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A COMPARATIVE STUDY OF THE PERFORMANCE OF THE INDEX FINGER AND THUMB AS TRIGGER MECHANISMS FOR POWER HAND TOOLS

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A DISSERTATION
SUBMITTED TO THE GRADUATE FACULTY
in partial fulfillment of the requirements for the
degree of
DOCTOR OF PHILOSOPHY

BY
YOSHIO IKEDA
Norman, Oklahoma
1980

A COMPARATIVE STUDY OF THE PERFORMANCE OF THE INDEX FINGER AND THUMB AS TRIGGER MECHANISMS FOR POWER HAND TOOLS

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Dedicated to Toshio Ikeda (1915-1969)
Father

PREFACE

The author wishes to express his sincere gratitude to all his acquaintances, fellow students, and friends whose help, cooperation, and encouragement made this investigation possible.

The author wishes to thank his doctoral committee for their advisement and comments: Drs. LaVerne Hoag, Jerry Purswell and Richard Krenek of the School of Industrial Engineering; Dr. Ronald Ratliff of the Department of Health, Physical Education, and Receation; and Dr. Mary Whitmore of the Department of Zoology.

Special thanks goes to his parents for their encouragement throughout his education, to his former Professor Tomonori Kumagai for his encouragement, to his fellow student, Robert Schlegel for his editing and help, and to all subjects for their benignantly participating in the pilot and main experiments.

Finally, but not least, the author wishes to express his indebtedness to his wife, Miyoko, for her patience and moral support and to his daughters, Hisane, Mizune and Ayane for their understanding.

ABSTRACT

The primary purpose of this study was to evaluate the use of the index finger and the thumb as trigger operators of power tools. The grip for holding a portable tool provides the foundation which allows the index finger and the thumb to perform their trigger functions. Thus, the secondary purpose of the study was to evaluate two types of power grip used in these trigger operations.

To achieve these goals, a series of experiments was designed to obtain fundamental knowledge of the performance characteristics of the index finger, the thumb and the grip. Three females and three males performed various types of isometric exercise. The measure of muscular strength was the five-second maximal voluntary contraction (MVC). For endurance, a relative strength score (RSS) was used. The RSS was defined as the ratio of the MVC, measured at fixed intervals, to the initial MVC at the beginning of exercise.

The following results were obtained:

1. When the index finger was excluded from the gripping activity, grip strength was reduced to 60% of

the strength developed with the full grip. If the thumb was restricted, grip strength was decreased to 82%. The force developed with an ulnarly deviated wrist was 89% of the force developed with the neutral wrist. Grip strengths with large and small grip spans were 93% and 86%, respectively, of the strength exerted with the medium grip span.

2. The close and far positions of the index finger provided 78% and 75%, respectively, of the strength developed with the midposition (13.58 kg).

3. The mean thumb strengths for the OPPOSITION (toward the palm) and the INWARD (toward the flexed fingers) directions were 88% and 71%, respectively, of the strength developed for the DOWN direction (6.75 kg). In the DOWN direction, the midposition of the thumb exhibited the greatest strength with a mean of 7.61 kg, followed by the high (7.48 kg) and low (5.17 kg) positions.

4. Negative exponential regression equations were used to describe the fatigue patterns for sustained isometric exercise. After two minutes of exercise, the thumb was able to exert 43% of its initial strength while the index finger maintained only 28% of its initial strength.

5. Negative exponential equations were also used to describe the fatigue patterns for rhythmic isometric exercise. After six minutes of exercise, the thumb was able to exert 53% of its initial strength whereas the index finger maintained only 40% of its initial strength.

From these results, recommendations for the design of trigger switches were made as follows:

1. The holding capability of the partial grip rather than the full grip should be considered for the design of the grip handle of a tool. The handle size should be so designed to accommodate the medium or slightly larger grip span.

2. If a tool requires a "high force" trigger, the index finger should be assigned as the trigger operator. However, in implementing this notion, one should note that the index finger is inferior in muscular endurance to the thumb.

3. The thumb had a much higher endurance capability in both continuous and rhythmic isometric exercises than did the index finger. Moreover, the grip strength with thumb operation was greater than with index finger operation. Therefore, it is recommended that the thumb be used rather than

the index finger when the force requirement is low.

4. Continuous force exertion caused much faster fatigue than did intermittent exertion. Hence, it is recommended that the duration of a single actuation of the trigger be as short as possible.

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CHAPTER I

INTRODUCTION

1.1 THE NEED OF A STUDY

As described by Braidwood (1967), one of the features distinguishing man from other primates is his use of tools. Although often primitive in design and function, tools have been used throughout the history of man. In his study of 19th century Latvian folk norms concerning agricultural tools, Drillis (1963) found that the tools used by the Latvians agreed with those optimally designed by biomechanical analyses. Furthermore, he reported: "The statement by the Greek philosopher Protagoras (480-411 B.C.) that 'man is the measure of all things' is still valid in all respects." Thanks to the cumulative nature of human culture, tools have improved remarkably in function and efficiency. Some basic functions of tools still exist today as seen in hammering, cutting, holding, and the like in which human muscular force is the primary source of power for tools.

With advances in science and technology, the availability of external power for hand tools has yielded greater production with less human effort. It seems, however, that the addition of external power has been rather intuitive and lacks a scientific basis. For example, the importance of weight distribution in hand held tools for balance has been pointed out only in relatively recent times (Greenberg and Chaffin, 1977). Several researchers have studied hand tools operated only by human muscular force (Chide, 1945; Roubal et al., 1962; Drillis, 1963; Drillis et al., 1963; Miller et al., 1971; Evans, et al., 1973; Konz, 1974 and 1979; Kreifeldt, 1974; Schultetus, 1974; Tichauer, 1976; Bullinger et al., 1976) whereas information concerning powered hand tools is relatively scant and insufficient (Konz, 1974 and 1979, and Tichauer, 1969).

There is little information available in the literature about the way to assign a finger to trigger a power tool and when it is available recommended assignments are controversial. The use of the thumb as a trigger finger has been recommended by Tichauer (1969) and Konz (1974 and 1979). However, this recommendation of thumb use has been criticized by Welch (1972) :

> It is unfortunate that a well-known worker in the field of ergonomics has recently been reported as advocating the replacement of finger squeeze actuating levers by thumb push buttons . . .

He argued that a major cause of tenosynovitis on repetitive assembly work was formerly the thumb push button. He further stated, "The employment of extension levers operated by all fingers has eliminated most tenosynovitis caused by excessive use of the thumb." However, it appears that his claim may not necessarily be due to thumb use but instead due to excessive use of the thumb. The repetitive motion found in various types of industrial work is believed to be one of the causal factors in hand/wrist injuries and diseases such as tenosynovitis, carpal tunnel syndrome, and related musculo-skeletal problems (Brain et al., 1947; Kendall, 1960; Tichauer, 1966; Hymovich and Lindholm, 1966; Phalen, 1966; Radin et al., 1971; Welch, 1972; Birtbeck and Beer, 1975). The advocates of thumb use, on the other hand, claim that the thumb is the strongest of the digits. However, their claim appears to be incorrectly referred to by Konz (1979) and to lack supporting evidence (Tichauer, 1969). Since the anatomical structure and functional characteristics of the index[1] are different from those of the thumb, comparison of the two must be done with care. First of all, the evaluation should be based on similar criteria. In the works previously cited, finger strength was the major criterion. It is well known that the amount of force exerted by muscles is a function of position as well as other factors. However, in most studies, the strengths of the thumb and fingers in terms of the maximum voluntary contrac-

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[1] The term "index" will be used to mean the index finger throughout this report unless explicitly stated otherwise.

tion (MVC) have been compared using only one position for each finger[2]. For measurements of the thumb, exertion force has been measured perpendicular to extended fingers with the ulnar side of the hand placed on a flat surface (Barter et al., 1957 cited by Konz, 1974). For measurements of the other fingers, the dorsal side of the hand was placed on the flat surface (Barter et al., 1957 cited by Konz, 1974). Konz (1974 and 1979) and Tichauer (1969) concluded that the thumb was strongest. It is apparent that performance of the index was not evaluated at its best position compared with that of the thumb. If maximum strength was the criterion for comparing the performance of each finger, the best position for each finger in terms of exertion force should have been used.

As previously described, there have been three trigger function assignments found in power tools; (a) the index, (b) the thumb, and (c) four fingers on a lever switch. With respect to types of grips, these can be classified into two categories: power grip and manipulative grip. When the index or the thumb is used as a trigger operator, the tool is held by the tight grip formed by the palm, thumb, and fingers excluding the finger assigned to the trigger. A tight grip does not necessarily mean that a high level of

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[2] The thumb is distinguished from the fingers in the English language; however, it will be referred to a finger throughout this paper.

force exertion is required on the grip handles during the entire course of operations but that such force exertion is available if necessary.

On the other hand, a high level of force exertion can not be required for holding the tool when four fingers are assigned to trigger the lever switch. This is especially true when the tool is in an idle period during the course of operations. Therefore, the application of a controlled amount of force to the grip handle and the lever switch requires the manipulative motions of fingers and results in the manipulative grip.

As pointed out by Welch (1972), the four finger operation of a lever switch seems to be a promising approach to protect tool users from occupational health problems. However, the manipulative grip differs greatly from the power grip. Furthermore, the manipulative grip by its nature is not applicable to every type of tool, especially to the portable tool which is not suspended.

The literature search failed to reveal information that would enable a person to appropriately evaluate the trigger function. There appeared to be little fundamental information available for the evaluation of four finger trigger operations because of the specific motions found in such operations. There is scant information available about the strength, with nothing available about the endurance of individual fingers. It is expected that with the continued advance of science and technology, more power tools will find their way into the marketplace. Humans should always be masters and never servants or victims of powered hand tools. An appropriate guideline with due regard for human characteristics should be available to a tool designer. The investigation of hand grips and the performance of the index and thumb with respect to power tools would provide tool engineers, researchers, and managers with the means and data useful for (re)design of an appropriate trigger mechanism.

1.2 OBJECTIVES OF THIS STUDY

The primary purpose of this study was to evaluate the use of the index finger and the thumb as trigger operators of power tools. This study assumed that no other fingers perform a trigger function better than the index or the thumb. The other three fingers of the hand lack relative independence in their muscular structure and tend to work together. Also, there has not been found any power tool in which the middle, ring, or little finger trigger a switch.

In portable tool operations, the grip for holding the tool provides the foundation which allows the index and the thumb to perform their trigger functions. The secondary purpose of this study was to evaluate the two types of power grips used in the index and the thumb trigger operation. To achieve this goal, it was necessary to collect some additional information. A series of experiments was designed to obtain fundamental knowledge of index, thumb, and grip performance associated with trigger operations with the following objectives:

1. To determine if there is a significant difference in strength between the two grips that are used in the index trigger operation and the thumb trigger operation.

2. To determine if grip strength is affected by gender, individual subject strength, grip span, and wrist orientation. Subject strength was classified as strong, average, or weak (see Section 3.3 for details).

3. To determine if index strength is affected by gender, individual subject strength, index finger position, and wrist orientation.

4. To determine if thumb strength is affected by gender, individual subject strength, thumb position, and wrist orientation.

5. To determine if there is a significant difference between the fatigue patterns of the index and thumb. Fatigue patterns of the thumb and the index were studied in two types of endurance exercise, sustained isometric and rhythmic isometric.

6. To determine if the fatigue patterns are affected by gender, individual subject strength, finger, and wrist orientation.

The criterion used for the evaluation of muscular strength was the MVC and that used for the evaluation of muscular fatigue patterns was the relative strength score. The relative strength score (RSS) was defined as the ratio of the MVC, measured at fixed intervals during the course of the exercise, to the initial MVC observed at the beginning of the exercise. Muscular fatigue patterns of the index and the thumb were compared using the relative strength scores vs. the elapsed time.

The final purpose of this study was to prepare recommendations for the design of a grip handle and trigger switches for portable powered hand tools.

1.3 ORDER OF PRESENTATION

To facilitate the presentation of this study, the following chapters are summarized as follows:

Chapter 2: Background and Literature Review

The background material is reviewed in this chapter. The review includes portable power tools and their task characteristics, functional consideration of grips, a functional review of the index and the thumb, the state of the art with respect to muscular strength and endurance, and the variables that affect these performances.

Chapter 3: Materials and Methods

This chapter provides the description of the experiment in detail. The description includes a statement of the problem, the experimental task, the experiments, the measurements, and the procedures.

Chapter 4: Results and Discussion

The results of the measurements are described with an appropriate discussion. The result presentation consists of grip strength data, index strength data, thumb strength data, fatigue patterns expressed in the form of negative exponential equations for the index and the thumb and for sustained isometric and rhythmic isometric exercises.

Chapter 5: Conclusions and Recommendations

Conclusions and recommendations for the design of a grip handle and trigger switches and for further studies are discussed in this chapter.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

2.1 INTRODUCTION

The purpose of this chapter is, in a broad sense, to define the subject of this study and to provide background material. The first section presents a review of the use of portable power tools in terms of trigger operation. Then, the characteristics of the human hand and fingers are reviewed in relation to such trigger operation. The second section reviews background material on different grips which are required for the operation of a portable tool. In the third section, the anatomical and functional characteristics of the thumb and the index finger are described. In the next section, the methodologies which have been previously used to examine hand/finger performance are reviewed and an evaluation of their appropriateness for this study is discussed. The last section of this chapter discusses the variables which affect human performance with respect to tool operation.

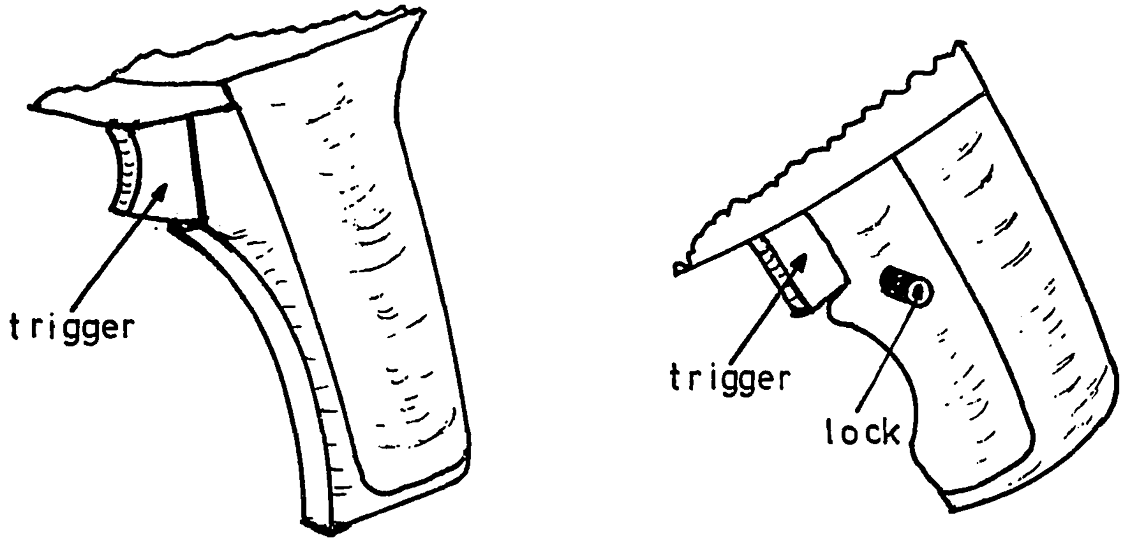
2.2 REVIEW OF POWER TOOLS AND THEIR TASK CHARACTERISTICS

A trigger operation is defined as the procedure of turning a power tool on/off using a trigger switch operated by a squeezing/releasing motion of the index or thumb with the rest of the fingers and hand grasping the tool handle.

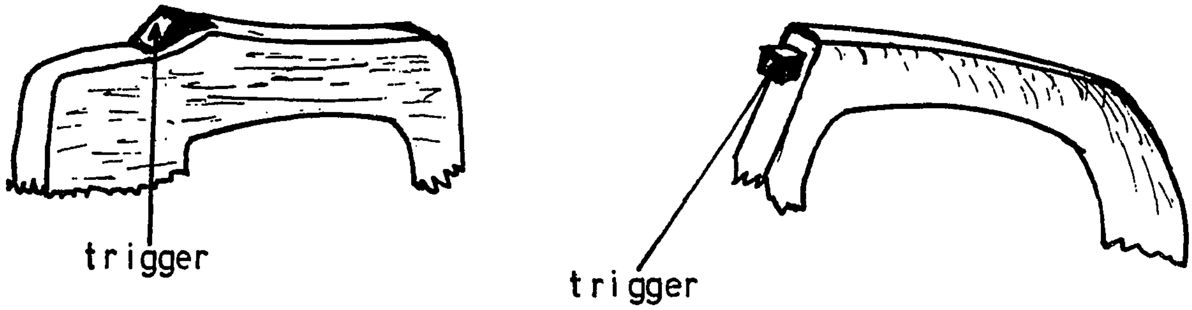
A review of commercially available tools revealed that tool designers have assigned the trigger function to either the index or the thumb. The tool handle was generally an elliptic cylinder having a major axis of 5.8 to 7.4 centimeters (cm) and a minor axis of 3.2 to 3.8 cm. A circular handle was not found in many types of power tools requiring a trigger operation. Typical switch and handle configurations appearing in commercial products are illustrated in Figure 1.

There were mainly two types of operating speeds available: (a) single speed and (b) variable speed. Single speed means that the speed of the tool is constant when it is in operation. On the other hand, variable speed implies the capability to change the speed during the course of operation. Further classification of variable speed tools will be made later.

Insofar as the single speed mode is concerned, the trigger operation of powered hand tools does not require fine psychomotor skills, complex hand/finger motions, speedy finger actions, or highly mental tasks. Whether the trigger is squeezed slightly, fully, or held in its mid-position does not affect the operation of the tool.



(a) Examples of an index trigger operation



(b) Examples of a thumb trigger operation

Figure 1: Typical grips and trigger arrangements

However, the operation of even single speed tools may involve complex motions or highly mental tasks if the entire process for a certain task is examined. Before a part is processed, it must be laid out. Laying out the task may involve high level mental work and calculations. Once the layout is done, a power tool is applied to a point or line on the work. During a period of tool operation, detailed lines on the work may demand complex motions of hand/fingers so that the tool follows the lines and the goal is achieved. However, it is clear that these mental tasks or complex motions are not directly related to the trigger operation as defined before. Provided the on/off motion of the trigger does not require excessive force exertion, little can be done by the trigger to improve the quality of the work. Therefore, it seems that the task aspects of single speed trigger operation do not add significant factors to the finger performance evaluations of this study.

From personal inspection of power tools and conversations with a tool manufacturer (Skil, 1979) and distributors in Oklahoma City, a variable speed tool may be classified into three types; (a) a speed selector switch (two to five speeds) or dial with a momentary contact (on/off) trigger, (b) a variable speed trigger without a speed selector or dial, and (c) a variable speed trigger with a speed selector or dial.

Some power tools are equipped with a speed control as well as a trigger switch. Different speeds are available using a selector or dial. With a selector, a discrete change of speed results whereas the change of speed is continuous with a dial. However, the trigger on this type of tool does not vary the speed. It functions only as an on/off switch as it does in the single, constant speed tool. Therefore, it seems that the characteristics of this tool are identical to the single speed tool.

The variable speed trigger used in (b) or (c), on the other hand, functions to switch on the tool and control the speed up to its designed and/or preset maximum. In (b) the maximum speed is fixed whereas in (c) different maximum speed settings are available. Insofar as trigger functions are concerned, the variable speed trigger plays the same role in (b) and (c).

In tools with a variable speed trigger, speed control is continuous between the beginning and the end of a switch range. Since there are no clear distinctive setting points[3], the operation requires fine psychomotor skills. However, it is difficult for the user to judge and to adjust the speed at each moment during the course of an operation because of limited sensory cues. The user must seek other

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[3] Force requirement for trigger operations were measured to ensure if such tactile cues might be available from trigger switches. See Appendix A for details.

cues such as sound, tool vibration, sight, smell, and proprioceptive and pressure feedbacks from the trigger finger. The desired speed must be controlled by the trigger finger under conditions in which minimal feedback is available. As a result, a lot of practice is required to build such skills. If such speed control were necessary and important for power tool operations, this study should have included this aspect of finger performance. This question prompted further investigation of products on the market. Further conversations with a power tool manufacturer (Skil, 1979) revealed their intention of the variable speed trigger as follows:

1. The variable speed trigger is intended to eliminate preparatory steps in a task rather than to provide various speeds. An example given was that of "drilling a hole". A punch is usually used to facilitate a following drilling step. The punching step may be replaced by immediate application of a drill with a slower speed. Once the preparatory drilling is done, drilling is continued at the proper (maximum as designed or chosen for the tool) speed to complete the task.

2. The manufacturer's intended purpose of a variable speed trigger is to provide a very slow speed and a selected (or designed) maximum speed. This sa-

tisfies the requirements of slow speed for the beginning of a task and the appropriate speed for the processing of certain types of material with certain tool bits.

3. If a specific speed is critical and important for a given task, such speed should be obtained with a speed selector or dial rather than the control of the variable speed trigger. The manufacturer recommends the use of a selector when the speed is important for a given task. The variable speed trigger is frequently promoted from the sales point of view.

The human hand (which shakes by its nature) is not as stable as a tool fixture. However, it is the only available fixture for the portable tool. Therefore, obtainable accuracy from a power tool is poor and limited in comparison with a machine tool. It is unreasonable to expect accuracy beyond a certain level using a variable speed trigger at the middle position of its range. From the economic and accuracy points of view, it is reasonable to assume that the right tool has been chosen to process a certain type of material and that it is used correctly. Whenever this assumption is violated, it seems that such operation is uneconomical. Furthermore, it is reasonable to assume that a speed change, if necessary, should be done by a selector or dial rather than by a variable speed trigger. It was assumed that the accuracy of the speed control by the finger for a variable speed trigger was not important and is not a major factor of this study. Hence, factors affecting fine psychomotor skills, mental tasks, and complex motions of the hand/fingers associated with trigger operations were not investigated by this study.

The major task involved in the trigger operation is, therefore, a physical task (i.e., muscular strength or muscular endurance). The functional grip and grip strength capability of the human hand is reviewed in the next section and the strength and endurance capability of the thumb and the index is reviewed in following sections.

2.3 FUNCTIONAL CONSIDERATION OF GRIP

2.3.1 Wrist Articulation

It is worthwhile to review grip studies because gripping is a necessary and fundamental action for any portable, power tool operation. Since the wrist or carpus is the joint which links the hand and forearm, the motion of the wrist (Dempster et al., 1947; Radonjic et al., 1971) will be reviewed briefly before the grip is discussed.

The motion of the wrist occurs in the carpal joints; (a) radio-carpal, (b) intercarpal, and (c) midcarpal. There is no important motion between the bases of the 2nd, 3rd, 4th and 5th metacarpals and the row of the hamate, the capitate, and the trapezoid. There are, however, two units of functional importance; (a) the proximal row of the carpal bones with the exclusion of the pisiform, and (b) the distal row of the carpal bones excluding the trapezium. The scaphoid bone forms a functional link between the two units. Figure 2 illustrates the location of the carpal bones and carpal joints.

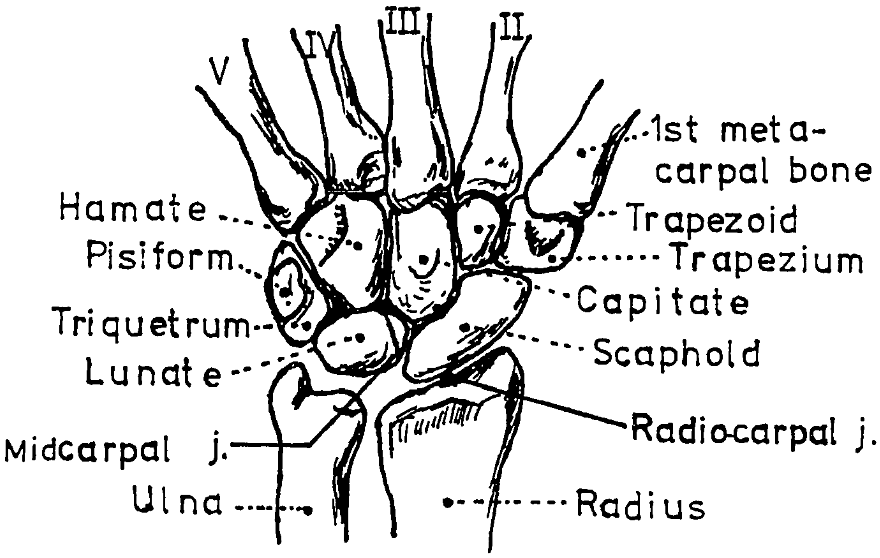


Figure 2: The carpal bones in relation to metacarpal and forearm bones

Extension of the wrist occurs primarily in the midcarpal joint and secondarily in the radio-carpal joint. The wrist extension is produced directly by the extensor carpi radialis longus, extensor carpi radialis brevis (ECRB) and extensor carpi ulnaris muscles, and indirectly by the extensor digitorum, extensor indicis proprius, extensor digitorum minimi, extensor pollicis longus and extensor pollicis brevis muscles. In contrast, wrist flexion occurs primarily in the radio-carpal joint and secondarily in the midcarpal joint. It is produced directly by the flexor carpi radialis, flexor carpi ulnaris and palmaris longus, and indirectly by the long flexors of the fingers and the abductor pollicis longus.

2.3.2 Functional Consideration of Grip

The gripping activities of the hand have been classified into several types such as the cylinder grip, pincer grip, plier grip, and so forth. Although this classification is expressive, it does not appear to have any particular functional or anatomical basis. Napier (1956) proposed that the movements of the hand can be divided into two main groups:

1. Prehensile movements in which an object is held partly or wholly within the compass of the hand.

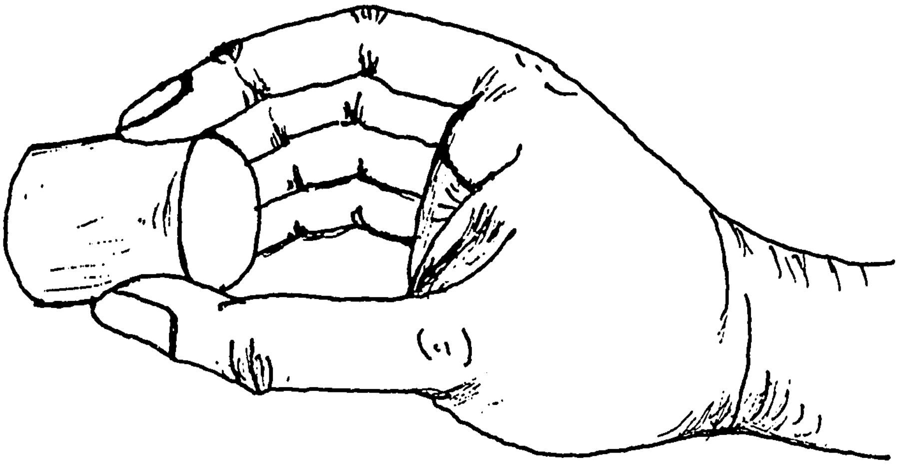
2. Non-prehensile movements in which no grasping is involved but by which objects can be manipulated by pushing or lifting motions of the hand as a whole or of the digits individually.

The prehensile grip is further divided into two grips: the power grip and the precision grip. "Power grip" is defined as forcible activities of the thumb and fingers against the palm while "precision grip" is the manipulation of an object between the thumb and fingers. The essential anatomical features of these two grips become clear when the thumb and other fingers are considered separately. The position of the thumb differs in the two grips. In the power grip, the thumb is adducted at the metacarpophalangeal (MP) and carpometacarpal (CM) joints while it is abducted at both joints in the precision grip. A pictorial presentation of the difference is shown in Figure 3.

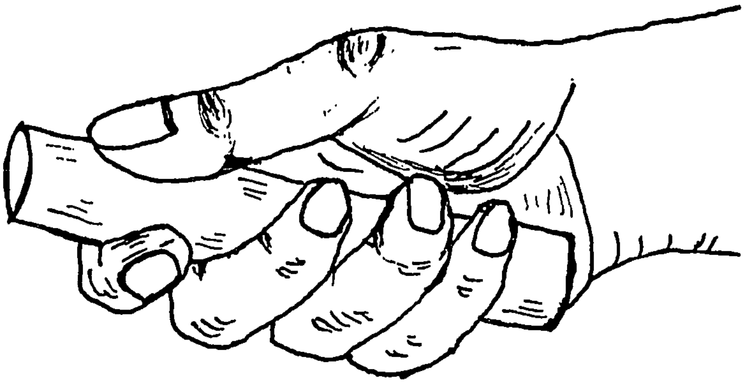
Landsmeer (1962) pointed out that power gripping consists of static and dynamic phases. The static concept indicates the final state of the power grip. The dynamic phase is comprised of a series of voluntary acts:

1. Opening the hand--the interphalangeal (IP) and the MP joints simultaneously extend

2. Choice of finger position--the fingers adjust at the MP joints,



(a) Precision handling



(b) Power grip

Figure 3: Two types of grip

Note that the thumb is abducted in (a) and it is adducted in (b).

3. Approach--as the fingers approach the object, the MP joints flex while the IP joints flex,
4. Grip--as the fingers take hold of the object, they are drawn by the flexor digitorum profundus so that they remain in a position that ensures an efficient grip.

The muscles which control hand movements may be classified as extrinsic (located in the forearm) or intrinsic (located in the hand). All extrinsic muscles except the abductor pollicis longus are involved in various forms of the power grip and are used in proportion to the desired force. The major intrinsic muscles used for the power grip are the interossei, used as phalangeal rotators, lumbricals, and hypothenar muscles. Thenar muscles are also used (Long et al., 1970). Therefore, the power grip can be considered as a total hand function in which the middle, ring and little fingers supply the major grip force by means of the extrinsic and interossei muscles. The index finger assists in the holding and the thumb supplies the necessary opposition by means of the thenar muscles.

The power (defined as the product of forces times velocity) which a muscle system delivers to an external inertial load is dependent on the size of the load. If the load is heavy, the muscle movement is slow and the power is limited by the slow speed. On the other hand, if the load is light, the muscle can move it rapidly and the power is limited by the speed of muscluar contraction. There may be a load or range of the load for which the power output is a maximum. This concept has been investigated by Suggs (1969), using the torque developed by the forearm. As the external load on the muscle is increased, the power output to the load is increased. Further increases in the load after reaching the maximum power will decrease the power output. His results show that the maximum power output is obtained when the load impedance (moment of inertia) is five to ten times the impedance of the muscle system involved.

