

**Biomechanical Models of the Finger in The Sagittal Plane**

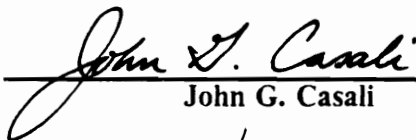
by

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in  
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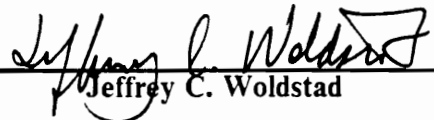
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(ABSTRACT)

Finger movements in the sagittal plane mainly consist of flexion and extension about the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints. The purpose of this study was to develop a biomechanical finger model and to validate it by comparing finger strength and muscular forces in static exertions which were predicted from the model and measured in experiments.

Two kinematic finger models were developed: one was with the assumption of constant tendon moment arms, and the other was with the assumption of non-constant tendon moment arms. Equations of static equilibrium were derived for these finger models using the principle of virtual work. Equations of static equilibrium for the finger models were indeterminate since only three equations were available for five unknown variables (forces). By reducing the number of variables based on information in the literature on muscular activities in finger movements, the amounts of force which muscles exerted to maintain static equilibrium against an external load were computed from the equilibrium equations. The muscular forces were expressed mathematically as functions of finger positions, tendon moment arms, lengths of phalanges, and the magnitude and direction of external load.

Equations of muscular forces were used to predict external finger strength and to compute internal muscular forces in static exertions against an external load.

Computer simulations were performed to compute finger strengths and muscular forces at various finger positions and directions of force exertions. For this, finger positions were controlled, and lengths of phalanges were measured.

Experiments were performed to measure finger strengths and muscular activity levels in submaximal contractions. Muscular activity levels were estimated by ratios of standardized EMG amplitude to exerted force. Measurements were taken in combinations of four finger positions and four directions of force exertions.

Validation of the biomechanical finger models was done by comparing the results of computer simulations and experiments. Significant differences were found between the predicted and measured finger strengths. However, the trends of finger strengths with respect to finger positions were similar in both the predicted and measured. Trends of variations in predicted and measured muscular activity levels were not different from each other. These findings indicate that the finger models and the procedure to predict finger strengths and muscular forces were correctly developed.

## Acknowledgements

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I wish to thank my parents for their devotion and unyielding support of my long education, my brother and sisters for their encouragement, and my wife, Won-Kyung, and three children, Dong-Eun, Soh-Eun, and Jae-Yong, for their patience and inspiration throughout the long and lonely process.

I dedicate this dissertation to my family.

# Table of Contents

<b>I. Introduction .....</b>	<b>1</b>
1.1 Background of the Study .....	1
1.2 Purpose of the Study.....	2
1.3 Organization of the Dissertation .....	2
<b>II. Functional Anatomy of the Hand and Finger .....</b>	<b>6</b>
2.1 Overview .....	6
2.2 Skeletal and Articular System of the Hand .....	7
2.2.1 Bones of the Hand and Finger .....	7
2.2.2 Articulations of the Hand and Finger .....	8
2.2.3 Fibrous Skeleton of the Hand and Finger .....	10
2.3 Muscular System of the Hand .....	14
2.3.1 Muscles of the Hand .....	14
2.3.2 Muscular Activities in the Finger .....	16
2.4 Mechanisms of Finger Movements .....	17
2.4.1 Mechanisms of Finger Flexion .....	19
2.4.2 Mechanisms of Finger Extension .....	22
2.5 Discussion and Summary .....	26

