeletal disorders (MSD), they are still on the rise. One particular area of concern is hand tool design, which if done improperly can increase the likelihood of Carpal Tunnel Syndrome and other MSD's.

These disorders, if ignored, can lead to debilitating injuries which could have been prevented. It is therefore important to examine how hand tools are used and simulate their use to determine what factors affect an individual's strength.

This study was aimed at identifying variables that affect dynamic grip strength, and the displacement at which the peak force occurs under a dynamic condition. This was done by simulating a cross action tool (eg. cutting or compression tool) motion using a LIDO Workset under laboratory conditions. The tasks variables included: wrist posture (45 degrees flexion, neutral, and 45 degrees extension), rate of closure (2.85, 8.60, and 14.4 cm/sec) and initial displacement (9 and 11 cm). Thirty male college students served as human subjects for the study. Each subject was screened for any upper-extremity disorders before being allowed to participate. The LIDO workset, Data translation board, Labtech software, an IBM compatible workstation, and an anthropometric measuring kit were other pieces of equipment used in the study.

A randomized block design was used to model the experiment and ANOVA was used to test whether the variables and interactions were significant. Along with the ANOVA, Tukey's test and a graphical approach were used to test for significant difference between levels of each variable and to evaluate the effects of the independent variables on the dependent variable.

The results of the analysis of the data recorded during the study showed that the greatest force of 408 newtons can be generated at a displacement of 5 cm, with a combination of 2.85 cm/sec velocity, neutral posture, and an initial handle displacement of 9 cm. And at 11 cm initial displacement, a force of 359 newtons can be generated at a displacement of 4.3 cm, with a combination of 2.85 cm/sec velocity and a neutral posture. Throughout the study, and as expected, it was found that a slower velocity allows an individual to produce greater forces. Also, when the wrist is deviated by 45 degrees in a flexion or extension positions, the forces generated are significantly reduced. An initial displacement of 9 cm allows individuals to produce higher forces, as opposed to 11 centimeters. It is speculated that beyond 11 centimeters, most individuals hands and muscles are stretched, creating a muscular disadvantage. Also it was found that at 2.86 and 14.4 cm/sec the dynamic forces generated were significantly higher and lower respectfully, than the static forces the subjects produced. Along with this information, dynamic grip strength profiles and three dimensional graphs have been produced and an attempt was made to develop reliable predictive dynamic grip strength models.

The conclusion reached from the results of the analysis was that wrist posture, velocity, and displacement had significant effects on the amount of force and on the displacement of the peak force.

Although the results of the predictive models proved to be of limited usage for industrial applications, they may be a starting point from which designers can build a foundation. And with the knowledge gained from this study, tool designers can now begin to evaluate hand tools and reduce the risk of MSDs.

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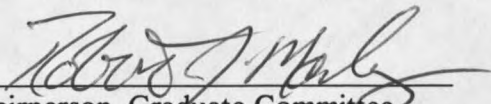
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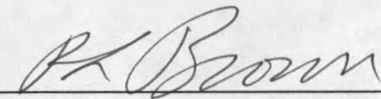
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ABSTRACT

Despite various efforts to reduce the risk of musculoskeletal disorders (MSD), they are still on the rise. One particular area of concern is hand tool design, which if done improperly can increase the likelihood of Carpal Tunnel Syndrome and other MSD's. These disorders, if ignored, can lead to debilitating injuries which could have been prevented. It is therefore important to examine how hand tools are used and simulate their use to determine what factors affect an individual's strength.

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The conclusion reached from the results of the analysis was that wrist posture, velocity, and displacement had significant effects on the amount of force and on the displacement of the peak force. Although the results of the predictive models proved to be of limited usage for industrial applications, they may be a starting point from which designers can build a foundation. And with the knowledge gained from this study, tool designers can now begin to evaluate hand tools and reduce the risk of MSDs.

CHAPTER 1

INTRODUCTION

Although today's society is experiencing great advancements in technology, the human body is being pushed to perform at a faster production rate and perform more detailed work than ever before. For example, the automotive mechanic must loosen or tighten a bolt in tighter areas of the car and the electronic technician must perform maintenance on smaller electronic devices. These types of activities are increasing the cases of musculoskeletal disorder (MSD). In 1992, repetitive strain injuries accounted for 56% of all gradual-onset workplace illness in the U.S., and were estimated to cost \$20 million every year in medical bills and employee absenteeism. Treatment often is not a cure. Because MSD can be permanently debilitating, the best medical advice is prevention. Therefore it is necessary to better clarify risks surrounding MSD. It is usually caused by excessive force, high frequency of repetition, awkward postures, vibrations, inadequate recovery, and extreme temperature conditions (Stock, 1991).

In the United States, the usage of hand tools accounts for approximately 10% of all industrial injuries (Mital, 1986). One of the most well-known MSDs is Carpal Tunnel Syndrome (CTS). In this situation, the median nerve becomes compressed in the wrist canal or can become inflamed (Armstrong and Chaffin, 1979). The inflammation leads to numbness, tingling in the fingers, pain in the hand, and a reduction of overall hand strength. There is documented data which indicates that people are developing CTS while

working with cross-action hand tools that require high gripping forces, such as staple guns, pliers, tongs, and wire crimpers (Armstrong, 1986; Hymovich and Lindhulm, 1966; Hoffman, et al., 1985).

Research on maximum grip strength can lead to an understanding of and possible solutions to these problems. Many research studies have been carried out, utilizing various methodologies, for the determination of maximum grip strength. The biomechanical method has been used by many researchers in the past to measure maximum grip strength. Biomechanics uses physics and engineering concepts to describe the motion of a body part and the forces acting on it. Of all the research methods available, the biomechanical method is an appropriate method for this study.

For the purposes of this study, there are two types of grip actions: static and dynamic. A static grip is one in which the hand exerts a force while remaining motionless, like a vice. A dynamic grip is one in which the hand exerts a force over a range of motion, before reaching a static grip.

Although many studies of grip strength have been reported, very little research has been done to determine the maximum dynamic grip strength; the majority of studies have been limited by the use of conventional hand dynamometers, which give only a static grip strength value. (These values, while useful in defining the absolute grip strength under controlled conditions, may not be applicable in the design of hand tools. Most actual gripping situations are dynamic.) For example, cross-action tools require a substantial amount of force at varied velocities of closing.

Such factors as the initial handle displacement and the dynamic resistance to handle closure become more relevant in such situations. These factors can only be examined in a study of dynamic grip strength.

Although there have been numerous grip strength studies, only one author, Frederick E. Fitzhugh, has done extensive research in the area of dynamic grip strength (Fitzhugh, 1973). While Fitzhugh's studies were done over twenty years ago with tools that are not as accurate as current technology, they have laid a foundation for current dynamic grip strength research. He looked at a variety of initial handle displacements and different velocities, and found where the maximum grip strength occurs. However, he only looked at specific points within a range. With this information, he visualized a three dimensional surface and speculated on its application to tool design. (See Figure 1.1)

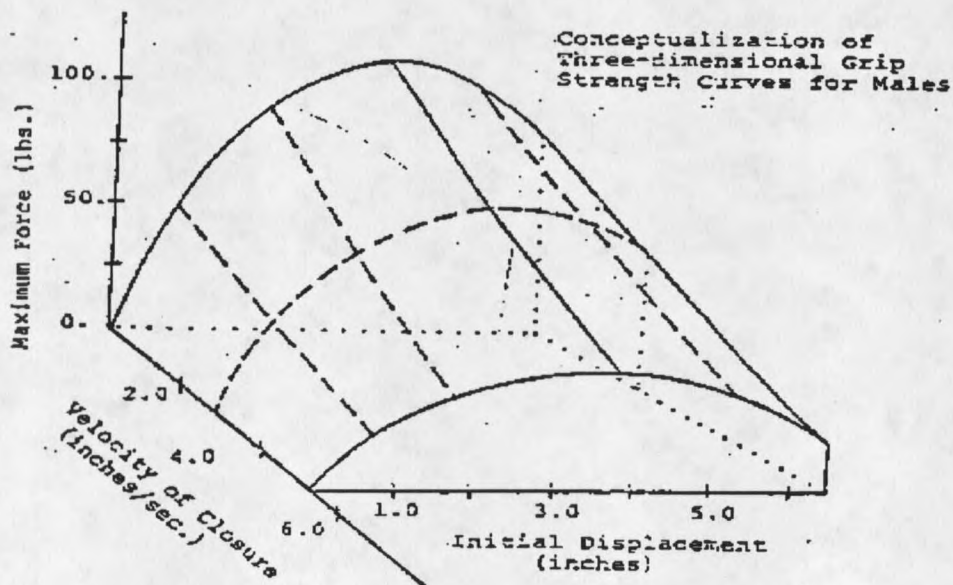


Figure 1.1: Conceptual Three Dimensional Surface Response (Fitzhugh, 1973a)

With today's technology, it is possible to examine the entire curve of the range of motion and to produce the actual surface response, similar to what Fitzhugh had visualized. In addition, Fitzhugh's studies did not examine deviated wrist postures, which is now known to be a key factor in the development of upper-extremity MSDs.

The present study is intended to determine the displacement of peak force and the maximum grip strength attainable through different velocities of closure, displacement of the handles, and different wrist postures. This information will be used to develop a three-dimensional curve of the dynamic grasping motion. This study will also examine the relation between anthropometric data and dynamic grip strength to develop predictive models.

With this information, toolmakers will be able to determine the maximum force that an individual is able to exert under different conditions. This will allow them to develop tools that better fit the population, thus reducing possible incidence of upper-extremity MSD.

CHAPTER 2

LITERATURE REVIEW

Introduction

Until recently, workers relied on trial and error procedures to find the right tool for the job. The tool was often judged on its effectiveness, how it felt, the balance, and its weight and shape. With the development of ergonomic principles, the following four guidelines have been developed to aid in selecting the correct tools (Putz-Anderson, 1988):

1. Avoid high contact forces and static loading.
2. Avoid extreme or awkward joint positions.
3. Avoid repetitive finger action.
4. Avoid tool vibration.

This paper will primarily research the areas of high contact forces and awkward positions to determine the effects they have on hand grip strength.

Anatomy / Physiology of the Hand

The hand is a complex system of muscles, tendons, bones, joints, and nerves, all working in unison to perform an array of tasks. Following is a brief overview of the functional structure of the hand.

The majority of the muscles of the hand and wrist lie in the forearm and narrow into tendons which cross the wrist and connect to the bones or ligamentous components of the hand. All of the muscles which provide the wrist movement pass over the carpus and insert into the bones of the metacarpals. The fingers are flexed by muscles in the forearm. The muscles are connected to the fingers by flexor tendons which pass through a channel in the wrist. This channel, the carpal tunnel, is formed by the bones of the back of

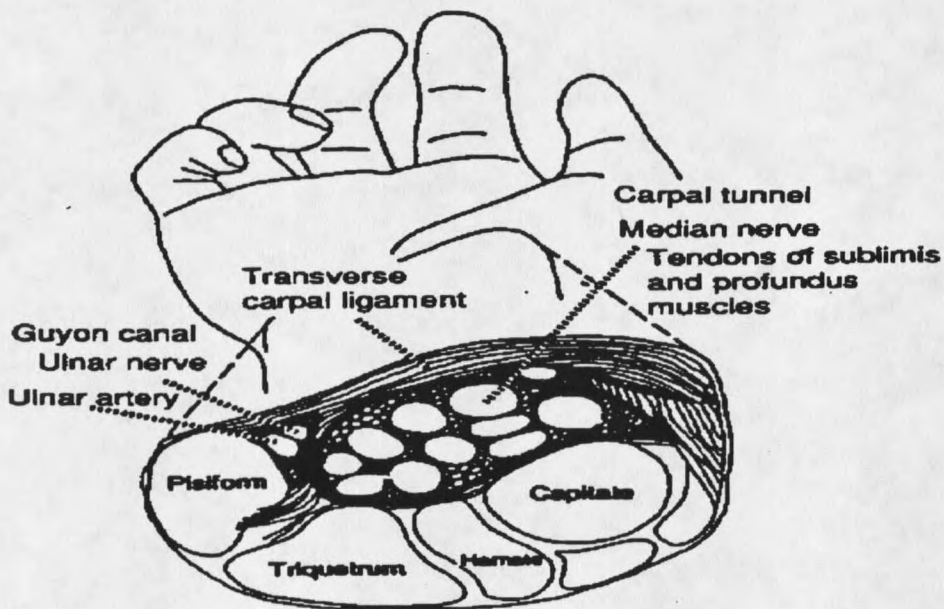


Figure 2.1: Anatomy of the Wrist (Kroemer, 1994)

the hand on one side and the transverse carpal ligament on the other. Through the carpal tunnel pass a host of anatomical structures, including the radial artery and the median nerve. (See Figure 2.1) The median nerve can be damaged due to repetitive motions (Kroemer, 1994). Repetitive motions cause the nerve to wear against the bone until permanent nerve damage occurs (Kroemer, 1994).

The tissues of each individual have a threshold of resistance to pathological change (Meagher, 1971). If the human hand uses a defective tool or exerts high grip strength for long periods of time, this threshold will be crossed and a musculoskeletal disorder (MSD), such as Carpal Tunnel Syndrome (CTS), may result (Kroemer, 1994). These disorders are characterized by pain, numbness, and a reduction in hand strength, and can often remain for the person's lifetime. For this reason, the hand tool designer must take extra care in specifying the size, shape, texture and length of the tool handle (Meagher, 1986).

The small muscles of the hand stabilize the hand during forceful use and act as modifiers of the long flexor and extensor muscles of the forearm during fine manipulative movements (Eastman Kodak, 1986). Therefore it is necessary to be certain the tool design features will not unduly stress these muscles with difficult openings and closures and handle sizes that are too large.

Biomechanics

The general concern in occupational biomechanics is to determine the internal and external forces a person can physically (mechanically) produce and tolerate. In an industrial setting, this means that the person's physical capabilities must be assessed along with the physical demands of a prospective job. In addition to the simple ability to perform, biomechanics is concerned with those physical attributes of the individual and job that have been found to produce harm to the musculoskeletal system (NIOSH, 1981).

Static Grip Strength Studies

In 1991 Fransson and Winkel performed a study in which a pair of channel-lock pliers were used to measure the resultant force (RF) between the jaws of the tool at different distances of handle separation. It was found that the RF varied according to the distance between the handles, and the highest RF was obtained at handle separation of 5.0 to 6.0 cm for females and 5.5 to 6.5 cm for males. It was also found that at wide (above 6.0 cm) handle separations, the RF was reduced by 10% for both genders (Fransson and Winkel, 1991).

Radwin and Oh did a study in 1993 which investigated the effect of handle size and trigger type on forces and exertions produced during pistol grip pneumatic power tool operation. The results of these experiments showed that handle span affected submaximal finger and palmer forces. Peak finger forces increased 24% for the student group and 30% for the worker group as handle span increased from 4 cm to 7 cm. Similarly, peak palmer force increased 22% for both groups as the handle span increased from 4-7 cm. Handle size affected grip strength, hand force, and exertion level. Large-handed subjects could exert greater forces on wider handle spans (Radwin and Oh, 1993).

In 1993, Dahalan and Fernandez conducted an experiment to determine the maximum acceptable frequency for a simulated gripping task at different gripping forces and durations using a psychophysical protocol. The subjects adjusted the frequency of grasping a modified hand dynamometer at set levels of forces and durations. They found that effects of gripping force and gripping duration did not have a significant effect on the

mean heart rate and the mean diastolic blood pressure, which indicated that physiological studies are not applicable for most hand grip strength studies.

The study also concluded that the maximum acceptable frequency exponentially decreased with increasing gripping force and duration of grip. Furthermore, it was documented that the gripping task at 70% maximum voluntary contraction was an unacceptable level (Dahalan and Fernandez, 1993).

In a study by Marley, Debree, and Wehrman in 1993; the effect of wrist, forearm, and elbow posture on maximum grip strength was evaluated. The study examined the effect of 30 different upper-extremity postural combinations on the maximum grip strength. The results revealed that wrist, forearm, and elbow postures are interactive and should be considered when assessing the capability to apply grip force in a non-standard posture. It also confirmed that the greatest strength can be obtained when the arm is in a standard posture, with a neutral wrist, 90 degree elbow flexion, and the upper arm adducted at the shoulder. Once the wrist, forearm, or elbow deviates from the normal, the grip strength is typically reduced. Specifically, in the flexion wrist position, the forces decreased greater than in the extension position; and, the pronation position produced higher forces than the supination position (Marley, Debree, and Wehrman, 1993).

The purpose of a study on static grip with dynamic wrist motion by Lehman, Allread, Wright, and Marras was to determine if the velocity and postures of the wrist had a significant effect on grip force. Subjects exerted a maximum static force on a dynamometer. Then the action was repeated and held while moving their wrist to a predetermined posture at a given velocity. The results showed that at all directions of motions, grip forces for all isokinetic conditions were significantly lower than for the isometric exertions.

Dynamic Grip Strength Studies

Fitzhugh performed a series of experiments in 1973, the first of which was to determine how the maximum force attainable in a dynamic grip was affected by the initial size opening of the grip and the velocity of closure. In the static case, the initial handle displacement of the pivoting-type handtool greatly affects the maximum force attainable in the grip. In the dynamic case, however, the effective displacement of the handles is changing while the force is approaching a maximum. The initial displacement of 8 cm resulted in greater forces generated, while for larger initial handle openings (above 8.9 cm), it is in many cases necessary to reposition the hand to obtain a better grip for further force application during the grasp. Also, it was found that the maximum force attainable in a grip exertion is very dependent on the velocity of closure. Fitzhugh documented that as the velocity of closure increases, maximum force attainable decreases almost linearly.

Fitzhugh used the following settings:

1. Four exertions consisting of a slow velocity (approx 2.286 cm/sec. at four different handle displacements: 6.86, 7.87, 8.6, and 10.16 cm).
2. Three exertions consisting of an initial prescribed handle displacement (8.6 cm) and three different closure velocities (0.0, 5.08, and 10.16 cm/sec.) (Fitzhugh, 1973a).

The objectives of Fitzhugh's second study were to confirm what was found in the first study, but with a larger population, and to develop a model of predicted grip strength based on anthropometric measurements. In this study the author developed models for individual and population grip strength.

The results confirmed those of the first study. It was found that slower velocities produced higher grip strength. Also, higher forces were generated when the initial displacement was between 3.25" and 3.5" at a mean force of 80 lb. Also in this study, the author developed models for individual and population grip strength. Fitzhugh's findings indicate that hand width, hand length, finger length, forearm girth, age, height, and weight correlate significantly with grip strength. Except for age, all these variables relate the size of the individual and therefore are not completely independent. Fitzhugh suggests more research be done on force capabilities of the hand in different orientations and modeling of the dynamic grip strength.

Orientation and Handle Displacement

Grip Strength and Hand/Wrist /Arm Orientation

The "position of function" of the hand, wrist, and arm has been looked at in several studies. The hand position was examined by Marley, et al. (1993). They determined that the forces exerted on a handgrip were higher with the hand in pronation than in supination.