Landsmeer (1962) proposed the terminology "precision handling" rather than "precision grip" based upon the observation that precision grip does not involve any forceful grasping of the object. The central fact in "handling" is that the object can be manipulated by means of the fingers. The MP and IP joints move independently. There is no distinguishing point between the static and dynamic phases as observed in the power grip. In precision handling, specific extrinsic muscles provide gross motion and compressive force and intrinsic muscles play an important role in handling or manipulation (Long et al., 1970). Therefore, precision handling can be considered a special function of the thumb and the index, assisted as necessary by the middle, ring and little fingers. Further discussion of functional movements of the fingers will be described in the next section of this chapter.

2.4 FUNCTIONAL REVIEW OF FINGER MOVEMENTS

A finger joint can be placed in any desired position within a functional range. Normal finger motion is characterized by coordination of the phalangeal movements and by the MP joint moving independently of the IP joint (Landsmeer, 1963). Two muscles, acting as flexor and extensor, can produce independent motion in the MP joint or in the IP joint only if one of them has reached its functional end position, i.e., full flexion for the IP joint and hyperextension for the MP joint. If neither reaches its functional end point, a third force is required for independent control of the MP and IP joints. The third force may be active muscular force, viscoelastic force, and/or rheologic force. It is difficult to measure the third forces with present techniques (Landsmeer, 1976). Because of this difficulty, muscle participation in finger movement is not thoroughly understood. However, the major roles of muscles in finger movement are described in the literature. Since this study is concerned with index and thumb performance, the review of finger movements will be limited to these two digits.

2.4.1 Anatomical and Functional Review of the Index

Muscles which attach to the index finger are the flexor digitorum profundus (FDP), flexor digitorum superficialis (FDS), extensor digitorum communis (EDC), extensor indicis proprius (EIP), first dorsal interosseous (FDI), palmer interosseous (PI), and lumbrical*. Figure 4 represents these muscles with their structural arrangements.

The first four muscles are extrinsic. Their anatomical characteristics are as follows;

1. The FDP originates from the upper three fourths of the shaft of the ulna and inserts into the terminal phalanx of the index. It is innervated by branches of the median nerve and ulnar nerve and is responsible for flexion of all phalanges.

2. The FDS has three heads: (a) humeral, (b) ulnar, and (c) radial. It inserts into the second phalanx of the index and is responsible for flexion of the middle phalanx. It receives its innervation from branches of the median nerve.

3. The EDC originates chiefly from the external epicondyle of the humerus and inserts into the second and third phalanges. It is innervated by a branch of the radial nerve and extends the index and the wrist.

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*The extensor carpi radialis longus is also located at the base of the metacarpal bone of the index. However, it is omitted from this review because of its major function of wrist extension.

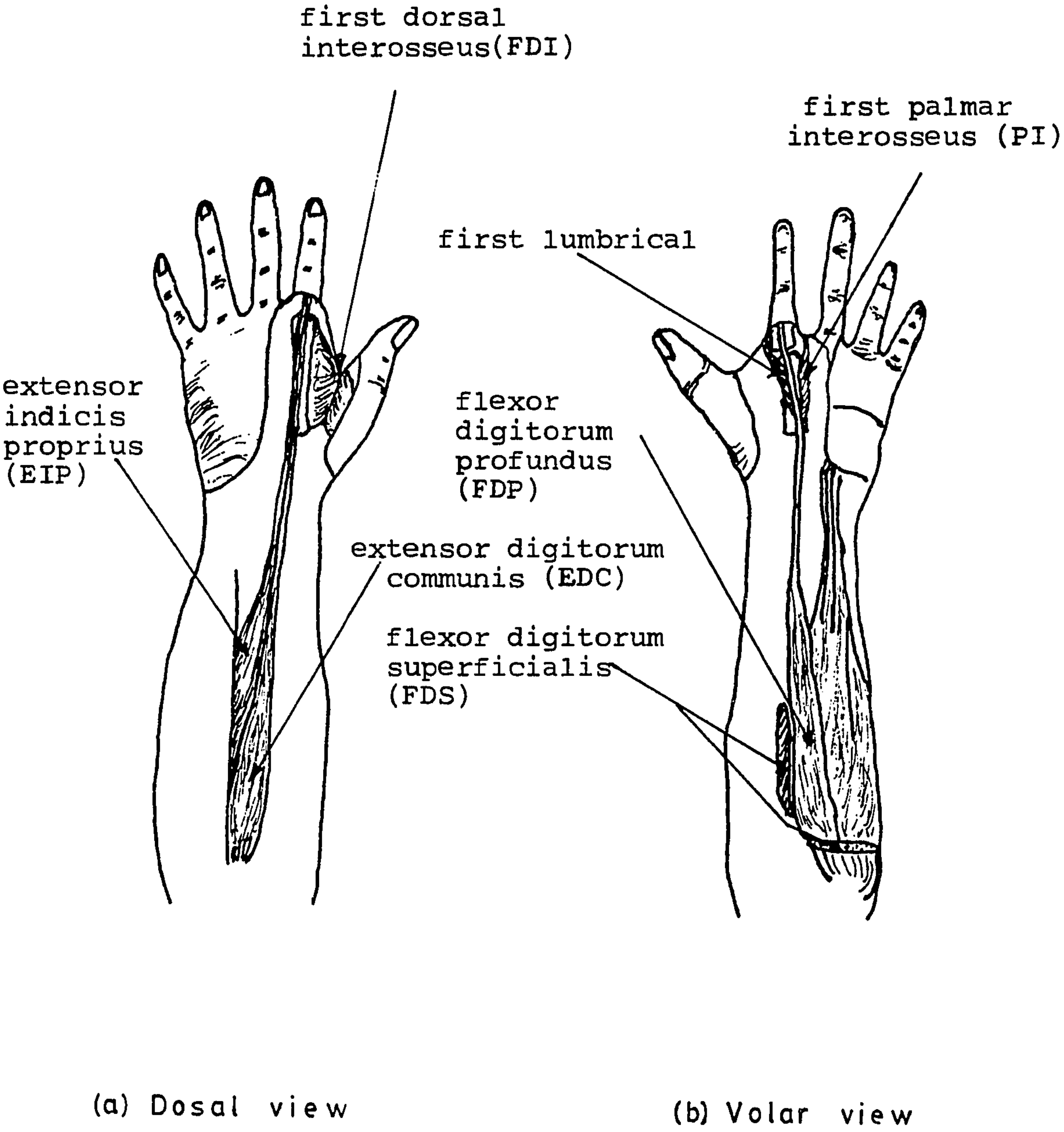


Figure 4: Muscles of the index finger

4. The EIP has its origin on the dorsal surface of the ulna and the interosseous membrane. It merges into the first tendon of the EDC and extends the index. Innervation is by a branch of the radial nerve.

The latter three muscles are intrinsic. They are oriented toward finger control rather than strong force exertion. The MP joint is controlled by four tendons, counting the EIP and EDC tendons as one tendon due to the fact that they show a close similarity in all types of finger motions (Landsmeer, 1955; Boivin et al., 1969). Three of them join at the level of the proximal IP joint:

1. The twin bellied FDI muscle inserts into the transverse part of the radial wing tendon.
2. The lumbrical proceeds from the oblique part of the radial wing.
3. The PI inserts into the ulnar side of the wing tendon.

Asymmetry of movement in the MP joint can be explained by the structure of the ligaments. Asymmetry of the attachment and size of the MP ligaments, as pointed out by Landsmeer (1955), plays an important role in flexion, extension, and abduction. This asymmetrical structure is remarkable in the index and the medius while there remains only asymmetry of position in the ring and the little finger.

The wing tendons of the interossei play an essential role in the patterns of extension, flexion, and abduction. The FDI and PI primarily participate in motions in which the IP joints are either extending or held extended and the MP joint is flexing or held flexed (Stack, 1962; Boivin et al., 1969). Since the action of the interossei produces hyperextension of the MP joint, they are not able to initiate the MP flexion. In other words, the extensor and flexor tendons bridge the MP joint and the proximal IP joint in such a way that they tend to extend the MP joint and to flex the proximal IP joint. However, this tendency is counterbalanced by the action of the lumbricalis and interossei through the wing tendons. Boivin and associates (1962) reported that the lumbricals and the interossei are shortest in length in this position.

The lumbrical and IP extension (either extending or held extended) are strongly interrelated. This holds true no matter what the position or movement of the MP joint (Backhouse and Catton, 1954; Stack, 1969; Long and Brown, 1964; and Boivin et al., 1969). Since the lumbricalis inserts into the FDP tendon, some tension of the FDP is necessary for the lumbricalis to work effectively. The FDP tendon beyond the origin of the lumbricalis does not participate in the movement during which the lumbricalis remains contracted without altering its length.

The IP joints are bridged by a tendinous apparatus. Shortening of the flexor muscles must be accompanied by lengthening of the extensor apparatus in the biarticular system of the IP joints. In the movement of the IP joints into flexion from the position of total joints extension during which the MP joint is held straight, the FDP and EDC are active as indicated by electromyography. There is absolutely no active participation of the lumbricalis and interossei (Stack, 1962; Landsmeer and Long, 1965). However, the PI is an adductor and the FDI is an abductor in addition to their roles of flexion at the MP joint. Therefore, they are active whenever adduction or abduction of the index takes place in the above movement.

The IP joints comprise one biarticular system in which the middle phalanx acts in positive flexion when the FDP is active. In this motion of flexion, the middle phalanx constantly loads the central tendon of the extensor mechanism (Landsmeer, 1963). To flex the second phalanx while the first phalanx remains in a fixed position, the FDS, extensors, and interossei cooperate. In this movement, the third phalanx is beyond control and becomes loosened because the lumbricalis remains limited to the second phalanx (Landsmeer, 1963). In other words, the terminal and middle phalanges are under the control of the terminal and central tendon of the extensor assembly, respectively.

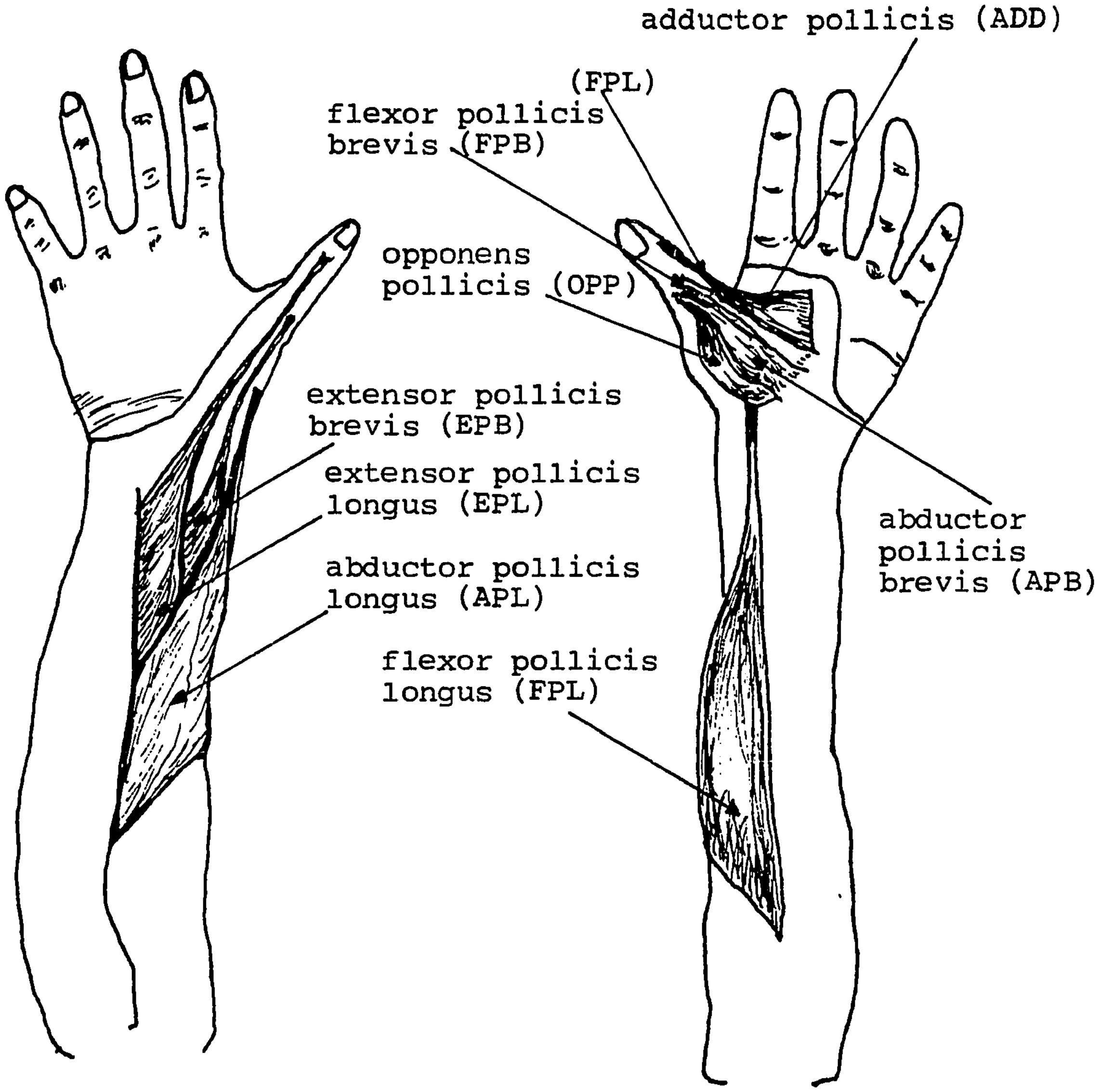
The IP joints flex and extend while the MP joint is held extended. The flexion phase of this movement evokes a marked activity in the EDC and EIP, a moderate activity in the FDP, and a minimal or silent activity in all the intrinsic muscles and in the FDS. In extension, the lumbricalis and the EDC are moderately active. However, the muscle activities of the FDI, FDP and FDS vary from minimal to zero (Stack, 1962; Boivin et al., 1969).

The finger movements described above have been free or unconstrained movements. Movements against a resisting force will now be described. It is interesting that free or unloaded motion toward the palm is purely extrinsic and the intrinsic muscles are entirely silent. However, movement toward the palm in contact with an object immediately evokes activity of the interossei. Phalangeal tendons of the interossei make essential contributions to loaded work. In grasping a cylindrical object, the first and second dorsal interossei come fully into play to oppose the action of the thumb (Landsmeer, 1963). On the other hand, the activity of the lumbricalis is the same as for unconstrained movement, i.e., extension of the IP joint. The lumbricalis in the loaded movement <u>away</u> from the palm is very active but it is silent in the movement <u>towards</u> the palm both loaded and unloaded (Landsmeer, 1976).

The FDP, of course, is the major functional tendon in the resisted motion of index flexion. In pinching actions involving the meeting of the tip of the thumb with the tip of the index, the proximal phalanx goes into ulnar deviation and the FDP, FDS, and FDI are active in ascending order (Chao et al., 1976). In palmar pinch actions, defined as the meeting of the pad of the abducted and medially rotated thumb with the pad of the index where the MP joint of the thumb is flexed and that of the IP joint is extended, the FDP and lumbricalis are most active (Close and Kidd, 1969). However, the FDP of the index exerts a smaller force during grasping compared to pinching actions. On the other hand, the extensors function actively during pinching but behave passively in grasping (Chao et al., 1976).

2.4.2 Anatomical and Functional Review of the Thumb

The thumb has a complex structure which can move it in many planes and axes. It is not surprising to find that control of these movements is not a simple contraction but a complicated interaction among the muscles. Muscles which articulate the thumb consist of the flexor pollicis longus (FPL), the extensor pollicis longus (EPL), the extensor pollicis brevis (EPB), the abductor pollicis longus (APL), the abductor pollicis brevis (APB), the opponens pollicis (OPP), the flexor pollicis brevis (FPB), adductor pollicis (ADD), and the first dorsal interrosseous (FDI). Figure 5 illustrates the muscles of the thumb.



(a) Dorsal view (b) Volar view

Figure 5: Muscles of the thumb

The first four muscles are extrinsic. Their anatomical and functional characteristics are as follows:

1. The FPL originates from the anterior surface of middle third of the radius. It inserts into the terminal phalanx of the thumb. It flexes the thumb by innervation from branches of the median nerve.

2. The EPL has its origin on the dorsal surface of the ulna and attaches to the base of the terminal phalanx of the thumb. It receives its innervation from a branch of the radial nerve and is responsible for extension of the terminal phalanx of the thumb and for radial deviation of the hand.

3. The EPB originates on the dorsal surface of the radius. It inserts into the base of the first phalanx of the thumb, and is innervated by a branch of the radial nerve. It extends the thumb and abducts the first metacarpal.

4. The APL originates on the dorsal surface of the radius, the ulna, and the interosseous membrane. It inserts into the base of the proximal phalanx of the thumb and is innervated by a branch of the radial nerve. It abducts the thumb and radially deviates the hand.

The latter five muscles are intrinsic. The OPP, APB and FPB are called the thenar triad. The FDI has been discussed in the previous section. The anatomical and functional characteristics of the remaining four muscles are as follows:

1. The APB originates from the ridge of the trapezium and transverse carpal ligaments. It inserts into the outer side of the proximal phalanx of the thumb. This muscle functions as the abductor of the thumb by innervation from a branch of the median nerve.

2. The ADD is made up of two heads. The origin of the transverse head is the 3rd metacarpal bone and has insertion at the inner side of the proximal phalanx of the thumb. The origin of the oblique head is the second metacarpal, trapezoid, and capitate. It receives the ulnar innervation and adducts the thumb.

3. The FPB originates from the transverse carpal ligament, the trapezium and scaphoid, and has insertion into the proximal phalanx of the thumb. It is innervated by a branch of the median nerve and rarely by a branch of ulnar nerve and is responsible for flexing the proximal phalanx of the thumb.

4. The OPP originates at the trapezium and the transverse carpal ligament. It inserts into the 1st metacarpal bone. It is stimulated by the median nerve and is responsible for flexion, adduction and opposition of the thumb.

Unlike the fingers, the thumb has a unique articulation because of its opposition to the other fingers as well as its flexion, extension, abduction and adduction. The opposition of the thumb involves complex movement as follows: (a) the entire thumb as a unit is abducted from the index metacarpal joint with the thumb MP joint remaining in a neutral position and the distal joint extended; (b) gradually the entire thumb rotates so that its volar surface is turned to face the volar surface of the index; (c) when the final rotation is reached, abduction occurs at the MP joint and the distal phalanx of the thumb becomes more extended. Opposition is possible because of the rotational movement of the MP base on the trapezium due to the configuration of the CM joint and the arrangements of the thenar muscles and ligaments. The opposition is enhanced by abduction of the proximal phalanx at the MP joint by the APB. This explanation is supported by evidence that total elimination of movement at the MP joint does not interfere with opposition of the thumb. On the other hand, fusion of the metacarpotrapezial joint eliminates opposition in the presense of a normal MP joint (Kaplan, 1966).

Movement patterns of the thumb have been studied extensively (McFarlane, 1962; Weathersby et al., 1963; Forrest and Basmajian, 1965; Close et al., 1969; Hirsch et al., 1974; and Landsmeer, 1976). Articulation of the thumb is a complicated interaction among muscles. For example, there are five muscles active in the flexion of only the IP joint of the thumb. However, the following description will be limited to a major participant in a certain type of thumb articulation. Abduction at the MP joint is essential for opposition of the thumb. Because the OPP acts only upon the MP joint, the important muscles acting in full opposition are the APB, and FPB. The ADD appears to be active in flexion of the MP joint and in all motions in which the metacarpal approaches the index no matter where the point of location. However, there is justification for considering separately the transverse head of the ADD from that of the oblique head and other intrinsics. The transverse head of the ADD is attached at a right angle to the longitudinal axis of the thumb while other thenar muscles are directly parallel to the axis. The important role of the transverse head of the ADD is to add power to the actions of pinching and grasping while other intrinsics position the thumb.

The APB stabilizes the MP joint in abduction and flexion, rotates the thumb medially, and extends the distal joint. The FPB and OPP behave in the same manner as the APB. Indeed, the thenar triad is found to be extremely active in both pad-to-pad and tip-to-tip oppositions. They are also active in a translation movement away from the palm if the thumb is moving against an external load. However, the FPB drops out from the triad (Landsmeer, 1976) or shows very slight activity (Forrest and Basmajian, 1965) when the thumb is unloaded. During full flexion (i.e., IP and MP joint flexion as well as CM joint flexion) in the plane parallel to that of the palm, the FPB is highly active but the OPP is only slightly active and the APB is silent.

The FPL is only active when the IP joint is flexed as in making an "O" with the index and the thumb, or simply flexing the IP joint. The EPL is active when the MP joint is extending or kept extended and the IP joint is either flexed or extended. The EPB is active when the IP joint is flexed and the MP joint is extended. However, it is not active when the IP joint is extended. The APL is active when the abduction and extension involve the entire thumb and the MP joint is flexed.

As mentioned previously for the index finger, unloaded motion toward the palm is purely extrinsic and movement toward the palm with load evokes activity of the thenar triad.

2.5 METHODOLOGICAL REVIEW AND STATE OF THE ART

Anatomy, physiology, kinesiology, biomechanics, and biochemistry form the frame of reference within which the phenomena of human physical activity are interpreted and evaluated. Because of the diverse nature of humans, criteria for evaluating performance are very broad and interdisciplinary. The selection of an appropriate methodology is essential for any study to be meaningful, efficient, and economically justified.

Some criteria which have commonly been used to evaluate human activity are strength, endurance, speed, balance, coordination, agility, flexibility, and body type (Hunsicker, 1974). Several physiological factors have been used as criteria; for example, heart rate, blood pressure, cardiac output, pulmonary ventilation and oxygen intake. However, measurable changes in these physiological indices require either the exercise of relatively large muscles or careful control to minimize psychological effects when performing very light work using small muscles.

In the evaluation of the performance of smaller muscles, a more selective method is employed. Strength measurement, for example, has frequently been used in hand/finger studies (Bechtol, 1952; Nemethi, 1952; Landsmeer, 1962; Toews, 1964; Mundale, 1970; Schmidt, 1970). Muscular endurance, biomechanics, and electromyography (EMG) have also been used. Some of these are relevant to provide this study with methodological background and will be reviewed below.

2.5.1 Muscular Strength

Muscle strength is used as a criterion in many human performance studies. There are basically two types of strength:

1. Static strength is manifested by a muscle that contracts without changing its length.
2. Dynamic strength is associated with all muscle contractions in which the length of the muscle changes.

Dynamic work is further divided into two classes; (a) positive work (concentric contraction) and (b) negative work (eccentric contraction). A muscle that shortens during contraction performs positive work; a muscle that lengthens performs negative work. Static work is measured with a device that provides an unlimited counterforce, using a dynamometer with a strain gage, spring, or hydraulic cylinder. This allows the determination of the maximum isometric or isotonic tension which can be maintained for only a few seconds. A major disadvantage of this measurement is that it is dependent on the subject's voluntary effort. However, the advantage of this procedure is that different individuals and different muscle groups can be compared at a physiologically identical level of effort (Simonson and Lind, 1971). Therefore, it appears to be appropriate for a study which compares index performance with thumb performance provided there is careful control of the variation in voluntary effort.

Thumb strength has been investigated by several researchers. Kroemer and Gienapp (1970) tested the thumb strength as a function of the flexion angle of the IP joint with the MP joint held extended in the plane parallel to the palm. They found that the forces exerted by the thumb at zero degrees (upright) and 30 degrees were not significantly different from each other. Likewise, the forces at 60 degrees and 90 degrees were the same. However, there was a trend of increased force with increased flexion angle of the IP joint. Thumb strength at the upright position is also reported by Hirsch and associates (1974).

Other data found in the literature are not direct measures of thumb strength. Measurements of pinching actions involve other finger strengths with the index or other fingers working against the thumb. In the lateral pinch, for example, the pulp of the thumb is located at the lateral aspect of the index finger which is assisted by the aligned middle, ring, and little fingers. In this measurement, the reading represents the strength of the thumb or the index whichever is weaker. Present knowledge does not permit further analysis in identifying the source of the measured force. Insofar as the thumb position is concerned, the lateral pinch may be interpreted as thumb force exertion with a 30 degree flexion angle of the IP joint and the MP joint extended in the plane parallel to the palm. Table 1 shows some strength data, measured at maximum voluntary contraction (MVC) levels, compiled from Barter and associates (1957, cited in Hertzberg,1972), Hirsch and associates (1974), Kroemer and Gienapp (1970), and Swanson and associates (1970).

Table 1

Thumb Strength (kg) as a Function of IP Flexion

IP flexion	force mean	SD	authors
0 degrees	9.48	.23	Hirsch et al.
0 degrees	7.26	1.72	Barter et al.
0 degrees	8.59	1.84	Kroemer and Gienapp
30 degrees	8.50		Swanson et al.
30 degrees	8.96	1.89	Kroemer and Gienapp
60 degrees	9.92	1.74	Kroemer and Gienapp
90 degrees	10.10	2.13	Kroemer and Gienapp

A review of the literature revealed a paucity of strength data for the index. Information is available from a study of each finger's contribution to grip strength performed by Hazelton and his associates (1975). In their study, five wrist positions were investigated: neutral, volar flexion, extension, ulnar deviation, and radial deviation. The study indicated that (a) regardless of wrist position, the percent of total force allocated to each finger is constant: index 25.4%, middle 33.9%, ring 25.2%, and little finger 15.2%, (b) the wrist position in which the least force is generated at the middle and distal phalanges is volar flexion, (c) the wrist position in which the greatest force is exerted at the middle and distal phalanges is ulnar deviation, (d) the force exerted by the distal phalanges is about 32% of the force developed with the middle phalanges in all wrist positions except the extended position where it is about 27%, and (e) the total force generated by the little and ring fingers is 70% of the total force produced by the long and index fingers. The study reported that the maximum total forces recorded at the middle and distal phalanges of four fingers were 72.6 and 49.4 kg, respectively. From this data, the maximum force of the index at the middle and distal phalanges can be estimated as 18.4 and 12.5 kg, respectively.

Another index strength measurement was reported by Dickson and Nicolle (1972). Flexion force exerted by fully extended fingers was measured at the pad of the distal phalanx. The results showed 4.6, 4.4, 3.2, and 2.8 kg for the index, middle, ring and little fingers, respectively. Measurement in similar positions were made by Barter and associates (1957, cited in Hertzberg, 1972) with the following results: 5.9, 6.4, 5.9, and 3.2 kg for the same finger order.

Further information about thumb or index strength was not found in the literature. Therefore, investigation of the MVC for each finger was considered useful and meaningful for this study as a means of evaluating index and thumb performance.

2.5.2 Muscular Endurance

Another method of evaluating static work is through the use of limited counterforce, such as holding a weight. Holding a weight is somewhat less dependent on motivation because it eliminates one of two sources of voluntary cooperation, i.e., the determination of maximum voluntary effort (Simonson and Lind, 1971). Therefore, only endurance at some fractions of the MVC is measured. The term endurance is often used for prolonged work but it can also apply to work near maximum exertion for a very short duration. Hence endurance can be described as a negative exponential function of the level of effort and it ranges from several seconds to several hours. Rohmert (1965, cited in Simonson and Lind, 1971; and cited in Astrand and Rodahl, 1977; Rohmert, 1973) investigated the course of isometric fatigue--a decrement in the amount of muscular tension as a consequence of prior activity--over several muscle groups of diverse function and strength levels. He reported that the pattern of fatigue appeared quite consistent across muscle groups and individuals when based on a fraction of the MVC (relative endurance). Endurance ranged from several seconds at or near the MVC to several hours at or near 15% of the MVC. Clarke and Gentry (1971) confirmed that this holds true using elbow-flexion and handgrip muscle groups.

However, the patterns of isotonic and rhythmic isometric exertion appear to be quite dissimilar between muscle groups. The rate of fatigue for the elbow flexors in isotonic exercise was approximately 43% faster than for the hand grip flexors (Clarke and Gentry, 1971). The fatigue rate for the supinator of the forearm in dynamic work was faster than that for the pronator of the forearm (Drosin, 1977). Also, the fatigue rate for the knee extensors in rhythmic isometric exercise was slower at the onset of exercise but became much steeper thereafter than for the elbow flexors (Ordway et al., 1977). Another common finding by these authors was that the muscle groups which had a higher initial strength than others also had a faster fatigue rate. A similar pattern of endurance for subjects was reported by Mundale (1970). Weaker subjects could maintain a higher proportion of their maximal strength during repetitive isometric contractions of the hand grip than individuals with superior strength.

Since both types of finger usage were found in various power tool operations and endurance data for the index and the thumb was not available in the literature, both types of muscular endurance for the index and thumb were investigated.

2.5.3 Other Techniques

The electromyograph (EMG) is a technique frequently used by researchers because it can trace out the electrical activity of muscles during various patterns and types of movements. The muscular activity may be quantified by measurement of the peak-to-peak amplitude, or by averaging the amplitude (root mean square). These measures can be used when great sensitivity is not required (Khalil and Otero, 1973). Such application has been used in the study of muscle participation in various types of finger movements (Long, 1964; Landsmeer and Long, 1965; Boivin et al., 1969; Long et al., 1970).

Another method of EMG quantification is the use of frequency in terms of the number of peak, zero crossings, or reversals of potential. A linear relationship between the frequency and muscle tension has been observed in isometric contractions. However, a leveling off is also observed as the load increases when isotonic contractions are performed (Khalil and Otero, 1973). One disadvantage which is frequently overlooked is that the EMG cannot define whether a muscle is shortening or lengthening. Furthermore, it is essential to realize that an absence of muscular activity indicated by the EMG does not necessarily mean that the muscle has no effect on the pattern of finger movement (Landsmeer and Long, 1965). Also, increased EMG activity does not necessarily mean that the force exerted by the muscles increases in proportion to the EMG increase (Bigland-Ritchie et al., 1975; Merton, 1954).

Despite these disadvantages, the EMG has contributed to various neuromuscular studies, especially in evaluating the contributions of specific muscles to different motions. However, it seems that the EMG is not appropriate for the comparison of index and thumb performance for the following reasons:

1. The muscles which articulate the index and the thumb are different in anatomical (and therefore functional) characteristics as well as in location.

2. Comparison of the quantified EMG signals is difficult due to the lack of a common base of evaluation for the index and the thumb. Note that flexion of the index is by extrinsic muscles while flexion of the thumb is by intrinsic muscles when working against an external force.