<b>III. Definitions of Finger Positions and Movements .....</b>	<b>28</b>
3.1 Overview .....	28
3.2 Four Basic Finger Positions .....	29
3.3 Resting Position of the Finger .....	30
3.4 Finger Movements about the MCP Joint ("Tapping") .....	32
3.5 Finger Movements about the PIP Joint ("Rocking") .....	32
3.6 Muscles in Finger Tapping and Rocking .....	33
3.7 Discussion and Summary .....	34
<b>IV. Literature Review of Biomechanical Finger Models .....</b>	<b>37</b>
4.1 Overview .....	37
4.2 Tendon Excursion Models .....	38
4.3 Static and Kinematic Models of The Finger .....	44
4.4 Methods for Establishing the Equilibrium Equations .....	54
4.5 Discussion and Summary .....	56
<b>V. Muscular Force and Electromyography .....</b>	<b>58</b>
5.1 Overview .....	58
5.2 Assessment of Maximal Voluntary Contraction .....	59
5.3 Electromyography and Muscular Force .....	61
5.4 Discussion and Summary .....	65
<b>VI. Biomechanical Models of the Finger .....</b>	<b>68</b>
6.1 Overview .....	68
6.2 Basic Assumptions of the Finger Models .....	69
6.3 Biomechanical Finger Models .....	72
6.3.1 Finger Model for Constant Tendon Moment Arms .....	74

6.3.2 Finger Model for Non-Constant Tendon Moment Arms .....	76
6.3.3. Comparison of the Models .....	78
6.4 Equilibrium Equations .....	79
6.5 Muscular Forces for Static Exertions .....	83
6.5.1 Directions of Force Exertions and External Load .....	83
6.5.2 Muscular Forces in the Constant Tendon Moment Arms Model .....	84
6.5.3 Muscular Forces in the Non-Constant Tendon Moment Arms Model .....	89
6.6 Discussion and Summary .....	92
<b>VII. Muscle Length-Tension Relationships .....</b>	<b>94</b>
7.1 Overview .....	94
7.2 Muscle Length-Tension Relationships .....	95
7.3 Normalized Muscle Length-Tension Curves .....	98
7.4 Discussion and Summary .....	105
<b>VIII. Applications of Biomechanical Finger Models .....</b>	<b>106</b>
8.1 Overview .....	106
8.2 Muscular Forces in Static Equilibrium .....	107
8.3 Finger Strengths in Various Finger Positions .....	110
8.4 Computer Simulation .....	117
8.4.1 Data for Simulation .....	118
8.4.2 Methods and Procedures of Simulation .....	119
8.4.3 Results .....	121
8.5 Discussion and Summary .....	132
<b>IX. Experiments: Finger Strength Tests and EMG Recordings .....</b>	<b>133</b>
9.1 Overview .....	133



9.2 Hypotheses to Be Tested .....	134
9.3 Subjects .....	135
9.4 Equipment .....	138
9.5 Experimental Variables .....	143
9.6 Experimental Design .....	145
9.7 Methods and Procedures .....	147
9.7.1 Anthropometric Data Collection .....	147
9.7.2 Finger Strength Test .....	149
9.7.3 EMG Recordings during Submaximal Contractions .....	150
9.7.4 Experimental Procedure .....	151
9.8 Data Analysis .....	153
9.9 Experimental Results .....	154
9.9.1 Finger Strengths .....	156
9.9.2 Muscular Activity Levels in Submaximal Contractions .....	164
9.10 Discussion and Summary .....	166
<b>X. Validation of Finger Models .....</b>	<b>176</b>
10.1 Overview .....	176
10.2 Comparisons of Finger Strengths .....	177
10.3 Comparisons of Muscular Activity Levels .....	190
10.4 Discussion and Summary .....	207
<b>XI. Conclusions .....</b>	<b>214</b>
11.1 Biomechanical Finger Models and Equilibrium Equations .....	214
11.3 Evaluation of Finger Models .....	216
11.3 Recommendations for Future Studies .....	217

<b>Bibliography .....</b>	<b>220</b>
<b>Appendix A. Glossary of Terms and Abbreviations .....</b>	<b>231</b>
<b>Appendix B. Muscles for Finger Movements .....</b>	<b>235</b>
<b>Appendix C. Experimental Data .....</b>	<b>257</b>
<b>Appendix D. Source Lists of Computer Programs .....</b>	<b>282</b>
<b>Vita .....</b>	<b>314</b>