When studying arm configuration, Tichauer (1978) found that the biceps act at best advantage when the forearm is supinated and when the arm is flexed 90 degrees at the elbow.

Kraft and Detels (1972) experimented with four different wrist position configurations and concluded that with normal function in finger, elbow, and shoulder, and with radial-ulnar position held constant, hand strength is poorer with the wrist in the 15 degree flexed position than with the wrist neutral or in extension.

This study also found that the grip strength is related to the velocity of the handle closure in a nearly linear manner with a negative slope.

Grip Strength and Handle Displacement

It is best to avoid gripping requirements in repetitive operations that spread the fingers and thumb apart more than 6.25 cm (Hertzberg, 1955). Cylindrical grasp should not exceed 5 cm in diameter (Pheasant and O'Neill, 1975). An isometric grip performed with parallel handles has been investigated by numerous authors, e.g., Cotten and Johnson (1971), Petrofsky et al. (1980), and Eastman Kodak Company (1986). Most of the studies describe an optimal handle separation, giving maximal force output. This varies between 3.8 cm and 6.4 cm, depending on gender and experimental design. A dynamic grip performed with angulated handles was studied by Fitzhugh (1973a and b). At a closing speed of 2.9 cm/sec, the highest force was developed when using an initial handle separation of 8.3 cm to 8.9 cm. The peak forces were reached at around 5.2 cm.

For cutting and compression tools, such as pliers, scissors, etc., the recommended distance between handles at the point of application of the greatest force is from 6.5 cm to 9.0 cm (Fransson and Winkel, 1991). It is recommended that the outside of the handles should not exceed 9.0 cm for a grip between the third finger and the palm at the base of the thumb (Greenberg and Chaffin, 1977). Figure 2.2 illustrates maximum grip forces as a function of grip span (Eastman Kodak, 1983).

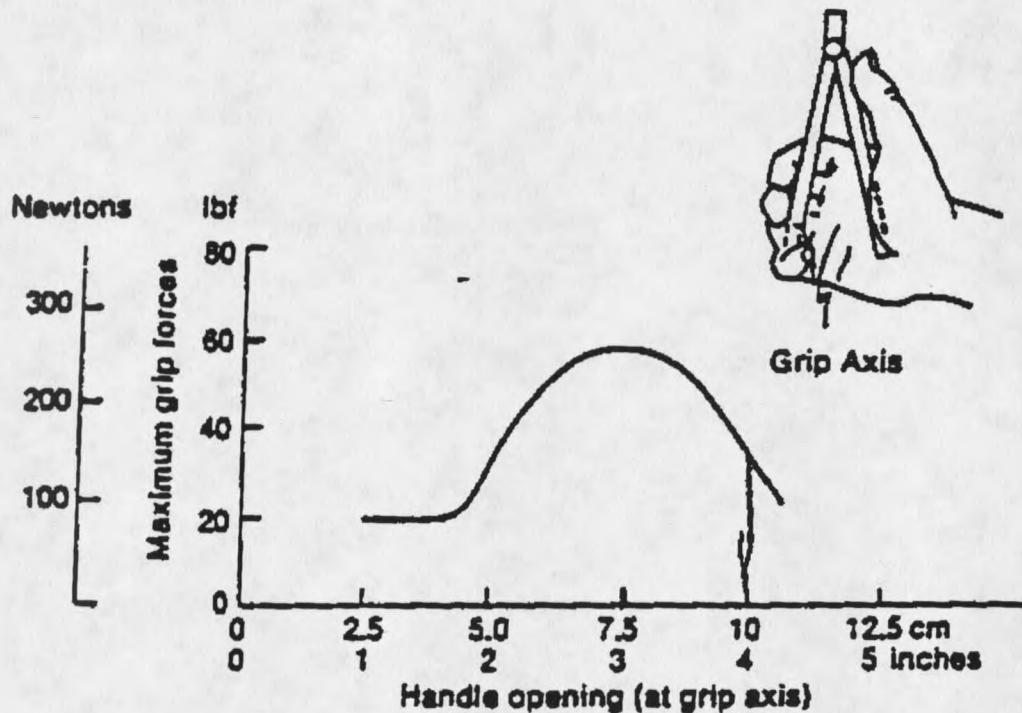


Figure 2.2: Grip Strength

The grasp data shown in Figure 2.3 are from a limited population, but they have proven useful in defining the dimensions of products or containers that are manually handled. From Figure 2.2 it can be seen that the most applicable grasp dimensions are from the oblique (Eastman Kodak Company, 1983).

In 1965, Montoye and Faulkner, looking at the optimum setting for an adjustable dynamometer, found that at grip settings of about 4.5-5.5 cm the performance varied little, regardless of hand size.

Fitzhugh found that the greatest forces were produced with an initial handle displacement between 7.9-8.9 cm, and the peak force occurs at approximately 5.2 cm.



True	4.5 (1.8)	5.5 (2.2)	5.9 (2.3)
Maximum	9.5 (3.7)	11.0 (4.3)	13.0 (5.1)

Span, in centimeters (inches),
50/50 Male/Female Mix

	5th Percentile	50th Percentile	95th Percentile
True	3.6 (1.4)	4.5 (1.8)	5.8 (2.3)
Maximum	9.5 (3.7)	11.0 (4.3)	13.0 (5.1)

Figure 2.3: Oblique Grasp

Summary

There is a growing need for studies of grip strength because of the increasing incidence of musculoskeletal disorder in the workplace. Due to the complexity of the hand, it is necessary to understand its physiological functions and the MSDs that can be caused when these functions are impaired. Static grip strength studies have shown the biomechanical limitations of the hand, including maximum strength for durations and decreased strength with increased hand span stretch and with other than neutral hand, arm, and wrist positions. The studies show that handle span has an effect on the grip strength and that maximum strength cannot be maintained over a period of time.

They conclude in addition that the maximum grip strength occurs when the arm, wrist, and forearm are all in the neutral position, and once the position deviates, the grip strength is reduced.

The limitation of these studies is that most industrial handle tasks are dynamic in nature; factors such as initial handle displacement and dynamic resistance to closure (which in turn affects the velocity of closure) become important in the determination of the grip force. Hence the values obtained from static grip force studies are not totally sufficient to help tool designers improve their products.

Dynamic grip strength studies support these findings and give data on recommended handle displacement. The dynamic studies deal with establishing relationships between grip strength, initial handle displacement, velocity of closure, handle type, and modeling grip strength based on anthropometric measures. The first study concludes that the optimal initial handle displacement is around 8.6 cm and that grip strength is related to velocity of closure in a nearly linear manner with negative slope. The second study used a larger sample size to validate those results. In addition, a general model was made for predicting individual grip strength capability from anthropometry. These studies also recommend areas for further research, including force capabilities of the hand in different orientations and modeling of the dynamic grip strength. Grip strength and orientation studies have shown the interaction between anthropometric measures and grip strength, and by modeling these they can predict an individual's dynamic grip strength.

They have also shown by interpolation that the maximum force occurs at a particular point; however, a true dynamic study would consider a wider range of motion to consider whether there is more than one maximum peak force or any other irregularities in the profile.

The handle displacement studies seem to indicate that there is a wide variation in data on the optimal handle span, probably due to many uncontrolled factors.

The best action now would be to study a wide range of motion and a variety of speeds for the dynamic grip strength to clarify what researchers have found. All of this leads to one conclusion: that there is a need for studies which consider the whole dynamic range of motion, and a need for a model which includes anthropometric data, dynamic grip strength and static grip strength.

CHAPTER 3

RATIONALE AND OBJECTIVES

In the past decade, the number of repetitive injury cases has been on the rise. This is due in part to the complexity of occupational jobs. These problems are gaining the attention of NIOSH and business because of the physical and financial effect they are having, including reduced productivity, lost work time, higher insurance costs and increased disability claims.

Hand strength studies have helped to identify factors that may be causes of or contributing factors to MSD: high force, awkward positions, repetitive motions, and pressure. These risk factors can act separately or in combination to cause MSD. These studies have also laid a foundation for understanding how the hand, wrist, and forearm work together. For example, they have revealed that as an individual deviates from the standard posture, there will typically be a reduction in hand strength. Even with all this information, some critical knowledge is currently missing from the known literature. Many occupational tasks are dynamic in nature and cannot be fully represented in a study of static grip strength. Some researchers have long recognized a need for studies of dynamic grip strength. Many suggestions for optimal forearm/wrist/hand orientations for grip tasks have been made, but few have been presented for dynamic forces.

Characteristics of the exertions made when using cross-action hand tools could be described better if the dynamic aspect were also considered.

The aim of this study will be to quantify maximum grip force during various dynamic exertions throughout different postures of the hand, wrist, and arm, which can simulate compression and cross-action tools, such as pliers and scissors, and to develop ergonomic criteria for such tools. This will be done by accomplishing the following three objectives:

1. To reveal the displacement of peak force, the optimum initial displacement, and the maximum force that an individual can produce given a particular speed of closure (2.85 cm/sec, 8.60 cm/sec, 14.40 cm/sec), wrist position (45° flexion, neutral, 45° extension), and displacement of handles (11 cm, 9 cm).
2. To develop a three-dimensional response curve of dynamic grasping motion at various wrist and arm positions. The three factors involved will be force (N), displacement of the handles (cm), and the rate of closing of the handles (cm/sec).
3. To design a regression model, using a stepwise multiple regression procedure to predict maximum grip strength, and displacement of peak forces based on anthropometric measures and tasks variables.

CHAPTER 4

METHODS AND PROCEDURES

Subjects

Thirty male subjects were randomly selected for this study; the sample size was determined on the basis of previous similar studies, as there has not yet been a study done similar enough to this one to determine statistical significance. The subjects chosen were first questioned about their medical history concerning the upper extremities. If the subjects were free from any disorders, such as carpal tunnel syndrome or other upper-extremity MSDs, they were used in the study. Then each subject was thoroughly familiarized with the experimental procedure and the equipment before beginning the data collection. Consent was duly obtained from each subject. (See Appendix A, Form I.)

Equipment

LIDO Workset, manufactured by Loredan Biomedical, Inc., is designed to provide functional testing and rehabilitation in a single device. The LIDO test validity, intra-test, and test-retest reliability have been shown to be extremely high (Matheson, et.al 1992). The actuator, shown in Figure 4.1, is the controlling component of the LIDO Workset system.

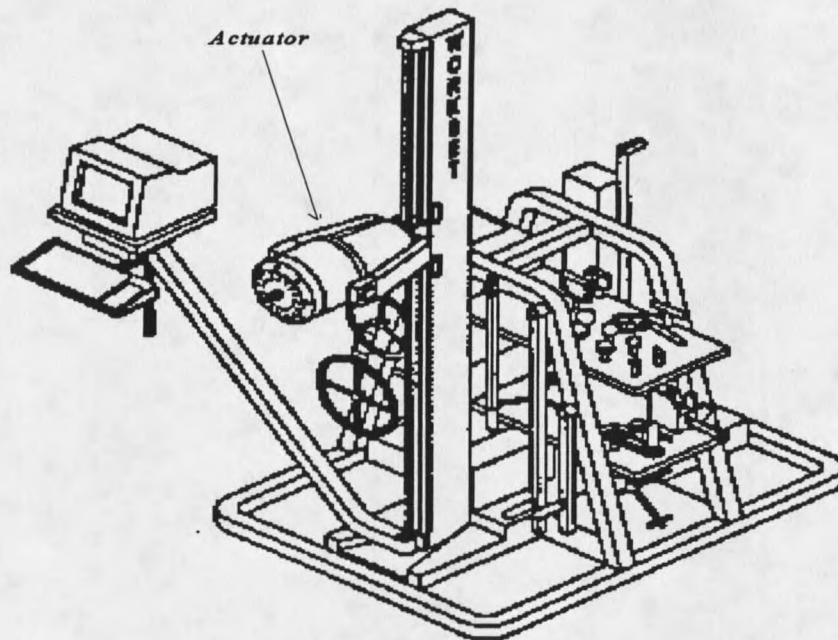


Figure 4.1: LIDO Workset

The tools attach to the actuator shaft and the exercise mode and motion are controlled through this unit. The workset utilizes a variety of attachments for simulating multiple exercise modes, high static and dynamic torque, and sensitive minimal torque. It can simulate diverse job tasks and daily activities. It offers isoforce, isovelocity, isometric, and continuous passive motion modes. These modes, plus the simulation functions of ramp up, ramp up/down, and breakaway, provide various biomechanical models for real-world situations. Dynamic torque on the LIDO machine can test limits as high as 162 Nm, and static torque test limits as high as 202.5 Nm, to allow practical testing of maximum strength of strong subjects.

This workset has the capability of generating full documentation of subject performance, including average and peak power or torque, average work, total work, and average range of motion. The LIDO is also capable of an analog output of the shaft torque and displacement, which in this experiment was connected to a microprocessor through an A/D board. The equipment allows variable spans, velocities, and resistances, and they can be varied through software control. It also has high and low dynamometer capabilities. The dynamometer used by the controller is dependent upon the high- or low-torque tool attachments. The LIDO has the ability to raise, lower, and adjust the rotation of the actuator to allow for different body positions. The LIDO comes with a controller with software that is capable of varying the rate of closure and the grip span.

In this study the LIDO was used to simulate dynamic gripping tasks. These tasks included a variety of closure speeds, ranges of motion, and wrist positions. Tool Attachment #52, the gripping device (see Figure 4.2), was used to measure maximum isovelocity grip strength, which was sent to the microprocessor via data acquisition software.

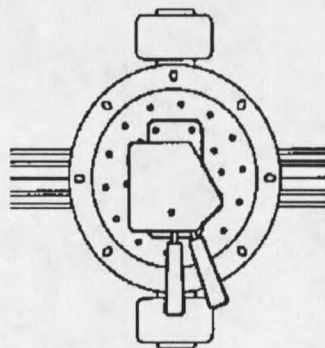


Figure 4.2: Gripping Device (front view)

A Digital Dec station 425c 486 processor was used to collect the data from the Data Transition (DT-2826) A/D board with LABTECH software.

LABTECH NOTEBOOK Software (Version 7.00) was used to provide the interface between the microprocessor and the instrumentation system. NOTEBOOK combines an iconic-based graphical interface, Iconview, with an easy-to-use menu system that provides a convenient way to create data acquisition and control setups by moving and connecting icons.

LABTECH NOTEBOOK allows monitoring and recording of all types of process variables, including voltage, current, displacement, discrete points and temperature. The block dialog box gives access to LABTECH's data acquisition and process control functions. A block dialog box is used to establish such settings as analog input or output, digital input or output and schedule factors. The schedule factors for the blocks include sampling rate, number of stages, stage duration, offset, scale factor, and triggering conditions.

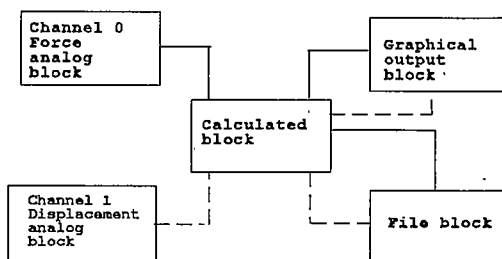


Figure 4.3 LABTECH blocks

In this experiment five blocks as can be seen in Figure 4.3 were used: two analog blocks, a calculated block, a graphical output block, and a file block.

The analog blocks were used for force and displacement signals; the calculated block was used to set the trigger point of the experiment; the graphical output block (with two traces) was used just for real-time verification; and the file block was used to collect the data and send the file to Quattro Pro.

The Data Translation (DT2824) series boards are high speed analog and digital I/O boards designed to be used by IBM or compatible personal computers. The analog input capabilities of the DT2824 series boards enable them to sample as high as 250 kHz. The DT2824-PGL A/D board used in this experiment was set and controlled by the software to sample at 100 Hz, per channel, twice the speed of the fastest closure rate in this experiment.

Along with the A/D board, a DT707 screw terminal accessory was used to interface between the Lido Workset and the Labtech Software. Channel zero was used for the force stream and Channel 1 for the displacement stream. This product permits all user connections (A/D, D/A) to the DT2824 series board to be made on screw terminals; it has 8 available channels.

"TTM" Martins Human Body Measuring kit is a set of measurement instruments designed for making objective and quantitative measurements on the sizes and forms of various parts of the human body. The kit essentially consists of instruments for measurement of distances in straight lines, on curves and circumferences, and on thicknesses. The kit was used for measuring the body height, hand length, hand breadth, middle phalange length, forearm girth, and wrist circumference.

The Jamar Hand Dynamometer was used to measure the maximum static grip strength (MVC) of each subject, and the Goniometer was used to adjust the subject and actuator to achieve the desired 90 degree elbow angle and 45 degree flexion and extension, wrist angles.

Procedures

Orientation and Familiarization Period

In the first part of this half-hour session, required anthropometric measurements of the hand and arm, stature, weight, and maximum static grip strength data were collected. Each subject performed the Phalen test to help insure none of the subjects had MSD or any other disorders which might bias the information.

Next, the subjects were familiarized with the experimental conditions and procedures to ensure the gathering of accurate information during the experiment.

The objectives of this portion of the familiarization period were: (1) to allow the subjects to become familiar with the use of the equipment, (2) to train the subjects on the proper position of the body, and (3) to increase confidence in the experimenter and increase cooperation and understanding between the experimenter and the subject.

Testing Protocol

Each research day the researcher allowed the equipment to warm for at least 30 minutes so that the voltages from the strain gauges could fully stabilize; then the equipment was calibrated by validating that the forces produced and displayed on the LIDO matched the forces transmitted to the spreadsheet. Also, each subject was given a period of re-familiarization in which they experienced the LIDO and reviewed the written instructions of the proper protocol.

Each subject was advised to maintain the specified posture during each trial. The standard posture was assumed to be standing erect, upper arm adducted, 90 degree elbow flexion, forearm parallel to the floor and mid-pronated with the wrist in a neutral posture.

The height of the actuator was adjusted for each subject to achieve the above posture. The subjects were also advised to grasp the device at the grip centroid, (marked on the handle) so that the mark was between the middle finger and the ring finger, with the dominant hand. This would ensure accurate and consistent calculation of the force produced. The subjects were also instructed to maintain a maximum force throughout the entire range of motion without jerking and to release the device when they reached the end of the range of motion. When the subjects were ready, a verbal cue was given to begin the exertion.

The marker was attached to the gripping device at a distance of 16.5 cm from the center of the actuator shaft. The span or the initial handle displacement at the effective point of application of force (grip centroid) was fixed at 9 cm and 11 cm, as seen in Figure 4.4.