The biomechanical approach has been used to predict the force produced by muscles using anthropometric data and musculoskeletal stucture information as model inputs. It has also been used to explain the internal force mechanism of muscles working against an external load.

The internal force mechanism, especially at the MP joint with a fixed load at the tip of the thumb, has been studied by Page and associates (1974). Their model consists of an external force vector applied to the tip of the thumb and counteractive muscle force. It yields six equations with ten unknowns. To solve these equations, some unknowns are considered to be unaffected in the force equilibrium and set equal to zero. The model estimates that the muscles of the MP joint must exert 45.36 kg force when a 4.56 kg load is placed near the end of the thumb.

Harris and associates (1966) investigated the stress-strain ratios of three muscles of the upper extremities by applying the law of mechanics to cadavers. The ratios were reported as follows: (a) 11952 kg/sq. cm for the EDC and (b) 7734 kg/sq. cm for the FDP and the FDS. Also, the ratio for the digital extensor was 60% greater than for the digital flexor.

Another example of the biomechanical approach is found in the study of muscle function. As pointed out by Landsmeer (1955), the finger can theoretically be controlled by only the extensor, one flexor, and the interossei. This indicates the redundancy of the lumbricals. However, the biomechanical model revealed that the lumbrical muscles make a contribution to finger motion by their passive properties (Thomas, 1965, and Thomas and associates, 1968).

The function of the collateral ligament at the MP joint of the middle finger was biomechanically explained by Pagowski and Pierarski (1977). The movements acting on the

MP joint are not constant, but change with the angle of flexion due to the function of the collateral ligament and the motion of the synovial fluid. On the other hand, the force distribution at the joint has been examined by Penrod and associates (1974). They reported that movement at the joint during low levels of muscle activity could be related to the concept of reciprocal innervation.

Biomechanical models of finger flexor tendon displacements have been developed by several investigators (Landsmeer, 1960; Dempster, 1961; Thomas, 1965; Fisher, 1969; Brand et al., 1975; Chao et al., 1976; Landsmeer, 1976; Armstrong and Chaffin, 1978). The solutions of these models are dependent on the model inputs such as tendon moment arms and tendon displacement. These dimensions can not be measured directly in intact hands.

Thermography has been used to detect the internal heat generation from the skin surface. In infrared photograghy, a picture of an object is taken using infrared wavelengths and a filter to block visible light while in thermography the amount of heat radiating from the surface of the skin is measured. Goller and associates (1971, cited in Gurney, 1973) made thermographic studies in determining the thermal function of the body surface subjected to localized pressure. They found a positive correlation between temperature variation and localized pressure. Since the thermograph can detect the radiation of surface heat, it can be applied to any physiological responses which manifest changes in heat. A typical example is muscular activity in which the blood flow increases in active muscles while the blood flow remains unchanged in resting muscles (Humphreys and Lind, 1963). However, its capability of heat detection is limited to surface radiation. It seems that application of thermography to this study would be difficult. By the same token as the EMG description, the comparison of temperature data between the index and thumb may be difficult.

2.6 DISCUSSION OF VARIABLES

The level of performance is a result of a number of interacting factors. These factors fall into three categories: (a) human, (b) task and (c) environmental. Task factors include type of task (physical, mental, psychomoter), its complexity and duration. The task factors related to this study have been discussed in Section 2.2.

The primary dependent variable of this study was strength, measured as the maximum force exerted by a muscular contraction. Environmental and human factors directly and indirectly affect the level of finger performance. Environmental factors include temperature, humidity, air velocity, heat radiation and noise while human factors include age, gender, body build, physical fitness, motivation, training and nutrition. Although these factors affect the dependent variable, this study was not primarily interested in the relationships between these variables and the dependent variable. Therefore, the human and environmental factors were held fixed to minimize their effects.

Temperature control is especially important for endurance measurement. Maximum endurance times have been obtained for hand-grip contractions with the forearm immersed in a water bath ranging from 14C to 20C[5]. The shortest endurance time was measured at 40C with and without artificially occluding blood flow and regardless of the force being exerted (Clarke et al., 1958; Lind, 1959; Clarke et al., 1966; Simonson and Lind, 1971). It was postulated that the reduction in endurance time at muscle temperatures above 27T[6] is due to a more rapid accumulation of metabolites with increasing muscle temperature. Below 18T, an increasing number of muscle fibers become inoperative because of interference with neuromuscular transmission (Simonson and Lind, 1971).

Muscle temperature, which is affected by ambient temperature, influences the level of performance. Montgomery and Williams (1977) investigated the relationships between forearm, hand, and finger blood flows and ambient temperature. With exposure to cold temperatures (10C), proximal digit segments showed a higher flow rate (3.9

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[5] The abbreviation "C" is used to mean the ambient temperature in degrees Celsius.

[6] To facilitate reading, the abbreviation "T" is used to mean the muscle temperature in degrees Celsius.

ml/(100ml/min)) than distal segments (<1.0ml). With exposure to high temperatures (46C), the distal segments had a higher flow rate (27.0ml).

The relationship between blood flow and endurance time at a given level of exertion and the effects of blood flow on manual dexterity have been studied (Humphreys and Lind, 1963; Mottram, 1973; Mottram and Lynch, 1973; and Bensel and Lockhart, 1974). In mild contractions (5 to 20% of MVC), the force could be maintained without fatigue and without any post exercise increase in blood flow. More powerful contractions produced both fatigue and large post exercise hyperemia even though blood flow reached a plateau during exercise. However, artificial occlusion of blood flow affected endurance time greater at a tension of one third MVC than at two thirds MVC (Start and Holmes, 1963; Humphreys and Lind, 1963). Likewise, intramuscular pressure during contraction cannot fully occlude the blood flow until the tension exerted is greater than 70% MVC.

The effect of temperature on muscle strength is relatively less pronounced. In the range of temperatures from 27T to 39T, MVC readings were constant. However, the MVC force decreased when the muscle temperature decreased below 27T (Clarke et al., 1958; Johnson and Leider, 1977).

Among human factors, the following are frequently studied in the area of grip force: body build as a hereditary factor, grip span, training, handedness, variation during the day, variation from day to day, age, gender, height, weight, and other anthropometric measurements. However, the correlation of grip strength with each individual factor has been poor. Bechtol (1954) observed a lack of correlation between the forearm musculature and grip strength.

The grip force can be increased by training specifically oriented towards gripping. This was observed in workers who use pliers or who milk cows (Bechtol, 1954). Likewise, a remarkable difference was found between office and supervisory workers, and skilled and semi-skilled workers (Nemethi, 1952). In contrast, the training effect was not observed by Toews (1964) in his case study of steel workers which compared pre- and post-employment grip strengths over the years. Various jobs were classified according to their gripping requirements: (a) non use of active grip, (b) use of a moderate grip often but seldom a maximum grip, (c) moderate grip often and a maximum grip occasionally or often. It was pointed out that the individual's grip strength remained constant for many years.

Although the study by Montoye and Faulkner (1965) did not support the existence of an optimum spacing of two grip handles, other evidence substantiates this claim. According to some researchers, the maximum force may be exerted at a distance of 3.8 to 5.1 centimeters (cm) regardless of the individual's grip size (Bechtol, 1954; Cotton and Bonnel, 1969; Cotton and Johnson, 1970). A puzzling finding came from the work of Cotton and Bonnel (1969) and Cotton and Johnson (1970). These researchers investigated grip strength using five grip spans, ranging from 4 cm to 9 cm at 1.3 cm intervals. Subject grip size was measured as the distance between the tip of the middle finger and the fleshy area between the index and the thumb. A frequency distribution of grip size was used to place the subjects into three groups: small, medium and large. The former study (1969) tested college women while the latter study (1970) tested college men. When the results of the small, medium, and large grip groups in the former study were compared with the corresponding groups in the latter study, the rank ordering of the grip span settings were similar to each other[7]. However, further examination of these two studies revealed that the large grip classification of the female group (13.75 cm to 15.00 cm) was similar to the small grip classification of the male group (13.70 cm to 14.70cm). Comparison of grip strengths between the large female and the small male groups indicated that the range rankings were very inconsistent. The results agreed only for the large grip span setting. One possible explanation for this discrepancy may be the difference in gender. It is both conceivable and understandable that there is a difference in

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[7] The results are available in the form of a Duncan multiple range test in Cotton abd Bonnel (1969) and Cotton and Johnson (1970).

absolute strength between the two genders. However, it is puzzling to note the dissimilar sequences in the grip span for the two groups. Gender difference alone does not adequately explain other evidence such as correlation of the middle finger length, and hand length to grip strength (Bowers, 1961).

Handedness vs. strength arouse another controversy. The majority of works support grip strength differences between the major and minor hand; ranging from 3% to 10% less in the minor hand (Nemethi, 1952; Bechtol, 1954; Schmidt and Toews, 1970; Toews, 1964). However, the dominant hand is not always superior to the minor hand. Toews (1964) found that 5% of his subjects had less grip strength in the major hand.

Variation of grip strength during the day was reported by Bechtol (1954). The lowest reading was observed during the early morning while the highest was from 4:00 to 8:00 pm. Variation of grip strength from day to day was not observed by Bechtol (1954) if the measurement was performed at the same time each day. On the other hand, a significant change in finger force but no significant change in grip strength during the course of a working day was reported by Dickson and Nicolle (1972).

Some findings support, while others do not support, the correlation of strength with one or more anthropometric factors. Schmidt and Toews (1970) observed that strength was directly related to height up to 180 cm. Grip strength was also proportional to age between 18 and 30. After 30 or so, grip strength became inversely proportional to age (Fisher and Birren, 1947; Schmidt and Toews, 1970; Keller et al., 1971). Body weight is probably the most documented single factor which correlates highly with grip strength (Jones, 1947; Bookwalter, 1950; Everrett and Sills, 1952; Bowers, 1961; Pierson and O'Connel, 1962; Lunde et al., 1972; Nwuga, 1975). However, Pierson and O'Connel (1962) did not find high correlations of height or age with strength. Bookwalter (1952) and Bowers (1961) also failed to find a high correlation between age and strength. It seems that multivariate analysis may provide better predictions of strength than any single factor, although certain single factors are significantly correlated with strength as discussed above (Fisher and Birren, 1947; Bookwalter, 1959; Bowers, 1961; Everrett and Sills, 1952). The selection of the best combination of factors is difficult because various researchers have used different combinations.

As wrist position changes, the amount of force exerted with the hand grip changes. The literature indicates that the wrist position of extension, flexion, and radial deviation are inferior to the neutral position or to ulnar deviation in terms of grip strength (Anderson, 1965 (cited in Skovly); Skovly, 1967; Kraft and Detels, 1972; Hazelton et al., 1975; Terrell, 1975). The inferiority of the flexed and extended positions to the neutral position can be explained anatomically. As the wrist position moves away from neutral, the effective functional lengths of the finger flexors and extensors change (Hazelton et al., 1975). During wrist flexion, the relative shortness of the extensors does not permit full flexion of the fingers and wrist. During wrist extension, the relative shortness of the flexors does not permit simultaneous full extension of the fingers and wrist (Flatt, cited in Skovly, 1967). However, it has not been decided whether the greatest force is exerted at the neutral position or at the ulnarly deviated position. Greatest force exertion was observed with ulnar deviation by Skovly (1967), and Hazelton and associates (1975). However, the neutral position was reported as superior by Anderson (1965, cited in Skovly, 1967) and Terrell (1975).

CHAPTER III

MATERIALS AND METHODS

3.1 THE PROBLEM STATEMENT

The trigger switch of a power tool is usually controlled by the index finger or thumb. Such operations usually do not allow the index finger or thumb to fully participate in the gripping activity. Although many studies on grip strength have been performed, relatively few have examined the special type of grip involved in trigger operations. Those that have involve studying of the individual finger contributions to the entire grip force (Hazelton et al., 1975). Therefore, four finger grip strength must be investigated as well as the individual strength of the index finger and thumb. For the sake of convenience, two grip types have been defined as follows: (a) thumb operation grip in which the handle of the tool is held by the four fingers with the thumb used for on/off manipulation of the trigger switch, and (b) index operation grip in which the handle is held by the thumb and all fingers except the index which is used as the trigger operator.

Grip span effects on strength have been studied (Bechtol, 1954; Montoye and Faulkner, 1965; Cotton and Bonnel, 1969; and Cotton and Johnson, 1970). Previous researchers have examined grip span as a function of handle size. However, grip span has not been studied as a function of handle size relative to individual hand size. From the biomechanical point of view, it seemed appropriate in the evaluation of strength to establish grip span relative to the individual's hand size. Therefore this study was designed to investigate the effects of grip span, relative to individual hand size.

Studies on the effect of wrist orientation on grip strength have produced contradictory results (Skovly, 1967; Hazelton et al., 1975; and Terrell, 1975). The two controversial wrist orientations with respect to grip strength were the neutral and ulnarly deviated positions. Thus, these positions were incorporated in this study. Other positions of the wrist were not investigated since previous researchers have agreed that the forces exerted in other positions are weaker than in the neutral and ulnarly deviated positions. Thus, the first part of this study was designed to generate further grip strength data to aid the evaluation of grip handles for power tools.

The second question concerned the strength capability of the index and the thumb in relation to trigger operation. Although some data about index and thumb strength can be found in the literature (Hazelton et al., 1975; and Konz, 1979), it was considered to be irrelevant because the measurement techniques were inconsistent with the purposes of this study. Therefore, the second part of the study was devoted to generating the index and thumb strength data needed for the evaluation of trigger design.

A third question related to trigger design was muscular endurance. Although muscular strength was used as one of the criteria to evaluate the performance capabilities of the grip, index and thumb, it is an instantaneous measure and does not include sustained performance over a prolonged period of time. In the third part of the study, muscular fatigue characteristics, measured by the strength decrement over time, were studied for the index and thumb.

In brief, this study was performed to generate strength data related to gripping a power tool, and both strength and endurance data for the index finger and thumb involved in trigger operations. The measurements were performed for two wrist orientations: (a) neutral and (b) ulnar deviation. Four fifths of each individual's movement range in degrees was used to define the ulnarly deviated wrist. Three grip handle spans, based on individual hand size, were used for each subject: (a) large, (b) medium and (c) small. The anatomical landmarks of the distal interphalangeal (DIP) joint (large), proximal interphalangeal (PIP) joint (small), the midpoint of the two (medium), along the midpoint of the fleshy area between the index and the thumb were used to set the grip span.

Fatigue characteristics were studied using only the best positions for each finger with respect to strength. The objective was to determine if fatigue patterns of the index and the thumb were different. The task used in the fatigue study included both continuous and intermittent exercises.

3.2 EXPERIMENTAL TASK

The strength measurement for all experiments was based on an isometric force exertion at the level of the maximal voluntary contraction (MVC). Each exertion lasted for five seconds.

In the sustained isometric fatigue study, the subjects continued to exert their maximum voluntary force for a maximum of two minutes.

In the rhythmic isometric fatigue study, all subjects performed a series of one second maximal voluntary contractions alternated with one second periods of rest. This task was performed for a maximum of six minutes.

3.3 EXPERIMENTAL DESIGN

Experiments were designed to generate fundamental data to aid in the evaluation of trigger operations as well as grips used in the operation of power tools. Two types of grip (index operation and thumb operation) and two potential trigger fingers (index and thumb) were examined. In all cases, performance was evaluated based on the MVC efforts.

3.3.1 Subjects

Prior to the selection of the subjects, a preliminary survey was conducted to generate the grip strength distribution of the student-aged population at the University of Oklahoma[8]. From this survey, weak, average, and strong persons were defined using a range of percentiles of the distribution. Table 2 shows the definition of the three classes of strength.

Table 2

Definition of Subject Strength

Strength	Percentile	Strength in kg female	 male
weak	6--10	22.2--24.4	36.6--39.7
average	44--55	32.2--34.0	53.5--56.2
strong	91--95	42.2--43.1	70.8--74.4

Six volunteer subjects were selected from the student population. Each gender group consisted of one weak, one average and one strong subject. Each subject was young and healthy and did not suffer from any known physical disability that would prevent participation in the study.

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[8] For details about the distribution, see Appendix B.

The independent variables used for the experiments consisted of gender, subject strength classification, grip span, finger position, and wrist orientation. Finger position and grip span are defined in the section on the respective experiments.

Two wrist orientations were used: neutral and ulnarly deviated. The deviated wrist position was defined as four fifths of each individual's wrist movement range measured in degrees from the neutral wrist position. The neutral wrist was defined by the alignment of three points. These three points were defined as follows: (a) the point at which the extensor digitorum tendon of the middle finger (EDT) meets with the MP joint, (b) the point at which the EDT intersects with the dorsal side of midcarpal region, and (c) the point at which the extensor digitorum muscle joins with the radius at the elbow joint.

Table 3 summarizies the independent variables associated with the anthropometric characteristics of each subject. Other independent variables, which are not listed in the Table 3, are finger position for the index and thumb strength studies and elapsed time from the beginning of exercise for the fatigue studies.

Table 3

Summary of Independent Variables

Subject	F.G.S.	R.W.D.	Setup	Grip Strength		%tile
				mean	S.D.	
strong-female	6.2	28(s) 33(t)	21	41.95	0.26	90
average-female	6.7	26(s) 38(t)	20	33.49	0.69	50
weak-female	6.7	38(s) 40(t)	29	24.39	0.69	10
strong-male	7.4	32(s) 36(t)	24	73.86	0.23	95
average-male	6.7	38(s) 40(t)	29	57.96	0.37	60
weak-male	6.4	40(s) 40(t)	30	36.67	0.69	6

Legend:
F.G.S. = functional grip span in centimeters,
R.W.D. = range of wrist deviation in degrees in the sagittal (s) and transverse (t) plane,
Setup = experimental setup of wrist deviation in degrees used for each of the subjects,
Grip Strength = full grip strength in kilograms,
%tile = percentile of the population; strength was measured in the medium span with a neutral wrist,
S.D. = standard deviation.

3.3.2 Grip Strength Experiment

The thumb or index operation grip is the foundation which allows the index or thumb to operate a power tool. This notion motivated part one of the experiments to determine whether or not grip type was considered before the choice of trigger fingers was made.

Part one of the investigation was designed to evaluate the two grips as follows:

1. To determine if there was a difference in grip strength between the index operation grip and the thumb operation grip.
2. To determine if these strengths were affected by gender, individual subject strength, grip span, and wrist orientation.

Grip span was set at one of three levels: large, medium, and small and was defined as a linear distance between tha thenar and hypothenar eminences and the volar side of the middle finger. The center of the outer surface of the primary handle was placed at the center (midpoint) of the fleshy area between the index and thumb while the center of the outer surface of the secondary handle was located at three different positions: (a) large span--the anatomical landmark of the distal IP joint of the middle finger, (b) small span--the landmark of the proximal IP joint of the middle finger, (c) medium span--the midpoint between the landmarks of the distal and proximal IP joints of the middle finger.

A nested factorial design (i.e., subjects nested under gender) with repeated measures was chosen for conducting the experimental tasks and analyzing the results. Table 4 gives a summary of the first experiment. Figure 6 shows a view for grip strength measurement.

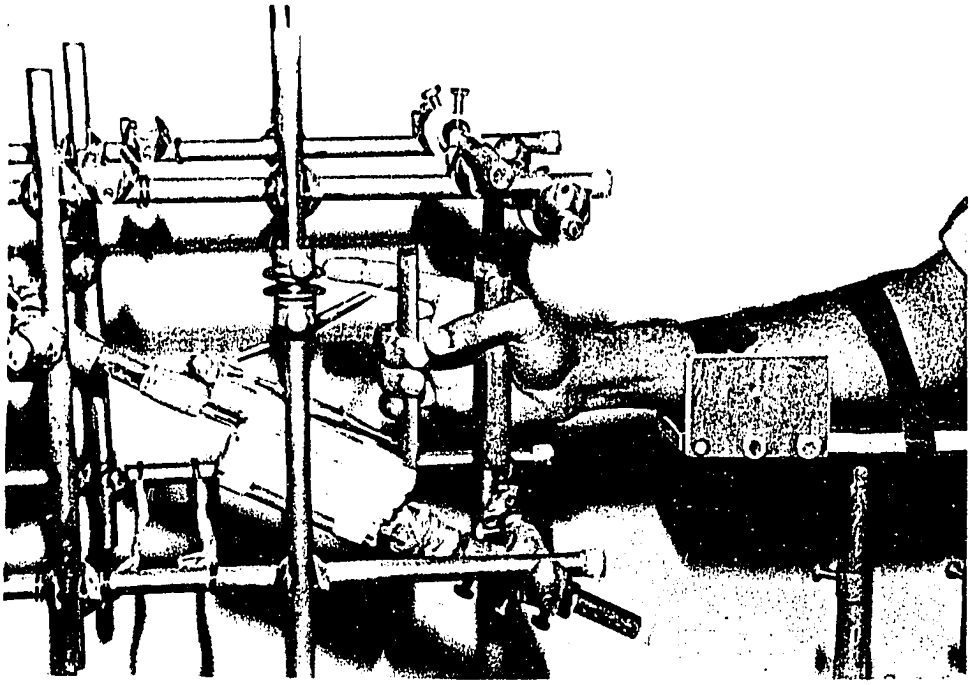


Figure 6: View for grip strength measurement

Table 4

The independent variables used for the grip strength experiment

Variable	Observation Levels
Gender	2: female and male
Subject strength	3: weak, average, and strong
Grip Span	3: small, medium, and large
Wrist orientation	2: neutral and ulnarly deviated

3.3.3 Index Strength Experiment

A pilot study prior to the experiment confirmed that the index finger can exert greater force when pulling towards the thenar eminence than in any other direction (Hazelton et al., 1975). Therefore, only this direction of pull was investigated.

The same criteria as used in the grip strength experiment were used to define individual subject strength and wrist position. The position of the index finger was set at one of three levels defined by the location of the center part of the force coupling device: (a) close position--the anatomical landmark of the PIP joint, (b) far position--the landmark of the DIP joint, and (c) middle position--the middle position between (a) and (b). As before, the midpoint of the thenar eminence was placed at the center of the primary handle. A view for index strength measurement is shown in Figure 7.

Part two of the investigation was conducted to obtain information about index finger strength. This experiment had two objectives as follows:

1. To determine which position allowed the index finger to exert the most force.
2. To determine if index strength was affected by gender, individual subject strength, index finger position, and wrist orientation.

Table 5 summarizes the independent variables used for the second experiment.

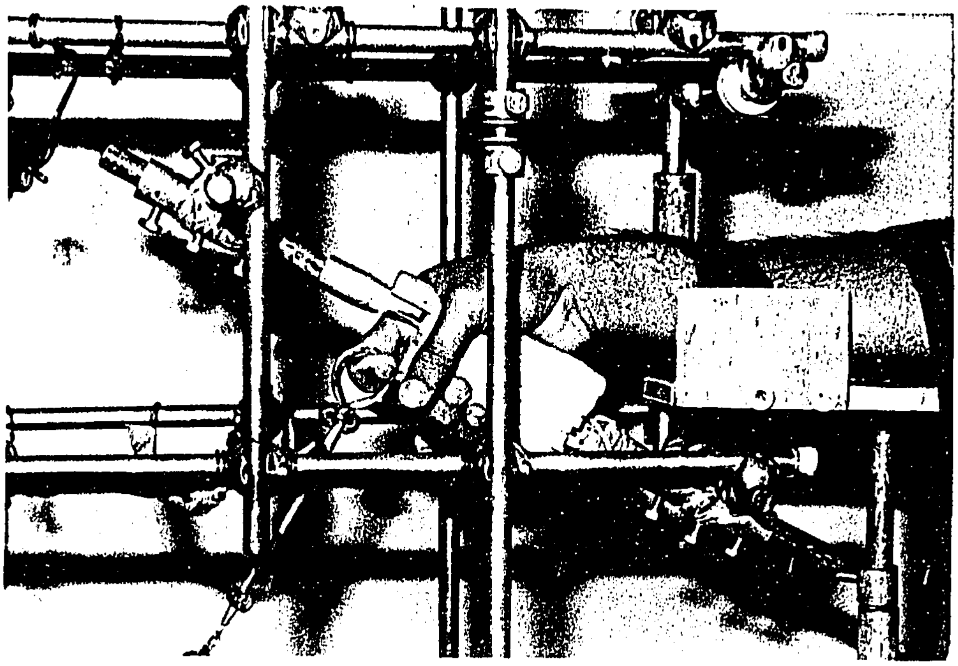


Figure 7: View for index strength measurement

3.3.4 Thumb Strength Experiment

The same criteria were used to define individual subject strength and wrist orientation as before. However, the thumb has diverse functional ranges which have not been investigated thoroughly. Therefore, the measurement of thumb strength must be performed at several positions and in several force directions. Part three of the experiment was designed to generate the thumb strength data. The position of the thumb was based on its functional range in the various positions possible while holding a power tool. This situa-

Table 5

The independent variables used for the index strength experiment

Variable	Observation Levels
Gender	2: female and male
Subject strength	3: weak, average, and strong
Wrist orientation	2: neutral and ulnar deviated
Finger position	3: close, middle, and far

tion restricts the allowable planes in which the thumb may move. Eight thumb positions were selected with the direction of the force located in a plane parallel to the sagittal plane and with the position of the distal phalanx as follows:

1. The IP and MP joints were kept extended or hyperextended. Force was exerted in a plane parallel to the palm and perpendicular to the handle axis.

   a) The CM joint was fully extended.

   b) The CM joint was flexed until the tip of the thumb nearly reached to the lateral side of the distal phalanx of the index finger.

   c) The CM joint was flexed at the midposition between a) and b).

2. The IP joint was flexed approximately 90 degrees but the MP joint was kept extended. Force was exerted in the same plane as in the first case but the force direction was parallel to the axis of the handle.

   a) The CM joint was fully extended.

   b) The CM joint was flexed until the tip of thumb nearly touched the index.

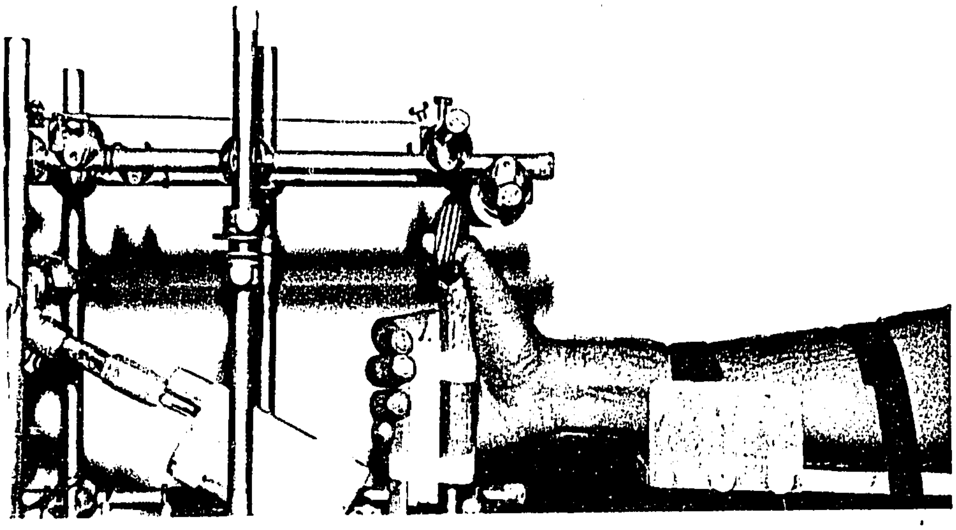
   c) The CM joint was flexed at the midposition between a) and b). Accordingly, the IP joint was slightly extended.

3. Finally, thumb oppositions to the palm were measured in two positions. The force direction was towards the plane of the palm.

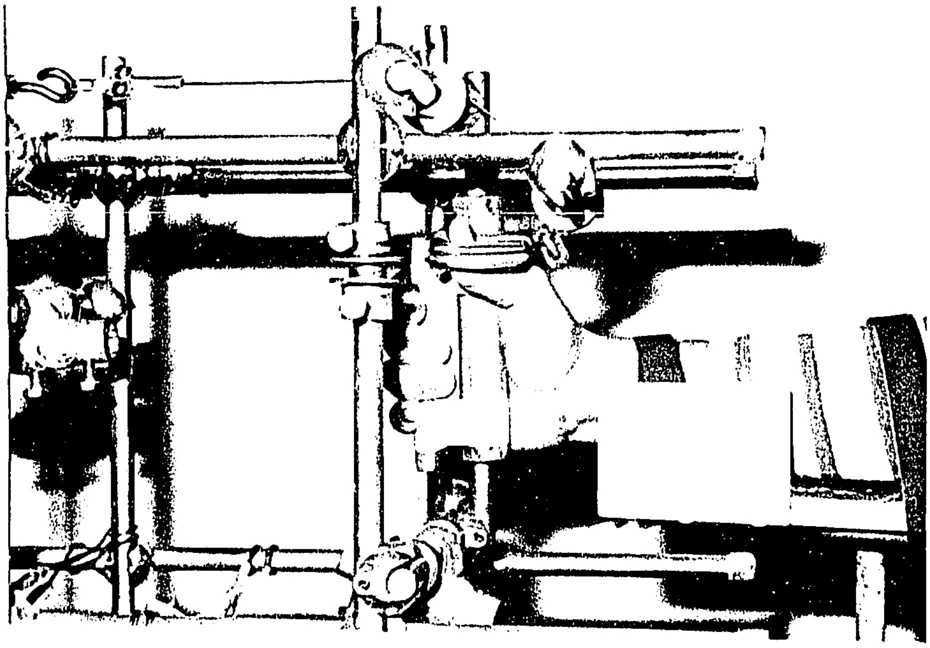
   a) The tip of the thumb was located at the place at which it nearly touched the upper lateral side of the index.

   b) The tip of the thumb was placed between the lateral sides of the second and third fingers.

Figure 8 shows the three force directions used in the measurements.