# List of Tables

Table 2.1 Roles of the muscles in finger joint movements .....	18
Table 3.1 Muscular activities in finger tapping and rocking .....	35
Table 6.1 Activations of the muscles in finger joint movements as considered in the finger models ...	71
Table 6.2 Comparison of finger models .....	80
Table 7.1 Tendon excursions in cm computed from the constant tendon moment arms model .....	99
Table 7.2 Tendon excursions in cm computed from the non-constant tendon moment arms model ...	100
Table 8.1 Data for computing finger strengths and muscular forces .....	120
Table 8.2 Computed finger strengths in N in the constant and non-constant tendon moment arms models .....	123
Table 8.3 Computed muscular forces in N in the constant tendon moment arms model .....	124
Table 8.4 Computed muscular forces in N in the non-constant tendon moment arms model .....	125
Table 8.5 ANOVA for predicted finger strengths .....	129
Table 9.1 Personal and anthropometric data of the subjects .....	139
Table 9.2 Experimental 4x4 factorial within-subject design .....	146
Table 9.3 Test sequences for the subject .....	148
Table 9.4 Means and standard deviations of measured finger strengths .....	157
Table 9.5 ANOVA for measured finger strengths .....	159
Table 9.6 Newman-Keuls comparisons for measured finger strengths .....	160

Table 9.7 Newman-Keuls comparisons of finger strengths with respect to finger positions .....	161
Table 9.8 Parameters of linear regression for measured finger strengths .....	163
Table 9.9 Means and standard deviations of RMS EMG amplitudes .....	165
Table 9.10 Means and standard deviations of standardized ratios of EMG amplitude/force .....	167
Table 9.11 Parameters of linear regressions for ratios of EMG amplitude/force .....	172
Table 9.12 ANOVA for ratios of EMG amplitude/MVC measured before and after daily tests .....	174
Table 10.1 ANOVA for overall data of predicted and measured finger strengths .....	178
Table 10.2 Results of Newman-Keuls comparisons for overall data of predicted and measured finger strengths .....	179
Table 10.3 ANOVA and Newman-Keuls tests for downward finger strengths .....	180
Table 10.4 ANOVA and Newman-Keuls tests for upward finger strengths .....	181
Table 10.5 ANOVA and Newman-Keuls tests for backward finger strengths .....	182
Table 10.6 ANOVA and Newman-Keuls tests for forward finger strengths .....	183
Table 10.7 Parameters of linear regressions for predicted and measured finger strengths .....	189
Table 10.8 Confidence limits of the slopes of predicted finger strengths .....	191
Table 10.9 Normalized muscular forces .....	193
Table 10.10 Normalized EMG amplitude/force .....	194
Table 10.11 Results of linear regression for predicted muscular activity levels .....	208
Table 10.12 Results of linear regression for measured muscular activity levels .....	209
Table 10.13 Results of t-tests for comparing the slopes between the predicted and measured muscular activity levels .....	210

# List of Illustrations

Figure 1.1 Structure of the Dissertation .....	3
Figure 2.1 Skeleton of the hand .....	9
Figure 2.2 Volar plate and lateral ligaments in finger joints .....	12
Figure 2.3 Extensor tendons and other parts of the fibrous skeleton of the finger .....	13
Figure 2.4 Sequence of finger flexion .....	21
Figure 2.5 Sequence of finger extension .....	23
Figure 2.6 Role of the interossei in MCP extension .....	25
Figure 3.1 Definition of three finger joint angles .....	31
Figure 4.1 Schematic diagram of tendon excursion in Landsmeer's first model .....	39
Figure 4.2 Schematic diagram of tendon excursion in Landsmeer's second model .....	40
Figure 4.3 Schematic diagram of tendon excursion in Landsmeer's third model .....	42
Figure 4.4 Forces in Spoor's finger model .....	45
Figure 5.1 A typical relation between exerted forces and EMG amplitudes .....	66
Figure 5.2 Typical variations of EMG amplitudes at different force levels in continuous isometric contractions .....	67
Figure 6.1 Schematic diagram of muscles and tendons in the index finger model .....	70
Figure 6.2 Four directions of external load and force exertions .....	85