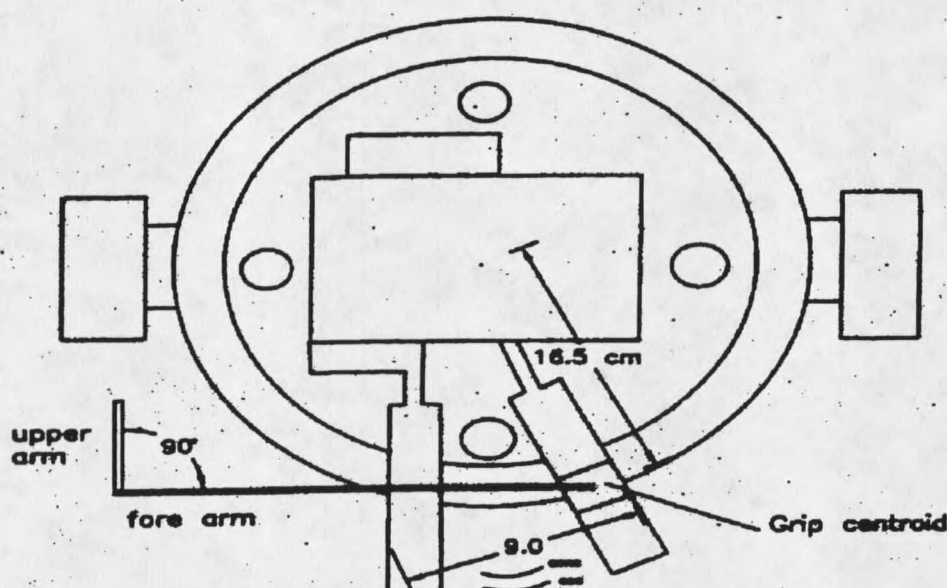


Figure 4.4: LIDO Dimensions

These initial displacements were selected based on the recommendations by Woodson, Kodak, and Fitzhugh, respectively. They determined that 9 cm initial displacement would accommodate the 5th percentile of a 50/50 male/female mix and that the 11 cm initial displacement would accommodate the 50th percentile of the same mix. These percentiles are also used in tool design; therefore, to accommodate the largest population for tool design, the 5th and the 50th percentiles were used. The handle displacement at the grip centroid was 2.1 cm at complete closure (center to center of tool).

The tool was operated in isovelocity mode. Three velocities were selected: 2.85 cm/sec, 8.6 cm/sec and 14.4 cm/sec.

These velocities are representative of what may be considered low, medium, and high for typical industrial tasks using cross-action tools. The velocities were then converted to angular velocity to achieve 10, 30, and 50 degrees per second, respectively, as the Workset only accepts angular velocity and displacement in whole angular units. All relevant calculations and LIDO dimensions can be found in Appendix C.

The wrist positions were 45 degrees flexion, neutral, and 45 degrees extension. They were used to document the effect of extreme deviation in dynamic exertions.

Subjects were given a two-minute rest after each condition and a maximum of eighteen exertions per session. The testing was split into two sessions to minimize confounding due to fatigue. This rest period was based on Fitzhugh's recommendation of 2-4 minutes after each trial, the Caldwell Regimen (Kroemer, 1994), and Marley and Wehrman's (1993) recommendation of a two-minute rest after each trial. The order in which the testing conditions were performed was selected randomly for each subject. (See Appendix B, Forms I- IV.)

Pilot Study 1

The first pilot study was done to get the LIDO, the A/D board, and the LABTECH software to work together. The first step was to look into the physical properties of the tool and determine how it might affect the voltage stream from the analog output port. The stream from the LIDO was unconditioned signal; it did not compensate for the mass of the tool.

Due to the sensitive nature of the LIDO, if a tool hangs parallel to the floor, the weight of the tool and the moment arm may introduce an unaccounted for voltage increase.

To determine the effect of the tool on the voltage stream, the mass of the tool and the center of gravity were calculated. Then, with analog output information that came with the LIDO (see Appendix C), it was determined that the resistance of the tool would generate a peak voltage difference of 145 millivolts within the range tested, which is insignificant with respect to the measured voltage range.

The next step was to determine the offset values for the force and displacement channels (channels 0 and 1, respectively). Each channel was looked at separately, and in each case, the raw stream was fed into a file without the gripping device moved. This revealed an offset voltage of -7.473 volts for the force and -5.967 volts for the displacement.

Next, to determine the scale factor for the force, the offset was entered into the block so that the readout from the LIDO would register zero in the file. Then a known force was applied to the tool, and the corresponding voltage change was recorded. This was done several times to be as precise as possible. From this voltage increase and a known force, a scale factor multiplier of 87.5 was calculated for the force block. Because of noise in the entire system due to the tool and other unknown variables, 100% accuracy was not possible. However, it was found that the force output could be recorded to within ± 4.6 lbs.

The same procedure was used to determine the displacement scale factor of 100, except that the tool was moved over a known displacement. The displacement was found to be accurate to within ± 0.05 degrees (see Appendix C).

Pilot Study 2

The second pilot study was done to justify reducing the number of replications from three to two. To perform three replications for each combination would have required a great deal of time for the researcher and the subjects. Therefore, five random subjects were used for two experiments. The first was to test whether there is a significant difference between replications of the displacement at which the subject reaches the peak force and a second experiment to test whether there is a significant difference between replications of peak force generated. The combination used to test replications was a displacement of 11 cm, velocity set at 30 cm/sec, and the wrist in the neutral position. Each subject exerted their maximum force each time, for three replications. Both experiments were analyzed using one-way, ANOVA. A 0.05 level of confidence was used to test whether there was a difference between replications. The null hypothesis is stated that $\tau_j = 0$ for all j , for both tests. No significant difference was found between the replications for displacement or peak forces, $F(2,4) = 0.107$, $P = 0.899$, and $F(2,4) = 0.047$, $P = 0.95$ respectively. Therefore it was possible to accurately perform the experiment with only two replications.

Once the LIDO and the Labtech software were set correctly, a few trials were taken to become familiar with the equipment and to begin to formulate the best way to evaluate the data. During this process it became clear that once a subject reached the end of the range of motion, they began to exert static force for a few milliseconds.

It was also noticed that it took a couple of trials to get used to the machine and that each subject, if not told to exert maximum strength would tend to "ride" the isokinetic movement of the handle instead of exerting maximum force throughout the range of motion (ROM). This was partly due to the fact that the controller will move the tool with as little as four ounces of force applied and the subject would hold on or "ride" the tool through the ROM. To eliminate these problems, the subjects were told to exert maximum effort throughout the ROM and to release the tool as soon as they reached the end of the motion. Also, a triggering point was used to begin the trial and a predetermined duration of sampling was used to reflect the true range of motion without this static grip at the end. Even with a triggering point and constant direction to the subject, the first centimeter of movement was lost in the collection process. This did not create a problem because the subject required a few millimeters to build up force anyway, so nothing was lost.

Experimental Design

A randomized block design with factorial treatment combinations with subjects as blocks and experiments as treatments was used for analyzing the data. Randomization of the sequence of experiments for the subjects was done on the basis of the randomization table developed for this purpose. (See Appendix B, Form I.)

Analysis of variance (ANOVA) method and Tukey's test were used for the analysis of the data collected from the experiments. Table 4.1 gives a summary of independent, dependent, and controlled variables for the experiments.

Table 4.1: Independent, Dependent, and Controlled Variables

Class	Variable
Independent	* Wrist posture (45 deg. flexion, neutral, 45 deg. extension) * Closure rate (2.85 cm/sec, 8.6 cm/sec, 14.4 cm/sec) (10, 30 and 50 degrees/sec) * Initial Handle Displacement (9 cm, 11 cm) (14 and 20 degrees) * Replicate trial (2X)
Dependent	* Peak force (N) * Displacement at peak dynamic force (cm)
Controlled	* Population - male - 18-40 year olds * Posture (Overall) * Environment - Temperature 20-24° C - Relative Humidity 45-55%

The model for the analysis of the experimental data was:

$$Y_{ijklm} = \mu + T_i + S_j + D_k + V_l + DV_{kl} + W_m + DW_{km} + VW_{lm} + \epsilon_{ijklm}$$

where, T = Replicate trial (I = 1,2) S = Subject (j = 1,2..30)

D = Initial displacement (k = 1,2)

V = Velocity (l = 1,2,3)

W = Wrist Posture (m = 1,2,3)

Hypothesis Testing

The following hypotheses were tested for determining whether wrist position, displacement, velocity, replication and interactions between the main effects had any effect on the dependent variables.

Main Effects:

$$H_0: T_i = 0 \text{ for all } I$$

$$H_1: T_i \neq 0 \text{ for at least some } I,$$

$$H_0: S_j = 0,$$

$$H_1: S_j \neq 0,$$

$$H_0: D_k = 0 \text{ for all } k,$$

$$H_1: D_k \neq 0 \text{ for at least some } k,$$

$$H_0: V_l = 0 \text{ for all } l,$$

$$H_1: V_l \neq 0 \text{ for at least some } l,$$

$$H_0: W_m = 0 \text{ for all } m,$$

$$H_1: W_m \neq 0 \text{ for at least some } m,$$

Critical region: reject H_0 at level $\alpha = 0.05$

if $F > F_{\alpha}(v_1, v_2)$ where v_1 and v_2 are degrees of freedom.

Interaction Effect:

$$H_0: TS_{ij} = 0,$$

$$H_1: TS_{ij} \neq 0,$$

$$H_0: TD_{ik} = 0 \text{ for all } I \text{ and } k,$$

$$H_1: TD_{ik} \neq 0 \text{ for at least some } I, k,$$

$$H_0: TV_{ik} = 0 \text{ for all } I \text{ and } k,$$

$$H_1: TV_{ik} \neq 0 \text{ for at least some } I, k,$$

$$H_0: DV_{kl} = 0 \text{ for all } k \text{ and } l,$$

$$H_1: DV_{kl} \neq 0 \text{ for at least some } k, l,$$

$H_0: TW_{im} = 0$ for all I and m ,

$H_1: TW_{im} \neq 0$ for at least some I, m ,

$H_0: DW_{km} = 0$ for all k and m ,

$H_1: DW_{km} \neq 0$ for at least some k, m ,

$H_0: VW_{lm} = 0$ for all l and m ,

$H_1: VW_{lm} \neq 0$ for at least some l, m ,

Critical region: reject H_0 at level $\alpha = 0.05$

if $F > F_{\alpha}(v_1, v_2)$ where v_1 and v_2 are degrees of freedom.

The following hypothesis was tested for determining whether the initial displacement under study has any effect on peak force and displacement at peak force in a dynamic grip strength task.

This same reasoning was used to examine the trial, velocity, wrist posture) and all interactions.

Null hypothesis: H_0 : Displacement has no effect on peak force in a dynamic grasping task.

Alternate hypothesis: H_a : Displacement has an effect on peak force in a dynamic grasping task.

Criteria of rejection of null hypothesis: From ANOVA summary on force, displacement at peak force, and Tukey's test, if there is no significant difference between the maximum grip strength at 95% confidence, then reject null hypothesis.

Justification for the criteria of rejection: Experimental conditions being the same for all the experiments, if there is a significant difference, reject the null hypothesis. Else, accept the null hypothesis.

CHAPTER 5

RESULTS AND DISCUSSION

Population Sample

Table 5.1 gives the descriptive statistics of the subject population involved in this study. In Table 5.2, mean values of body height, body weight, hand length, hand breadth, and static grip strength measurements of the subjects are compared with the corresponding anthropometric values given for U.S. adult males (Kroemer, et al. 1993, and Damon, et al., 1966). Hypothesis testing for the means for a sample size of thirty was performed to determine if the population of male MSU students was similar to that of the U.S. male population at large regarding the measured characteristics.

The following statistic was used for this testing:

$$\tau = \frac{\bar{X} - \mu_0}{s/\sqrt{n}}$$

where,

$\bar{x}$ = mean of the anthropometric measure of subject sample,

μ_0 = corresponding value of anthropometric measure for U.S. males,

s = standard deviation of measures of subject sample, and n = sample size.

Null Hypothesis: $H_0: \mu = \mu_0$ and Alternate Hypothesis: $H_a: \mu \neq \mu_0$

where μ = MSU male student population mean. Rejection criteria: Reject null hypothesis

if $t > t_{0.05, 29}$

Table 5.1: Descriptive Statistics for Subject Population

	Number of Cases	Min.	Max.	Mean	Std.Dev
Age	30	17.0	44.0	26.7	6.70
Stature	30	167.0	193.0	179.1	6.00
Weight	30	61.0	122.0	81.1	13.80
Hand Length	30	16.8	22.0	18.9	1.04
Hand Breadth	30	8.2	9.6	8.8	0.37
Static Grip	30	40.0	66.0	53.1	6.90
Wrist Cir.	30	16.0	20.0	17.2	0.88
Wrist Breadth	30	3.5	5.6	4.0	0.48
Wrist Width	30	4.0	6.7	6.0	0.47
Md. Phalangeal	30	7.5	9.0	8.2	0.46
Forearm Girth	30	25.0	32.0	27.9	1.80

Note: Linear measures are cm; weight and force are kg

Table 5.2: Statistical Comparison of Anthropometric Values

Measure	Subject	Pop.	STD	t	Df
Stature (cm)	179.1	170.0	6.04	2.72*	29
Body Weight (kg)	81.1	78.50	13.76	0.99	29
Static Grip (kg)	53.0	54.80	6.90	-1.38	29
Hand Breadth (cm)	8.8	8.89	0.40	-0.68	29
Hand Length (cm)	19.3	19.38	1.04	-0.53	29

* Significant at 0.05 level of Alpha

As can be seen in Table 5.2, the stature of the subject population was significantly greater than the average, given value of the U.S. adult male height (which is not an important factor in determining dynamic grip strength). However, body weight, hand length, hand width and static grip strength of the subject population (which are important factors) were not significantly different from those of the assumed U.S. adult male population.

Since none of the main factors were significantly different, any correlations between ergonomic results and anthropometric measurements can be trusted without any real biases. This will allow for tool designers to be confident when using this information in designing tools.

Diagnostics and Residual Analysis

For the valid use of inferential procedures in regression analysis, certain assumptions that underlie the ANOVA model must be validated. These validations include checking that the residuals are normally and independently distributed with homogeneous variances. This was done by plotting the studentized residuals against the estimates. Also observations with studentized residuals that were over the recommended limits of ± 3.0 , are considered outliers and are removed. (Hicks, 1993). Several outliers were found in both plots (see Appendix D: Figures 1 and 2 for plot). Table 5.3 shows that force values for cases 136, 208, 271, 274, 506, 734, 748, 811, and 1000 were outside the recommended limit of ± 3.00 (Hicks, 1993). Also, from table 5.3 the displacement values for cases 370, 550, 931, and 951 were found to be outside the recommended limit of ± 3.00 . The final analysis of the collected data was performed without the outlier values; because of the size of the experiment, the loss of the outlier data points will have minimal effect.

However, to compensate for the loss of the outlier values, the degrees of freedom for the force and displacement were reduced from 1080 to 1071 and 1080 to 1076, respectively, and SYSTAT automatically adjusted for the loss of these outlier points by using Type III sum of squares.

Table 5.3: Peak Force and Displacement Residuals

Variable	Outlier (Case No.)	Measured value	Studentized residual
Force	136	32.7	-3.20
	208	75.9	3.16
	271	29.5	-3.02
	274	17.3	-3.60
	506	56.0	-3.30
	748	77.9	3.37
	811	28.0	-3.28
	1000	78.0	3.66
Displacement	370	3.7	-3.25
	550	4.8	-3.18
	931	4.0	-3.37
	951	5.7	-3.09

Below is a summary table of the descriptive statistics from this experiment. Table 5.4 provides an overview of the peak forces generated under each condition and the point in the ROM where the peak occurred.

Table 5.4: Descriptive Statistics for Peak Force and Displacement of Peak Force

(cm/sec) (cm)			Average Peak Force (N)			Dis. of Peak Force (cm)	
Wrist Posture	Velocity	Initial Dis.	Minimum	Mean	STD.	Mean	STD.
Flexion	2.85	9.0	170	326	59.8	4.55	0.61
Flexion	8.60	9.0	105	406	68.2	4.00	0.41
Flexion	14.40	9.0	133	251	49.6	3.59	0.31
Flexion	2.85	11.0	149	285	75.2	3.83	1.37
Flexion	8.60	11.0	150	255	62.6	3.16	1.20
Flexion	14.40	11.0	110	236	58.6	2.64	1.20
Neutral	2.85	9.0	284	408	59.6	4.96	0.52
Neutral	8.60	9.0	242	344	51.8	3.97	0.48
Neutral	14.40	9.0	191	290	47.3	3.78	0.41
Neutral	2.85	11.0	252	359	63.8	4.27	1.10
Neutral	8.60	11.0	176	328	60.6	3.82	1.20
Neutral	14.40	11.0	115	280	56.1	3.23	1.00
Extension	2.85	9.0	190	368	73.5	5.00	0.46
Extension	8.60	9.0	145	278	53.4	4.38	0.44
Extension	14.40	9.0	128	231	47.1	4.37	0.48
Extension	2.85	11.0	213	348	63.9	5.25	0.81
Extension	8.60	11.0	192	265	62.7	4.45	1.00
Extension	14.40	11.0	145	250	48.1	4.23	0.76

Although the maximum force is not shown, a t-test was performed on the minimum and maximum forces. A significant difference was found between the minimum and the maximum forces generated, $t = 21.59$, $P = 4.25E-14$. The mean minimum forces was 171.68 (N) and the maximum force was 434.04 (N).

Analysis of Variance (ANOVA) for Peak Force

Table 5.5 provides an ANOVA summary for peak force. According to the summary, neither the trial nor any interactions within the trial significantly affected the force generated. The table also shows that subject, displacement, wrist posture, velocity, and all the interactions did have significant effect on the force.

Table 5.5: ANOVA Summary for Peak Force

Source	Df	SS	MS	F-Ratio	Probability
Trial	1	4.339	4.339	0.102	0.750
Subject	29	53180.903	1833.824	42.941*	0.000
Displacement	1	2268.023	2268.023	53108*	0.000
Velocity	2	41286.503	20643.252	483.383*	0.000
Posture	2	19363.666	9681.833	226.710*	0.000
Dis. x Velocity	2	1862.872	931.436	21.811*	0.000
Dis. x Posture	2	2081.422	1040.711	24.369*	0.000
Posture x Vel.	4	2834.507	708.627	16.593*	0.000
Error	1027	43858.849	42.706		
Total	1071	166741.084	37154.751		

*Statistically significant at $\alpha = 0.05$

Post Hoc Test for Main Effects

As expected, the ANOVA summary showed that there is a significant difference between subjects; which was expected because of the inherent uniqueness of individuals. The ANOVA also shows that the various levels within the variables of displacement, posture, and velocity are significantly different from one another.

Tukey's test was used to determine the nature of these relationships.

Tukey's test is a procedure for making all pairwise comparisons among means. A single value is calculated and used to compare all differences. Any difference between pairs of means that exceeds the value is declared significant, and a matrix of pairwise comparison is used to show the relationships.

Displacement. Because the displacement factor has only two levels, a comparison of the level means is adequate to see any differences. Displacement positions 1 (9 cm) and 2 (11 cm) had means of 309 and 289.5 Newtons respectively, which indicates that each subject at displacement 1, the shorter span, generated a greater force than displacement 2, the wider span. The ANOVA showed that the two levels were found to be significantly different.