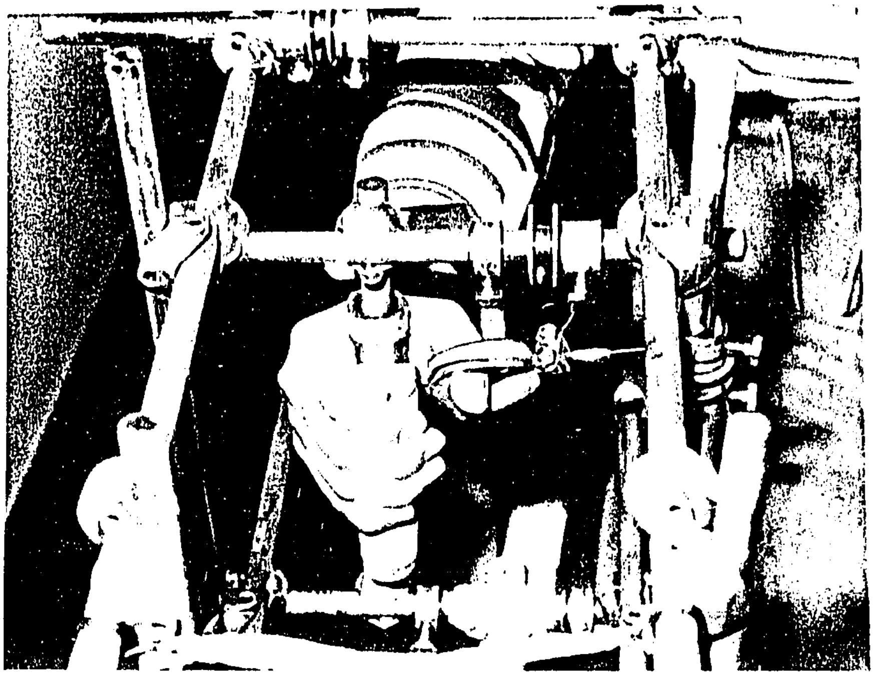


(a) force is exerted in DOWN direction



(b) force is exerted in horizontal direction

Figure 8: View for thumb strength measurement



(c) force direction is opposition

Figure 8: View for thumb strength measurement

This experiment had two purposes:

1. To determine which position allowed the thumb to exert the greatest force.
2. To determine if thumb strength was affected by gender, individual subject strength, thumb position and wrist orientation. position, and wrist position.

Table 6 presents a summary of the experimental design for the thumb strength experiment.

Table 6

The independent variables used for the thumb strength experiment

Variable	Observation Levels
Gender	2: female and male
Subject strength	3: weak, average, and strong
Wrist orientation	2: neutral and ulnarly deviated
Thumb position	8: vertical up, middle and low; horizontal out, medium and in; opposition up and low

3.3.5 Muscular Endurance Experiments

The first three experiments were concerned with the evaluation of muscular performance in the relatively short period (5 sec) necessary to measure the MVC. Experiments four and five were designed to determine if there were differences in the fatigue patterns found in the course of sustained and rhythmic isometric exercises. The fatigue patterns were defined in terms of muscular force decrement vs. the elapsed time. Experiment four used a continuously sustained isometric exercise while the fifth experiment employed a rhythmic, maximal isometric exercise.

The positions of the index and the thumb were fixed for these series, based upon the results of the previous experiments where the position of maximal strength was determined. The middle position was used for the index finger while the middle position with movement parallel to the handle axis (DOWN) was employed for the thumb.

The purposes of these experiments were:

1. To determine if there were differences between the two fingers in the fatigue patterns for the continuous and rhythmic isometric exercises.
2. To determine if such fatigue patterns were affected by gender, individual subject strength, and wrist orientation.

Table 7 provides a summary of both experiments.

Table 7

The independent variables used for muscular fatigue studies

Variables	Observation Levels
Gender	2: female and male
Subject strength	3: weak, average and strong
Wrist orientation	2: neutral and ulnarly deviated
Time	sustained exercise: 5 second interval between one-second samplings up to 2 minutes of elapsed time, rhythmic exercise: 15 second interval between one-second samplings up to 6 minutes of elapsed time.

3.4 EQUIPMENT AND MEASUREMENTS

The equipment used in this study can be classified into three categories: anthropometric measurement, force measurement, and environmental control. All experiments were conducted in an environmental chamber where a constant temperature of 22.2C +/- 0.5C and a humidity level of 75% +/- 4% were maintained for all trials.

The anthropometric measurement apparatus included a functional hand anthropometer and a protractor. The functional hand anthropometer was used to measure the functional grip size of the subjects. The protractor was built to ease measurements of the functional range of wrist movement.

The force measurement apparatus consisted of a restraint system, various handles and rings, a force transducer (Interface: Load Cell, SM-250), a signal conditioner and amplifier (Narco Biosystem: Strain Gage Coupler, Type 7172; Channel Amplifier, Type 7070), a 20K minicomputer (DECLAB-11/03) with analog-to-digital converter (A/D), a strip chart recorder (Brush: Model 200), a digital voltmeter (Fluke: Model 8000A), a tone generator to cue the subject, and a switch to initiate computer program execution.

The restraint system was constructed to accommodate the many desired hand/finger positions and consisted of a wooden chair, a vertically adjustable armrest, and a steel rod frame. The configuration of the system is shown in Figure 9. The system was adjustable in every direction so that any desired grip span, finger position, or wrist position was quickly obtained. In all configurations, two handles were attached to the frame. The primary handle was fixed to the frame so that, once set, wrist position remained constant. The secondary handle or ring was connected to the force transducer which was fixed to the other end of the rigid frame. The primary and secondary handles were parallel to each other.

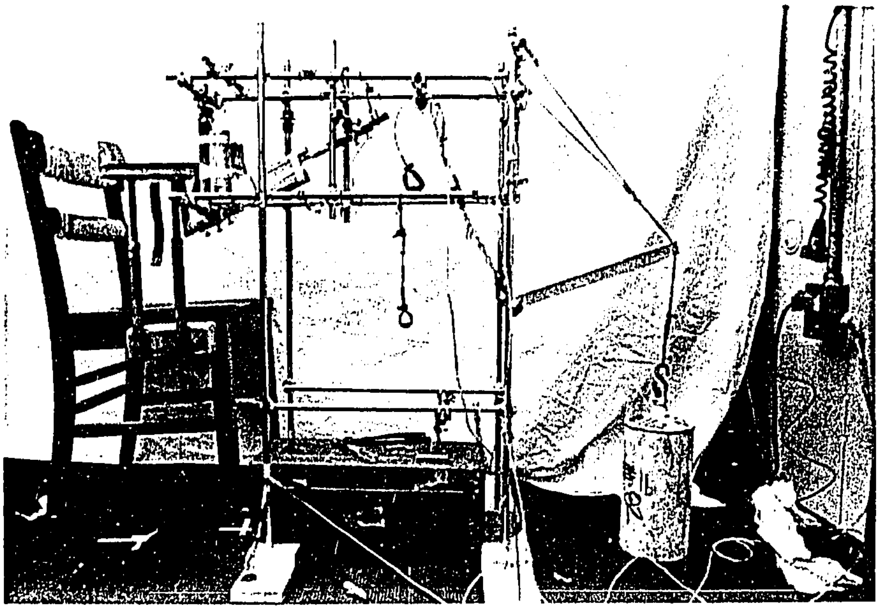


Figure 9: Restraint system used in all experiments

The primary handle used for both strength and endurance measurements was 2.54 cm wide and 2.22 cm thick with a 1.27 cm radius of curvature. It was constructed of wood and was mounted on a steel rod having a diameter of 1.27 cm. The secondary handle used in the grip strength measurements was 2.54 cm wide and 0.95 cm thick with a 2.54 cm radius of curvature. It was also wooden and was attached to thin steel cables which were connected to the hook of the force transducer.

For the finger strength measurements, two force rings were prepared to accommodate different finger sizes. Each ring consisted of a metal loop, a wooden pad for cushioning and a connecting cable. The large ring was 2.86 cm in diameter while the small ring was 1.91 cm in diameter.

Figure 10 illustrates the experimental setup of the force measurement apparatus. The strain gage was connected to an amplifier which was connected to the computer through an A/D converter. The computer had two main functions: (a) sampling, calculating, and recording the force data, and (b) timing the experiments. A switch was used to initiate the computer program which sampled and summarized data. The computer was also used to time each trial and to cue the subject by means of a tone generator connected to a digital-to-analog converter (D/A).

The strip chart recorder and the voltmeter were used to monitor the progress of each trial and to ensure that all hardware was operating properly. Actual measurements were performed by the computer.

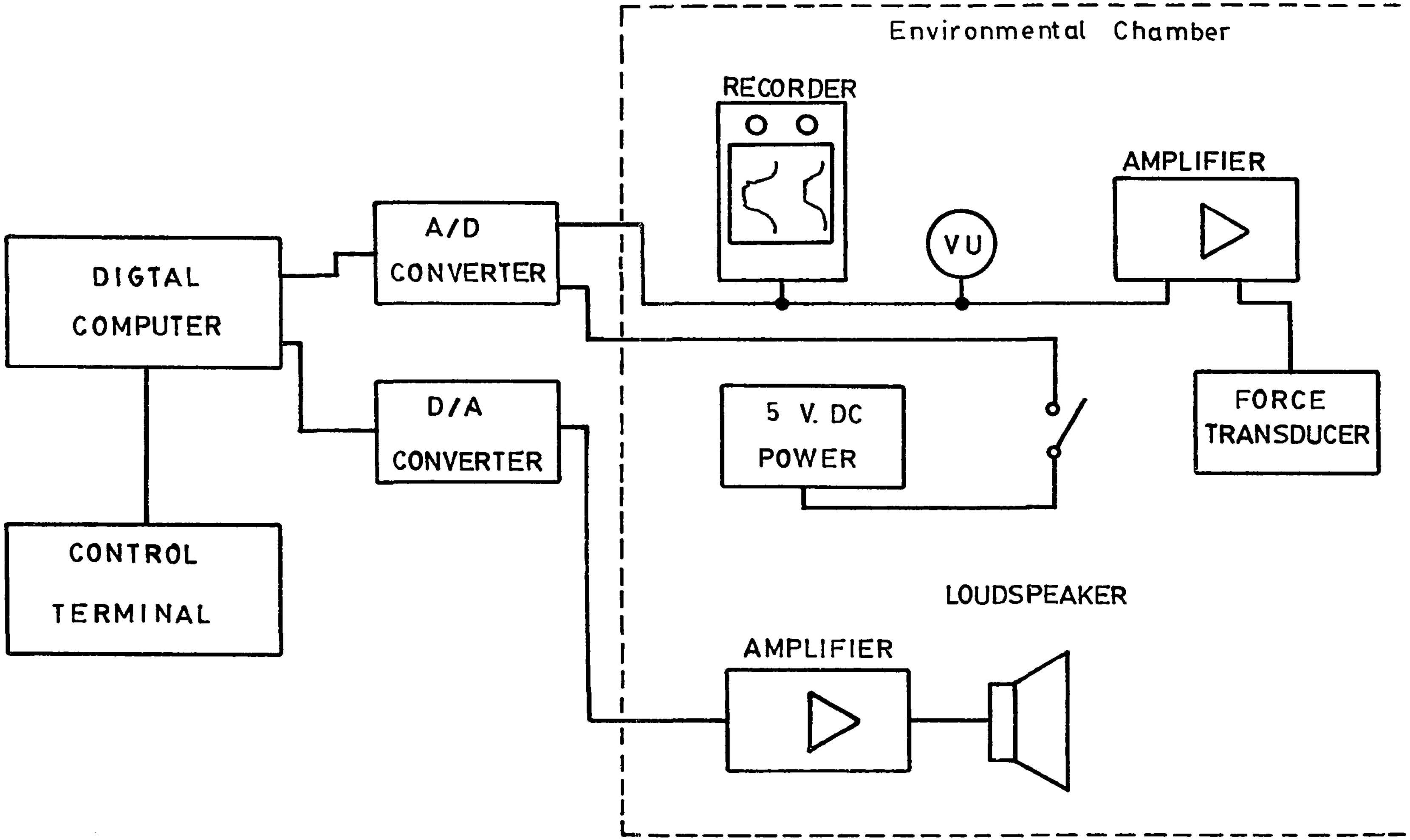


Figure 10: Diagram of the force measurement apparatus setup

3.5 MEASUREMENTS

The measurements made in this study were anthropometric measurements for subject description and experimental measurements of force under various conditions.

The anthropometric measurements consisted of functional grip span and functional range of ulnar deviation. Hand size was defined as the linear distance from the thenar and hypothenar side of the hand to the volar side of the middle finger with the hand grasping the anthropometer. To measure consistently, it was further defined as follows: (a) the thenar and hypothenar eminences were placed against one side of the anthropometer with the midpoint of the fleshy area between the index and the thumb against the midpoint of the anthropometer; (b) the midpoint of the middle phalanx of the middle finger was placed against the midpoint of the other side of the anthropometer. A typical measurement is shown in Figure 11.

The functional range of wrist deviation was measured using the protractor. Three points defined in Subsection 3.3.1 were necessary to measure the angle with the subject in a seated position, the palm and forearm were placed flat on a desk. As the tip of the middle finger tapped the desk, palpation was applied to detect these three points which were then marked with water soluble ink. Next, the wrist was ulnarly deviated on the plane of the desk (transverse plane) as far as possible from the position in which the three points were aligned (i.e., zero degrees). The angle at the

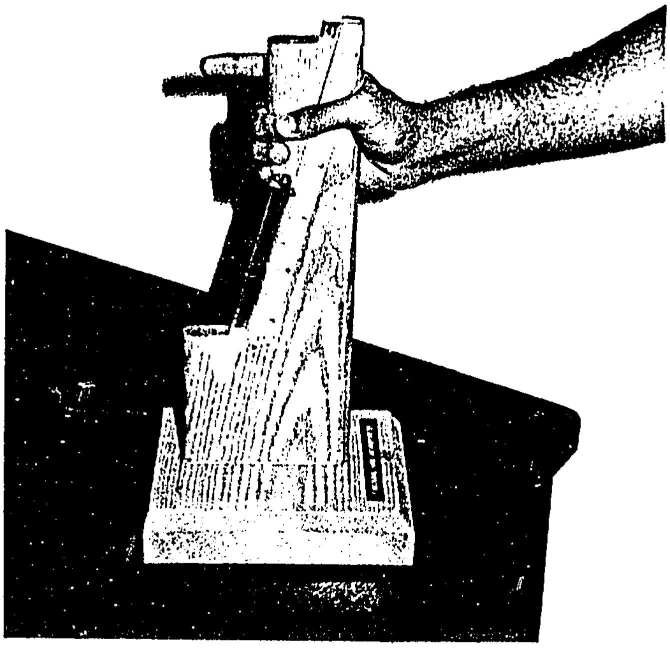


Figure 11: View of measuring functional grip span

end of motion was then measured as the functional range of wrist deviation. A second measurement was performed in the sagittal plane following the same procedure.

3.5.1 Experimental Measurements

The experimental measurements taken in this study were force measurements. For the strength experiments, the subject was instructed to make a maximal voluntary contraction when the tone sounded and to maintain the contraction for the duration of the tone (Caldwell et al., 1974). The measurement was made by the computer which was programmed as follows:

1. When the initiation signal was given by the experimenter, the computer sounded the tone and awaited a significant force exertion.

2. When appreciable amount of force (0.5 kg) was detected, the clock was set at zero and the computer began sampling at the rate of 20 samples per second. It continued sampling until five seconds had elapsed.

3. After five seconds, sampling was stopped and the tone was turned off. The data was printed out with the following statistics: (a) the mean value (MV), the maximum (MAX), the minimum (MIN), the standard deviation (SD), and the maximum one-second moving average (MAVG). To calculate the MAX, MIN, MV, and SD, only the middle three seconds data were used; that is, the first second (to allow neuro-muscular response) and the last second (to avoid neuro-muscular fatigue) data were excluded. In the MAVG calculation, the computer searched for the highest average of one second duration which occurred during the five second bout of exercise.

4. After the data printout was completed, the computer was reset for the next measurement.

In all strength measurements, the forearm and upper arm were restrained so that their contribution to the force in the measurements of grip, index, and thumb strength was kept to a minimum. For consistency, the angle at the elbow joint was placed at 120 degrees and that of the shoulder joint was abducted 30 degrees from the torso. Furthermore, the elbow was restrained by a stop attached to the back of the armrest which prevented the arm from moving backwards.

The subjects were not given quantitative feedback of performance but they were given qualitative feedback which was necessary to maintain the cooperative atmosphere. The same methodology was applied to the measurements of grip strength, index strength, and thumb strength.

The same apparatus was used to measure fatigue patterns of muscular performance as was used for the strength measurements. However, the computer programs used for the measurements were different. Two programs were employed, one for the continuously sustained isometric exercise (CONT) and the other for the rhythmic isometric exercise (RYTH). The program CONT was prepared to sample and to process data as follows:

1. When the computer received the initiation signal, it sounded the tone and awaited a significant force exertion.

2. When an appreciable amount of force was detected, the clock was set at zero and sampling was begun.

3. Data was sampled every other second at the rate of 20 samples per second while the subject continuously exerted force at the MVC level.

4. At the end of each one second sampling period, data was summarized into the MV, SD, MAX, and MIN. These values were stored in the computer memory for later printout.

5. Sampling was stopped after two minutes or sooner if the sampled data effectively fell to zero (<0.5 kg).

6. The data was printed and the computer was reset for the next measurement.

The program RYTH was similar to CONT with the exception of the subject cues and the sampling procedure. RYTH sounded the tone and waited for an appreciable amount of force. As soon as this was detected, the clock was set to zero and data sampling was begun at the rate of 20 samples per second. At the end of each one second sampling period, the tone was turned off for a one second rest period. At the end of the rest period, the tone sounded requesting that the subject again exert maximum force. This procedure was repeated for six minutes or until the sampled data effectively fell to zero.

The statistics printed out by RYTH were same as those by CONT except for the total number of data points used for calculation. To allow for neuro-muscular response time[9] the first 5 data points (i.e., 300 milliseconds) were ignored. Therefore, only 15 data points were used to obtain the mean value for rhythmic isometric exercise whereas all 20 data points were used for sustained exercise.

3.6 PROCEDURES

Before starting the experiments, anthropometric measurements of each of the subjects were made. Subjects then performed MVC exercises to familiarize themselves with the experimental procedures. Since the same equipment and procedures were used to measure strength throughout the investigation it was felt that extensive training was not needed prior to each experiment. However, additional familiarization was allowed each of the subjects when the measurements of rhythmic isometric exercise were made.

The subjects were informed of the pre-trial requirements before appearing at the laboratory as follows: (a) refrain from any heavy eating or drinking at least one hour before the trial, (b) refrain from heavy exercise, especially that which involves heavy usage of the hands and arms for at least a day before the experiment.

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[9] Simple reaction time usually ranges from 150 to 200 msec. (McCormick, 1976).

3.6.1 Experimental Procedures

The basic experimental procedures, which are outlined in Figure 12, consisted of: (a) equipment preparation, (b) subject preparation, and (c) measuring and recording strength.

The procedure used to prepare the equipment is illustrated in Figure 13. Before the subjects arrived at the laboratory, the environmental chamber was set at the desired temperature and humidity level. The dynamometer was calibrated and tested using known weights. The apparatus was adjusted for the desired measurement. The operation of the computer program was tested using both known weights and the researcher's strength.

Upon arrival, the subjects were prepared for the tests in the environmental chamber. They were briefed on the nature of the experimental procedure. Several marks were inked on the subjects' hands and forearms so that the wrist orientations and hand/finger positions were consistent. The subjects were trained to exert a maximum voluntary contractile force.

Random numbers were generated by the computer to establish the experimental sequence of subjects, wrist orientations, and handle/ring spans.

The grip span was adjusted to the individual's hand size by moving the secondary handle to or away from the pri-

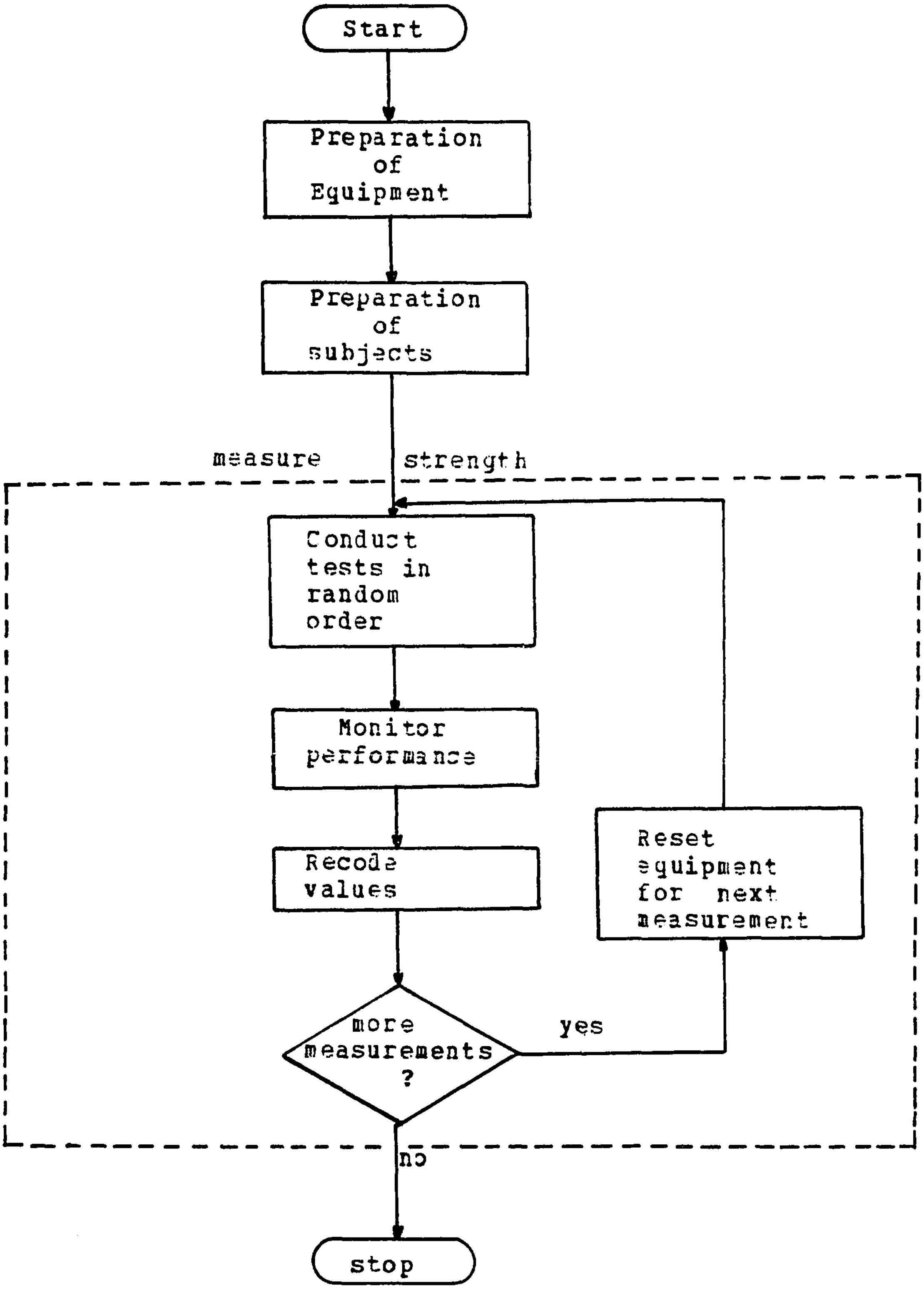

Figure 12: Basic procedure used throughout experiments

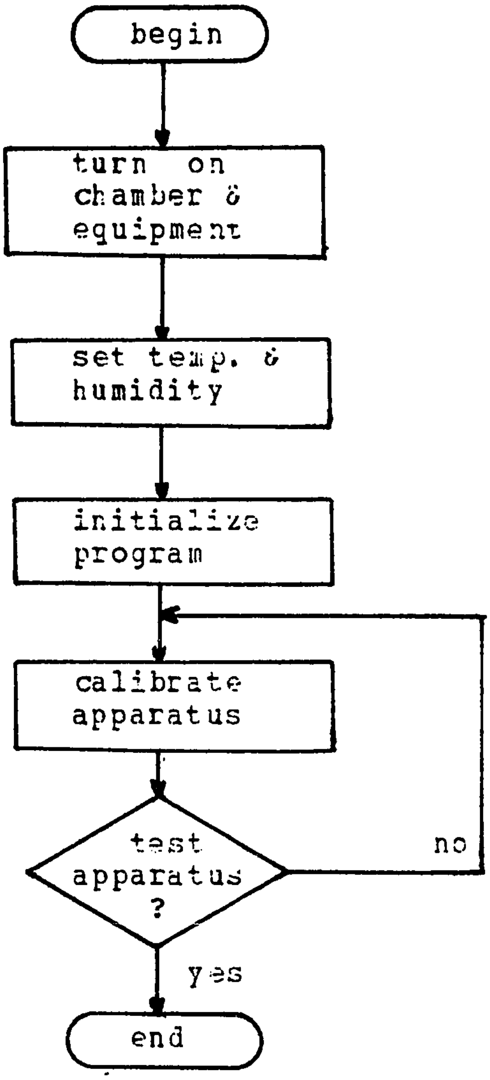

Figure 13: Procedure for preparing equipment

mary handle in reference to the anatomical landmarks previously defined. The index position was adjusted by moving the force ring to or away from the primary handle in reference to the anatomical landmarks previously mentioned. The thumb position was adjusted by using a pulley to change the direction of force and by moving the force ring to or away from the primary handle.

When all adjustments were completed, strength measurements were made by recording the force exerted during a five second maximal exertion on the dynamometer. During the measurement, subjects were encouraged to apply as much force to the apparatus as possible. The procedure used in the muscular endurance measurements is shown in Figure 14 and Figure 15. After the subjects were familiar with the procedures, they performed the experimental tasks in random and counter-balanced sequence to minimize the effect of fatique.

A minimum period of twelve minutes rest was allowed between measurements (Clarke, 1962). A tone generator was used to direct the subjects in performing the experimental tasks throughout all trials. A test was stopped when the subject could no longer continue. A sufficient time was allowed before the initiation of the first trial so that the subject could adjust to the ambient temperature set in the environmental chamber. To minimize the variations of other uncontrolled factors, experiments were held at the same time of day.

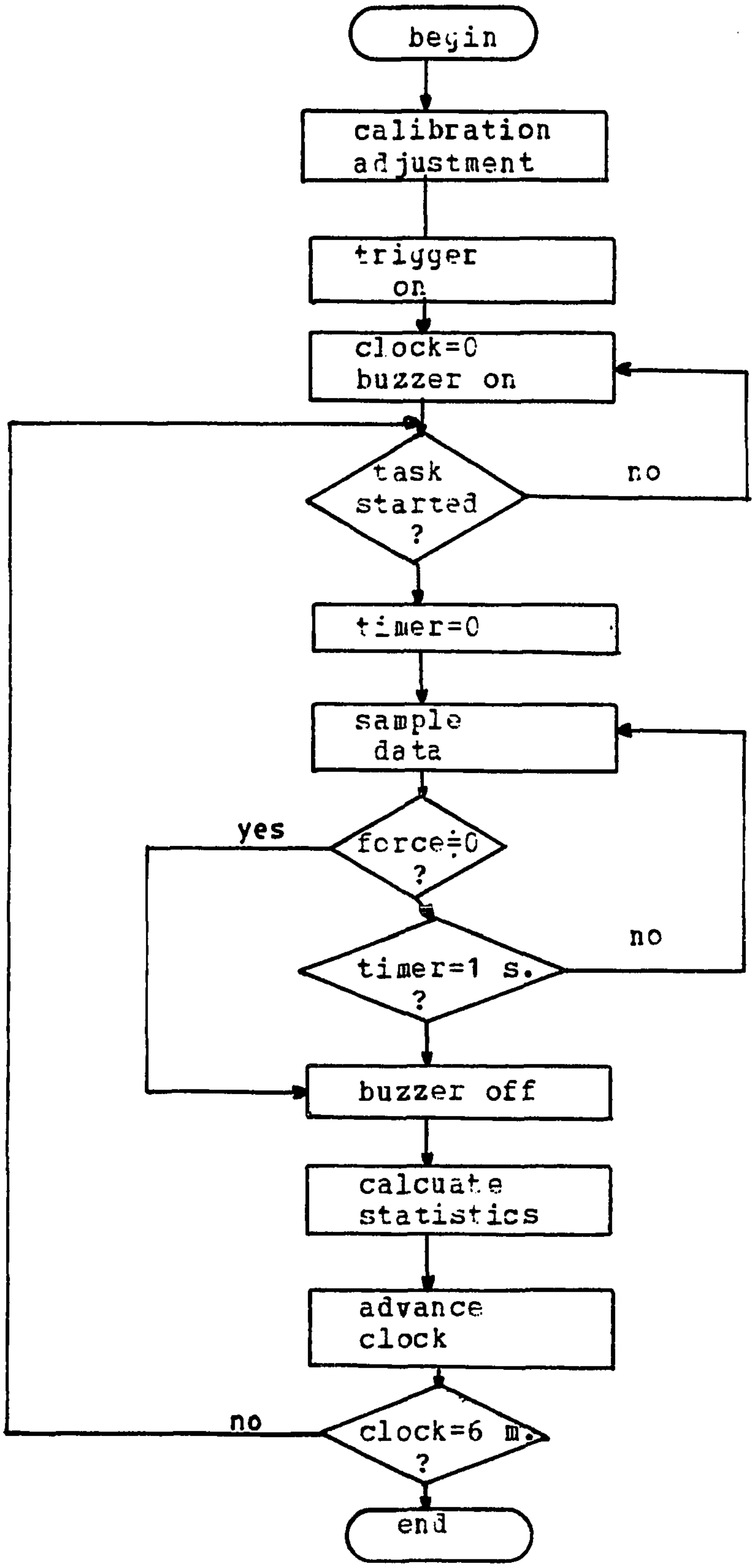

Figure 14: Rhythmic isometric exercise test procedure

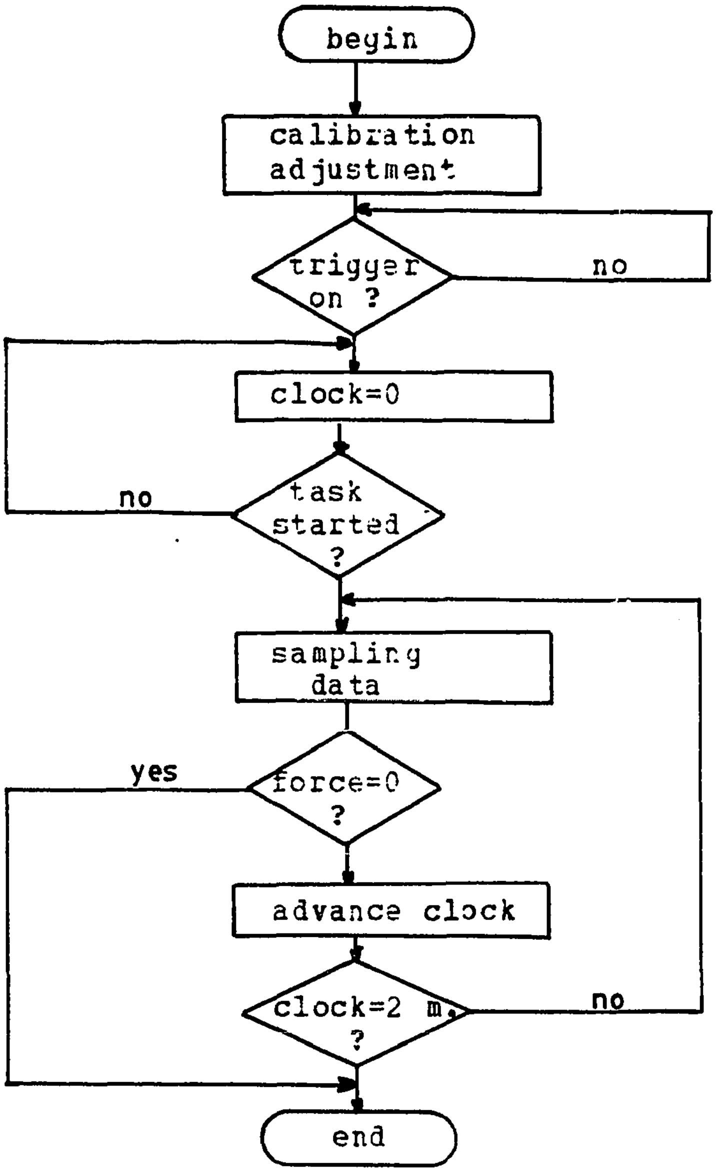

Figure 15: Continuous isometric exercise test procedure

CHAPTER IV

RESULTS AND DISCUSSION

To examine the significant effects of the independent variables on the dependent variable, statistical analyses were performed using the software packages of the Statistical Analysis System (SAS), Biomedical Computer Programs (BMDP), and the Statistical Package for the Social Sciences (SPSS) available at the University of Oklahoma (Barr at al., 1976; Dixon, 1977; and Nie et al., 1975). The data was analyzed in two forms. First, the raw data was used directly as the values of the dependent variable for the analysis of strength performance. As mentioned earlier, most of the raw data collected was of two types: the mean value of the three second samples (MV) and the maximum one-second moving average (MAVG). Although the t-test comparing MV and MAVG was not significant, MAVG was used throughout the analyses for the following reasons: (a) MAVG is more accurate than MV in evaluating maximum strength, (b) the SD of MAVG is smaller than that of MV, and (c) the mean strength for one-second samples coincides with the one-second measurement used in the fatigue studies.