Figure 7.1 Muscle models with contractile and elastic components .....	96
Figure 7.2 Diagram of the typical muscle length-tension relationship .....	97
Figure 7.3 Schematic diagram of normalized muscle length-tension relationship .....	102
Figure 8.1 Parameters in finger models .....	108
Figure 8.2 Flow diagram of computer program .....	122
Figure 8.3 Finger strengths predicted from the constant tendon moment arms model .....	126
Figure 8.4 Muscular forces required against an external load .....	127
Figure 9.1 Schematic diagram of Hypotheses I and II .....	136
Figure 9.2 Schematic diagram of Hypothesis III .....	137
Figure 9.3 Positions of L-shaped beam and load cell and force directions .....	141
Figure 9.4 Schematic diagram of equipment configuration .....	144
Figure 9.5 Typical curves of exerted muscular forces and RMS EMGs .....	155
Figure 9.6 Measured finger strengths .....	158
Figure 9.7 Ratios of EMG amplitude/force .....	168
Figure 10.1 Predicted and measured finger strengths in downward force exertions .....	185
Figure 10.2 Predicted and measured finger strengths in upward force exertions .....	186
Figure 10.3 Predicted and measured finger strengths in backward force exertions .....	187
Figure 10.4 Predicted and measured finger strengths in forward force exertions .....	188
Figure 10.5 Predicted and measured muscular activity levels in downward force exertions .....	195
Figure 10.6 Predicted and measured muscular activity levels in upward force exertions .....	198
Figure 10.7 Predicted and measured muscular activity levels in backward force exertions .....	201
Figure 10.8 Predicted and measured muscular activity levels in forward force exertions .....	204
Figure 10.9 Predicted finger strengths with additional FDP capabilities .....	212

# I. Introduction

## *1.1 Background of the Study*

The hand is one of the important features which distinguish human beings from other animals. The hand, located at the distal end of the upper limb, is characterized by versatility of the digits. The four fingers and the thumb have multiple articulations. Major functions of the digits, such as touch, grip, and grasp are associated with flexion of the digits. Extension of the digits is generally considered as a reversal of flexion. Flexion and extension are the major movements of the digits even though they also can abduct and adduct, to some extent.

Flexion and extension of a finger are said to occur in the sagittal plane. Finger movements in the sagittal plane are described by individual or coordinated movements of three phalanges of the finger: proximal, middle, and distal. The proximal and middle phalanges can move independently, but the movement of the distal phalanx is largely dependent upon the movement of the middle phalanx. Therefore, the finger is frequently simplified to a two-joints (bi-articular) system.

Understanding the mechanisms of finger flexion and extension and associated forces in the proximal and middle phalanges about the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints is helpful to describe various functions of the finger. This knowledge is applicable in design of tools, controls, and data entry devices such as computer keyboards.

## *1.2 Purpose of the Study*

Functions of the finger can be understood by developing biomechanical finger models and by analyzing the forces associated with force exertions. The purpose of this study is to develop a biomechanical finger model and to validate it.

Since the basic movements of the finger are flexion and extension, the biomechanical finger model is in the sagittal plane. It includes only static exertions about the MCP and PIP joints. To validate the model finger strengths and muscular forces in static exertions against external load are predicted and compared to experimental results.

## *1.3 Organization of the Dissertation*

This study consists of literature review, biomechanical modeling, computer simulation, and experiments. It is divided into chapters and has the structure represented in Figure 1.1.