Wrist Posture. Table 5.6 gives the results of the post hoc test of posture on force. Tukey's test shows that the values of force for different postures of the wrist were all significantly different one from another. As can be seen in Figure 5.1, the means for the flexion, neutral, and extension postures were found to be 273, 335, and 290 Newtons, respectively. It can also be seen that at the neutral position the subjects produced the greatest force, with extension second and flexion lowest.

Table 5.6: Tukey's Test Probabilities of Wrist Posture on Peak Force

	Flexion	Neutral	Extension
Flexion	1.00		
Neutral	0.00*	1.00	
Extension	0.00*	0.00*	1.00

*Statistically significant at $\alpha = 0.05$

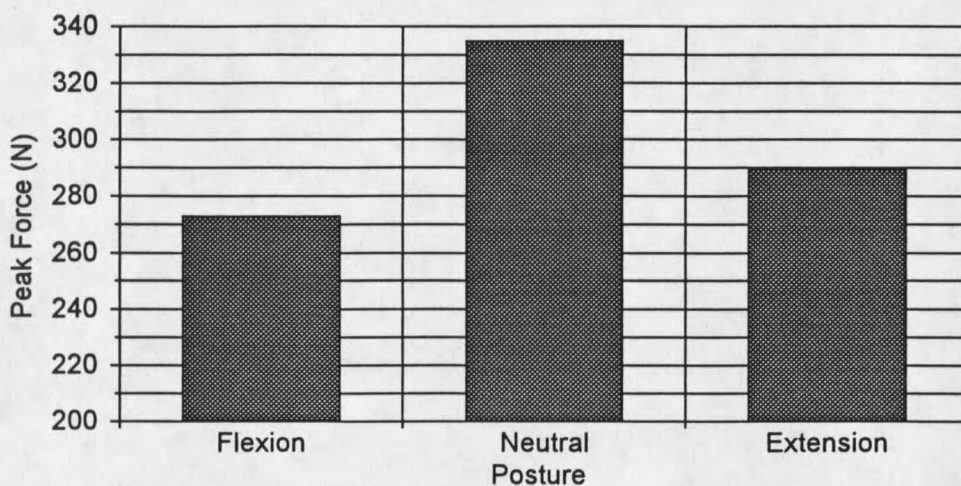


Figure 5.1: Wrist Posture in Peak Force

Velocity. Table 5.7 gives the result of the post hoc test of velocity on force. As can be seen from the table the values of force for each velocity were all significantly different from each other. As can be seen in Figure 5.2, the mean values were found to be 349, 292, and 256 Newtons, respectively. The mean force for each velocity indicates that the greatest force is produced at the slowest speed and that as the velocity decreases, the peak force increases in a steady fashion, as would be expected because of the contraction of the muscles.

Table 5.7: Tukey's Test Probabilities of Velocity on Peak Force

	2.85 cm/sec	8.6 cm/sec	14.4 cm/sec
2.85 cm/sec	1.00		
8.6 cm/sec	0.00*	1.00	
14.4 cm/sec	0.00*	0.00*	1.00

*Statistically significant at $\alpha = 0.05$

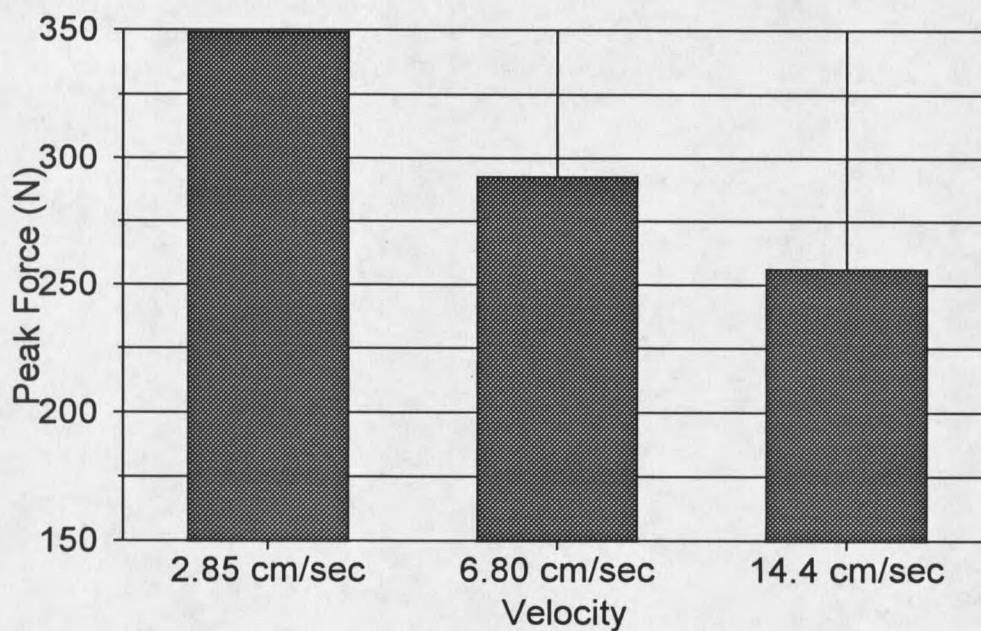


Figure 5.2: Velocity in Peak Force

Dynamic force versus Static force under different velocities

To compare the dynamic forces versus static forces of the subjects, a Z-test was used to determine whether there was a significant difference between dynamic forces and static forces.

Table 5.8 is a summary of the Z-test, it can be seen that at a velocity of 2.86 and 14.4 cm/sec the dynamic forces are significantly higher and lower respectively. However at 8.60 cm/sec the forces were not significantly different.

Table 5.8: Z-test of Dynamic versus Static forces

	Velocity	Static
	2.86 cm/sec	0 cm/sec
Mean	350.03	321.18
Z	2.34	
Probability	0.009	
	8.60 cm/sec	0 cm/sec
Mean	299.99	321.18
Z	1.86	
Probability	.015	
	14.40 cm/sec	0 cm/sec
Mean	253.92	321.18
Z	6.10	
Probability	<0.001	

As can be seen from Figure 5.3 below, the subjects are able to generate greater dynamic forces at a slower velocity, as can be expected due to the muscle contraction under dynamic conditions. Also as the velocity increases the subjects can match their static force at a point and then at higher velocities, they begin to drop below their static strength.

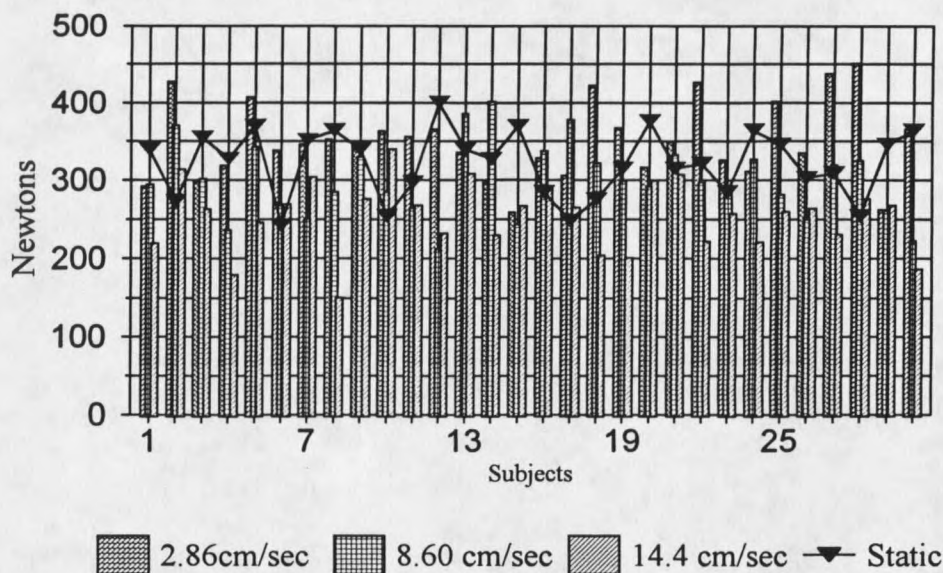


Figure 5.3 Dynamic versus Static forces

Post Hoc Tests for Interactions on Force

The ANOVA summary (see p. 40) shows that each of the main effects interacts with the others. To understand the relationships between each of the effects, it was necessary to perform Tukey's test and graphically analyze the results.

Displacement vs. Velocity. Table 5.9 gives the results of the Tukey's post hoc test of displacement versus velocity on force. It shows that all the combinations are significantly different except D1V2, D2V2 and D1V3, D2V3. These two points of interaction can be better understood by viewing Figure 5.4. The mean values were found to be 367.3, 303.9, 258.2, 331.5, 293.1, and 255.3 Newtons, respectively.

Table 5.9: Post Hoc Test of Displacement vs. Velocity on Force

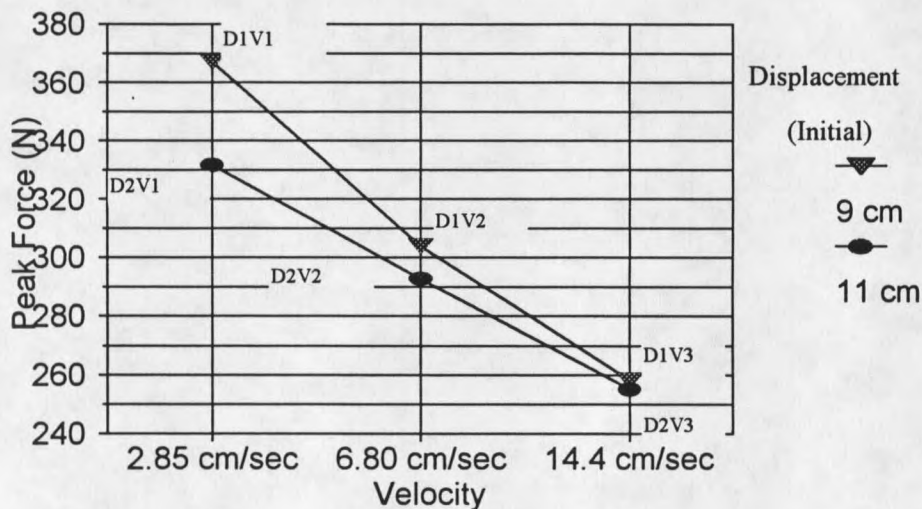
	D1V1	D1V2	D1V3	D2V1	D2V2	D2V3
D1V1	1.00					
D1V2	0.00*	1.00				
D1V3	0.00*	0.00*	1.00			
D2V1	0.00*	0.00*	0.00*	1.00		
D2V2	0.00*	0.12	0.00*	0.00*	1.00	
D2V3	0.00*	0.00*	0.99	0.00*	0.00*	1.00

Note: D1V1= displacement 9 cm, velocity 2.85 cm/sec D1V2 = displacement 9 cm, velocity 8.60 cm/sec

D1V3= displacement 9 cm, velocity 14.4 cm/sec D2V1 = displacement 11 cm, velocity 2.85 cm/sec

D2V2= displacement 11 cm, velocity 8.60 cm/sec D2V3 = displacement 11 cm, velocity 14.4 cm/sec

*Statistically significant at $\alpha = 0.05$

**Figure 5.4: Displacement vs. Velocity in Peak Force**

This figure shows that peak force steadily decreases for both displacements as the velocity increases. It also appears that displacement 1 decreases at a faster rate until a point at which it will either parallel or eventually cross displacement 2. Tukey's test showed that there is no difference between D1V2 and D2V2 or between D1V3 and D2V3. This may be due to the fact that as the velocity increases it is easier to grasp the tool, at any of the displacements.

Displacement vs. Wrist Posture. Table 5.10 shows that interactions D1W1, D1W3 and D1W1, D2W3 and D1W3, D2W3 are not significantly different from one another. However, the rest of the combinations are different. The mean values were found to be 289.7, 292.7, 289.7, 298.2, 292.7 and 298.2 Newtons, respectively.

Table 5.10: Post Hoc Test of Displacement vs. Wrist on Peak Force

	D1W1	D1W2	D1W3	D2W1	D2W2	D2W3
D1W1	1.00					
D1W2	0.00*	1.00				
D1W3	0.99	0.00*	1.00			
D2W1	0.00*	0.00*	0.00*	1.00		
D2W2	0.00*	0.12	0.00*	0.00*	1.00	
D2W3	0.44	0.00*	0.83	0.00*	0.00*	1.00

Note: D1W1= displacement 9 cm, wrist 1 Flexion D1W2 = displacement 9 cm, wrist 2 Neutral

D1W3= displacement 9 cm , wrist 3 Extension D2W1 = displacement 11 cm, wrist 1 Flexion

D2W2= displacement 11 cm, wrist 2 Neutral D2W3 = displacement 11 cm, wrist 3 Extension

*Statistically significant at $\alpha = 0.05$

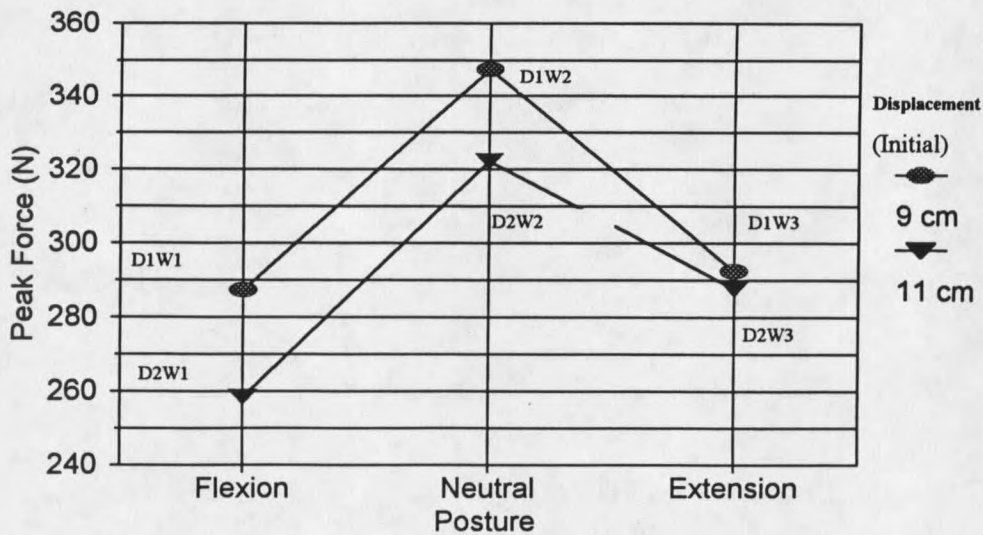


Figure 5.5: Initial Displacement vs. Wrist Posture on Peak Force

Figure 5.5 shows that in both the neutral and flexion postures, peak force decreases as the displacement increases. However, for the extension posture, peak force does not change significantly with the different displacements. The reason that the extension posture force does not increase with displacement may be due to the length-tension relationship. The length-tension curve of a resting muscle is largely determined by the amount of connective tissue in the muscle and the properties of that tissue. A maximum contraction or active tension is possible only at the resting length. By increasing the length, there is a decrease in the area of overlap between the tissues, reducing the active tension of the muscle. Similarly, when the muscle shortens, an overlap occurs between the filaments, causing interference, and the active tension decreases. Although it appears that the muscle is lengthened and shortened by the same proportion in the extension and flexion postures, may not be true internally. Internally the muscle in the flexion posture is stretched to a greater degree than in the extension posture.

This would be consistent with the biomechanical theory of length tension and explain why in the extension posture subjects are able to generate a greater force than in the flexion posture. Also, it appears that the length-tension effect is not as severe in this particular combination of extension and initial displacement. This suggests that the length-tension curve is skewed toward the extension deviation and that this skewness is most pronounced with the wider initial displacement. This would explain why at the extension posture, different displacement has little effect.

Velocity vs. Wrist Posture. It can be seen in Table 5.11 that there were four combinations that were not significantly different for the different Velocity vs. Wrist postures. The mean values were found to be 307.3, 384.2, 356.4, 271.5, 336.4, 287.3, 244.1, 285.3, and 240.6 Newtons, respectively.

Table 5.11: Post Hoc Test of Velocity vs. Wrist Posture on Peak Force

	V1W1	V1W2	V1W3	V2W1	V2W2	V2W3	V3W1	V3W2	V3W3
V1W1	1.00								
V1W2	0.00*	1.00							
V1W3	0.00*	0.00*	1.00						
V2W1	0.00*	0.00*	0.00*	1.00					
V2W2	0.00*	0.00*	0.01*	0.00*	1.00				
V2W3	0.04*	0.00*	0.00*	0.08	0.00*	1.00			
V3W1	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	1.00		
V3W2	0.01*	0.00*	0.00*	0.18	0.00*	1.00	0.00*	1.00	
V3W3	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	1.00	0.00*	1.00

*Statistically significant at $\alpha = 0.05$

Figure 5.6 shows that for each posture, as the velocity increases, the force decreases in a linear fashion. The extension posture starts significantly higher at the slower velocity, but at the faster velocities its forces are not significantly different from those of the flexion forces. This may be due to the fact that in the awkward postures the muscle is not able to respond fast enough to increase the force. It is also interesting to note that at 14.4 cm/sec the forces generated by the flexion and extension are almost identical.

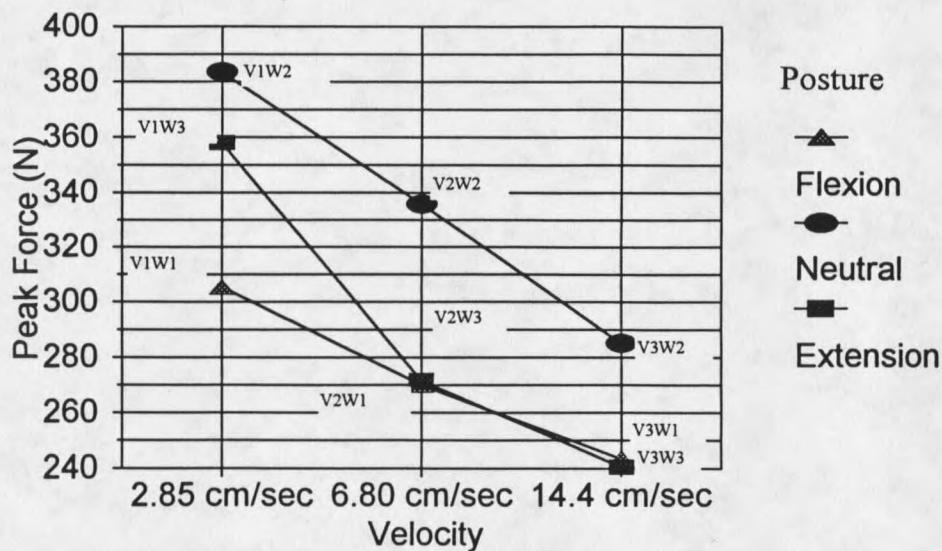


Figure 5.6: Velocity vs. Posture on Peak Force

Analysis of Variance (ANOVA) for Displacement

Table 5.12 shows that subject, displacement, velocity, and wrist posture were significant factors affecting the displacement of the peak force. Also, displacement versus wrist posture was a significant interaction affecting displacement.