For the fatigue studies, a relative strength score (RSS) index was obtained by dividing each observation value by the initial observation value. This related the various strength values to a common base for each subject. This index was used to obtain regression curves of the fatigue characteristics. The index was further multiplied by 100 (percentage) and used in an analysis of variance (ANOVA).

4.1 GRIP STRENGTH PERFORMANCE

The index operation and the thumb operation grips were evaluated in terms of strength and analyzed by the ANOVA. Table 8 depicts the significant effects as well as significant interactions (alpha = 0.0001 to 0.054).

Table 8

Significant effects and interactions for grip strength

Source	DF	SS	F	PR > F
Wrist orientation (W)	1	384.01	34.30	0.004
Grip span (P)	2	421.75	6.80	0.018
WxP	2	304.61	16.03	0.001
Grip type (T)	1	1572.06	45.33	0.002
PxT	2	35.54	10.68	0.005
Gender (G)	1	8025.37	7.25	0.054
TxG	1	316.44	9.13	0.039
Subject (S(G))	4	4426.03	115.83	0.000
PxS(G)	8	247.93	3.25	0.003
TxS(G)	4	138.71	3.63	0.009
WxTxS(G)	4	198.75	5.20	0.001

All main effects and some interactions were highly significant. Since the subjects were selected based on their strength (see Table 3) and full grip strength was highly correlated to partial grip strength (see Table 9), it was expected that individual subject strength (S(G)) and gender (G) would be significant. Indeed, they were highly signicant, which confirms the appropriateness of the subject classification.

Table 9

Coefficients of correlation between the three grip strengths with significance levels

	full grip	no thumb grip	no index grip
full grip	1.000 0.000	0.94833 0.0039	0.93045 0.0071
no thumb	0.94833 0.0039	1.000 0.000	0.93033 0.0071
no index	0.93045 0.0071	0.93033 0.0071	1.000 0.000

The primary purpose of the experiment was to determine if there was a significant difference in strength between the two grip types. The difference in strength was significant (alpha = 0.002). The strength of the thumb operation grip ranged from 68% to 99% of full grip strength with an average of 82%. The strength of the index operation grip ranged from 53% to 79% of full grip strength with an average of 60%. The amount of reduction in strength agreed with previous work performed by Hazelton et al. (1975) where the contribution of each finger to the full grip had been studied. The mean values of grip strength are listed in Table 10. The reason for the reduced performance of the index operation grip is straightforward and obviously due to the lack of the index finger in gripping. However, the attributable factor for the decreased performance of the thumb operation grip is rather indirect. Although the thumb was placed at the upright position with comfortable flexion, the thenar eminence and the lateral side of the thumb were able to fully participate in gripping. The reduced force can be explained by the lack of efficient opposition of the thumb. In the full grip, the thumb stabilizes the thenar eminence by its opposition against the force applied by the four fingers (Bechtol, 1954 and Long et al., 1970). The thumb operation grip partially restricts the thumb from opposing the fingers.

In a study of full grip strength, Terrell (1975) pointed out that the ulnarly deviated wrist allowed 85.1% of the strength in the neutral position. Other researchers have reported that the greatest force was exerted when the wrist was ulnarly deviated (Skovly, 1967; Hazelton and associates, 1975). Because of the conflicting results, the ef-

Table 10

Mean strength of the three grips (kg)

Subject	Full grip (kg)	No Thumb force (kg)	No Thumb % of full	No Index force (kg)	No Index % of full
Strong-Female	41.95	28.48	67.9	22.16	52.8
Average-Female	33.49	29.88	89.2	18.76	56.0
Weak-Female	24.39	24.15	99.0	19.31	79.2
Strong-Male	73.86	53.53	72.5	41.53	56.2
Average-Male	57.96	49.27	85.0	30.74	53.0
Weak-Male	36.67	34.77	94.8	27.72	75.6

fect of wrist orientation was investigated. In this study, the neutral wrist position produced greater force than the ulnarly deviated position (alpha=0.004). Furthermore, analysis of individual subject data confirmed the superiority of the neutral wrist (alpha=0.0005 to 0.001) with exception of one subject (alpha=0.427). On the average in this study, the ulnarly deviated wrist generated 89% of the force developed in the neutral wrist position.

Further investigation was made of the relationship between wrist angle and grip strength. The coefficient of correlation was not significant (r=-0.15281). Although the negative coefficient of correlation indicated that strength decreased as the wrist deviated, the experiment did not provide sufficient data to investigate the relationship thoroughly. The relationship between the amount of wrist deviation and grip strength remains unclear.

From the biomechanical point of view, the deviated wrist hampers the efficiency of the flexors of the thumb, middle, ring, and little fingers. Anatomically, the line passing through the middle finger, called the axial line of the hand, is relatively straight when the wrist is neutrally positioned (Basmajian, 1970). When the wrist is deviated, this axial line is bent at the carpal tunnel region and lines of the ring and the little finger are bent further. As a result, part of the force exerted by the flexor muscles compresses the carpal tunnel region. Therefore, the deviated wrist results in inefficient use of the flexing force.

The ability to flex and to oppose the thumb may also be reduced by the deviated wrist. The deviated wrist lengthens the thumb extensors, resulting in enhanced activity of these muscles. As stated earlier, one of the major contributions of the thumb to gripping is its opposition against the counterforce exerted by the fingers (Bechtol, 1954). The flexing function of the thumb is hampered by the deviated wrist since the maximum available force for antagonists is partially cancelled by the enhanced extensor activities. As a result, a lower force was exerted by the grip of the deviated wrist than that of the neutral wrist.

The effect of grip span (P) on strength performance was also signicant (alpha=0.018). The greatest force was developed with the medium span, followed by the large and small spans. The mean levels of performance for the large and small spans were 93% and 86% of the force exerted by the medium span. It is well known that the force which any muscle fiber can exert depends upon the length of the muscle fiber. The force is at a maximum for a length equal to 1.2 times the resting length and decreases at shorter and longer lengths (Astrand and Rodahl, 1978). The medium grip span provides this optimal muscle fiber length. The advantage of the medium span can be further explained from the biomechanical point of view. The force applied to the grip handle is utilized more efficiently with the medium span than with the large span. The amount of contact area between the hand and the surface of a handle is inversely related to the size of the grip span. In the large span, the amount of contact area is small which results in inefficient use of available force. In the small span, the amount of contact area is large but shortened muscle fibers are also present. Hence, the medium span is the best position for force exertion.

In examining the anatomical structure of the flexor tendon attachment to the phalanges, the superiority of the medium span to the other spans becomes clearer. The tendons of the FDS are attached to the base of the middle phalanges while those of the FDP are at the base of the distal phalanges. Therefore, the forces exerted by both the FDS and the FDP are efficiently applied to the grip handle in the medium span whereas the force exerted by the FDS is not efficiently utilized in the large span because of the extended position of the PIP joint. Unfortunately, the length of the phalanges of the subjects was not measured. It was not possible to make a further biomechanical analysis to investigate whether there was a difference in performance between the small span and the large span.

The Duncan multiple range test detected a significant difference in strength between the medium and small spans. However, there was no significant difference between the medium and the large, and between the large and the small spans. Statistically, comparisons between the means of a factor may be obscured by a significant interaction (Montgomery, 1976). Because both W and P were fixed factors and their interaction was significant, comparisons between means of P may be obscured by the WxP interaction.

The significant WxP interaction resulted because the force exerted with the large span was greater with the deviated wrist than with the neutral wrist. On the other hand, the small and medium spans with a neutral wrist provided greater force than a deviated wrist.

The interactions of PxT, TxG, and PxS(G) were found to be significant (see Figure 16). However, none of these interactions conflicted with the result that the index operation grip and the thumb operation grip both produced greater force at the medium span with the neutral wrist position than any other position.

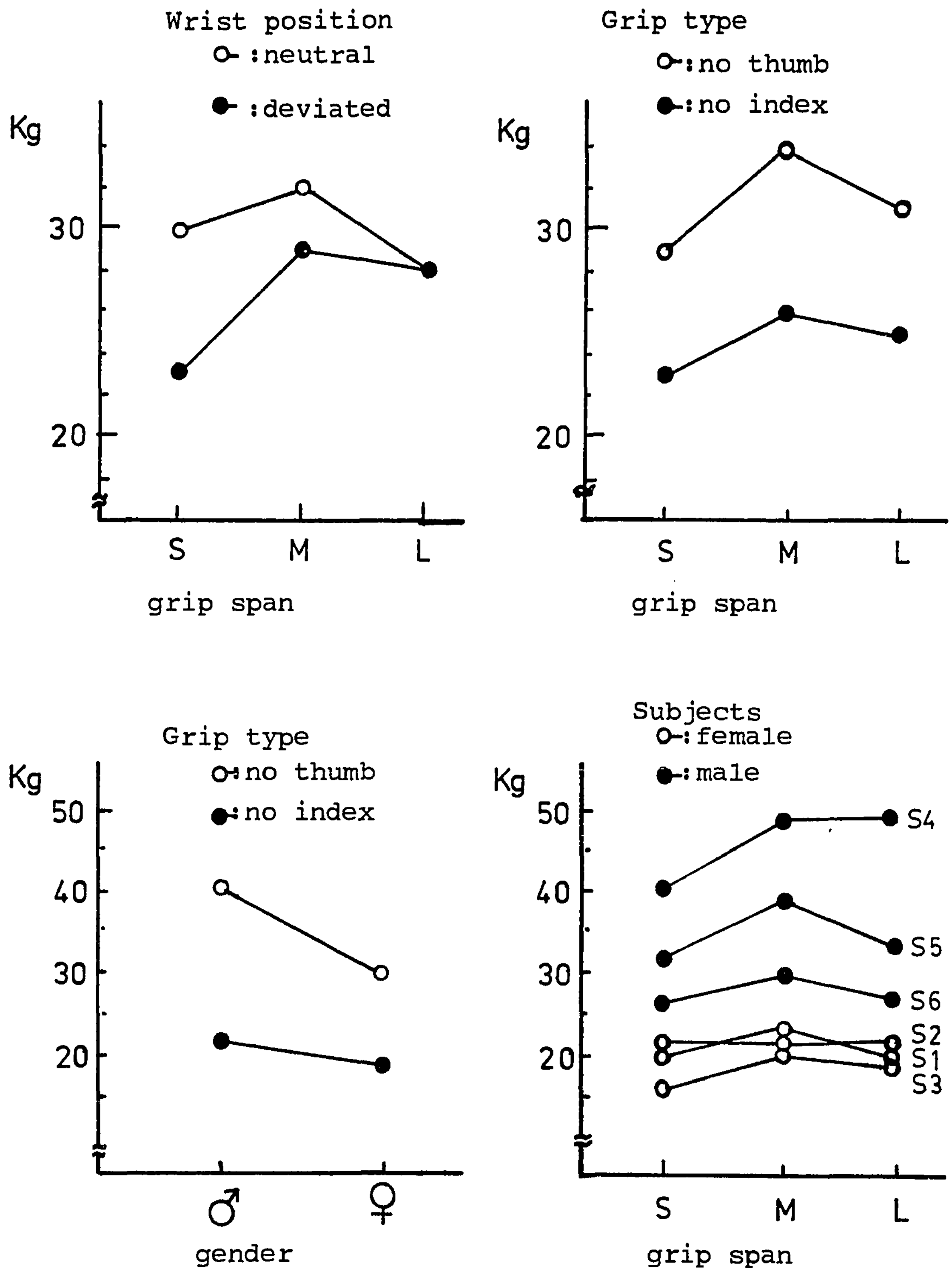

Figure 16: Mean grip strength as a function of various significant factors

4.2 STRENGTH PERFORMANCE OF THE INDEX

The strength performance of the index finger was evaluated as a function of gender (G), individual subject strength S(G), finger position (P), and wrist orientation (W). However, grip span was fixed at the medium span throughout all trials. Table 11 shows the main effects and significant interactions (alpha < 0.10). The effects of P and S(G) on performance were significant. On the other hand, W and G were not significant. Again, the differences between subjects were highly significant. However, the effect of gender was not significant. The mean strengths for the female group and the male group were 9.2 and 13.78 kg, respectively. Further analysis of the individual subject data revealed that the index strength of the weak-male subject was less than that of the strong-female and average-female subjects.

Table 11

Main effects and significant interactions for index strength

Source	DF	SS	F	PR>F
Wrist orientation (W)	1	46.95	3.54	0.1332
Index position (P)	2	158.68	9.61	0.0075
Subject (S(G))	4	469.18	57.50	0.0001
Gender (G)	1	377.53	3.22	0.1473
WxS(G)	4	53.11	6.51	0.0005
PxS(G)	8	66.05	4.05	0.0012
WxPxS(G)	8	52.50	3.22	0.0070

Unlike grip strength, the strength of the index finger was not affected by wrist orientation (alpha=0.133). This lack of significance may be explained anatomically and biomechanically as follows: (a) because of the location of the index flexors, the muscle fiber lengths are less affected by the deviated wrist than are those of other finger flexors, and (b) the axial force direction of the index flexors is less hampered by the deviated wrist than it is for the other finger flexors. Close examination of the data for the indivdual subjects resulted in the following: (a) one subject performed better with the deviated wrist than with the neutral wrist, (b) all other subjects performed better with the neutral wrist. As a result, the interaction between W and S(G) was signicant.

The effect of finger position was highly significant. The Duncan multiple range test indicated that the midposition differed from the close and far positions. The close and far positions allowed 78% and 75% of the strength developed with the midposition. Table 12 shows index finger strength as a function of finger position.

Table 12

Mean index strength (kg) as a function of position

Index finger position		
close	medium	far
10.64	13.58	10.26

The superiority of the midposition to other positions may be explained by the anatomical fact that the FDP and FDS tendons are attached to the base of the distal and middle phalanges, respectively. Because of these arrangements, the distal and middle phalanges exert a greater force in the midposition than in any other position. No statistical difference between the close and far positions was found. The amount of contact area covered by the phalanges is affected not only by individual hand size but also by phalangeal size. In this experiment, finger position was based on hand size but not on phalangeal length (i.e., the thickness of the test ring did not change throughout the experiment). This situation made further elaboration of the biomechanical analysis impossible.

An analysis of the mean values with respect to P and S(G) showed that all but one subject exhibited the greatest force at the midposition. This subject was stronger at the far position. However, the difference (0.34 kg) between the two positions was negligible (see Figure 17).

The interactions of PxS(G) and WxPxS(G) were significant because the forces exerted at different positions, especially the close and far positions, varied among the subjects. Figure 17 illustrates the index finger strength as a function of wrist orientation and index position.

In summary, it was found that for five of the six subjects the index exerted greater force at the midposition

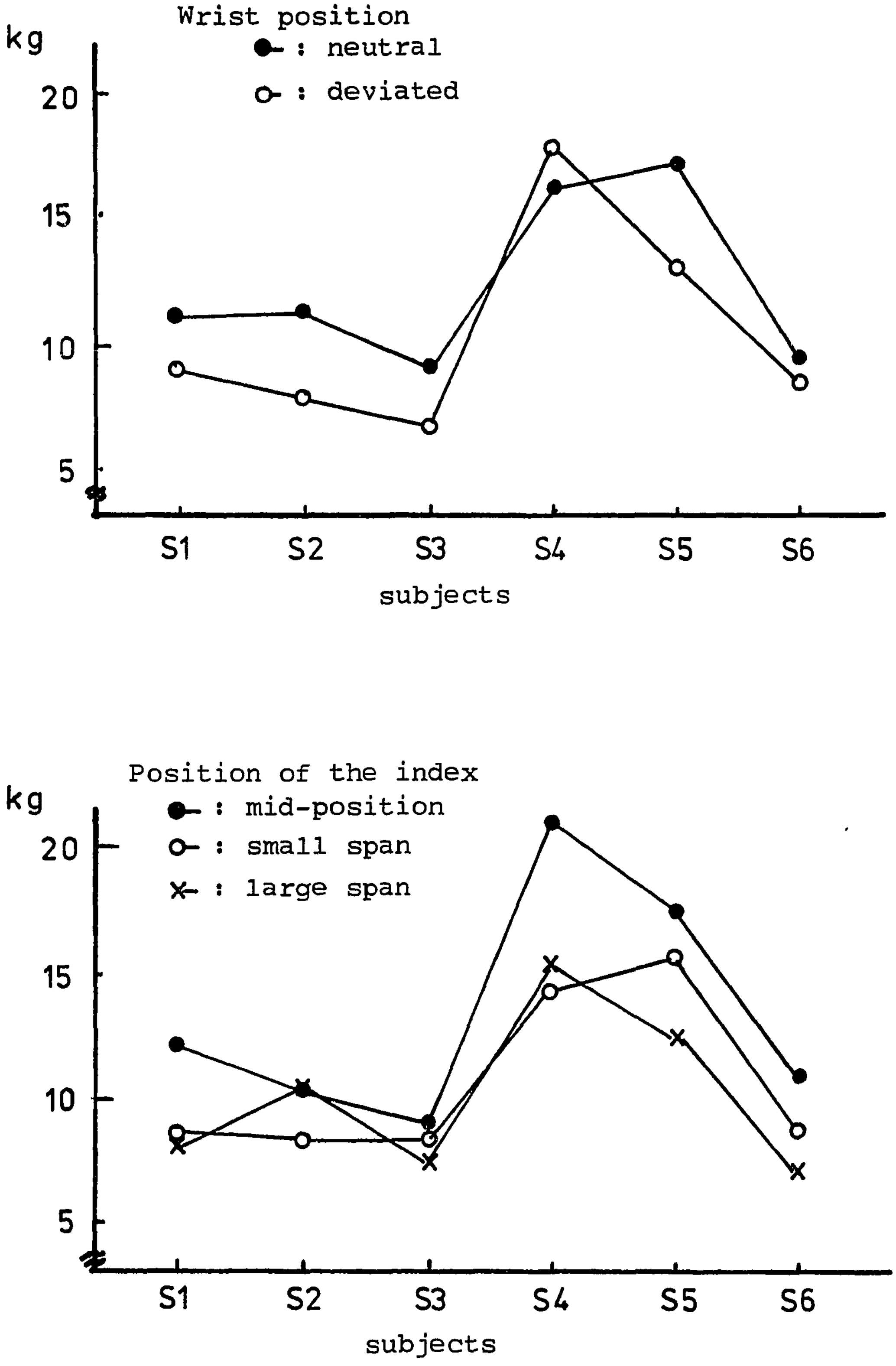

Figure 17: Index finger strength as a function of wrist orientation and index position

than any other position for both the neutral and deviated wrist.

4.3 STRENGTH PERFORMANCE OF THE THUMB

The effects of wrist orientation (W), thumb position (P), individual subject strength (S(G)) and gender (G) on thumb strength were analyzed by the ANOVA. The main effects and significant interactions are listed in Table 13. The effect of S(G) was significant as expected. However, the effect of G on strength was not significant (alpha=0.288). The mean levels of performance for the female and male groups were 4.89 and 6.78 kg, respectively. Further examination of the mean values for the individual subjects revealed that the weak-male subject exerted the least force among all subjects. As stated earlier, the subjects were selected on the basis of their full grip strength. The weak-male subject was stronger in grip strength than the average-female and weak-female subjects. These facts suggest that full grip strength is not a good predictor of individual thumb strength for a given individual.

The effect of wrist orientation on strength was significant (alpha=0.032). The mean thumb strength with the deviated wrist was 87% of the strength developed with the neutral wrist. As previously mentioned, this result can clearly be explained by the anatomical structure of the thumb. The muscles of the APL, the EPL and the EPB act as

Table 13

Main effects and significant interactions for thumb strength

Source	DF	SS	F	PR>F
Wrist orientation(W)	1	33.89	10.33	.032
Thumb position(P)	7	237.25	9.63	.000
WxP	7	37.23	3.96	.004
Gender (G)	1	171.59	1.50	.288
WxPxG	7	24.75	2.64	.032
Subject (S(G))	4	457.94	67.55	.000
PxS(G)	28	98.51	2.08	.005

antagonists to the flexors of the thumb (see Figure 4). When the wrist is ulnarly deviated, the effect of the antagonists is more pronounced than with the neutral wrist. Thus, the deviated wrist adversely affected thumb performance.

The effect of thumb position on strength was highly significant (alpha=0.0001). The positions of the thumb were classified into three categories[10] based upon the direction of force exertion: (a) vertical direction parallel to the sagittal plane (DOWN), (b) horizontal direction parallel to the sagittal plane (INWARD), and (c) horizontal direction perpendicular to the sagittal plane (OPPOSITION). Each direction had two or three thumb positions with eight positions in total.

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[10] For details, see Subsection 3.3.4.

Through the Duncan multiple range test, it was determined that the greatest force was exerted in the DOWN direction, followed by the OPPOSITION and INWARD directions. The mean levels for the INWARD direction and OPPOSITION were 71% and 88% respectively of the strength developed in the DOWN direction. Table 14 shows thumb strength as a function of thumb position.

Table 14

Mean thumb strength (kg) as a function of position

Thumb positions

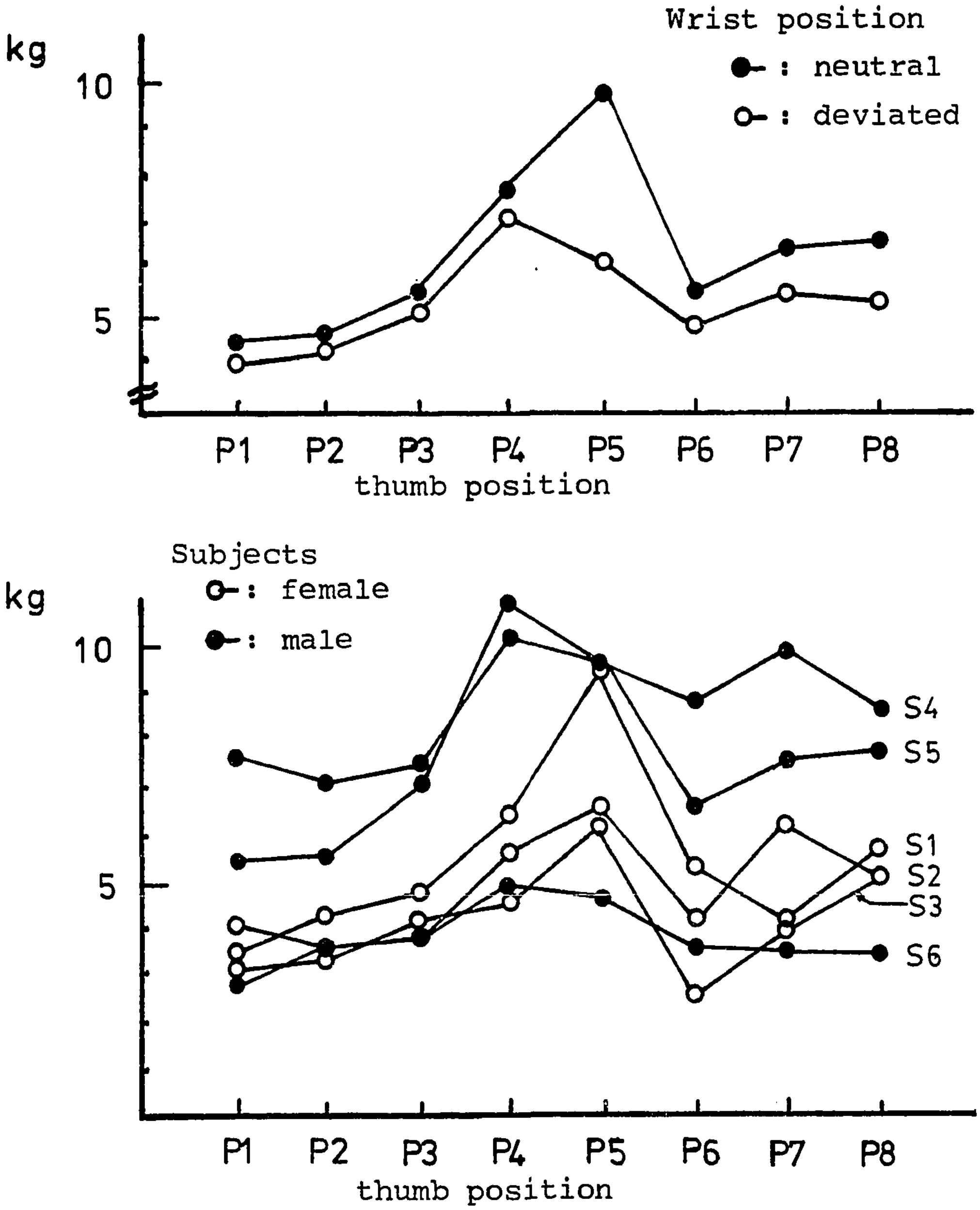
P1 = 4.47 P2 = 4.65 P3 = 5.30
P4 = 7.48 P5 = 7.61 P6 = 5.17
P7 = 5.95 P8 = 6.02

INWARD: P1=outside, P2=middle, P3=inside
DOWN: P4=high, P5=middle, P6=low
OPPOSITION: P7=medium-high, P8=middle

The positional differences in strength can be interpreted by examining the number and size of the muscle fibers in each force exertion. First, the major muscles which participate in the DOWN force direction (i.e., flexion of the thumb) are the FPL and the FPB. They are extrinsic muscles of the hand and are much larger in size than the intrinsic muscles. Therefore, the DOWN direction provided the greatest force. On the other hand, both OPPOSITION and the INWARD direction use the intrinsic muscles.. The thenar triad is the most active muscle group in the OPPOSITION and INWARD force directions. The OPP muscle further participates in OPPOSITION whereas the thumb stabilizer of the FPL drops out in the INWARD direction with the IP joint is extended (Forrest and Basmajian, 1965; Forrest and Kahn, 1968; Landsmeer, 1976). Also, the number of muscles participating in OPPOSITION is larger than those participating in the INWARD direction.

The PxS(G) interaction was significant, indicating that thumb strength was affected by the interaction of thumb position with individual subject strength. Graphical inspection of the mean values for each P and S(G) indicated that the greatest force was developed with the midposition in the DOWN direction for the females and with the high position in the DOWN direction for the males. Note that the difference in the mean values between the two positions was very small (0.13 kg).