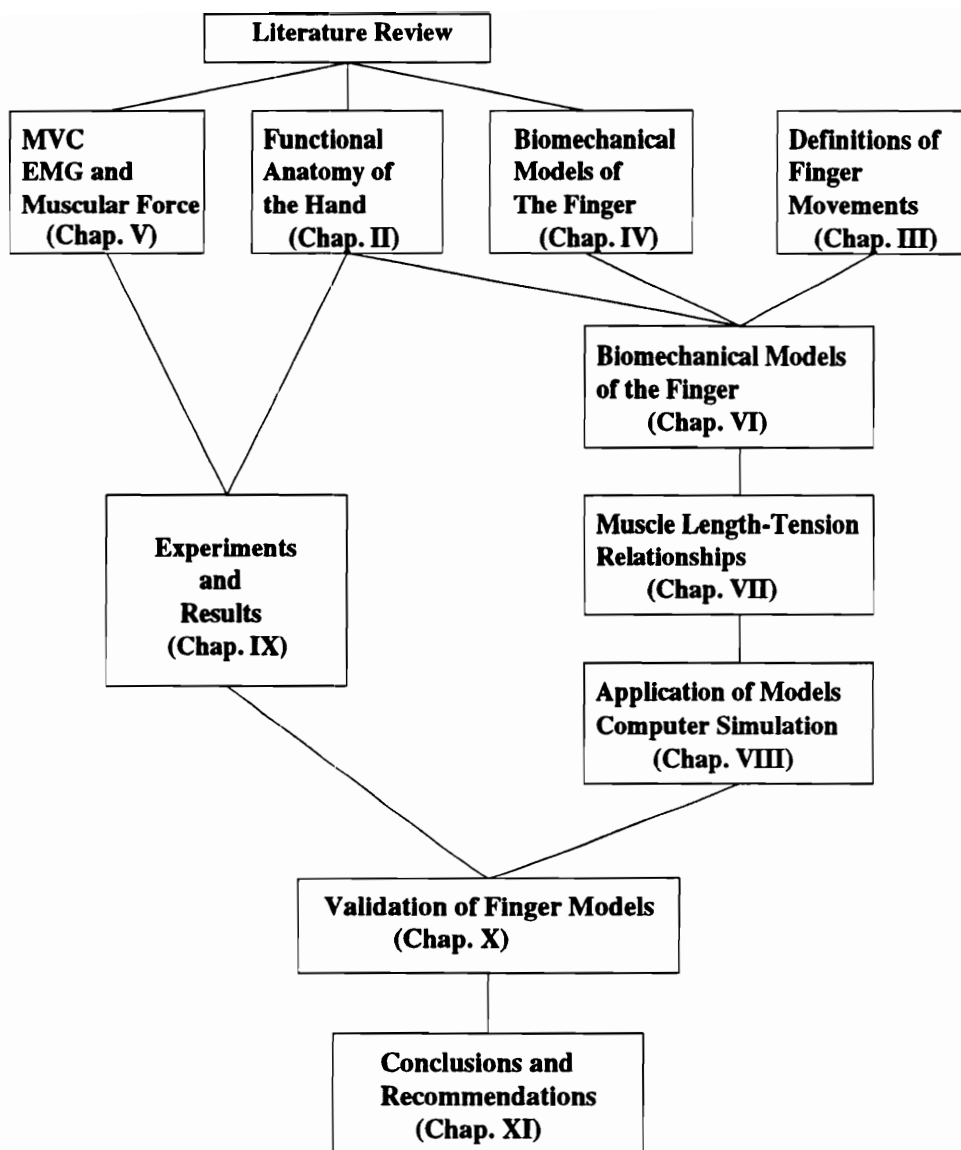


Figure 1.1 Structure of the dissertation.