Table 5.12: ANOVA Summary for Displacement

Source	Df	SS	MS	F-Ratio	Probability
Trial	1	0.747	0.747	0.107	0.744
Subject	29	2526.762	87.130	12.454	0.000
Displacement	1	676.550	676.550	96.700	0.000
Velocity	2	2394.446	1197.223	171.120	0.000
Posture	2	2519.057	1259.528	180.026	0.000
Displacement x Velocity	2	21.256	10.628	1.519	0.219
Displacement x Posture	2	601.298	300.649	42.972	0.000
Posture x Velocity	4	73.200	18.300	2.616	0.034
Error	1032	7220.267	6.996		
Total	1076	16033.583	3557.751		

Statistically significant at $\alpha = 0.05$

Post Hoc Test for Main Effects

As in the ANOVA summary for peak force, there is no need to perform a comparison test to verify that subjects are different one from another. Displacement, posture, and velocity effects were found to have a significant effect on the point of displacement. And once again, Tukey's test was used to determine the nature of these relationships.

Displacement. The displacement factor has only two levels, and a comparison of the level means can be seen in Figure 5.7. Initial displacement 1 (9 cm) and 2 (11 cm) had means of 4.3 and 3.9 cm, respectively, which shows that at the narrower initial span, peak force was reached sooner than at the wider initial span. One reason subjects are not able to reach their peak sooner

with displacement 2 may be due to a poor mechanical advantage. At the wider span, some of the subjects with smaller hands are not able to exert their peak force until towards the end of the ROM. It is also theorized that at the wider displacement, as the subject is closing the tool, they reposition once they reach a more comfortable hold on the tool. It is speculated that this theory would reveal a double peak. The first peak would occur just before the subject repositioned on the tool, and then a second peak of greater force would occur later in the span.

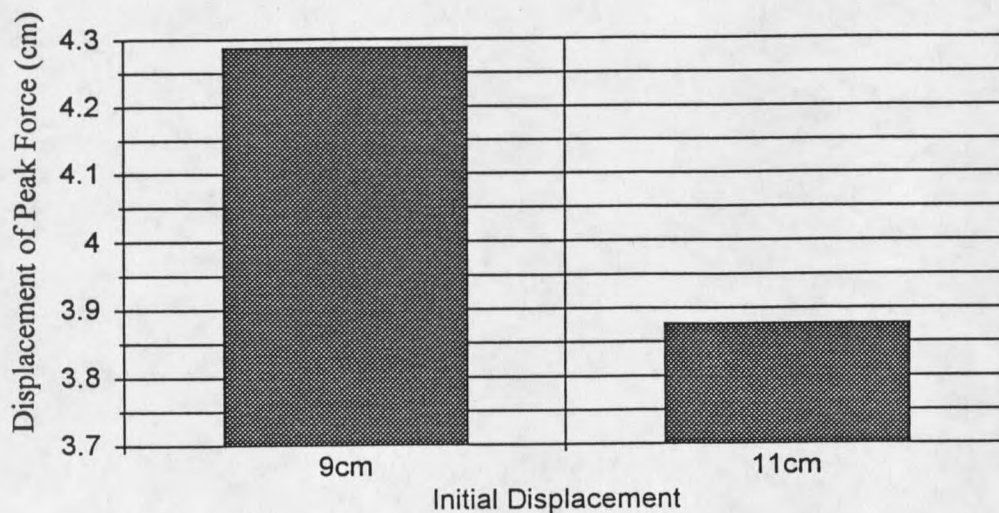


Figure 5.7: Displacement of Peak Forces

Wrist Posture. Table 5.13 shows that the displacement at peak force for different postures of the wrist were all significantly different from one another. The mean displacements for the flexion, neutral, and extension postures were found to be 3.7, 4.1, and 4.7 cm, respectively. As can be seen in Figure 5.7 subjects were able to reach their peak earlier in the span in the extension posture, than with the neutral and flexion postures.

Table 5.13: Tukey's Test for Wrist Posture

	Flexion	Neutral	Extension
Flexion	1.00		
Neutral	0.00*	1.00	
Extension	0.00*	0.00*	1.00

*Statistically significant at $\alpha = 0.05$

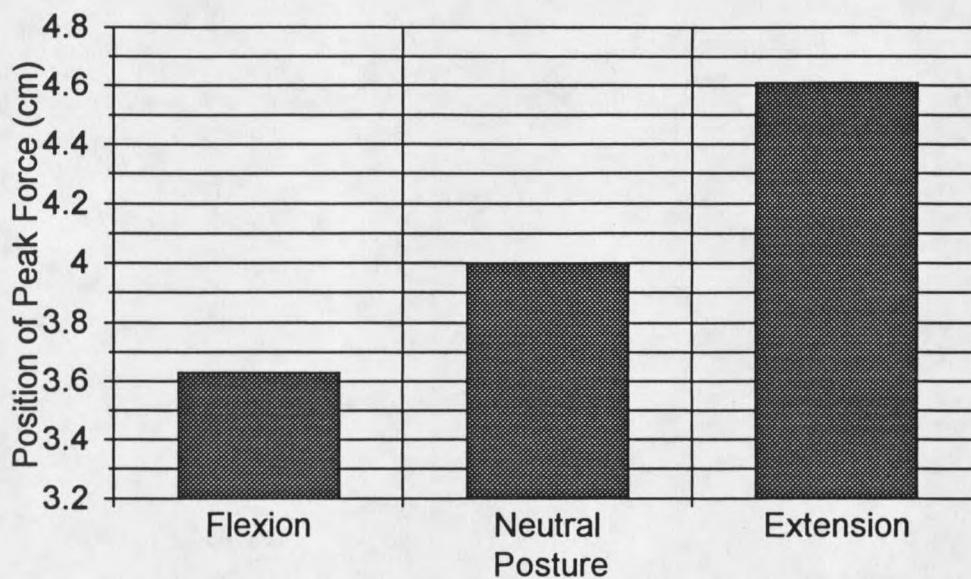


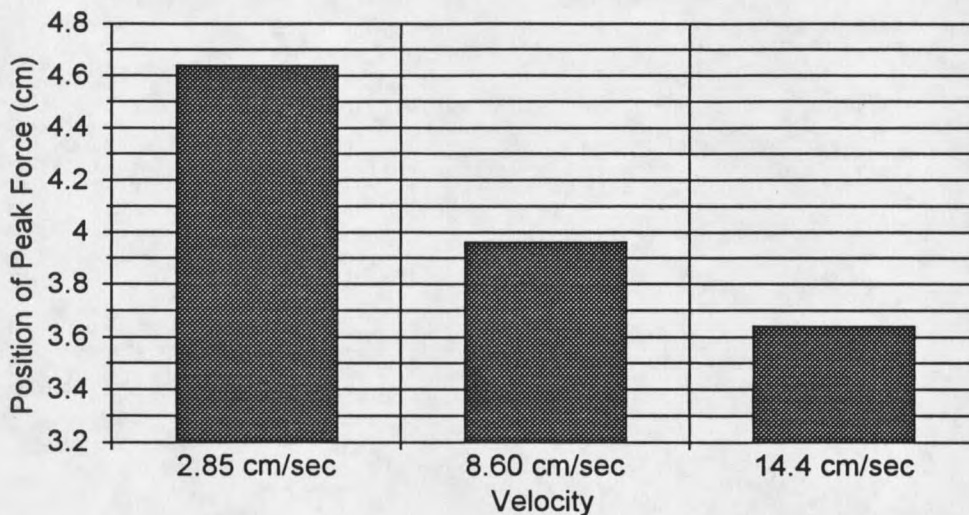
Figure 5.8: Displacement of Peak Forces at Different Postures

Table 5.14 gives the results of the post hoc test of velocity on displacement. From the table below one can see that the velocity for each displacement is significantly different from the others. The mean displacement at peak force for each velocity indicates that the peak force is reached at a wider point in the span at the slowest speed and force decreases as the velocity increases. As can be seen in Figure 5.9, the mean values are 5.4, 4.2, and 3.5 cm, respectively for the 2.85, 8.60, and 14.4 cm/sec velocities.

Table 5.14: Tukey's Test of Velocity on Displacement

	2.85 cm/sec	8.6 cm/sec	14.4 cm/sec
2.85 cm/sec	1.00		
8.6 cm/sec	0.00*	1.00	
14.4 cm/sec	0.00*	0.00*	1.00

*Statistically significant at $\alpha = 0.05$

**Figure 5.9: Displacement of Peak Force for Different Velocities**

Post Hoc Test for Interaction on Displacement

The ANOVA summary shows that the only interaction is between displacement and wrist posture. To understand the relationship between these effects, a Tukey's test was performed and the results were graphically analyzed.

Displacement vs. Wrist Posture. Table 5.15 gives the results of the post hoc test of displacement vs. wrist posture on displacement. The table shows that combinations D1W1,

D1W2 and D1W3, D2W3 are not significantly different from one another. The displacements were found to be 5.6, 5.8, 6.3, 4.4, 5.3, and 6.7 cm, respectively.

Table 5.15: Post Hoc Test of Displacement vs. Wrist on Displacement

	D1W1	D1W2	D1W3	D2W1	D2W2	D2W3
D1W1	1.00					
D1W2	0.18	1.00				
D1W3	0.00*	0.00*	1.00			
D2W1	0.00*	0.00*	0.00*	1.00		
D2W2	0.02*	0.00*	0.00*	0.00*	1.00	
D2W3	0.44	0.00*	0.95	0.00*	0.00*	1.00

Note D1W1= displacement 9 cm, wrist 1 flexion D1W2 = displacement 9 cm, wrist 2 neutral

D1W3= displacement 9 cm, wrist 3 extension D2W1 = displacement 11 cm, wrist 1 flexion

D2W2= displacement 11 cm, wrist 2 neutral D2W3 = displacement 11 cm, wrist 3 extension

*Statistically significant at $\alpha = 0.05$

As expected, there appears to be a greater variation of displacements of peak forces with the wider span. (See Figure 5.10) This may be because it was difficult for some of the subjects with shorter hands to grasp the tool and exert force.

When one considers the length-tension curve as discussed earlier, it may not be coincidence that the peak forces for the extension posture are nearly in the same displacement.

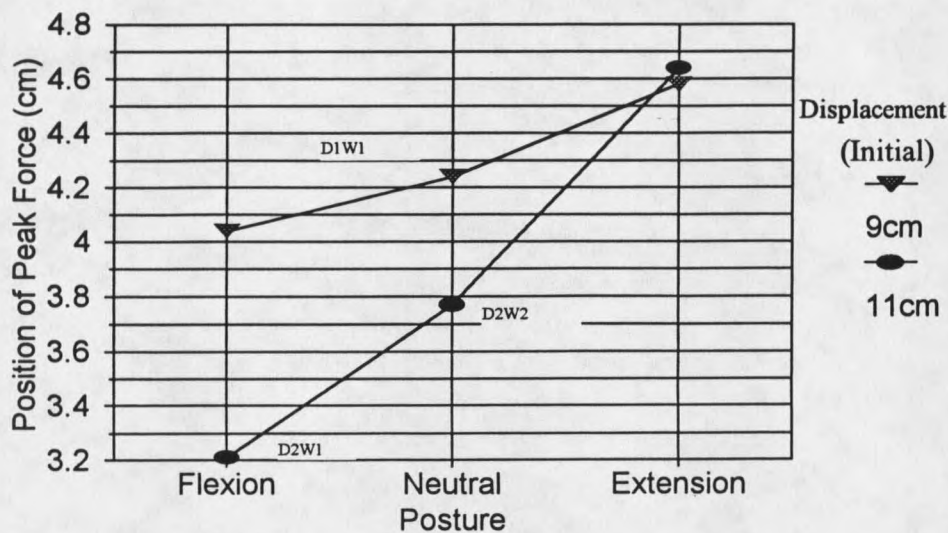


Figure 5.10: Displacement vs. Wrist Posture

Dynamic Curves

Four graphs have been developed to summarize the mean forces and displacements produced.

Although the ranges of motion were 9 and 11 cm, the initial 1 cm was discarded due to recording technology.

The graphs indicate (1) at what point in the span the peak force occurs, and (2) how long it can be maintained. The first graph (see Figure 5.11) reveals the forces generated for each wrist posture at displacement 1.

The force for each posture builds up slowly and then drops off fairly fast. However, the flexion and extension postures can maintain the peak forces across a wider span than the neutral posture.

This is probably due to the tension-length relationship.

At the resting position or neutral posture, a subject is able to generate force in a linear fashion until they reach their peak and then drop. As for the other postures, because of the reduced overlap of connective tissue, once the peak is reached it can be maintained, but not increased.

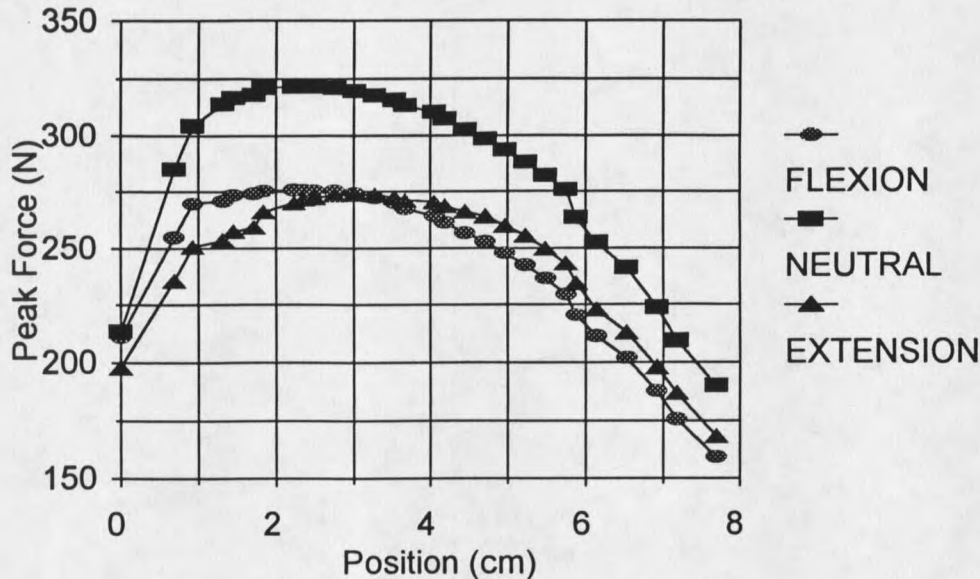


Figure 5.11: Mean Posture Forces (9 cm initial span)

Figure 5.12 shows the mean forces for each wrist posture at the wider span. It can be seen that the forces are built up at a fairly rapid rate and then stabilize throughout most of the range. The peak appears to occur towards the end of the ROM before dropping off. This is probably due to the length of the span and the repositioning effect.

If each profile were examined it would reveal that a repositioning effect is taking place. It can also be seen that at the wider span the peak forces are lower than in the shorter span for all three postures.

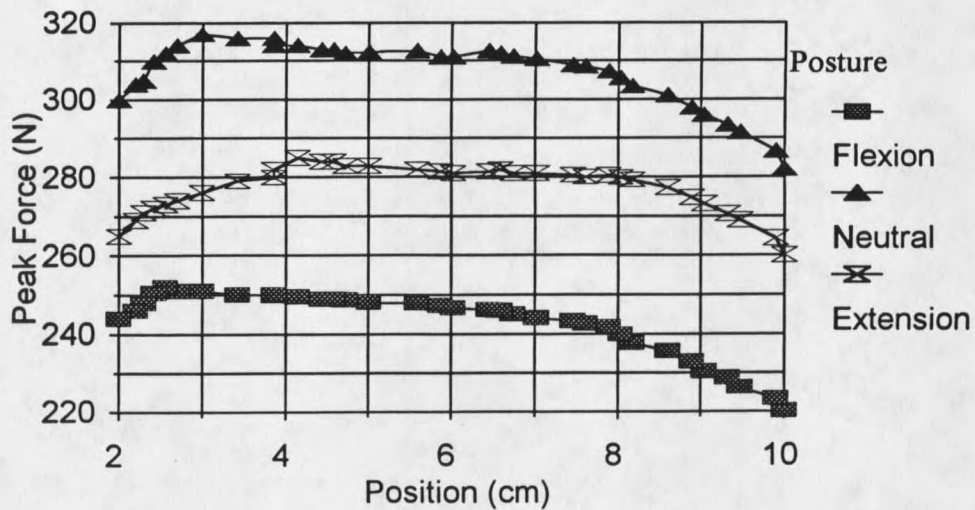


Figure 5.12: Mean Forces for Different Postures (11 cm initial span)

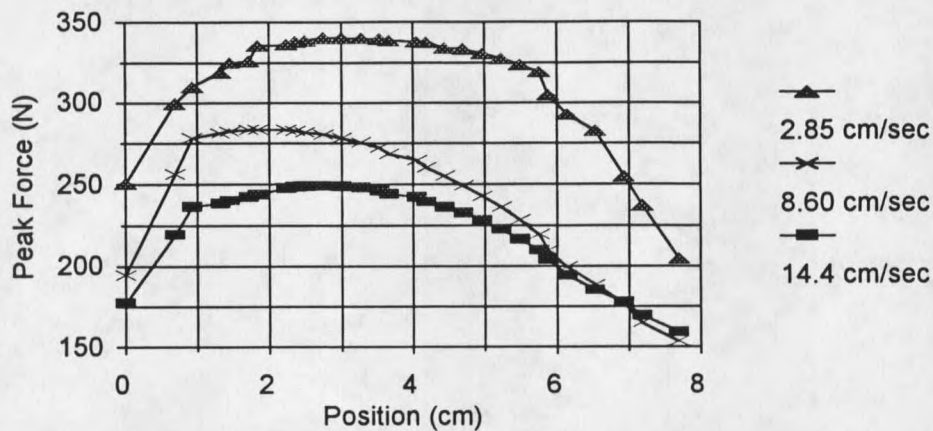


Figure 5.13: Mean Peak Forces for Different Velocities (9 cm initial span)

Figure 5.13 shows the mean peak forces for the different velocities at the shorter span. At the slowest speed the peak force can be reached earlier in the span and maintained longer than the other two speeds, which again seems to support the length-tension relationship.

Figure 5.14 shows the mean peak forces for different velocities at the wider span. With this span, the force is reached sooner and maintained longer in all three velocities than in the shorter span.