The significant WxP interaction also indicated that thumb strength was affected by thumb position and wrist position. Examination of the data for each W and P revealed that the neutral wrist position allowed the thumb to exert a greater force than did the deviated wrist position. However, the interaction may be observed at the middle position in the DOWN direction (see Figure 18). Thumb strength as a function of wrist orientation and thumb position is shown in Figure 18.



force directions

horizontal	vertical-down	opposition
P1= outside	P4= high	P7= medium-high
P2= middle	P5= middle	P8= middle
P3= inside	P6= low	

Figure 18: Thumb strength as a function of wrist orientation and thumb position

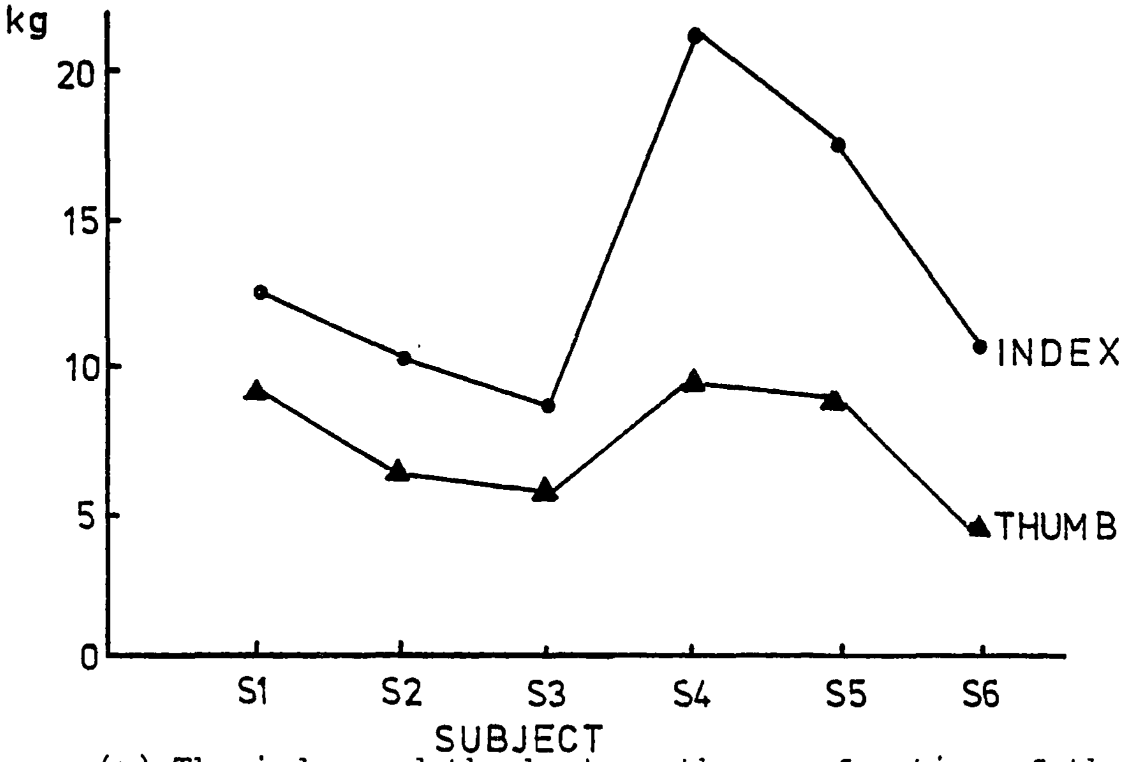
4.4 COMPARISON OF INDEX AND THUMB STRENGTH

On the basis of the ANOVA results, the strongest position for the index finger was the midposition. The strongest position for the thumb was the midposition in the DOWN direction. The data for these two positions was extracted from the data collected; mean values under various experimental conditions were calculated to allow for quantitative comparison between the two digits.

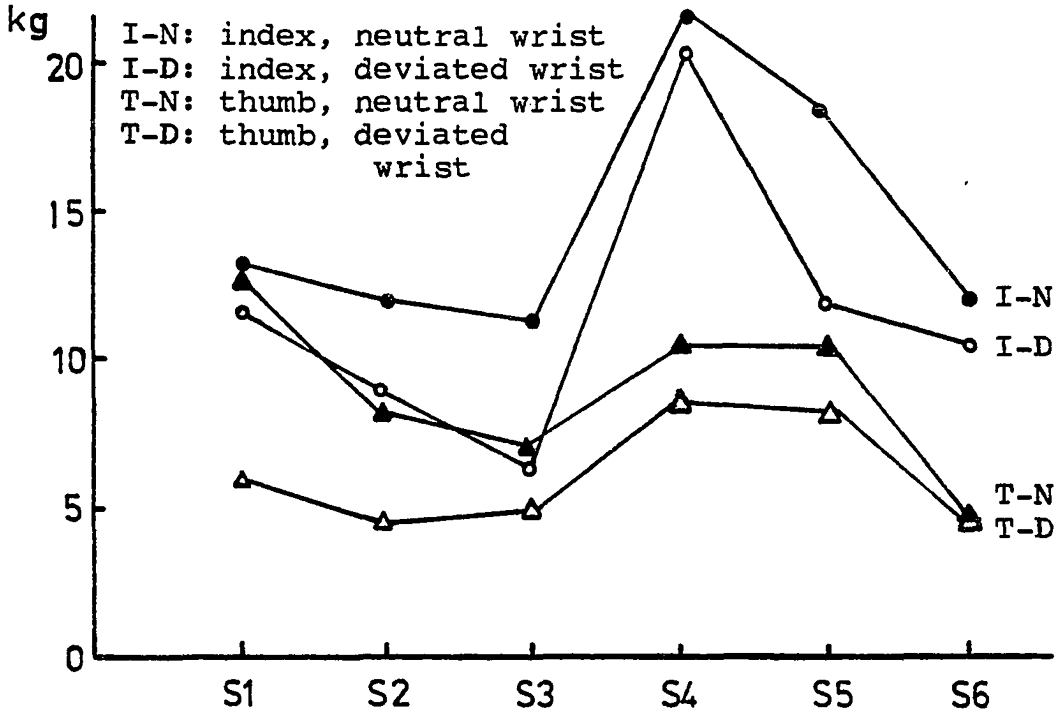
The force exerted by the thumb at its strongest position was, on the average, only 56% of the force (13.59 kg) developed at the strongest position of the index. The mean values of each finger strength are illustrated in Part (a) of Figure 19.

When the mean values are compared, it can be seen that the strength performance for both fingers was reduced by a deviated wrist. On the average, the performance of the thumb with a deviated wrist was reduced to 68% of the strength (9.04 kg) developed with a neutral wrist. On the other hand, the strength performance of the index with a deviated wrist was decreased to 83% of the strength (15.10 kg) exerted by a neutral wrist. The effect of a deviated wrist is shown in Part (b) of Figure 19.

The reduction in strength for the female group was more pronounced with a deviated wrist than for the male group. The mean strength of the thumb with a deviated wrist for the female group was 54% of the strength (9.59 kg) developed with a neutral wrist while for the male group it was 84% of the strength (8.49 kg) developed with a neutral wrist. On the other hand, the mean value of the index strength with a deviated wrist was 73% of the strength (12.24 kg) exerted with a neutral wrist for the female group; in the male group it was 87% of the strength (17.75 kg) developed with a neutral wrist.



(a) The index and thumb strength as a function of the subject



(b) The index and thumb strength as a function of the wrist position and the subject

Figure 19: Mean strength values for the best index and thumb positions

4.5 RESULTS OF FATIGUE STUDY

Computational problems were encountered in the analysis of the fatigue data. When all the data points were employed in the ANOVA for a nested factorial model, either the memory storage space or the required processing time exceeded the allowable capacity of the University Computing Service at the University of Oklahoma.

However, the results of the non-linear regression analysis of fatigue patterns using the full set of data provided a very close fit to the observed data. The residual sums of squares were very small, 0.00705 for the sustained isometric exercise and 0.00279 for the rhythmic isometric exercise. Therefore, alternating data points were omitted from the ANOVA to overcome the computational difficulty and the analysis was performed using one-half of the collected data set.

4.5.1 Fatigue Patterns Resulting from Sustained Isometric Exercise

The relative strength scores as a function of time are presented in Table 15. At 30 seconds from the beginning of exercise, the index strength had declined by 44% whereas the thumb strength had decreased by 32%. The decrements after 90 seconds were 69% and 64% for the index and the thumb, respectively. During the course of the two minute exercise, index strength declined by 72% and thumb strength declined by 67%.

Table 15

Relative strength scores for sustained exercise

Time	Index finger		Thumb	
(sec)	observed	predicted	observed	predicted
0	1.000	0.961	1.000	0.991
12	.725	.751	.862	.851
24	.578	.603	.752	.736
36	.494	.499	.616	.641
48	.446	.426	.575	.563
60	.389	.374	.511	.499
72	.354	.338	.452	.447
84	.295	.313	.396	.404
96	.302	.295	.371	.369
108	.267	.282	.314	.339

It has been shown that the use of the negative exponential equation is adequate to describe the fatigue patterns of muscular force exertions (Rohmert, 1960; Clarke and Gentry, 1971; and Ordway et al., 1977). To analyze the fatigue patterns, a non-linear regression analysis was performed. The analysis indicated that the fatigue patterns of the thumb and the index were adequately described by the form:

$$RSS = a \exp(-bt) + c,$$

where RSS = the relative strength score at time t,

a, b, and c = the parameters of the function.

The equations of the relative strength scores were as follows:

$$\text{Index: } RSS = 0.709\exp(-0.0293t) + 0.252$$

$$\text{Thumb: } RSS = 0.785\exp(-0.0164t) + 0.206.$$

The predicted values from these equations are listed along with the observed values in Table 15. Some of the regression equations are graphed in the following figures. Other equations are found in Appendix F. As shown in Figure 20, the rate of strength decrement for the index was greater than for the thumb.

From the ANOVA, it was determined that all the main effects except gender (G) were significant. The main effects and significant interactions are listed in Table 16. There was a significant difference between the performances of the two digits (F). The strength decrement of the index was greater than that of the thumb although the index manifested a much greater initial strength as discussed earlier.

Table 16

Main effects and significant interactions for sustained exercise

Source	DF	SS	F	PR>F
Wrist orientation (W)	1	1060.36	11.95	< .05
Finger (F)	1	10064.57	11.25	< .05
WxF	1	2253.68	4.99	< .10
Time (T)	8	176000.96	62.79	< .001
FxT	8	2286.30	6.16	< .001
Gender (G)	1	4146.79	1.47	> .10
WxG	1	1093.09	12.32	< .025
FxTxG	8	727.65	1.96	< .10
Subject (S(G))	4	11277.11	31.94	< .001
FxS(G)	4	3578.90	10.04	< .001
WxFxS(G)	4	1804.96	5.11	< .005
TxS(G)	32	11211.64	3.97	< .025

The finger positions used for this experiment offer some explanations for the superior performance of the thumb as compared to the index. The FDP and FDS are the most active muscles in flexion of the fingers. Although the FDP tendon of the index acquires a certain independence in the forearm region, the index flexor and other finger flexors are attached to a common muscle (see Figure 4). In the experiment, the other three fingers were used for grasping the handle. Thus, part of the force available to the index had to be shared with these other fingers. On the other hand, the FPL, which is an independent muscle, is the major flexor of the thumb. In flexion of the thumb, the FPL is assisted by intrinsic muscles such as the APB, the OPP, the FPB, and to a slight extent by the ADD (Forrest and Kahn, 1968; and Basmajian, 1970). Therefore, there are differences between the two digits in the number of muscle fibers and the anatomical structure of the musculo-tendon mechanism.

The main effect of the subject strength S(G) was significant. This indicated that the mean levels of the relative strength score varied among the subjects. The mean relative strength scores over the entire testing period are listed in Table 17.

The significant effect of time (T) indicated that there was a strength decrement from the beginning to the end of the exercise for both fingers. The significant FxT in-

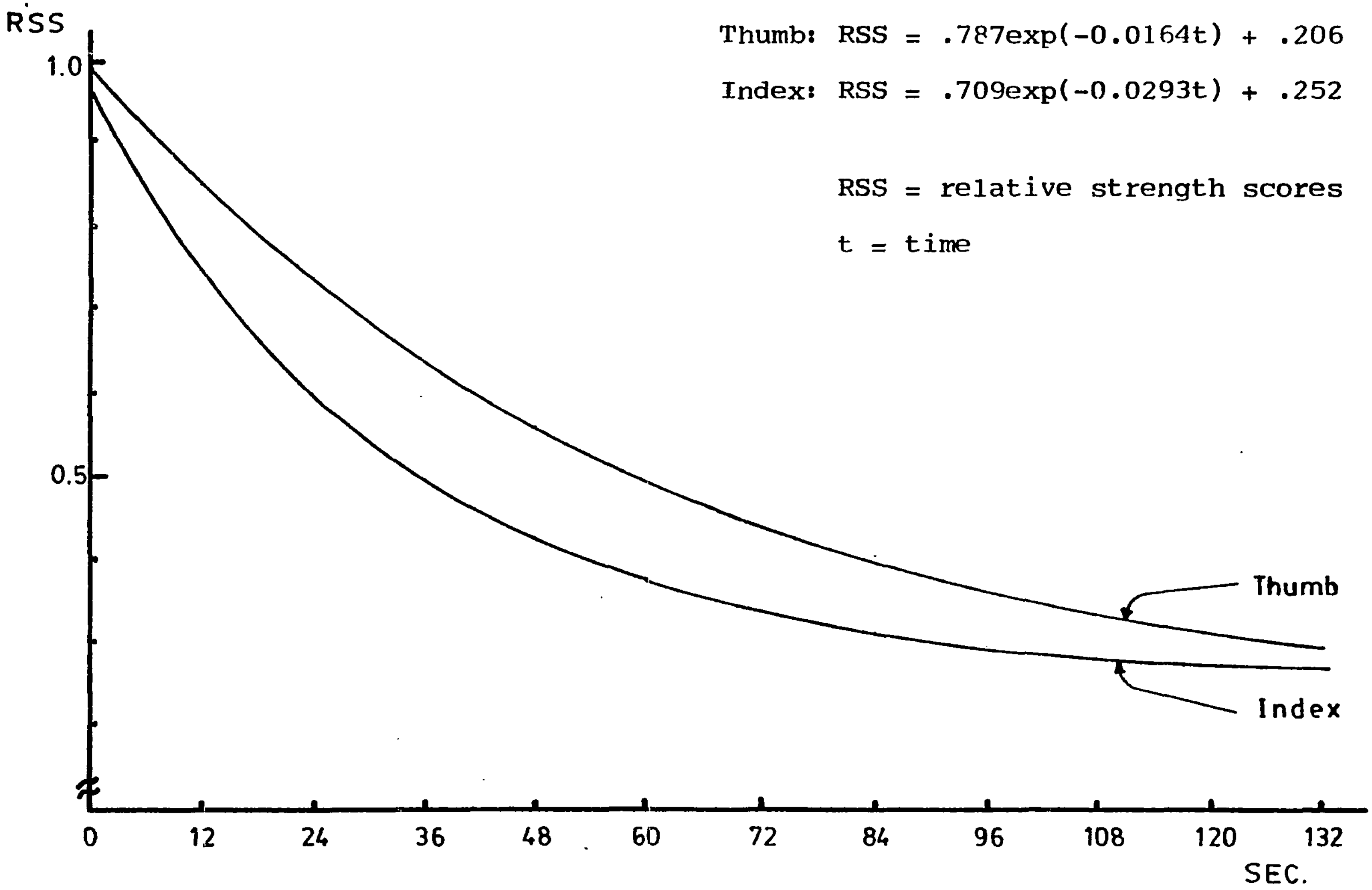


Figure 20: Index and thumb fatigue patterns for sustained exercise

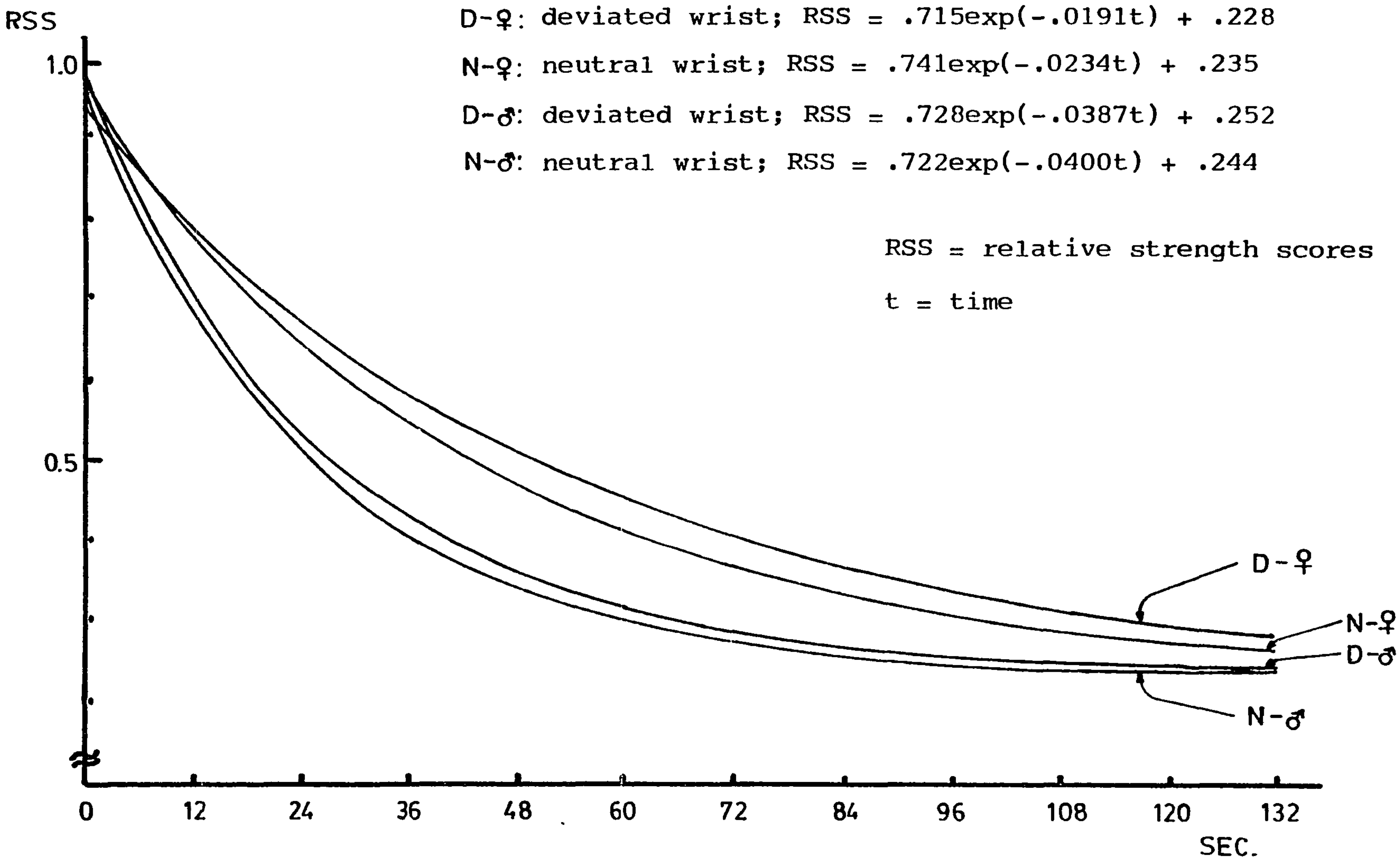


Figure 21: Index fatigue patterns for sustained exercise by gender and wrist orientation

Table 17

Mean relative strength scores for sustained exercise by subjects

Female group			Male group		
strong	average	weak	strong	average	weak
0.622	0.548	0.583	0.499	0.551	0.529

teraction resulted because the index finger manifested a greater strength decrement than did the thumb. The WxF interaction was significant because the thumb demonstrated a greater strength decrease with a deviated wrist than did the index (see Figure 20). This effect due to wrist orientation agreed with the results of the MVC strength study.

The significant WxG interaction revealed that, in the deviated wrist position, there was a greater decrement in index finger strength for the female group than for the male group. However, thumb strength decreased more with the male group than with the female group (see Figure 21 and 22). The effect of the deviated wrist was much greater for thumb strength than for index strength (see Figure 20).

The TxS(G) interaction was significant, indicating that the fatigue patterns during the course of the exercise were different among the subjects. This result did not agree with the findings of previous researchers. Caldwell (1964) reported that stronger subjects showed a greater strength decrement than did weaker ones but still maintained greater strength at the end of the sustained exercise. On the other hand, Rohmert (1960) and Caldwell (1963) found that there was no clear relationship between subject strength and endurance defined as the time for which a constant force could be maintained. This study found a significant TxS(G) interaction but did not find a clear relationship between individual subject strength and time (see Figure 24).

The FxS(G), FxTxG, and WxFxS(G) were also significant. The significant FxTxG interaction indicated that during the course of exercise, the index had a greater rate of strength decrement than did the thumb and the male group demonstrated a greater decrement than did the female group (see Figure 23).

4.5.2 Fatigue Patterns Resulting from Rythmic Isometric Exercise

The relative strength scores for the rhythmic isometric exercise are listed in Table 18.
At 96 seconds from the beginning of the exercise, the index and the thumb scores were, on the average, reduced to 59% and 61%, respectively. After the six minutes of exercise, the mean level of the index scores was further decreased to only 40% of the initial strength. The mean level of the thumb scores remained relatively stable at 53% of the initial strength.

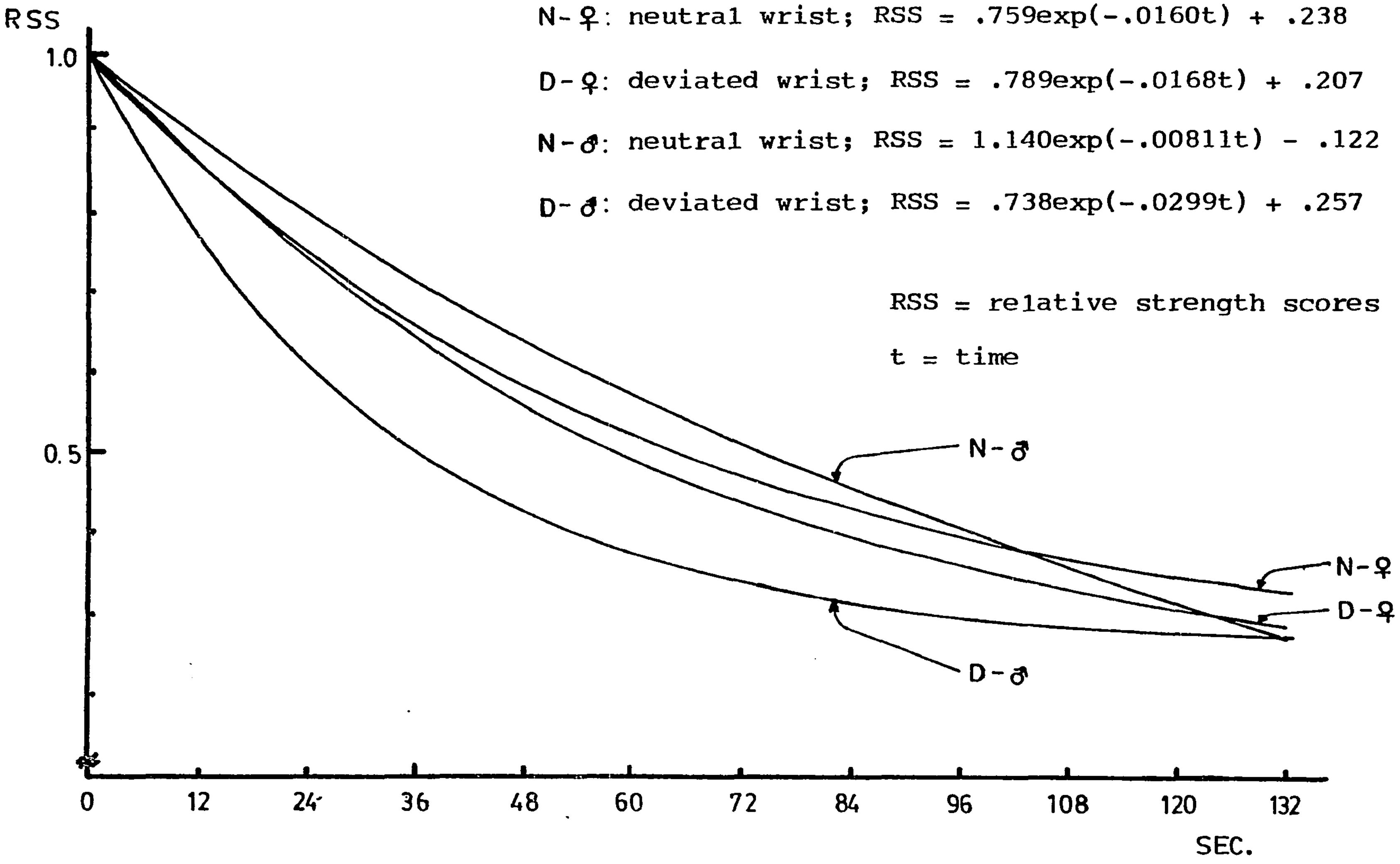
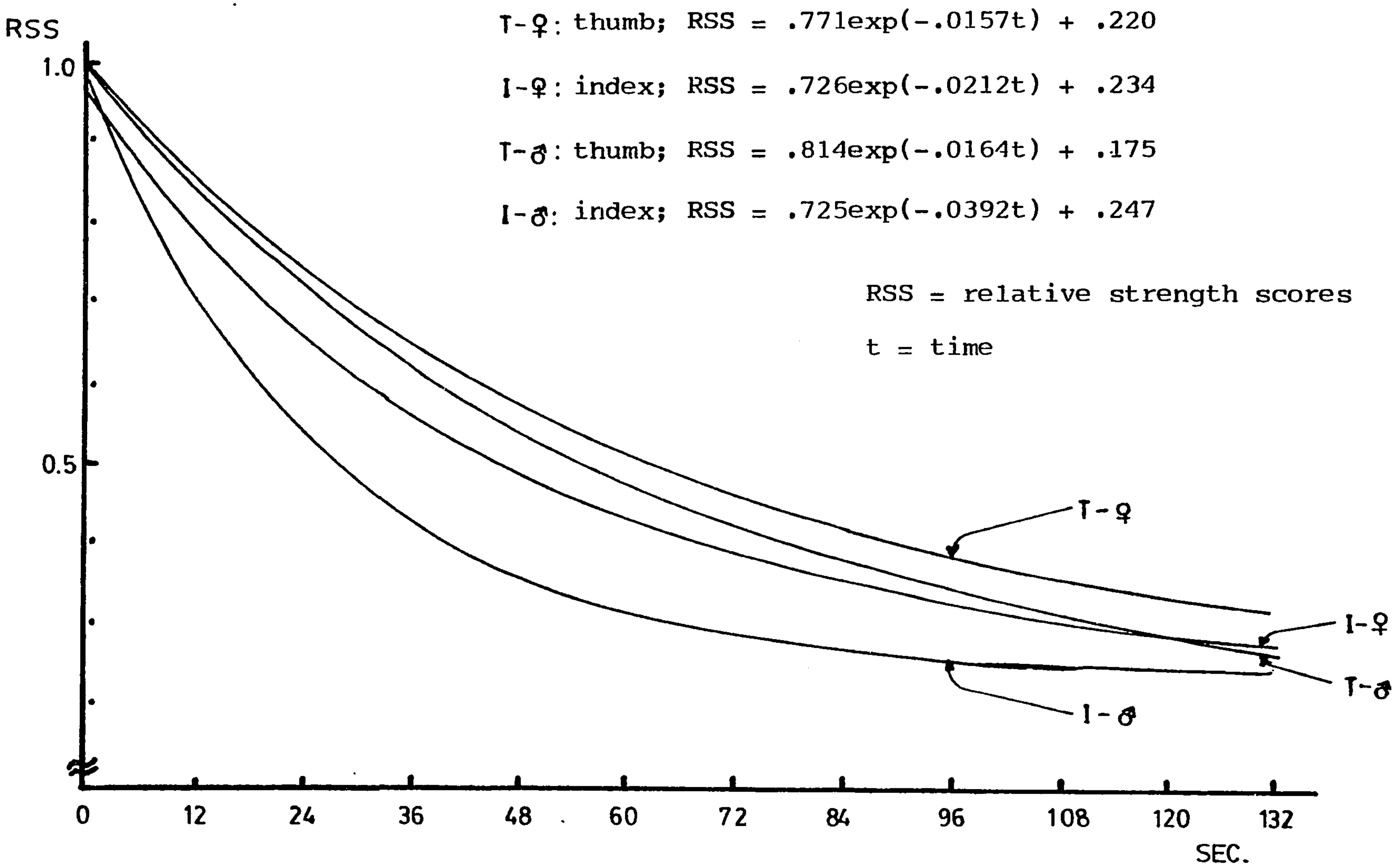


Figure 22: Thumb fatigue patterns for sustained exercise by gender and wrist orientation



T-♀: thumb; $RSS = .771\exp(-.0157t) + .220$

I-♀: index; $RSS = .726\exp(-.0212t) + .234$

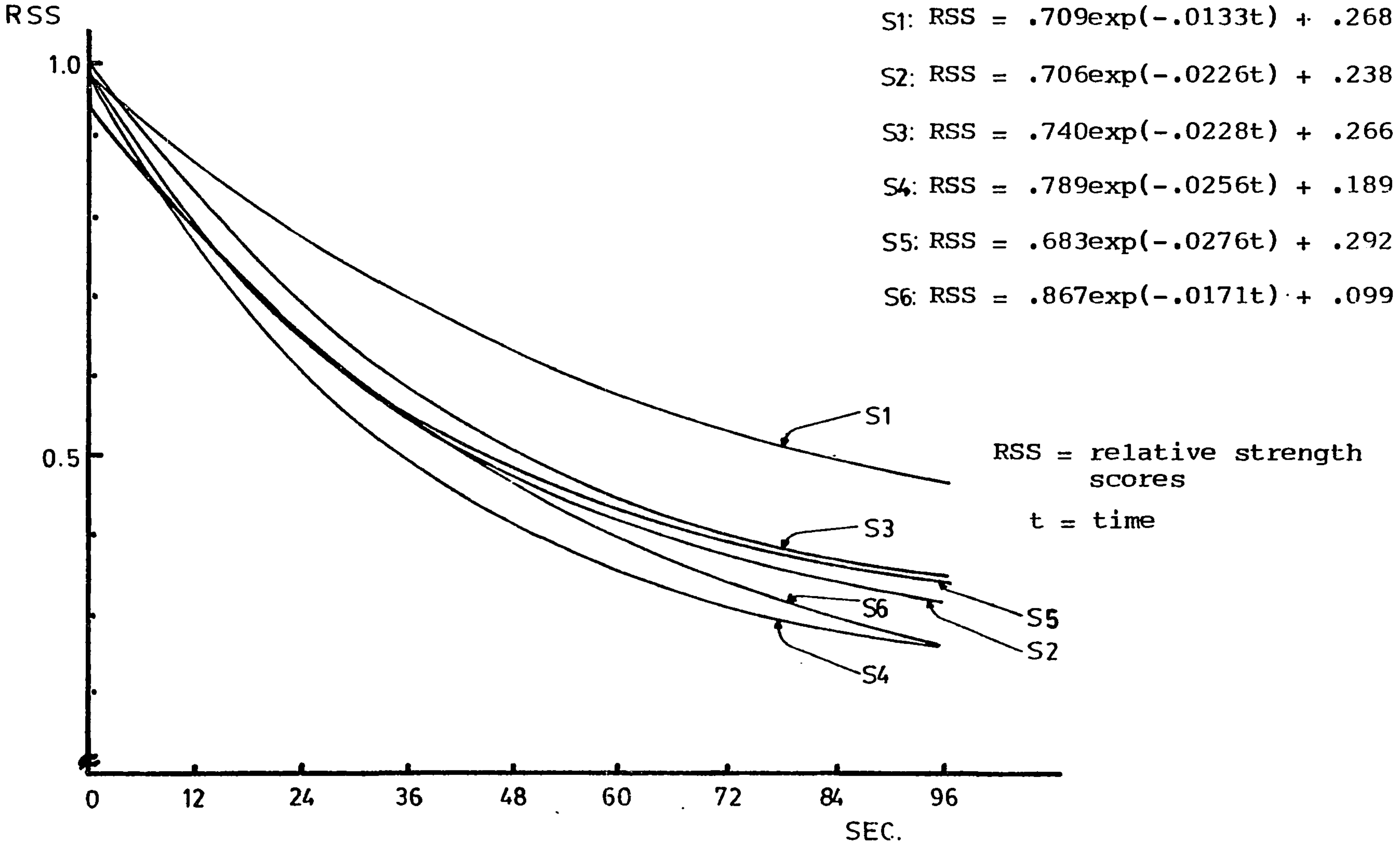
T-♂: thumb; $RSS = .814\exp(-.0164t) + .175$