In chapter II, skeletal and articular systems of the hand are briefly explained. Then muscles of the hand and their functions are studied. Finally, mechanisms of finger flexion and extension are discussed. Chapter III includes definitions of basic finger positions and movements. Muscles involved in each finger movement are discussed. Chapter IV is a review of literature on biomechanical models of the finger. Analytical and mathematical models of tendon excursion, static and kinematic models of the finger are reviewed. Methods for establishing the equilibrium equations are compared. In chapter V, methods of muscular strength assessment are reviewed. Tests of maximal voluntary contraction (MVC) and relationships between muscular forces and EMG are discussed. Chapter VI describes the development of biomechanical finger models with constant and non-constant tendon moment arms. Equilibrium equations are derived in order to compute muscular forces in static exertions. Muscular forces are expressed as mathematical functions of joint angles, tendon moment arms, length of phalanges, and external loads. Chapter VII consists of a review of muscle length-tension relationships and development of muscle length-tension models of the hand muscles. Tendon excursions are computed using the finger models developed earlier. Exertable muscular forces for specific finger positions are expressed as functions of finger positions. Chapter VIII describes two applications of the finger models. Procedures to estimate finger strength and muscular forces in static exertions are explained. Computer simulations are performed to get the numerical values of finger strengths and muscular forces in static exertions against given external loads in various finger positions. Procedures and results of simulations are explained. In Chapter IX, hypotheses are proposed to validate finger models and predicted results. Then experimental methods and procedures are explained. Results of experiments are also presented. In Chapter X, the predicted and measured results are compared to validate the finger models. Differences between the predicted and

measured data are explained. Chapter XI presents the conclusions from this study and provides recommendations for future studies.

## **II. Functional Anatomy of the Hand and Finger**

### ***2.1 Overview***

In this chapter, the structure of the hand and mechanisms of finger movements are reviewed. Skeletal and articular systems of the hand and finger are explained. Muscles of the hand and their activities in finger movements are summarized. Finally, mechanisms of finger flexion and extension are explained.

## *2.2 Skeletal and Articular System of the Hand*

### **2.2.1 Bones of the Hand and Finger**

The skeleton of the hand consists of 19 long bones: 5 metacarpals and 14 phalanges. The metacarpals are numbered from the radial to the ulnar side so that the metacarpal bone of thumb is numbered 1, and that of little finger is numbered 5. The phalanges, two in the thumb and three in each finger, are numbered from proximal to distal: 1 (proximal), 2 (middle), and 3 (distal) (Figure 2.1).

The long bones of the hand are divided into five digit "rays." Each ray is a polyarticulated chain comprising the metacarpals and phalanges. The base of each metacarpal articulates with the distal row of the carpi, the bones of the wrist. They articulate against the radius and ulna, bones of the forearm. The radiocarpal articulation has two axes of movement, flexion/extension and abduction/adduction. For simplicity, one may add a third movement, pronation/supination, although it actually occurs in the forearm. The wrist thus has three axes of movement or degrees of freedom.

The lengths of the metacarpals vary. The thumb metacarpal is the shortest, the index metacarpal is the longest, and the lengths of other metacarpals decrease from the third to the fifth digit. Yet, the proximal and particularly the middle phalanges of the middle and ring finger are longer than those of the index finger. As a result, the middle finger and usually the ring finger are longer than the index finger.

The skeleton of the hand can be divided into two groups: "fixed" and "mobile" elements. The fixed elements include the distal row of the carpal bones and the attached central metacarpals. Yet, between the different skeletal pieces composing the so-called

fixed portion, small displacement is possible, sufficient to assure a discrete suppleness but permitting stability without rigidity. The mobile elements include two parts: the peripheral metacarpals, and the phalanges, which form the skeleton of the digits and make closure of the fingers possible.

### **2.2.2 Articulations of the Hand and Finger**

The hand is a multi-articular system which consists of carpals, metacarpals, and phalanges. The articulations between metacarpal bones and carpal bones are called carpometacarpal (CM) joints.