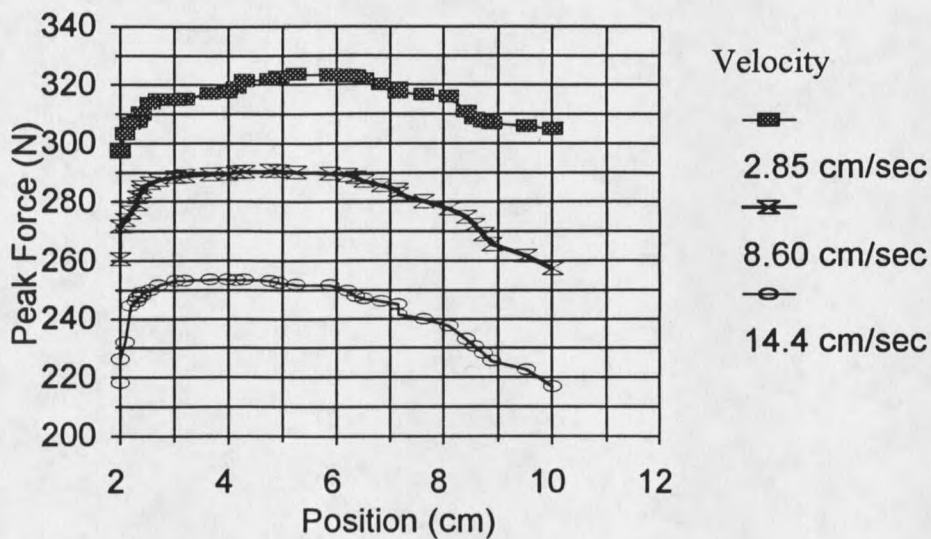


Figure 5.14: Mean Forces for Different Velocities (11 cm initial span)

Summary

When comparing the 11 cm graphs to the 9 cm graphs, there appears to be a similar pattern. It is interesting to note that, while the wider span tends to produce less force, approximately 95% of the peak force is reached relatively early in the ROM and maintained longer than in the shorter span. The actual peak force is reached closer to the end of the range of motion, which supports the theory of repositioning. With the shorter span, however, the forces

build up more slowly and the peak is reached earlier in the ROM. This span produces a greater peak force, but the majority of the peak force is not maintained nearly as long as in the wider span.

Prediction of Peak Forces

To develop predictive models of the data, the following procedures were used. If a linear regression model was not sufficient to explain the variation in the means, the next step was to apply a second-degree (or quadratic) model. For both methods, the first step towards developing an equation for peak forces is to find the correlation between each of the variables in order to reduce the number of variables which might lead to multi-collinearity.

Table 5.16: Pearson Correlation (Pairwise)

	WT	HT	HL	HW	MP	WC	FG	WB	WW	SG
WT	1.00									
HT	0.18	1.00								
HL	0.40	0.34	1.00							
HW	0.35	0.53	0.49	1.00						
MP	0.22	0.37	0.61	0.36	1.00					
WC	0.75	0.15	0.22	0.40	0.07	1.00				
FG	0.86	0.09	0.35	0.38	0.12	0.68	1.00			
WB	-0.01	-0.04	0.03	0.24	0.12	-0.02	-0.06	1.00		
WW	0.44	0.24	0.11	0.12	0.02	0.50	0.42	-0.78	1.00	
SG	0.23	0.14	0.38	0.40	0.43	0.09	0.22	0.08	0.03	1.00

From Table 5.15 it can be seen that wrist circumference is moderately correlated to weight and forearm girth is highly correlated to weight, and forearm girth is moderately correlated with wrist circumference. It also shows that wrist width has a moderately negative correlation with wrist breadth. The rest of the variables are poorly correlated with one another. It was interesting to note that there is a poor correlation between static grip and all other variables; it was expected that there would be a moderate to high correlation between static grip and forearm girth, and weight.

Thus a stepwise multiple regression procedure was used to determine equations using velocity, wrist posture, and anthropometric data. It is believed that useful predictive equations of dynamic strength for ergonomic practitioners would be composed of various combinations of these variables. Diagnostic tests were used to help assure that there were no major departures from the assumptions of multiple linear regression models. The general criteria for appropriateness and efficiency of these models consists of (1) outlier detection via residual plots, (2) evaluation of the F ratios generated for each model and each independent variable within the model, and (3) evaluation of R^2 values.

The residual plots for outlier detection can be seen in Appendix D, Figures 3-6. None of the residual plots revealed any major trends or abnormalities. Each plot had several outliers, which were removed as done in the ANOVA section. Results of the linear method and these procedures are provided in Equations 1 to 4, which follow in the next pages.

Equation 1 represents peak force as a function of velocity and the inclusion of anthropometric variables for the grip span of 9 cm.

Equation 1

$$PF = 62.521 - 1.575 (Vel) - 0.173 (Age) - 0.179 (HT) + 0.099 (WB) + 0.720 (SG)$$

$$F(5,534) = 101.6 \quad R^2 = 0.488$$

PF = Peak Force (measured in kg)

Vel = Velocity (2.85, 8.60, 14.4 cm/sec)

HT = Height (measured in cm)

WB = Wrist Breadth (measured in cm)

SG = Static Grip Strength (measured in kg) Age = Age (measured in years)

Equation 2 represents displacement of peak force as a function of velocity, wrist posture and the inclusion of anthropometric variables for the grip span of 9 cm.

Equation 2

$$P = 0.343 - 0.190 (Vel) + 0.014 (Wrist) - 0.025 (SG) + 0.031 (WT) + 0.020 (HT) + 0.521 (HW) - 0.382 (WC) + 0.207 (WW)$$

$$F(8,531) = 65.11 \quad R^2 = 0.495$$

P = Displacement (cm)

Vel = Velocity (2.85, 8.60, 14.4 cm/sec)

Wrist = Wrist (-45 = 45 degrees flexion, 0 = neutral, 45 = 45 degrees extension)

WT = Weight (measured in kg)

HT = Height (measured in cm)

HW = Hand Width (measured in cm) WC = Wrist Circumference (measured in cm)

WW = Wrist Width (measured in cm) SG = Static Grip Strength (measured in kg)

Equation 3 represents peak force as a function of velocity, wrist posture and the inclusion of anthropometric variables for the grip span of 11 cm.

Equation 3

$$PF = -21.864 - 1.077(Vel) + 0.072 (Wrist) + 0.705 (SG) + 3.186 (HL) - 3.205 (HW) - 3.168 (MP) - 3.254 (WC) + 0.888(WB) + 14.470 (WW)$$

$$F(9,530) = 71.230 \quad R^2 = 0.547$$

PF = Peak force Vel = Velocity (2.85, 8.60, 14.4 cm/sec)

Wrist = Wrist (-45 = 45 degrees flexion, 0 = neutral, 45 = 45 degrees extension)

HL = Hand Length (measured in cm)

HW = Hand Width (measured in cm)

WC = Wrist Circumference (measured in cm)

MP = Middle Phalangeal (measured in cm)

WW = Wrist Width (measured in cm)

WB = Wrist Breadth (measured in cm)

SG = Static Grip Strength (measured in kg)

Equation 4 represents displacement of peak force as a function of velocity, wrist posture and the inclusion of anthropometric variables for the grip span of 11 cm.

Equation 4

$$P = -16.216 - 0.188 (\text{Vel}) + 0.032 (\text{Wrist}) + 0.029 (\text{Age}) + 0.026 (\text{WT}) + 0.073 (\text{HT}) + 0.733 (\text{HW}) + 0.023 (\text{WB}) \quad F(7,528) = 56.350 \quad R^2 = 0.428$$

P = Displacement (cm) Vel = Velocity (2.85, 8.60, 14.4 cm/sec)

Wrist = Wrist (-45 = 45 degrees flexion, 0 = neutral, 45 = 45 degrees extension)

Age = Age (measured in years) HT = Height (measured in cm)

HW = Hand width (measured in cm) WB = Wrist Breadth (measured in cm)

WT = Weight (measured in kg)

These regression models suggest that, at best, Peak Force and Displacement could be estimated with about 50 percent accuracy (based on Multiple R^2). Thus, the equations developed may be of limited use as the accuracy would most likely be unacceptable in most industrial situations.

In the following equations a second-degree (or quadratic) model was applied. It had appeared that figures 5.10 - 13 followed a quadratic form. By choosing a polynomial of a high enough degree an acceptable model was hoped to be found. The following two equations on the next two pages are second-degree models.

Equation 5 represents peak force as a function of velocity, wrist posture, displacement, and the inclusion of anthropometric variables for the grip span of 11 cm.

Equation 5

$$PF = -66.877 - 5.884(\text{Vel}) + 0.422(\text{Wrist}) + 0.243(\text{WT}) + 15.863(\text{HL}) - 10.544(\text{HW}) - 15.459(\text{MP}) - 26.681(\text{WC}) - 3.349(\text{FG}) + 5.459(\text{WB}) + 98.938(\text{WW}) + 3.908(\text{SG}) + 0.621(\text{DI}) - 0.007(\text{DISP})$$

$$F(13,5386) = 246.207 \quad R^2 = 0.611$$

PF = Peak force Vel = Velocity (2.85, 8.60, 14.4 cm/sec)

Wrist = Wrist (-45 = 45 degrees flexion, 0 = neutral, 45 = 45 degrees extension)

WT = Wrist thickness (measured in cm) HL = Hand Length (measured in cm)

HW = Hand Width (measured in cm) MP = Middle Phalangeal (measured in cm)

WC = Wrist Circumference (measured in cm) FG = Forearm Girth (measured in cm)

WB = Wrist Breadth (measured in cm) WW = Wrist Width (measured in cm)

SG = Static Grip Strength (measured in kg)

DI = Displacement squared (measured in cm²)

DISP = Displacement cubed (measured in cm⁴)

Equation 6 represents peak force as a function of velocity, wrist posture, displacement, and the inclusion of anthropometric variables for the grip span of 9 cm.

Equation 6

$$PF = 3.848 - 6.825(Vel) + 0.188 (Wrist) + 6.162 (POS) - 2.671 (HL) 0.705 + 11.957 (HW) + 15.183 (MP) + 2.615 (FG) - 14.470 (WW) + 3.646 (SG) - 0.029 (DISP) \quad F(10,5929) \\ = 390.246 \quad R^2 = 0.630$$

PF = Peak force Vel = Velocity (2.85, 8.60, 14.4 cm/sec)

Wrist = Wrist (-45 = 45 degrees flexion, 0 = neutral, 45 = 45 degrees extension)

HL = Hand Length (measured in cm) HW = Hand Width (measured in cm)

MP = Middle Phalangeal (measured in cm) FG = Forearm Girth (measured in cm)

WW = Wrist Width (measured in cm) POS = Initial Displacement (measured in cm)

SG = Static Grip Strength (measured in kg)

DISP = Displacement cubed (measured in cm⁴)

These two quadratic regression models suggest that, at best Peak Force could be estimated with about 61 percent accuracy (based on Multiple R^2). Although none of the results from the model development are particularly useful, they may form a foundation from which engineers can perform future research on dynamic hand tool motions.

Three-Dimensional Surface Response Curves

In this section, four three-dimensional curves have been developed and plotted below. Each plot could help tool designers to develop optimum hand tools, while reducing the risk of musculoskeletal disorders.

Figure 5.15 shows the range of the peak forces, and it clearly shows that as the velocity increases, the force decreases. It can also be seen that the neutral posture produces the highest forces.

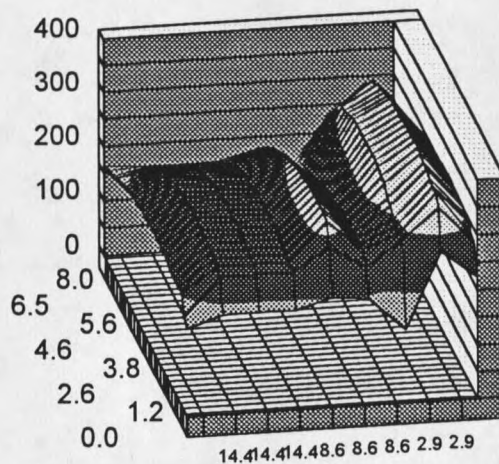


Figure 5.15: Three Dimensional Curves of Velocities at 9 cm

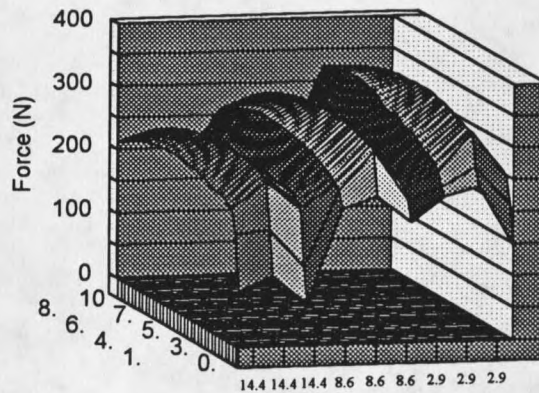


Figure 5.16: Three Dimensional Curves of Different Velocities at 11 cm

Figure 5.16 shows a similar curve to the previous one, except for the wider displacement.

The wider displacement seems to cause a faster rise and an abrupt drop of the force.

Figure 5.17 shows the peak forces for the different postures. It shows distinctions

between the postures. The greatest forces were produced in the neutral posture.

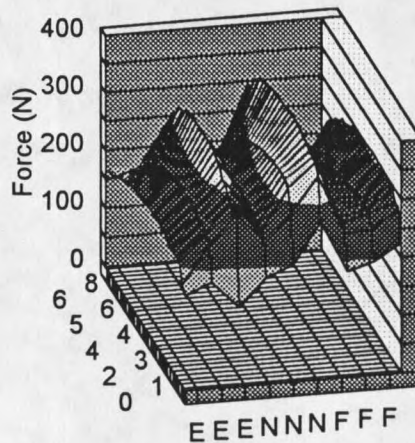


Figure 5.17: Three-Dimensional Curves of Wrist Postures at 9 cm

It can be seen in Figure 5.18 that even at the wider displacement, there is a clear distinction between the postures. However, the peak forces generated are not as high as in the shorter displacement.

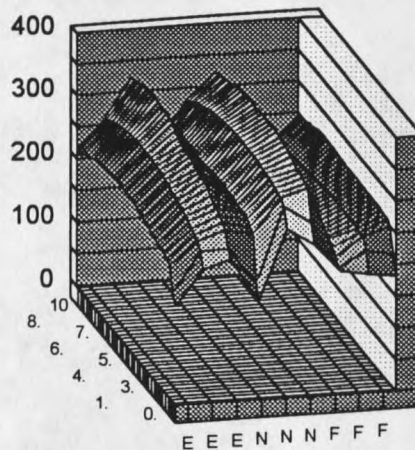


Figure 5.18: Three Dimensional Curves of Wrist Postures at 11 cm

Overall Discussion

This study has verified that the slower the velocity of the closure, the higher the dynamic grip forces generated. Likewise at higher velocities, the forces generated are greatly reduced, which confirms Fitzhugh's studies, (Fitzhugh 1972-1973). It has also shown that a deviation from the neutral posture would significantly reduce the amount of force an individual is able to produce. It was also determined that the initial displacement can play an important role in the amount of force generated. An initial displacement of 9 cm allowed for greater forces to be produced than at 11 cm displacement, which also coincided with Fitzhugh's findings (Fitzhugh 1972-1973).

The three-dimensional curves help to illustrate the effects of velocity, wrist posture, and initial displacement on peak force and displacement of peak force.

The graphs, curves, and figures of this paper illustrate the details of dynamic grasping. Designers will now have a foundation of basic information which will allow them to consider handtool operations in a dynamic settings. For example, If a designer knows the peak force required and the type of material to be cut, crimped or bent, he can now optimize the velocity of closure, and initial displacement, and select or recommend the best wrist posture. If all variables are considered and a risk assessment is made, the chances of MSDs will be greatly reduced. With this information, designers will now have a whole new avenue to explore to improve working conditions surrounding cross-action handtools.

In addition to information on these variables and interactions, this study has provided a table of both minimum, and mean dynamic strength criteria, which can be used to reduce the risk of injury, when designing for a particular job. For example, in most industrial application of the cross-action tool, it would be better to design around the minimum force required than to push some part of the group into a higher risk area.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Following are the conclusions derived in terms of the objectives of this study:

1. The maximum force that an individual can produce given a velocity of 2.85 cm/sec with the wrist in the neutral posture and an initial displacement of 9 cm was found to be 408 Newtons. The peak force occurred at 4.3 cm for this particular combination. Overall, the peak force for any combination occurred between 3.2 cm and 5.25 cm. The optimum initial displacement was found to be 9 cm, with an average peak force of 309 Newtons. These results confirm the findings of Fitzhugh, although the point of peak force is different; this could be attributed to the methods of measurements.
2. The three-dimensional response curves of dynamic grasping that were produced have helped to identify the effects of the independent variables. However, greater insights to these variables were found with plots of the significant effects and interactions.
3. Four regression models have been developed to predict maximum dynamic grip peak force and displacement of peak forces based on anthropometric measures.

It was found that none of the models could predict the displacement or peak force with any high degree of accuracy. Therefore, it is best that peak force and displacement of peak force be derived through industrial simulation.

Recommendations for Future Research

1. Because of technology, the improved ability to do research in the area of dynamic grasping leaves a wide range of opportunities to examine. There is a vast amount of information to be gleaned surrounding dynamic grip strength. This study only touched the surface of the theory of regrasping at wider displacements. Instead of averaging the profile of each subject over a span, it could be important to take a closer look at individual profiles.
2. Now that a foundation has been laid for dynamic grip strength, a study of different variables such as shape of handles, environment, and vibration could help to reveal the effects they would have on maximum grip strength in a purely industrial setting.
3. This study looked into the effects of the wrist at three postures. However, it may be necessary to consider ulnar and radial deviations of the wrist to get a total picture. By deviating the wrist in the ulnar or radial postures, a greater insight may be reached as to why in the extension posture, displacement had little effect.

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APPENDICES

APPENDIX A
PRELIMINARY FORMS

FORM I
SUBJECT CONSENT FORM
FOR
PARTICIPATION IN DYNAMIC GRIP STRENGTH EXPERIMENT

You have been invited to participate in a study titled "Dynamic Grip Strength." This study will use a biomechanical method to determine the extreme limits of the hand in a dynamic motion setting for a combination of factors often observed in industry. The results of the study are expected to aid industrial engineers in determining the maximum limits of dynamic grasping for any cross-action tools, and ultimately, will lead to reduced risk of musculoskeletal illness from unsafe and excessive demands.

The objective of this study is to determine the points of peak force over a known range of motion (ROM). This study will reveal the maximum forces that an individual can produce given a particular speed of closure (2.5 cm/sec, 7.5 cm/sec, 12.5 cm/sec), wrist position (45 degrees flexion, neutral, 45 extension) and distance between handles (11 cm, 9 cm).

If you decide to participate, you will be required to exert a maximum force for each grasp of the tool under different conditions. There will be a half-hour orientation and familiarization session, followed by 3 one-hour test sessions. There will be a total of 54 trials made, with 2-3 minutes of rest between each trial. Therefore, you will be expected to participate for a total of about 3 ½ hours of observations spread over a period of 3-7 days.

During the orientation and familiarization session, personal information will be collected. This will include height, weight, hand length, hand breadth, length of middle phalange, wrist circumference, forearm girth, and static grip strength.

Because the tasks involve the musculature of the upper extremities, you may

FORM I (Continued)

experience some minor soreness in these muscles and/or stiffness in the involved joints. Neither the I&ME Department nor Montana State University can provide compensation for such conditions or any other health problems that might arise as a result of this experiment.

You have voluntarily agreed to participate in the experiment and hence will not be monetarily compensated for your effort. Since your participation is completely voluntary, you may choose to withdraw from participation at any time and for whatever reason. Such a withdrawal will not affect your relationship, if any, with the I&ME Department or with Montana State University. All information obtained during this study by which you could be identified will be held in strict confidence.