I-♂: index; $RSS = .725\exp(-.0392t) + .247$

RSS = relative strength scores

t = time

Figure 23: Index and thumb fatigue patterns for sustained exercise by gender



S1: RSS = .709exp(-.0133t) + .268

S2: RSS = .706exp(-.0226t) + .238

S3: RSS = .740exp(-.0228t) + .266

S4: RSS = .789exp(-.0256t) + .189

S5: RSS = .683exp(-.0276t) + .292

S6: RSS = .867exp(-.0171t) + .099

RSS = relative strength scores

t = time

Figure 24: Index and thumb fatigue patterns for sustained exercise by subject

Table 18

Relative strength scores for rhythmic exercise

Time (sec)	Index finger observed	Index finger predicted	Thumb observed	Thumb predicted
0	1.000	.966	1.000	.988
32	.729	.783	.780	.790
64	.661	.662	.689	.676
96	.589	.582	.604	.612
128	.545	.528	.585	.575
160	.486	.493	.563	.554
192	.467	.469	.544	.542
224	.465	.454	.516	.535
256	.446	.443	.544	.531
288	.406	.436	.544	.529

An exponential regression analysis was made for the rhythmic exercise. Clarke and Gentry (1971) reported that the two components model, that is,

$$RSS = a \exp(-bt) + c \exp(-dt) + e$$

was adequate to decribe the fatigue patterns of rhythmic isometric exercise for elbow flexion. In their model, they claimed that the first component (a and b) operated predominantly during the first 30 seconds of exercise and disappeared thereafter while the other component (c and d) was dominant for the remaining exercise time. In contrast, Ordway et al. (1977) reported that a one-component model was sufficient to describe the fatigue patterns of elbow flexion and knee extension. The current study is in agreement with the latter. Therefore, the same model as used in the analysis of the continuous exercise was used for the regression analysis of the rhythmic exercise. The appropriate regression equations were as follows:

$$\text{Index: } RSS = 0.543\exp(-0.0128t) + 0.423$$

$$\text{Thumb: } RSS = 0.409\exp(-0.0147t) + 0.521.$$

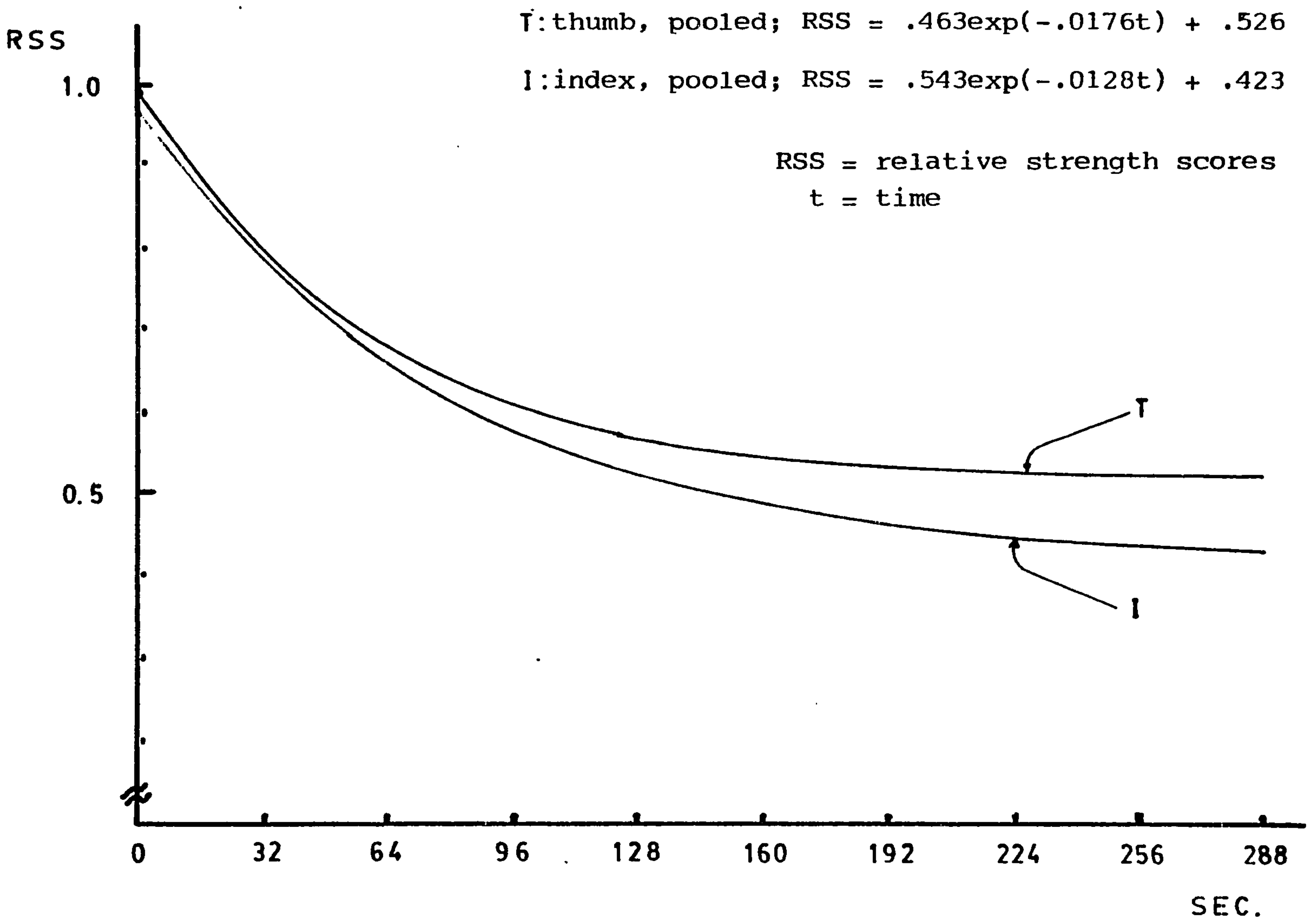
Figure 25 illustrates the fatigue patterns of the index and the thumb for the rhythmic exercise. As in the patterns for the sustained exercise, the index finger exhibited a greater strength decrement than did the thumb.

An ANOVA was performed on the relative strength scores of the rhythmic exercise. The main effects and significant interactions are presented in Table 19. The main effects of finger (F), time (T), and individual subject strength S(G) were significant whereas gender (G) and wrist orientation (W) were not significant.

Table 19

The main effects and significant interactifors on rhythmic exercise

Source	DF	SS	F	PR>F
Wrist orientation (W)	1	2.83	---	---
Finger (F)	1	4203.83	9.65	< .05
Time (T)	9	114887.96	201.12	< .001
FxT	9	168 9.67	9.42	< .001
Gender (G)	1	1753.26	---	---
FxTxG	9	486.09	2.79	< .05
Subject (S(G))	4	8576.83	30.44	< .001
WxS(G)	4	1280.83	4.54	< .01
FxS(G)	4	1742.20	6.18	< .001
WxFxS(G)	4	3137.07	11.13	< .001

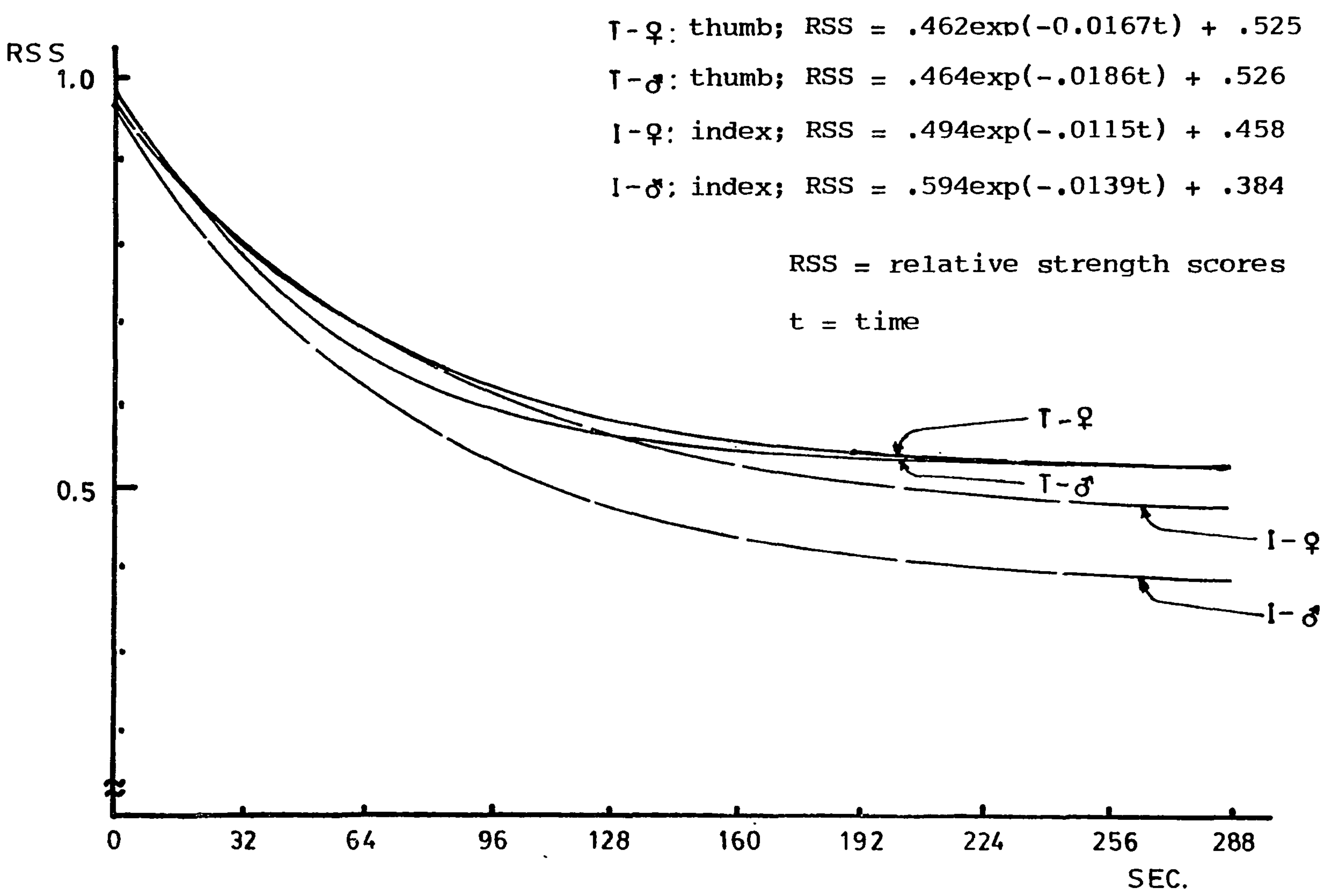


T: thumb, pooled; $RSS = .463\exp(-.0176t) + .526$

I: index, pooled; $RSS = .543\exp(-.0128t) + .423$

RSS = relative strength scores
t = time

Figure 25: Index and thumb fatigue patterns for rhythmic exercise



T-♀: thumb; RSS = .462exp(-0.0167t) + .525

T-♂: thumb; RSS = .464exp(-.0186t) + .526

I-♀: index; RSS = .494exp(-.0115t) + .458

I-♂: index; RSS = .594exp(-.0139t) + .384

RSS = relative strength scores

t = time

Figure 26: Index and thumb fatigue patterns for rhythmic exercise by gender

There was a significant decline in the strength of both fingers during the course of the exercise as indicated by the significant time (T) effect (see Figure 25). The significant effect of F resulted because the fatigue pattern of the index was faster than that of the thumb. This result indicated that during the course of the exercise, the fatigue rates were dependent upon the muscle groups involved. This result also agrees with Ordway et al. (1977) who studied the fatigue patterns of elbow flexion and knee extension and with Clarke and Gentry (1971) who investigated the fatigue rates of hand grip and elbow flexion.

The significant FxT interaction was because the index showed a greater strength decrease than did the thumb during the course of the exercise. The significant FxTxG interaction revealed that the index demonstrated a greater force decrease than did the thumb, although the male group had a greater rate of decline than the female group (see Figure 26).

Individual subject strength was significant. However, the mean values of the relative strength scores over the entire testing period by subject were unrelated to the subject's initial strength (see Table 20). Fatigue patterns of rhythmic exercise for each subject are illustrated in Figure 27.

The WxS(G) interaction was significant although the main effect of W was not significant. These results indi-

Table 20

Mean relative strength scores for rhythmic exercise by subject

Female group strong	 average	 weak	Male group strong	 average	 weak
0.639	0.688	0.556	0.577	0.620	0.591

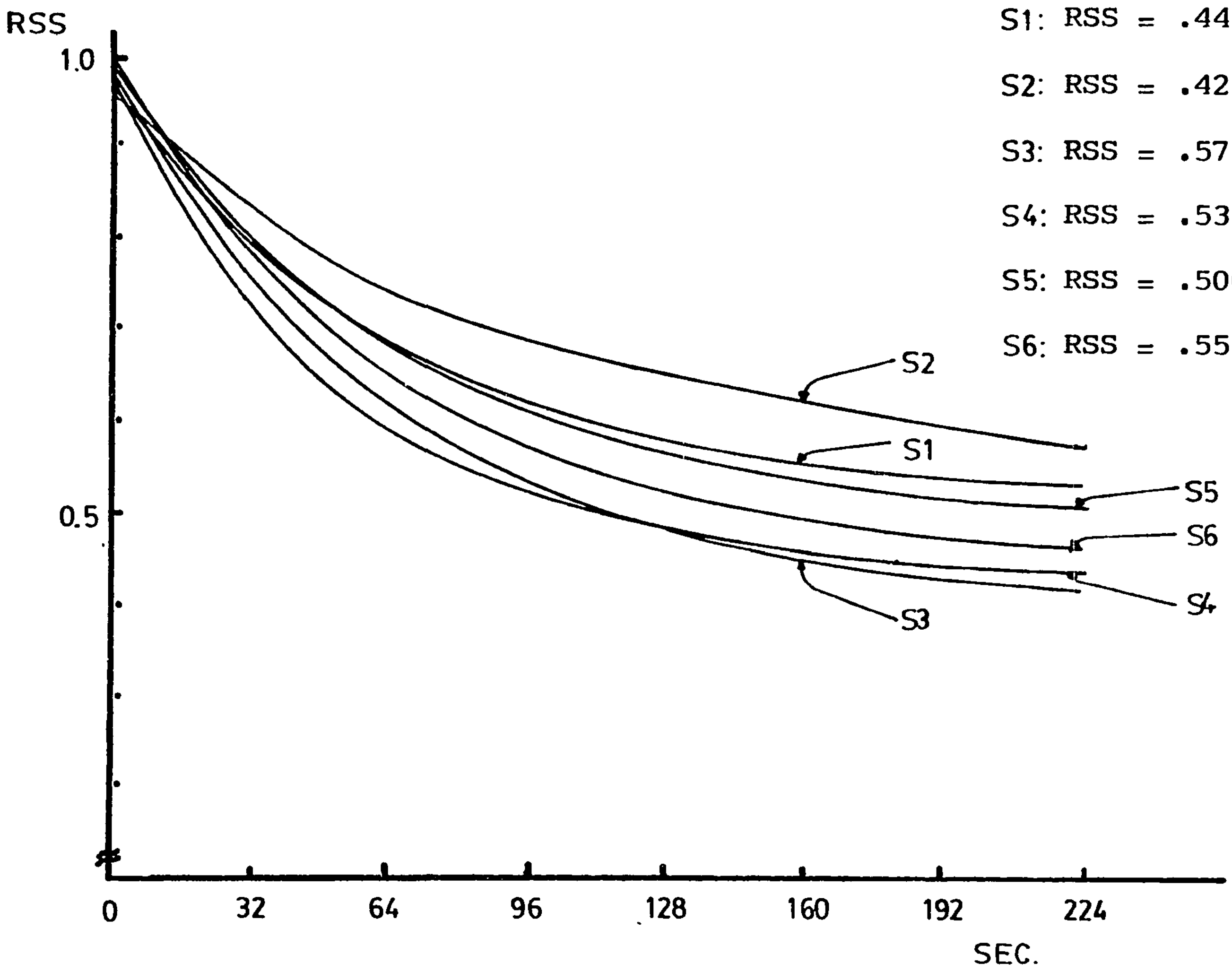
cated that the effect of wrist orientation on the fatigue patterns was not universal but was dependent upon the individual. In fact, two subjects demonstrated higher mean scores with the deviated wrist position than with the neutral wrist position (see Table 21 and Figure 28).

The significant FxS(G) and WxFxS(G) interactions indicated that the mean levels of the relative strength scores were affected by finger, subject, and wrist position. Graphical analysis of the mean values over these factors revealed that there was no general tendency for the subjects to maintain their initial strength.

Table 21

Mean relative strength scores for rhythmic exercise by subject and wrist orientation

	SUBJECTS					
Wrist	Strong		Average		Weak	
orientation	female	male	female	male	female	male
Neutral	0.615	0.563	0.692	0.636	0.584	0.577
Deviated	0.670	0.551	0.684	0.604	0.539	0.604



S1: $RSS = .446\exp(-.0158t) + .527$

S2: $RSS = .429\exp(-.00983t) + .529$

S3: $RSS = .578\exp(-.0149t) + .402$

S4: $RSS = .533\exp(-.0188t) + .437$

S5: $RSS = .500\exp(-.0145t) + .492$

S6: $RSS = .551\exp(-.0155t) + .449$

RSS = relative strength scores

t = time

Figure 27: Fatigue patterns for rhythmic exercise by subject

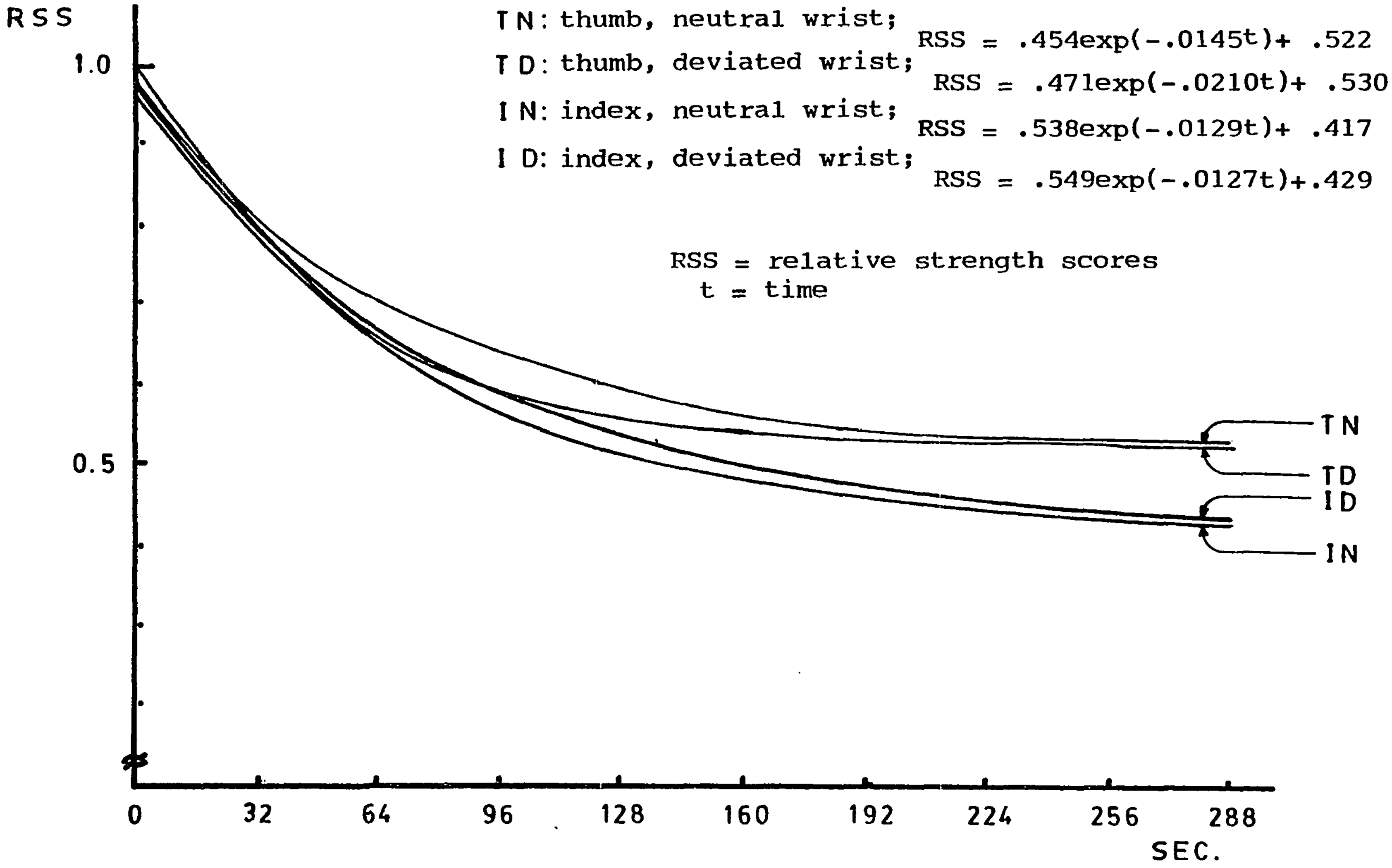


Figure 28: Index and thumb fatigue patterns for rhythmic exercise by wrist orientation

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

One should use considerable care in assigning either the index finger or the thumb as the trigger operator of a power tool. When the index finger was omitted from the gripping activity, the partial grip strength averaged 60% of the strength developed with the full grip. If the thumb was restricted in the gripping activity, the partial grip strength averaged 82% of the full grip strength.

Both wrist orientation and grip span were important factors in determining partial grip. With respect to wrist orientation, the force exerted with a deviated wrist averaged 89% of the force developed with the neutral wrist. Grip strength was also affected by the grip span. The medium span exhibited a greater strength than did the small and large spans which provided 93% and 86%, respectively, of the strength exerted by the medium span.

The subjects were selected to represent the 6-10th, 44-55th and 91-95th population percentiles based on full grip strength. In terms of strength, the rank order of the subjects in the full grip strength test was not the same as the order for the partial grip strength tests. For example, the average-female subject was stronger than the strong-female subject in the thumb operation grip test. Also, the weak-female subject was stronger than the average-female subject in the index operation grip test. The mean grip strength for the female group was 58% of the strength for the male group, which was 35.59 kg. A tool designer should take these strength differences into consideration when assigning the trigger function.

The index finger exerted the greatest force at the midposition. The close and far positions provided 78% and 75%, respectively, of the strength developed with the midposition (13.58 kg).

The wrist orientation did not affect the strength performance of the index finger. The finger flexor tendons spread out in a fan shape in the palm region. Therefore, the index flexors are radially deviated when the wrist is in the neutral position. They are straightened when the wrist is ulnarly deviated. Thus, the position of the deviated wrist does not hamper index performance significantly. It was concluded, therefore, that the index finger exerts the greatest force when its PIP joint flexes 90 degrees and exerts force toward the thenar eminence.

Unlike the fingers, the thumb has a wide range of motion. It can adduct, abduct, oppose, flex, and extend. Three force directions were selected and investigated in this study. The greatest force exertion occurred in the DOWN direction. The mean for the OPPOSITION and INWARD directions were 88% and 71%, respectively, of the strength developed with the DOWN direction (6.75 kg). Among the positions in the DOWN direction, the midposition exhibited the greatest strength with a mean of 7.61 kg, followed by the high position (7.48 kg) and the low position (5.17 kg). It was concluded that the thumb exerts the greatest force when it is placed at the middle or higher position with a neutral wrist and exerts force downward.

Comparison of the best positions of the index and thumb in strength revealed that on the average, thumb strength was only 56% of the index strength (13.59 kg). The mean index strength for the female group using a deviated wrist was 73% of the strength developed with a neutral wrist (10.24 kg). For the male group, the mean index strength with a deviated wrist was 87% of the strength exerted with a neutral wrist (17.75 kg). The mean thumb strength for the female group using a deviated wrist was 54% of the strength developed with a neutral wrist (9.59 kg). For the male group, the mean thumb strength with a deviated wrist was 84% of the strength devloped with a neutral wrist (8.49 kg).

A larger difference in strength between the two fingers was found in the male group than in the female group. The thumb strength within the female group was 70% of the index strength (7.39 kg) while the thumb strength within the male group was only 47% of the index strength (16.56 kg).

Muscular endurance of the index and thumb was investigated using continuous isometric exercise and evaluated by the ability of muscles to maintain the initial strength over the sustained time period. Negative exponential regression equations were adequate to describe the relative strength scores of the fatigue patterns as follows:

$RSS = 0.0769\exp(-0.0305t) + 0.247$ for the index finger with a neutral wrist across all times and subjects,

$RSS = 0.0699\exp(-0.0282t) + 0.258$ for the index finger with a deviated wrist across all times and subjects,

$RSS = 0.863\exp(-0.0126t) + 0.146$ for the thumb with a neutral wrist across all times and subjects,

$RSS = 0.748\exp(-0.0223t) + 0.241$ for the thumb with a deviated wrist across all times and subjects.

Details of the coefficients of the equations for other trials are listed in Appendix F.

Both the index and the thumb underwent a strength decline during the course of the sustained isometric exercise. The index had a greater rate of decrement than did the thumb. After the two-minute exercise, the thumb maintained, on the average, 43% of its initial strength while the index exerted only 28% of its initial strength. This result was more pronounced in the performance of the male group than that of the female group.

Through the ANOVA, it was learned that there was no significant difference in the fatigue patterns for the two genders. However, the effect of gender interacted with that of wrist position. The deviated wrist adversely affected the performance of the index finger more for the female group than for the male group while it affected thumb performance more for the male group than for the female group.

The mean levels of the relative strength score in the sustained exercise varied from one subject to another. This study failed to substantiate previous findings which 1) that stronger subjects maintained greater strength over the entire period of exercise (Caldwell, 1964) and 2) that there was no relationship between individual subject strength and the fatigue patterns (Rohmert, 1960).

Because many tools use repeated on/off operation of the trigger switch, the strength parameters of the index and the thumb were evaluated using rhythmic isometric exercise. Negative exponential regression analysis was used for these data. In contrast to the two-component model as proposed by Clake and Gentry (1971), a one-component model was sufficient to describe the relative strength scores as follows:

$RSS = 0.538\exp(-0.0129t) + 0.417$ for the index finger a neutral wrist across all times and subjects,

$RSS = 0.549\exp(-0.0127t) + 0.429$ for the index finger a deviated wrist across all times and subjects,

$RSS = o.454\exp(-0.0145t) + 0.522$ for the thumb with a neutral wrist across all times and subjects,

$RSS = 0.471\exp(-0.0210t) + 0.530$ for the thumb with a deviated wrist across all times and subjects.

The coefficients of the equations for other trials are listed in Appendix G.

Both the index and the thumb demonstrated a strength decrement during the course of the isometric exercises. The index showed a greater rate of strength decrease than did the thumb and the male group showed a greater rate of strength decrease than did the female group. After the six-minute exercise, the index maintained, on the average, only 40% of its initial strength whereas the thumb maintained 53% of its initial strength. With continuous exercise, both the index finger and the thumb showed more fatigue over time than they did in rhythmic exercise (see Figure 29).

The position of the wrist did not affect performance in the rhythmic exercise. However, the significant interaction of WxS(G) indicated that the deviated wrist did affect the performance of some subjects. In the continuous exercise it had an adverse effect. This was not true for the rhythmic exercise. In fact, some subjects maintained greater index strength with a deviated wrist than with a neutral wrist. However, the deviated wrist adversely affected thumb performance in the rhythmic exercise for all subjects but at a level which was not statistically significant.