The CM joint of the thumb is a highly mobile joint, located between the base of the first metacarpal bone and the trapezium. This joint is called a saddle (or sellar) joint because its articular surface is saddle-shaped. This configuration provides much freedom of movement: flexion/extension in a plane perpendicular to the palm of the hand, abduction/adduction in a plane parallel to the palm, and a few degrees of rotation.

The CM joints of the four fingers and of the thumb have articular capsules which are reinforced by carpometacarpal ligaments which limit the fingers to slight gliding of the articular surfaces upon each other. The metacarpal bone of the little finger has the greatest range of movement while the metacarpal bones of the index and middle fingers are almost immovable.

Metacarpophalangeal (MCP) joints, the "knuckles", articulations between metacarpal bones and proximal phalanges, are ellipsoid in type. On the palmar aspect of these joints, the rounded articular heads of the metacarpal bones are partly divided, so they appear similar to condyles. Possible movements of MCP joints are flexion/extension, abduction/adduction, and circumduction.

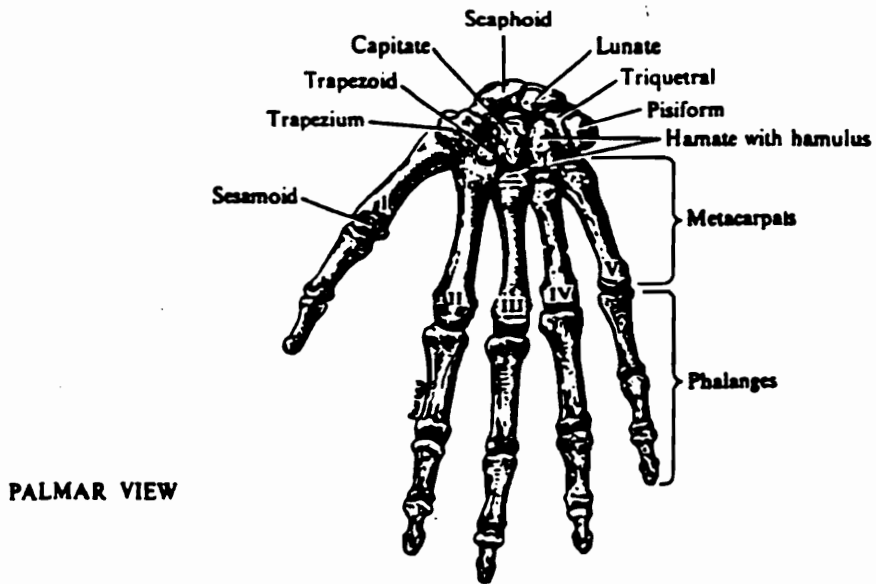
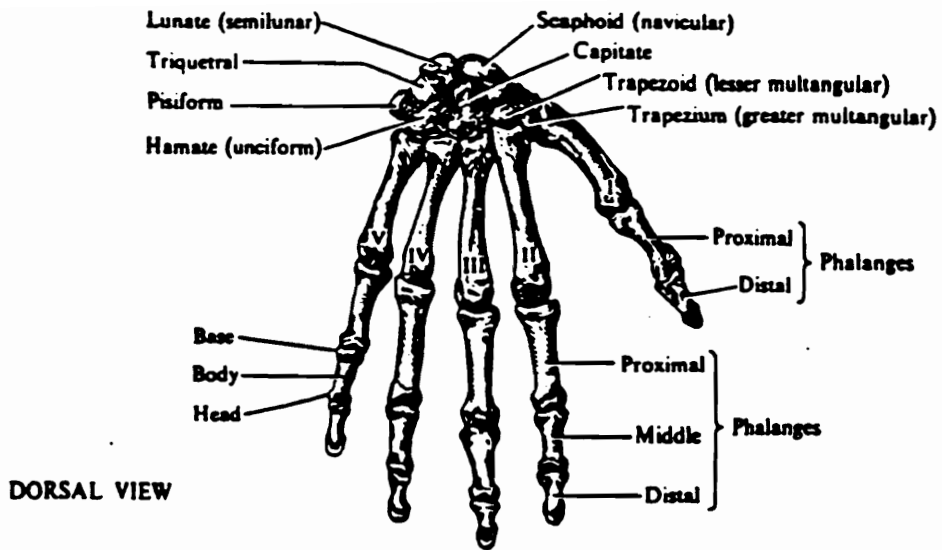