If at any time you have questions regarding this research, you may contact either Bob Howell, 107-C Paisley Ct., Bozeman, MT 59717, (406) 586-7980, or Dr. Robert Marley, Industrial & Management Engineering Dept, 315 Roberts Hall, Montana State University, Bozeman, MT 59717, (406) 994-3971.

By signing below, you are indicating that you have read all of the above information and are willing to participate. You may keep a copy of this form.

Signature of Participant

Date

Dr. Robert Marley or Bob Howell

Date

FORM II

INSTRUCTIONS FOR A DYNAMIC GRASPING EXPERIMENT

The objective of this study is to determine the points of peak force over a known displacement. This study will reveal the maximum forces that an individual can produce given a particular speed of closure (2.85 cm/sec, 8.60 cm/sec, 14.4 cm/sec), wrist position (45 degrees flexion, neutral, 45 extension) and displacement of handles (11 cm, 9 cm). You will perform 16-18 exertions per session, with a 2-4 minute rest period between each exertion.

The standard neutral posture (referred to as the starting position) for this study is standing erect, arm adducted , 90 degree elbow flexion, forearm parallel to the floor and mid-pronated with the wrist in a neutral angle (flexion). You will be asked to grip the tool and then exert maximum effort over the entire range of motion, and then once the tool has reached the end of the motion release the tool.

PLEASE DO NOT BE AFRAID TO ASK FOR AN EXTENDED REST PERIOD. If you're tired or do not feel that you are performing at normal capacity, please inform me of any discomforts and we will extend the rest period or reschedule another convenient time.

Your cooperation in this test is greatly appreciated.

APPENDIX B
DATA COLLECTION FORMS

FORM I

TEST CONDITIONS

- 1: Displacement 9 cm, Velocity 2.85 cm/sec, and Wrist position 45° Flexion
- 2: Displacement 9 cm, Velocity 2.85 cm/sec, and Wrist position Neutral
- 3: Displacement 9 cm, Velocity 2.85 cm/sec, and Wrist position 45° Extension
- 4: Displacement 9 cm, Velocity 8.60 cm/sec, and Wrist position 45° Flexion
- 5: Displacement 9 cm, Velocity 8.60 cm/sec, and Wrist position Neutral
- 6: Displacement 9 cm, Velocity 8.60 cm/sec, and Wrist position 45° Extension
- 7: Displacement 9 cm, Velocity 14.4 cm/sec, and Wrist position 45° Flexion
- 8: Displacement 9 cm, Velocity 14.4 cm/sec, and Wrist position Neutral
- 9: Displacement 9 cm, Velocity 14.4 cm/sec, and Wrist position 45° Extension
- 10: Displacement 11 cm, Velocity 2.85 cm/sec, and Wrist position 45° Flexion
- 11: Displacement 11 cm, Velocity 2.85 cm/sec, and Wrist position Neutral
- 12: Displacement 11 cm, Velocity 2.85 cm/sec, and Wrist position 45° Extension
- 13: Displacement 11 cm, Velocity 8.60 cm/sec, and Wrist position 45° Flexion
- 14: Displacement 11 cm, Velocity 8.60 cm/sec, and Wrist position Neutral
- 15: Displacement 11 cm, Velocity 8.60 cm/sec, and Wrist position 45° Extension
- 16: Displacement 11 cm, Velocity 14.4 cm/sec, and Wrist position 45° Flexion
- 17: Displacement 11 cm, Velocity 14.4 cm/sec, and Wrist position Neutral
- 18: Displacement 11 cm, Velocity 14.4 cm/sec, and Wrist position 45° Extension

FORM II

PHYSIOLOGY DATA OF THE SUBJECTS AND COLLECTION SHEET

Name: _____

Subject #: _____

Date: _____

Time: _____

Age (Years): _____

Body Weight (kg): _____

Height (cm): _____

Hand Length (cm): _____

Hand Width (cm): _____

Mid. Phal.(cm): _____

Wrist Cir. (cm): _____

Forearm Girth (cm): _____

Static Grip (kg): _____

Wrist Breadth (cm): _____

Wrist Width (cm): _____

Pref. hand: R___ L___

Trial # _____

Comb. No. 1: 9 cm, 2.85 cm/sec, 45F

Rep# 1

Max. Force: _____(kg) Position: _____(cm)

Rep# 2

Max. Force: _____(kg) Position: _____(cm)

Trial # _____

Comb. No. 2: 9 cm, 2.85 cm/sec, Neutral

Rep# 1

Max. Force: _____(kg) Position: _____(cm)

Rep# 2

Max. Force: _____(kg) Position: _____(cm)

Trial # _____

Comb. No. 3: 9 cm, 2.85 cm/sec, 45E

Rep# 1

Max. Force: _____(kg) Position: _____(cm)

Rep# 2

Max. Force: _____(kg) Position: _____(cm)

Trial # _____

Comb. No. 4: 9 cm, 8.60 cm/sec, 45F

Rep# 1

Max. Force: _____(kg) Position: _____(cm)

Rep# 2

Max. Force: _____(kg) Position: _____(cm)

Trial # _____

Comb. No. 5: 9 cm, 8.60 cm/sec, Neutral

Rep# 1

Max. Force: _____(kg) Position: _____(cm)

Rep# 2

Max. Force: _____(kg) Position: _____(cm)

Trial # _____

Comb. No. 6: 9 cm, 8.60 cm/sec, 45E

Rep# 1

Max. Force: _____(Kg) Position: _____(cm)

Rep# 2

Max. Force: _____(kg) Position: _____(cm)

FORM II (Continued)

Trial # _____	Comb. No. 7: 9 cm, 14.4 cm/sec, 45F
Rep# 1	Max. Force: _____(kg) Position: _____(cm)
Rep# 2	Max. Force: _____(kg) Position: _____(cm)
Trial # _____	Comb. No. 8: 9 cm, 14.4 cm/sec, Neutral
Rep# 1	Max. Force: _____(kg) Position: _____(cm)
Rep# 2	Max. Force: _____(kg) Position: _____(cm)
Trial # _____	Comb. No. 9: 9 cm, 14.4 cm/sec, 45E
Rep# 1	Max. Force: _____(kg) Position: _____(cm)
Rep# 2	Max. Force: _____(kg) Position: _____(cm)
Trial # _____	Comb. No. 10: 11 cm, 2.85 cm/sec, 45F
Rep# 1	Max. Force: _____(kg) Position: _____(cm)
Rep# 2	Max. Force: _____(kg) Position: _____(cm)
Trial # _____	Comb. No. 11: 11 cm, 2.85 cm/sec, Neutral
Rep# 1	Max. Force: _____(kg) Position: _____(cm)
Rep# 2	Max. Force: _____(kg) Position: _____(cm)
Trial # _____	Comb. No. 12: 11 cm, 2.85 cm/sec, 45E
Rep# 1	Max. Force: _____(kg) Position: _____(cm)
Rep# 2	Max. Force: _____(kg) Position: _____(cm)
Trial # _____	Comb. No. 13: 11 cm, 8.60 cm/sec, 45F
Rep# 1	Max. Force: _____(kg) Position: _____(cm)
Rep# 2	Max. Force: _____(kg) Position: _____(cm)
Trial # _____	Comb. No. 14: 11 cm, 8.60 cm/sec, Neutral
Rep# 1	Max. Force: _____(kg) Position: _____(cm)
Rep# 2	Max. Force: _____(kg) Position: _____(cm)
Trial # _____	Comb. No. 15: 11 cm, 8.60 cm/sec, 45E
Rep# 1	Max. Force: _____(kg) Position: _____(cm)
Rep# 2	Max. Force: _____(kg) Position: _____(cm)

FORM II (Continued)

Trial # _____

Comb. No. 16: 11 cm, 14.4 cm/sec, 45F

Rep# 1

Max. Force: _____ (Kg) Position: _____ (cm)

Rep# 2

Max. Force: _____ (kg) Position: _____ (cm)

Trial # _____

Comb. No. 17: 11 cm, 14.4 cm/sec, Neutral

Rep# 1

Max. Force: _____ (kg) Position: _____ (cm)

Rep# 2

Max. Force: _____ (kg) Position: _____ (cm)

Trial # _____

Comb. No. 18: 11 cm, 14.4 cm/sec, 45E

Rep# 1

Max. Force: _____ (kg) Position: _____ (cm)

Rep# 2

Max. Force: _____ (kg) Position: _____ (cm)

FORM III

Random Sequence of Test Conditions for Subjects

Test Cond.	SUBJECT #														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	10	7	11	18	11	15	12	17	16	18	7	2	10	11	7
2	1	12	7	1	5	16	4	9	1	13	14	15	11	7	11
3	18	10	14	16	16	12	14	15	9	12	5	7	12	3	5
4	9	5	6	14	10	3	6	5	7	5	9	5	9	6	12
5	13	8	5	17	3	11	5	3	17	6	4	3	3	8	8
6	7	14	8	6	14	13	9	14	18	9	10	9	17	10	15
7	16	2	4	2	9	9	2	2	10	11	13	11	1	17	9
8	2	9	3	15	13	7	8	7	14	1	1	18	6	16	1
9	5	15	10	7	7	6	3	18	11	10	3	12	14	14	4
10	14	11	2	9	15	18	17	1	15	14	11	8	7	4	16
11	15	6	18	10	101	5	18	13	3	3	18	16	5	13	3
12	3	13	1	13	12	17	16	4	12	16	17	17	18	1	13
13	12	18	12	3	8	10	13	16	4	2	8	10	2	2	10
14	11	3	16	4	17	1	7	8	6	17	15	13	13	12	14
15	8	16	15	12	4	14	10	11	13	4	12	4	8	9	18
16	6	17	9	11	18	4	15	10	2	15	16	14	15	15	6
17	17	1	13	5	6	8	1	12	5	8	2	1	16	5	17
18	4	4	17	8	2	2	11	6	8	7	6	6	4	8	2

FORM III (Continued)

Test Cond.	SUBJECT #														
	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	14	15	3	14	9	17	8	14	14	13	14	1	12	15	1
2	11	14	5	3	15	12	5	4	18	3	11	2	6	9	9
3	2	6	9	2	1	5	7	8	1	2	15	17	3	12	16
4	8	4	17	8	3	9	14	7	15	8	6	8	9	3	5
5	10	1	4	11	6	1	9	10	7	10	9	12	13	14	6
6	13	10	8	9	11	16	4	16	2	17	2	3	17	7	2
7	9	2	14	16	13	10	1	3	13	11	8	13	11	6	11
8	6	7	3	5	16	7	3	12	16	12	5	5	14	18	14
9	1	16	6	1	2	4	10	6	8	7	3	14	5	8	13
10	7	3	18	4	8	11	15	1	12	6	1	18	4	13	17
11	12	12	16	18	18	13	17	11	11	15	10	10	2	17	10
12	5	8	12	12	17	18	2	13	6	1	12	11	15	2	15
13	17	9	7	6	14	8	18	2	17	5	16	7	1	5	12
14	15	5	11	7	7	15	6	18	9	9	7	4	7	1	18
15	3	13	2	17	5	2	12	15	3	14	17	6	18	16	4
16	18	18	10	13	2	14	16	17	4	4	4	15	16	4	3
17	4	17	13	10	4	3	11	5	5	18	13	16	10	11	8
18	16	11	15	15	10	6	13	9	10	16	18	9	8	10	7

RESTRICTION BLOCK

[illegible]

APPENDIX C
CALCULATIONS

CALCULATIONS FOR VELOCITIES AND DURATIONS

1. Linear velocity $v = 2.85, 8.6, \text{ and } 14.4 \text{ cm/sec}$

Angular velocity $w = v / r$

where 'r' is the radius or distance between actuator center and grip centroid

and $r = 16.5 \text{ cm}$

$w = v / 16.5 \text{ radians / sec or}$

$w = (2.85 / 16.5) * 180 / 3.14 = 10, 30, \text{ and } 50 \text{ deg/sec}$

2. Duration $d = s / v$

where 's' is the span

$s = \text{fully open (11 cm) - fully closed (4.6) = 6.4 cm}$

$s = \text{fully open (9 cm) - (4.6) = 4.4 cm}$

3. Scale factor and Offset

	Scale factor	Offset
Force	87.5	-7.473
Displacement	100	-5.967

4. Tool Specifics

2.5 mV/in-lb

Mass = .89 kg Center of mass = 2.8 cm

6.5 inch moment arm

$6.5 " 2.2046 = 14.3 \text{ in-lb} = 35.7 \text{ mV}$

APPENDIX D
RESIDUAL PLOTS

Figure 1:

Studentized Residual vs. Estimate
for Peak Force

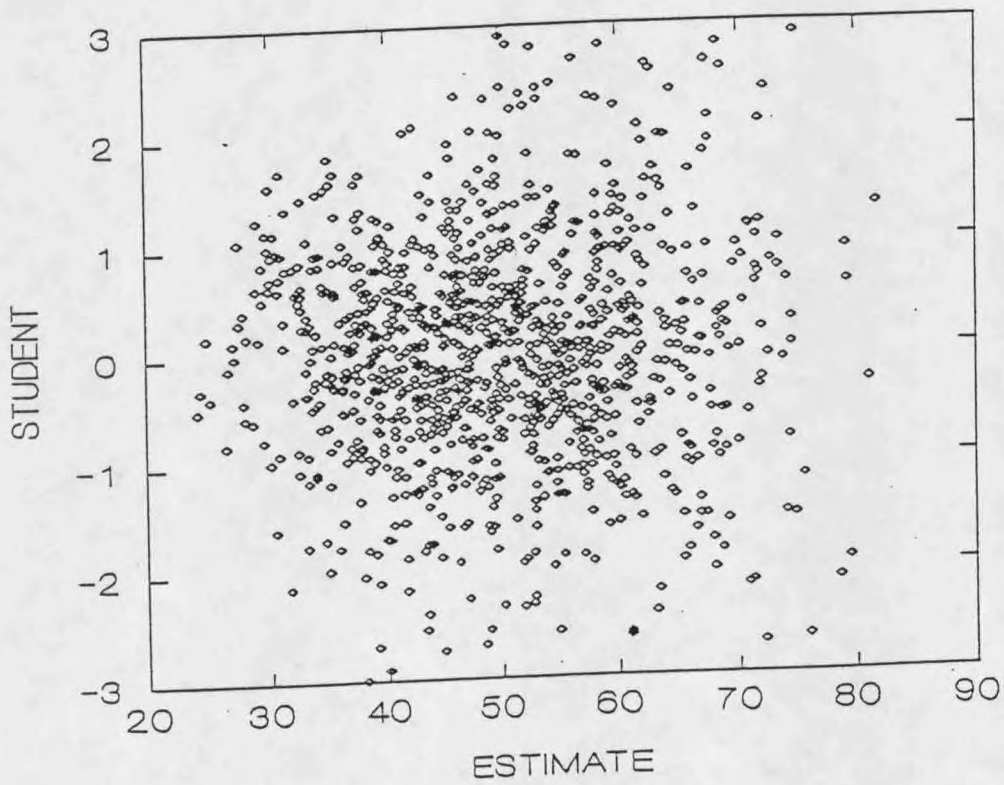


Figure 2:

Studentized Residual vs. Estimate
for Displacement of Peak Force

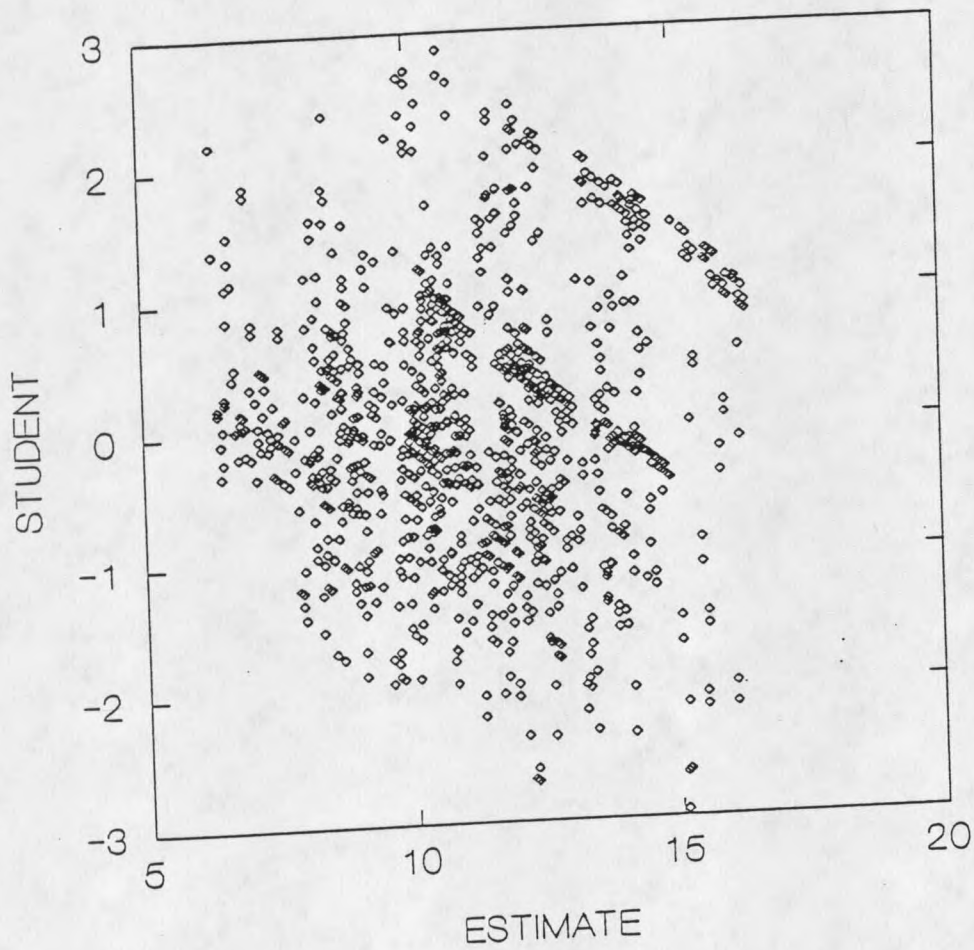


Figure 3:

Studentized Residual vs. Estimate
for Regression of Peak Force at 9 cm

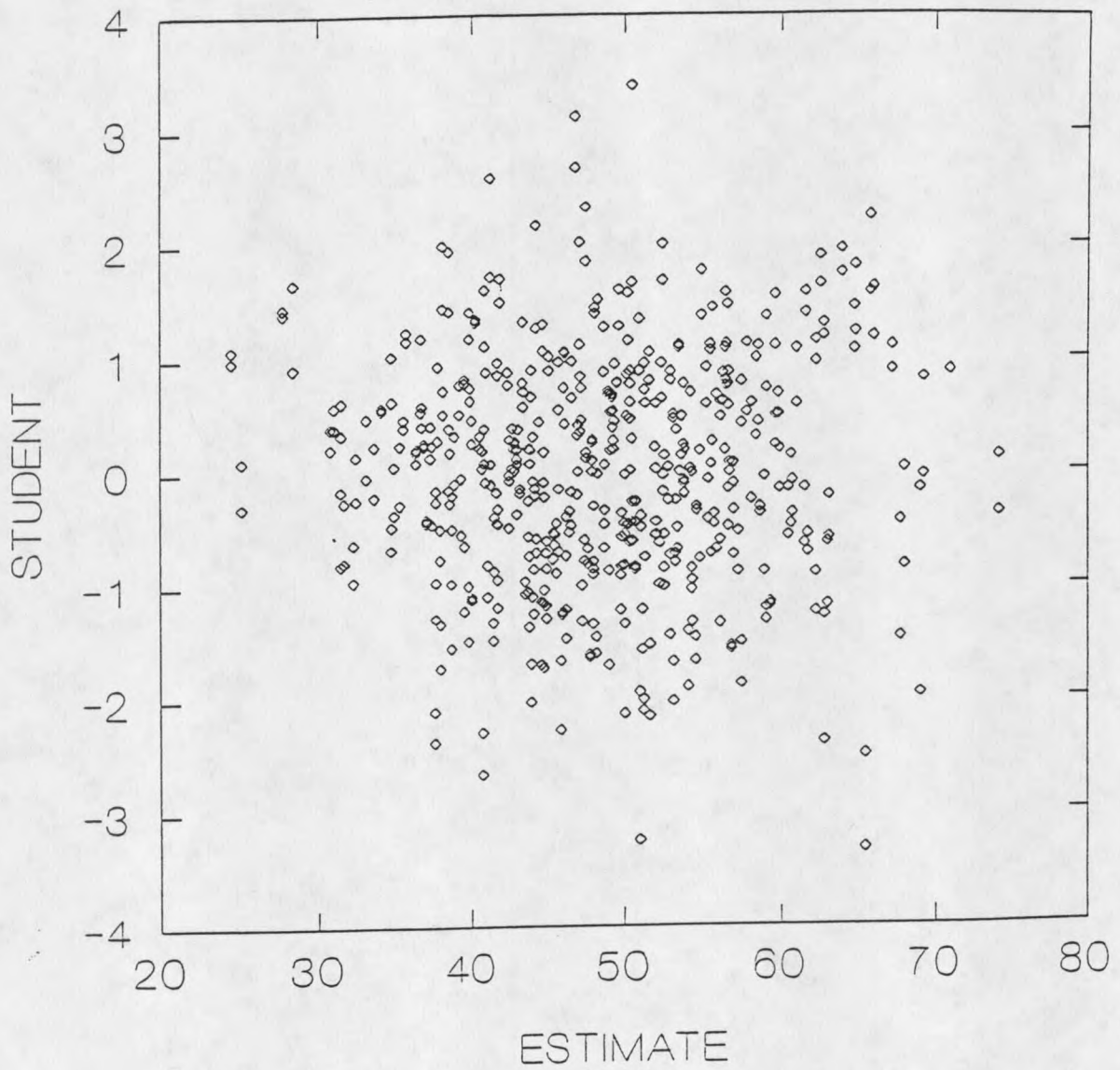


Figure 4:

Studentized Residual vs. Estimate
for Regression of Displacement of Peak Force at 9 cm

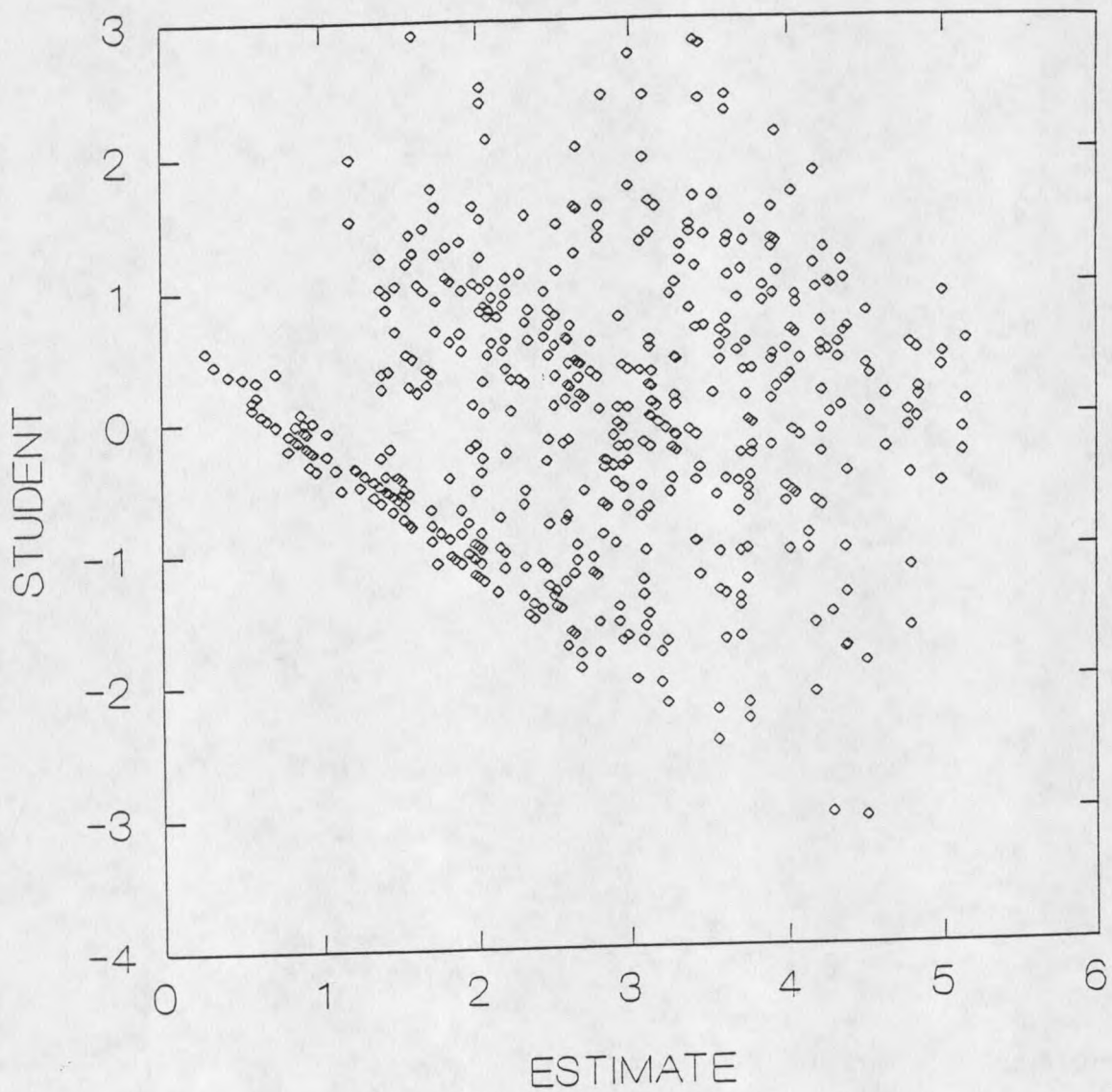


Figure 5:

Studentized Residual vs. Estimate
for Regression of Peak Force at 11 cm

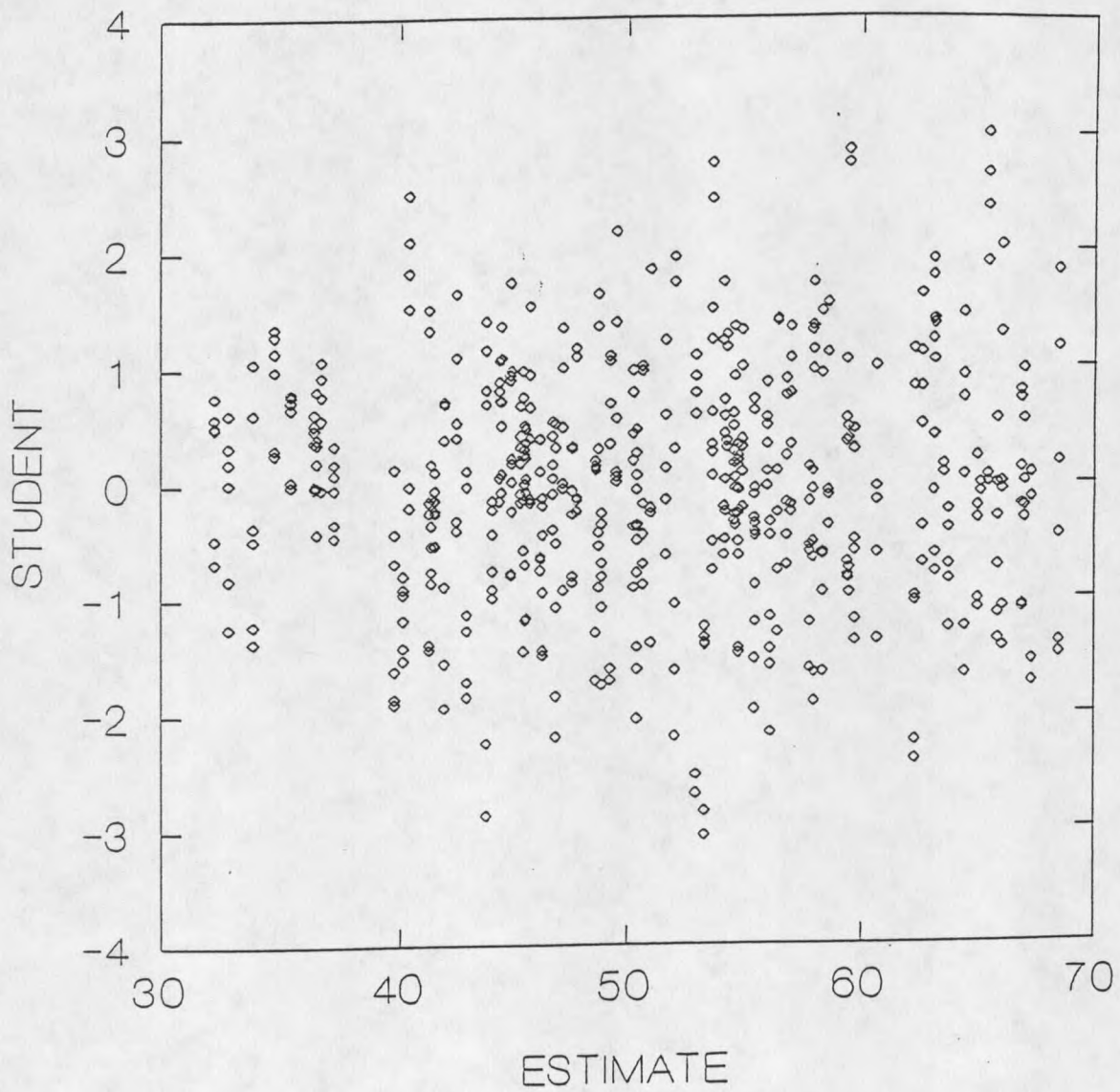
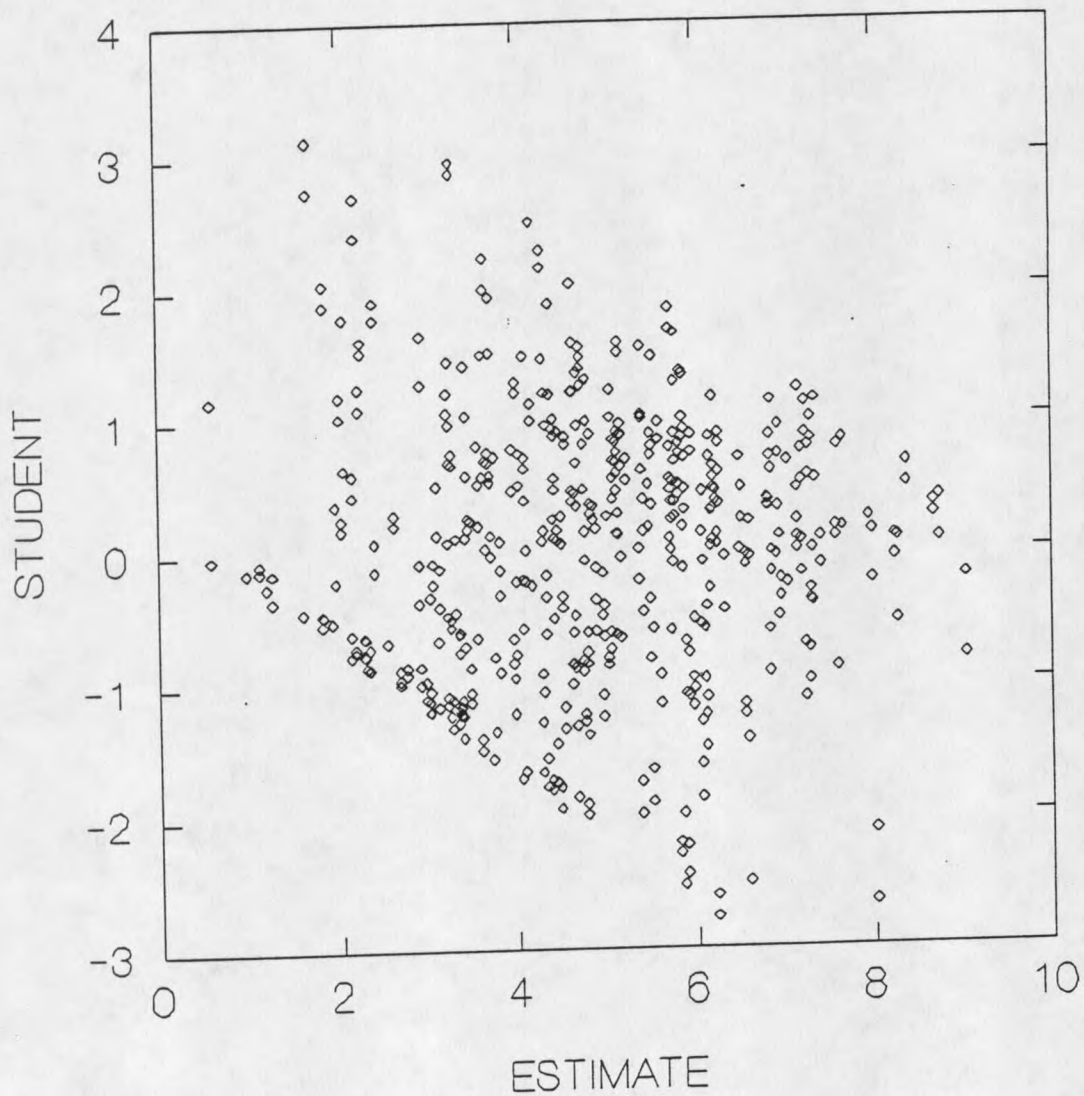


Figure 6:

Studentized Residual vs. Estimate
for Regression of Displacement of Peak Force at 11 cm



APPENDIX E

RAW DATA

REP	SUBJECT	DISPLACE	VELOCITY	WRIST	FORCE	POSITION
1	1	1	1	1	62.4	7.7
1	1	1	1	2	74.6	7.5
1	1	1	1	3	81	10.7
1	1	1	2	1	49.4	8.9
1	1	1	2	2	65.4	12.9
1	1	1	2	3	48.1	13.3
1	1	1	3	1	53.6	13.3
1	1	1	3	2	53.2	13.5
1	1	1	3	3	37.4	10.5
1	1	2	1	1	46.6	4.3
1	1	2	1	2	69.2	4
1	1	2	1	3	63.7	7.7
1	1	2	2	1	49.6	10.3
1	1	2	2	2	63	15.5
1	1	2	2	3	53.4	16.7
1	1	2	3	1	41	19.8
1	1	2	3	2	51.3	16.7
1	1	2	3	3	50.9	15.8
1	2	1	1	1	55.7	7.3
1	2	1	1	2	67	6
1	2	1	1	3	52.8	7
1	2	1	2	1	49.4	8.9
1	2	1	2	2	54.5	9.9
1	2	1	2	3	44.5	10
1	2	1	3	1	45.3	13.5
1	2	1	3	2	46.6	12.1
1	2	1	3	3	36.3	9.9
1	2	2	1	1	41.9	14.3
1	2	2	1	2	57.5	9.4
1	2	2	1	3	56	4
1	2	2	2	1	44.5	10.6
1	2	2	2	2	52.1	15.2
1	2	2	2	3	50.9	4
1	2	2	3	1	41	10.3
1	2	2	3	2	49.4	12.3
1	2	2	3	3	44	10.9
1	3	1	1	1	61.5	8.3
1	3	1	1	2	57	11
1	3	1	1	3	55.8	6.2

1	3	1	2	1	48.7	10.3
1	3	1	2	2	57.7	8.9
1	3	1	2	3	41.2	7.1
1	3	1	3	1	47.9	10.1
1	3	1	3	2	50.2	10.3
1	3	1	3	3	38.9	7.9
1	3	2	1	1	48.3	8.3
1	3	2	1	2	54.9	10.3
1	3	2	1	3	45.1	3.7
1	3	2	2	1	46.8	6.9
1	3	2	2	2	45.1	6.3
1	3	2	2	3	49.6	6.3
1	3	2	3	1	45.1	6.6
1	3	2	3	2	43	6.9
1	3	2	3	3	39.3	6.3
1	4	1	1	1	49.4	6.4
1	4	1	1	2	72	7.7
1	4	1	1	3	52.4	6.6
1	4	1	2	1	52.4	11.5
1	4	1	2	2	59.4	10.1
1	4	1	2	3	34.2	7
1	4	1	3	1	29.1	9.9
1	4	1	3	2	32.7	9.7
1	4	1	3	3	26.9	10.3
1	4	2	1	1	45.7	8.3
1	4	2	1	2	63.9	4.3
1	4	2	1	3	61.8	3.4
1	4	2	2	1	37	8.3
1	4	2	2	2	59	8
1	4	2	2	3	42.5	3.7
1	4	2	3	1	34	8.3
1	4	2	3	2	40	8.6
1	4	2	3	3	36.3	8.9
1	5	1	1	1	66	10
1	5	1	1	2	83	12.1
1	5	1	1	3	87.4	7.3
1	5	1	2	1	53.9	13.7
1	5	1	2	2	69.2	10.7
1	5	1	2	3	49.2	9.9
1	5	1	3	1	46.8	13.7

AGE	WT	HT	HL	HW	MP	WC
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
17	82	183	18.1	8.7	7.6	17.5
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
24	80	178	20	8.6	8.1	16
19	104	188	20.5	9.4	8.8	18.7
19	104	188	20.5	9.4	8.8	18.7
19	104	188	20.5	9.4	8.8	18.7

[illegible]

FG	WB	WW	SG
28	3.8	6.2	56
28	3.8	6.2	56
28	3.8	6.2	56
28	3.8	6.2	56
28	3.8	6.2	56
28	3.8	6.2	56
28	3.8	6.2	56
28	3.8	6.2	56
28	3.8	6.2	56
28	3.8	6.2	56
28	3.8	6.2	56
28	3.8	6.2	56
28	3.8	6.2	56
28	3.8	6.2	56
28	3.8	6.2	56
28	3.8	6.2	56
28	3.8	6.2	56
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
28	3.5	5.8	45
32	4.5	6.6	58.5
32	4.5	6.6	58.5
32	4.5	6.6	58.5

[illegible]