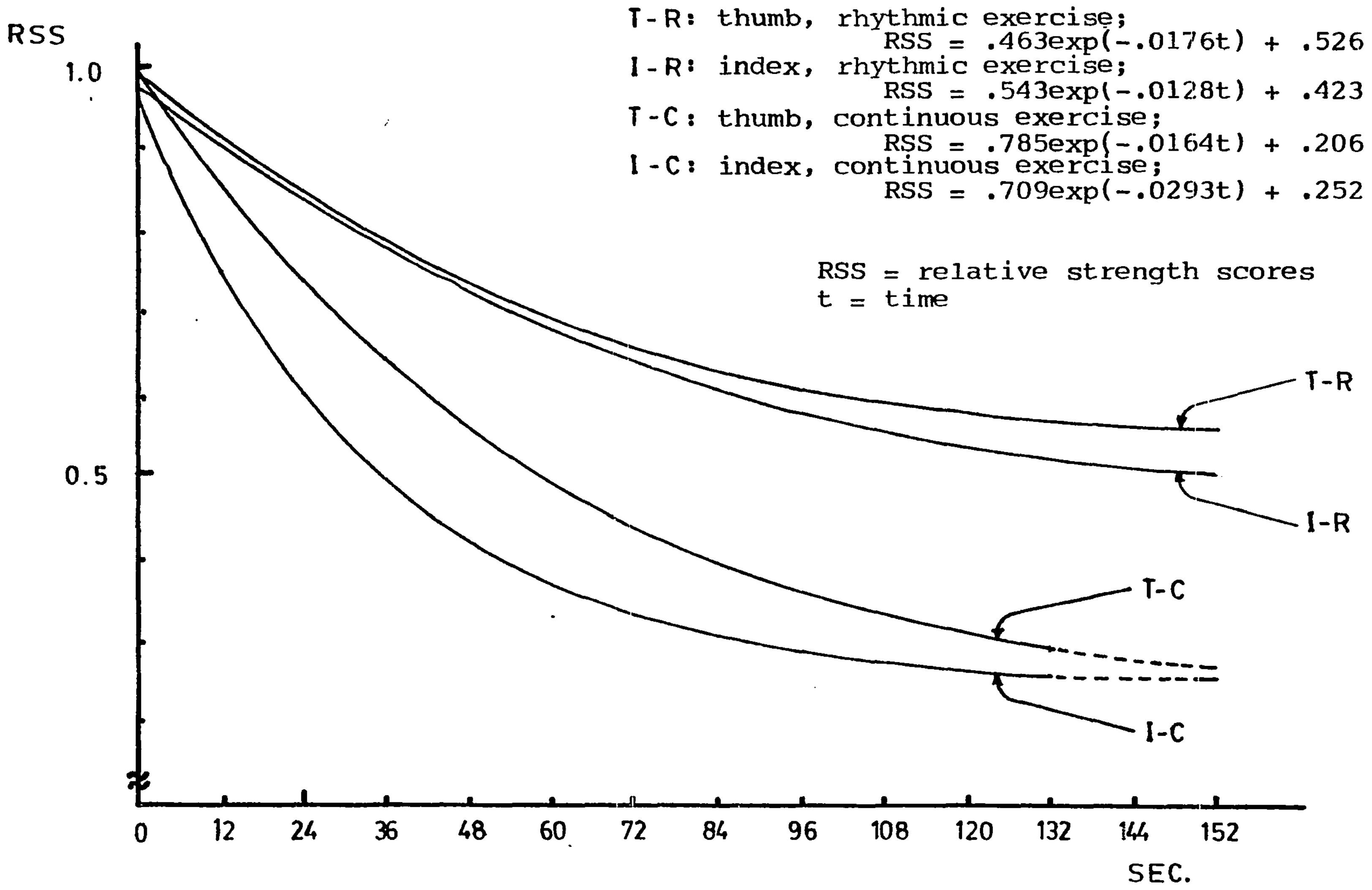


Figure 29: Index and thumb fatigue patterns for sustained and rhythmic exercises

5.2 RECOMMENDATIONS

In tool design, both trigger and grip design deserve more attention. Before the index or thumb is assigned as the trigger operator of a portable power tool, one should consider the large reduction in grip strength. The partial grip is the only available fixture for the portable tool. Therefore, the holding capability of the partial grip should be considered in the design of the grip handle. The size of the grip handle also affects the strength of the partial grip. Since the partial grip can exert its maximal strength at the medium or larger span, the handle size should be designed to accommodate these spans.

The findings of previous studies and of this study have shown the effect of wrist orientation on grip strength. Whenever the wrist position is deviated in any direction from the neutral position, grip strength is decreased. It is recommended that the handle of any tool be designed to avoid the deviated position of the wrist. This requires that the weight of the tool be evenly distributed so that rotational torque due to unbalanced weight is minimized.

Insofar as individual finger strength is concerned, the index finger is nearly twice as strong as the thumb. If a tool requires a "high force" trigger, the index finger should be used for the trigger operation. When implementing this recommendation, one should, however, note that the index finger is inferior to the thumb in muscular endurance.

The index finger fatigues much faster than the thumb in both the sustained isometric and rhythmic isometric exercises. The duration of the high trigger force should be kept to a minimum or through the implementation of a secondary locking switch. The index finger is in the best position to exert force when it is placed in the midposition with the PIP joint flexed at 90 degrees or less. The installation of the trigger should accommodate the index in this midposition.

In general, a high force requirement is inadvisible in any kind of tool design because it invites acute muscular fatigue and tends to cause chronic tenditis and carpal tunnel syndromes. If reduction of the required force is technically feasible, the thumb should be used to operate the trigger. Although the thumb is inferior to the index in strength, it has a much greater ability to maintain its initial strength for both continous isometric and rhythmic isometric exercise. Based on the partial grip strength, the thumb should be used as the trigger operator because the thumb operation grip allowed the hand to exert more force than did the index operation grip. Therefore, the thumb is recommended rather than the index finger as a trigger operator.

The thumb can exert the greatest force in the vertical direction with the DIP flexed about 90 degrees and its proximal phalanx comfortably extended. The deviated wrist position adversely affects thumb performance not only for instant strength but also sustained strength. The location of the trigger switch should not introduce a deviated wrist position when the thumb is actuating the switch. If the vertical direction of force exertion of the thumb is not technically feasible, the recommended alternative is opposition toward the palm. It is recommended that the thumb not exert force in the sagittal plane with extended phalanges inward towards the hand. Here, the thumb exerts its lowest force compared with other force directions.

For tool design in general, it is recommended that the duration of single actuation of the trigger be kept to a minimum. Whether the index or the thumb is used as the trigger operator, continuous force exertion causes much faster fatigue than does intermittent exertion.

This study was limited to a fixed size testing apparatus (test handle and ring). Recommendations for further research include (a) anthropometric measurements of phalangeal sizes and biomechanical analysis to clarify the positional efficiency for the fingers to exert force, (b) anthropometric measurements and biomechanical analysis to examine the functional relationship between the amount of force applied to the handle and the amount of wrist deviation, and (c) exploration of tactile sensors in relation to finger manipulaton of a trigger switch. This study determined that the midposition yielded superior strength for both the partial grip and index finger performance but failed to provide further explanation for the difference between the large and small positions. It would be useful if further information were available to the tool designer concerning the relationship between grip handle in thickness and width and individual hand and finger length.

An investigation which biomechanically evaluated the efficient use of the hand and fingers has been previously examined by very few researchers. The text by Maul and Solf (1969) and the article by Bullinger and Solf (1976) cover recommendations for tools and control devices. For example, a convex grip handle shape was recommended so that the index, ring, and little fingers could have more contact area on the surface of the handle compared with a conventional handle. However, this approach appears impractical because of the variation in individual hand size and phalangeal length. It is impossible and uneconomical to make a tool which fits all individuals. However, this approach would be scientifically useful in developing a rule of thumb for tool engineers and others to further improve the quality of usefulness of the tool.

This study found that ulnar deviation of the wrist adversely affected the thumb and partial grip strength. However, the index finger strength was relatively free from this effect. Biomechanical analysis in conjunction with an appropriate experimental measure would be useful to explain the difference in the deviated wrist effect between the thumb and grip and the index performances.

Since the arm, hand, and fingers compose the fixture of a portable tool, further study of the qualitative aspects of hand/finger performance would contribute to additional improvements in tool design. Further studies should include hand, finger and arm coordination, eye-hand coordination, tactile sensor feedback, and psychomotor skills.

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Appendix A

FORCE REQUIREMENT TO TRIGGER POWER TOOLS

Table A-1 presents the force requirements for triggering power tools which are currently available in the market. Most of the tools used for this review were electrical drills.

The required forces to trigger ranged from 0.57 kg to 1.32 kg.

TABLE A-1. FORCES REQUIRED TO TRIGGER POWER TOOLS IN KILOGRAMS

Brands	Tool types	Forces onset	Forces end	Forces range
A	3/8" drill, Model A variable speed	1.22	2.13	0.91
	3/8" drill, Model B variable speed	0.91	1.70	0.79
B	1/2" drill, variable speed	1.13	1.70	0.57
	1/4" drill, variable speed	0.91	1.81	0.90
	3/8" drill, variable speed	3.18	4.50	1.32
	Circular saw single speed	2.49	--	--
C	1/4" drill, variable speed	1.36	2.04	0.68
	3/8" drill, variable speed	1.36	2.04	0.68
D	1/4" drill, single speed	3.18	--	--

Appendix B

FULL GRIP STRENGTH DISTRIBUTION OF A STUDENT-AGED POPULATION

The term "full grip strength" means the grip strength developed with the MVC effort where all digits and a hand were allowed to fully exert a force. The grip strength was measured at the medium grip span, relative to a subject's hand size, in a neutral wrist position for a five second period. The mean value of the middle three second data points was used to describe the grip strength.

TABLE B-1. FULL GRIP STRENGTH DISTRIBUTION OF FEMALE STUDENT-AGED POPULATION IN KILOGRAM

Strength	Frequency	Cumulative percentage	Strength	Frequency	Cumulative percentage
18.37	1	2	33.79	1	52
19.05	1	3	34.02	2	55
19.96	1	5	34.25	1	56
22.23	1	6	34.93	1	58
23.81	1	8	35.38	2	61
24.04	1	9	35.83	3	66
25.86	2	13	36.74	1	67
26.31	1	14	38.10	2	70
26.99	2	17	38.56	1	72
27.22	1	19	39.01	3	77
27.67	1	20	39.46	2	80
28.12	1	22	39.92	1	81
28.58	2	25	40.37	2	84
29.03	2	28	40.82	1	86
29.26	1	30	41.28	1	88
29.94	1	31	42.19	2	91
30.39	2	34	42.64	2	94
30.85	2	38	43.09	1	95
31.30	2	41	44.45	1	97
32.21	2	44	48.54	1	98
33.11	2	47	49.90	1	100
33.57	2	50			

Mean	33.669	Std. err.	0.862	Median	33.680
Mode	35.834	Std. dev.	6.893	Variance	47.507
Kurtosis	-0.260	Skewness	-0.040	Range	31.525
Minimum	18.371	Maximum	49.896		

Subjects measured: 64

TABLE B-2. FULL GRIP STRENGTH DISTRIBUTION OF MALE STUDENT-AGED POPULATION IN KILOGRAM

Strength	Frequency	Cumulative percentage	Strength	Frequency	Cumulative percentage
28.12	1	1	54.89	2	49
28.58	1	1	55.11	1	49
32.66	1	2	55.34	2	51
34.02	1	3	55.79	2	52
35.83	2	4	56.25	3	54
36.29	2	5	56.70	4	57
37.65	2	7	57.15	1	57
38.56	1	7	57.61	3	59
39.01	2	9	58.06	5	63
39.46	1	9	58.51	1	63
39.92	2	11	59.42	2	64
40.82	1	11	59.88	5	68
41.28	2	13	60.33	1	68
42.19	2	14	61.24	1	69
42.64	1	14	62.60	2	70
43.55	2	16	63.05	1	71
44.45	2	17	63.50	1	72
44.68	1	18	63.96	3	74
44.91	1	18	64.41	6	78
45.36	1	19	65.32	3	80
45.81	1	20	65.77	2	81
46.27	3	22	66.23	3	83
46.49	1	22	67.59	1	84
46.72	1	23	68.49	2	85
47.17	2	24	68.72	1	86
47.63	3	26	68.95	2	87
48.08	4	29	69.40	1	88
48.99	1	30	69.85	2	89
49.22	1	30	70.76	4	91
49.44	1	31	70.99	1	92
50.35	2	32	71.22	1	93
50.80	1	33	71.69	1	93
51.26	2	34	73.48	2	95
51.71	1	35	74.39	1	95
52.16	3	37	74.84	1	96
52.61	4	39	75.30	2	97
53.07	3	41	76.66	1	98
53.52	4	44	77.34	1	99
53.98	3	46	77.57	1	99
54.43	2	47	78.93	1	100

Mean	55.552	Std. err.	0.910	Median	55.339
Mode	64.411	Std. dev.	11.224	Variance	125.973
Kurtosis	-0.548	Skewness	-0.081	Range	50.803
Minimum	28.123	Maximum	78.926		

Subjects measured: 152

Appendix C

PARTIAL GRIP STRENGTH DATA

The term "partial grip strength" means the grip strength developed by the MVC effort where the grip was restricted in the use of either the thumb or the index finger.

TABLE C-1. PARTIAL GRIP STRENGTH DATA IN KILOGRAM

	Subjects					
Code	S1	S2	S3	S4	S5	S6
000	22.96	31.35	25.95	46.16	47.75	36.98
	22.30	27.84	15.13	45.36	44.81	34.99
001	23.96	23.28	14.67	44.24	26.80	27.18
	19.19	19.76	18.61	38.94	25.17	27.20
010	29.20	30.37	24.82	54.56	52.50	34.04
	27.76	29.38	23.47	52.50	46.04	35.49
011	20.38	18.62	19.38	47.34	32.41	26.92
	23.95	18.90	19.23	35.71	29.08	28.52
020	24.25	22.39	24.37	51.50	44.82	27.57
	26.05	21.91	18.14	52.81	38.22	23.88
021	19.71	19.51	17.76	48.87	27.13	24.86
	19.93	18.77	17.27	39.11	23.02	20.46
100	17.49	14.37	19.36	42.48	29.67	22.74
	17.42	22.98	18.23	41.36	27.09	23.17
101	17.01	16.17	11.25	29.07	29.08	19.01
	16.95	17.13	12.38	35.91	24.78	17.60
110	18.56	25.77	25.49	46.32	43.65	32.87
	24.31	18.25	19.77	57.53	40.09	29.21
111	22.68	18.05	19.23	46.73	33.63	19.42
	18.34	19.41	17.51	42.03	30.09	22.58
120	15.53	26.59	22.29	54.75	36.06	30.83
	19.94	22.10	17.18	55.34	36.86	33.48
121	20.14	19.64	19.46	46.97	29.70	25.85
	21.44	17.85	17.87	40.07	25.82	18.61

Experimental conditions are shown in the three digit code as follows:

(1) the hundredth digit···the wrist position
0 = the neutral wrist
1 = the deviated wrist
(2) the tenth digit······ the grip span
0 = small
1 = medium
2 = large
(3) the first digit····· the grip type
0 = the thumb operation grip
1 = the index operation grip

Appendix D

INDEX FINGER STRENGTH DATA

TABLE D-1. INDEX FINGER STRENGTH DATA (KG)

	Subjects					
Codes	S1	S2	S3	S4	S5	S6
00	10.76	8.30	8.17	11.77	17.60	8.76
	10.02	7.71	8.97	11.00	20.00	7.74
01	13.30	11.77	11.27	25.69	19.91	11.44
	13.92	11.91	11.25	17.79	19.35	12.31
02	8.08	11.60	6.97	15.00	14.87	8.11
	8.38	13.55	8.11	15.70	12.89	8.78
10	6.36	9.00	7.50	19.39	10.92	10.58
	7.26	7.38	7.96	15.41	14.91	7.87
11	11.45	8.72	6.50	21.36	11.33	10.29
	12.12	8.77	6.20	19.22	15.10	9.91
12	9.44	9.79	5.82	17.33	11.39	5.65
	8.08	7.59	7.28	14.93	11.25	5.56

Experimental conditions are shown in the two digit codes, defined as follows:

(1) the tenth digit ······ wrist position
0 = the neutral wrist
1 = the deviated wrist

(2) the first digit ······ index finger position
0 = the small span
1 = the medium span
2 = the large span.

Appendix E

THUMB STRENGTH DATA

TABLE E-1. THUMB STRENGTH DATA IN KILOGRAMS

	Subjects					
Codes	S1	S2	S3	S4	S5	S6
00	3.02	3.86	2.91	8.34	5.80	3.06
	4.49	4.50	2.90	7.43	4.43	3.06
01	4.30	3.51	3.73	6.57	6.50	3.54
	4.45	4.28	4.32	5.94	5.56	3.08
02	5.20	3.87	4.12	7.98	6.11	3.65
	5.60	3.84	4.95	8.42	7.41	3.85
03	7.02	5.26	4.13	11.08	19.61	4.45
	6.26	6.55	4.17	11.32	9.60	4.91
04	14.09	9.78	6.79	11.42	5.86	4.82
	11.86	6.99	8.05	9.24	14.80	4.78
05	5.28	4.41	2.44	12.95	7.77	2.84
	5.61	3.84	3.32	6.81	6.79	3.64
06	4.04	7.22	4.14	9.59	8.56	3.30
	3.85	7.07	4.17	13.08	6.97	4.26
07	6.30	6.31	5.72	11.23	8.39	3.84
	5.25	6.16	4.65	8.75	10.75	3.37
10	3.00	3.80	3.65	8.31	6.22	2.76
	3.78	3.87	3.21	6.45	5.39	3.02
11	4.41	4.22	2.90	7.27	5.03	3.40
	3.97	3.31	3.22	8.30	5.95	3.85
12	3.96	4.55	3.51	6.91	7.15	3.47
	4.94	3.53	4.28	6.83	8.82	4.25
13	7.09	6.04	5.15	9.29	10.23	5.52
	5.63	5.16	4.92	10.32	10.88	4.80
14	5.18	4.87	5.15	8.93	7.99	5.10
	6.51	4.84	4.57	8.30	8.25	4.46
15	5.57	4.45	2.43	6.68	5.54	3.96
	4.89	3.68	2.27	8.75	5.81	4.35
16	4.75	5.42	4.08	8.50	6.68	3.21
	4.21	5.49	3.81	9.25	8.13	3.08
17	3.55	5.69	6.29	8.09	5.88	2.84
	5.30	5.41	3.89	6.83	6.11	3.92

Experimental conditions are shown in two digit codes, defined as follows:

(1) the tenth digit-- wrist position
0 = neutral wrist
1 = deviated wrist

(2) the first digit-- thumb position and force direction

0 = outside-horizontal
1 = middle-horizontal
2 = inside-horizontal
3 = high-vertical
4 = middle-vertical
5 = low-vertical
6 = medium high-opposition
7 = middle-opposition

For details of position definitions, see Subsection 3.3.4.

Appendix F

REGRESSION EQUATIONS FOR SUSTAINED ISOMETRIC EXERCISE

Regression equations for sustained isometric exercises are presented in this appendix. Table F-1 includes the index fatigue patterns resulting from the sustained isometric exercise. The thumb fatigue patterns are shown in Table F-2.

Table F-1

Regression Equations for the Index Fatigue Patterns of the Sustained Exercise

Subject or Group	Wrist position	Regression equation	Mean initial strength in Kg.
S1	neutral(N)	RSS = 0.615exp(-0.0281t) + 0.359	13.17
S2	N	RSS = 0.807exp(-0.0195t) + 0.141	11.52
S3	N	RSS = 0.741exp(-0.0264t) + 0.261	9.27
S4	N	RSS = 0.787exp(-0.0305t) + 0.178	20.34
S5	N	RSS = 0.681exp(-0.0838t) + 0.321	14.58
S6	N	RSS = 0.799exp(-0.0311t) + 0.184	10.02
female S's	N	RSS = 0.741exp(-0.0234t) + 0.235	11.32
male S's	N	RSS = 0.722exp(-0.0400t) + 0.244	14.98
all S's	N	RSS = 0.719exp(-0.0305t) + 0.247	13.15
S1	deviated(D)	RSS = 0.671exp(-0.0229t) + 0.325	10.26
S2	D	RSS = 1.62 exp(-0.0034t) + 0.824	10.59
S3	D	RSS = 0.753exp(-0.0285t) + 0.274	8.32
S4	D	RSS = 0.773exp(-0.0343t) + 0.184	19.71
S5	D	RSS = 0.686exp(-0.0280t) + 0.280	12.05
S6	D	RSS = 0.757exp(-0.0506t) + 0.248	9.49
female S's	D	RSS = 0.715exp(-0.0191t) + 0.228	9.72
male S's	D	RSS = 0.728exp(-0.0387t) + 0.252	13.75
all S's	D	RSS = 0.699exp(-0.0282t) + 0.258	11.74

RSS = relative strength score and t = time in seconds.

Table F-1 (continued)

Subject or Group	Wrist position	Regression equation	Mean initial strength in Kg.
S1	N & D	RSS = 0.676exp(-0.0226t) + 0.303	11.71
S2	N & D	RSS = 0.779exp(-0.0135t) + 0.096	11.06
S3	N & D	RSS = 0.747exp(-0.0245t) + 0.268	8.80
S4	N & D	RSS = 0.779exp(-0.0322t) + 0.181	20.03
S5	N & D	RSS = 0.646exp(-0.0442t) + 0.312	11.32
S6	N & D	RSS = 0.773exp(-0.0391t) + 0.218	9.76
female S's	N & D	RSS = 0.726exp(-0.0212t) + 0.234	10.52
male S's	N & D	RSS = 0.725exp(-0.0392t) + 0.247	14.37
all S's	N & D	RSS = 0.708exp(-0.0293t) + 0.252	12.44

N & D = neutral and deviated wrist positions are pooled,
RSS = relative strength score, and
t = time in seconds.

Table F-2

Regression Equations for the Thumb Fatigue Patterns of the Sustained Exercise

Subject or Group	Wrist position	Regression equation	Mean initial strength in Kg.
S1	neutral(N)	$RSS = -0.626\exp(0.0078t) + 1.588$	7.49
S2	N	$RSS = 0.751\exp(-0.0208t) + 0.224$	5.46
S3	N	$RSS = 0.837\exp(-0.0118t) + 0.161$	5.28
S4	N	$RSS = 1.246\exp(-0.0075t) - 0.253$	11.81
S5	N	$RSS = 1.141\exp(-0.0073t) - 0.122$	7.29
S6	N	$RSS = -2.841\exp(1.973t) + 3.786$	5.75
female S's	N	$RSS = 0.759\exp(-0.0160t) + 0.238$	6.08
male S's	N	$RSS = 1.140\exp(0.0081t) - 0.122$	8.28
all S's	N	$RSS = 0.863\exp(-0.0126t) + 0.146$	7.18
S1	deviated(D)	$RSS = -0.635\exp(0.0065t) + 1.637$	6.70
S2	D	$RSS = 0.720\exp(-0.0375t) + 0.309$	4.30
S3	D	$RSS = 0.750\exp(-0.0375t) + 0.263$	5.33
S4	D	$RSS = 0.811\exp(-0.0366t) + 0.231$	9.56
S5	D	$RSS = 0.795\exp(-0.0341t) + 0.265$	6.54
S6	D	$RSS = 0.500\exp(-0.0586t) + 0.477$	6.47
female S's	D	$RSS = 0.789\exp(-0.0168t) + 0.207$	5.44
male S's	D	$RSS = 0.737\exp(-0.0299t) + 0.257$	7.52
all S's	D	$RSS = 0.748\exp(-0.0223t) + 0.241$	6.48

RSS = relative strength score and t = time in seconds.

Table F-2 (continued)

Subject or Group	Wrist position	Regression equation	Mean initial strength in Kg.
S1	N & D	$RSS = 11.329\exp(-0.0004t) - 10.388$	7.10
S2	N & D	$RSS = 0.715\exp(-0.0288t) + 0.284$	4.88
S3	N & D	$RSS = 0.752\exp(-0.0184t) + 0.249$	5.31
S4	N & D	$RSS = 0.820\exp(-0.0202t) + 0.182$	10.69
S5	N & D	$RSS = 0.779\exp(-0.0195t) + 0.246$	6.92
S6	N & D	$RSS = -1.599\exp(0.0034t) + 2.502$	6.11
female S's	N & D	$RSS = 0.771\exp(-0.0157t) + 0.220$	5.76
male S's	N & D	$RSS = 0.814\exp(-0.0164t) + 0.174$	7.90
all S's	N & D	$RSS = 0.285\exp(-0.0164t) + 0.206$	6.83

N & D = neutral and deviated wrist positions are pooled,
RSS = relative strength score, and
t = time in seconds.

Appendix G

REGRESSION EQUATIONS FOR RHYTHMIC ISOMETRIC EXERCISE

Regression equations for the rhythmic isometric exercises are presented in this appendix. The index fatigue patterns are shown in Table G-1. Table G-2 includes the thumb fatigue patterns resulting from the rhythmic isometric exercise.

Table G-1

Regression Equations for the Index Fatigue Patterns of the Rhythmic Exercise

Subject or Group	Wrist position	Regression equation	Mean initial strength in Kg.
S1	neutral(N)	RSS = 0.470exp(-0.0111t) + 0.457	10.86
S2	N	RSS = 0.460exp(-0.0060t) + 0.463	11.44
S3	N	RSS = 0.599exp(-0.0199t) + 0.369	9.89
S4	N	RSS = 0.661exp(-0.0134t) + 0.299	18.39
S5	N	RSS = 0.515exp(-0.0132t) + 0.440	15.26
S6	N	RSS = 0.597exp(-0.0129t) + 0.416	9.41
female S's	N	RSS = 0.485exp(-0.0125t) + 0.449	10.73
male S's	N	RSS = 0.591exp(-0.0132t) + 0.385	14.35
all S's	N	RSS = 0.538exp(-0.0129t) + 0.417	12.54
S1	deviated(D)	RSS = 0.486exp(-0.0073t) + 0.502	11.58
S2	D	RSS = 0.440exp(-0.0114t) + 0.519	10.58
S3	D	RSS = 0.616exp(-0.0122t) + 0.353	9.62
S4	D	RSS = 0.630exp(-0.0184t) + 0.343	19.68
S5	D	RSS = 0.511exp(-0.0143t) + 0.472	14.23
S6	D	RSS = 0.668exp(-0.0121t) + 0.330	9.69
female S's	D	RSS = 0.506exp(-0.0105t) + 0.466	10.59
male S's	D	RSS = 0.599exp(-0.0145t) + 0.383	14.53
all S's	D	RSS = 0.549exp(-0.0127t) + 0.428	12.56

RSS = relative strength score and t = time in seconds.

Table G-1 (continued)

Subject or Group	Wrist position	Regression equation	Mean initial strength in Kg.
S1	N & D	RSS = 0.471exp(-0.0092t) + 0.487	11.22
S2	N & D	RSS = 0.438exp(-0.0090t) + 0.502	11.01
S3	N & D	RSS = 0.601exp(-0.0157t) + 0.367	9.76
S4	N & D	RSS = 0.643exp(-0.0158t) + 0.324	19.04
S5	N & D	RSS = 0.512exp(-0.0138t) + 0.456	14.75
S6	N & D	RSS = 0.632exp(-0.0125t) + 0.373	9.55
female S's	N & D	RSS = 0.494exp(-0.0115t) + 0.458	10.66
male S's	N & D	RSS = 0.594exp(-0.0139t) + 0.384	14.44
all S's	N & D	RSS = 0.543exp(-0.0128t) + 0.423	12.55

N & D = neutral and deviated wrist positions are pooled,
RSS = relative strength score, and
t = time in seconds.

Table G-2

Regression Equations for the Thumb Fatigue Patterns of the Rhythmic Exercise

Subject or Group	Wrist position	Regression equation	Mean initial strength in Kg.
S1	neutral(N)	RSS = 0.431exp(-0.0208t) + 0.522	6.33
S2	N	RSS = 0.422exp(-0.0107t) + 0.562	5.63
S3	N	RSS = 0.500exp(-0.0077t) + 0.450	6.09
S4	N	RSS = 0.417exp(-0.0235t) + 0.560	11.08
S5	N	RSS = 0.486exp(-0.0095t) + 0.518	9.31
S6	N	RSS = 0.591exp(-0.0217t) + 0.437	5.70
female S's	N	RSS = 0.433exp(-0.0117t) + 0.522	6.02
male S's	N	RSS = 0.480exp(-0.0167t) + 0.514	8.70
all S's	N	RSS = 0.454exp(-0.0145t) + 0.522	7.36
S1	deviated(D)	RSS = 0.484exp(-0.0249t) + 0.533	5.96
S2	D	RSS = 0.410exp(-0.0116t) + 0.562	5.45
S3	D	RSS = 0.675exp(-0.0169t) + 0.346	5.44
S4	D	RSS = 0.451exp(-0.0247t) + 0.523	7.95
S5	D	RSS = 0.524exp(-0.0200t) + 0.496	8.80
S6	D	RSS = 0.377exp(-0.0175t) + 0.592	5.84
female S's	D	RSS = 0.492exp(-0.0214t) + 0.521	4.95
male S's	D	RSS = 0.449exp(-0.0205t) + 0.537	7.53
all S's	D	RSS = 0.471exp(-0.0210t) + 0.530	6.24

RSS =relative strength score and t = time in seconds.

Table G-2 (continued)

Subject or Group	Wrist position	Regression equation	Mean initial strength in Kg.
S1	N & D	RSS = 0.459exp(-0.0234t) + 0.529	5.15
S2	N & D	RSS = 0.416exp(-0.0111t) + 0.562	5.54
S3	N & D	RSS = 0.535exp(-0.0168t) + 0.469	5.77
S4	N & D	RSS = 0.434exp(-0.0241t) + 0.541	9.52
S5	N & D	RSS = 0.489exp(-0.0147t) + 0.521	9.06
S6	N & D	RSS = 0.488exp(-0.0203t) + 0.516	5.77
female S's	N & D	RSS = 0.462exp(-0.0167t) + 0.525	5.49
male S's	N & D	RSS = 0.404exp(-0.0184t) + 0.526	8.12
all S's	N & D	RSS = 0.462exp(-0.0176t) + 0.526	6.80

N & D = neutral and deviated wrist positions are pooled,
RSS = relative strength score, and
t = time in seconds.

Appendix H

LIST OF ABBREVIATIONS

ADD: adductor pollicis
ANOVA: analysis of variance
APB: abductor pollicis brevis
APL: abductor pollicis longus

BMDP: Biomedical Computer Programs

C: ambient temperature in Celsius
cm: centimeter
CM: carpometacarpal
CONT: computer programs used for continuous isometric exercise experiments

DIP: distal interphalangeal
DOWN: This is used to mean one of the force directions used for the thumb strength experiment. The thumb exerts a force in a vertical direction parallel to the sagital plane.

ECRB: extensor carpi radialis brevis
ECRL: extensor carpi radialis longus
EDC: extensor digitorum communis
EDT: 3rd extensor digitorum tendon
EIP: extensor indicis proprius
EMG: electromyography
EPL: extensor pollicis longus

FDI: first dorsal interosseous
FDP: flexor digitorum profundus
FDS: flexor digitorum superficialis
FPB: flexor pollicis brevis
FPL: flexor pollicis longus

INWARD: This is used to mean one of the force directions used for the thumb strength experiment. The thumb exerts a force in the horizontal direction parallel to the sagital plane inward towards the flexed fingers.
IP: interphalangeal

G: gender, a factor used in the ANOVA

kg: kilogram

MAVG: maximum one-second moving average
MAX: maximum
min: minute(s)
MIN: minimum
msec: millisecond
ml: milliliter
MP: metacarpophalangeal
MV: mean value
MVC: maximal voluntary contraction

OPP: opponenes pollicis
OPPOSITION: This is used to mean one of the force directions used for the thumb strength experiment. The thumb exerts a force in a horizontal direction perpendicular to the sagital plane, opposing to a palm.

P: grip span, index finger or thumb position, a factor used in the ANOVA for the respective experiment.
PI: palmer interosseous
PIP: proximal interphalangeal

RSS: relative strength score
RYTH: computer programs used for rhythmic isometric exercise experiments

SAS: Statistical Analysis System
sec: second
SD: standard deviation
S(G): individual subject strength, a factor used in the ANOVA
SPSS: Statistical Package for the Social Science
sq.cm: square centimeter

T: muscle temperature in Celsius; or grip type or time, a factor used in the ANOVA

W: wrist orientation, a factor used in the ANOVA