Figure 2.1 Skeleton of the hand.

( from Pansky, 1979 )

Proximal interphalangeal (PIP) joints are articulations between the proximal and middle phalanges; distal interphalangeal (DIP) joints are between the middle and distal phalanges. The PIP and DIP joints are surrounded by thin fibrous articular capsules, reinforced on their palmar surfaces by thick palmar ligaments over which glide the flexor tendons. On each side the joint is reinforced by obliquely oriented collateral ligaments. Both the PIP and DIP joints are hinge joints in which only flexion/extension are possible.

### **2.2.3 Fibrous Skeleton of the Hand and Finger**

The fibrous skeleton consists of the aponeuroses, ligaments, and fibrous sheaths attached to the bones and the dermis. The major role of the fibrous skeleton is to unite bony segments and to stabilize the transverse and longitudinal arches of the hand.

Each finger contains three joints which are mobile within certain limits. At every joint, two collateral ligaments and one volar plate reinforce the articular capsule to stabilize the joint. The collateral ligaments resemble strong rounded cords placed on the sides of the joints. During flexion of the joint, the collateral ligaments become tense, thereby preventing abduction or adduction of the flexed finger.

The volar plate is a glenoid fibrocartilage which has a firm distal insertion on the anterior aspect of the base of the phalanx. The cartilaginous part of the volar plate is thick and rigid; it has little or no elasticity and prevents hyperextension of the joint. The membranous portion of the volar plate is supple and lax; it folds on itself accordion-like during finger flexion. The volar plate limits extension in the PIP joint more than in the other digital joints. The two proximal attachments of the volar plate of the PIP joint insert into the proximal phalanx on each side of the flexor tendons and blend with their



fibrous sheaths. Some hyperextension is possible at the MCP and PIP joints. The volar plates and the collateral ligaments of the finger are shown in Figure 2.2.

The tendons which descend from the forearm through the wrist into the hand are encased by synovial sheaths and digital tendon sheaths. These tubular structures contain lubricating fluid within them and surround both flexor and extensor tendons. They guide the tendons, yet allow the joints of the digit to have freedom of movement and to remain within a small volume.

The extensor tendons diverge on the back of the hand and go to a different finger where they insert into the middle and distal phalanges. Opposite the MCP joint, each tendon is bound by fibrous tissue to the collateral ligaments and serves as the dorsal ligament of the joint. Beyond the MCP joint, the tendon spreads out into a broad aponeurosis which covers the dorsal surface of the proximal phalanx. These are called the extensor hoods and are reinforced by the tendons of the interossei and lumbrical muscles. Opposite the PIP joint, the tendon is divided into three slips, an intermediate and two collateral. The intermediate slip insert into the base of the middle phalanx. The two collateral slips continue distally along the sides of the middle phalanx, unite by their contiguous margins, and insert into the dorsal surface of the distal phalanx. The extensor tendons and other parts of the fibrous skeleton are shown in Figure 2.3.

The common flexor tendon sheath contains all the tendons of the flexor digitorum superficialis and flexor digitorum profundus, while the tendon of the flexor pollicis longus has its own sheath. The common flexor tendon sheath is continuous distally beyond the middle of the palm as the digital sheath only for the little finger. The tendon sheath for the flexor pollicis longus extends distally to the terminal phalanx of the thumb, where the tendon inserts.

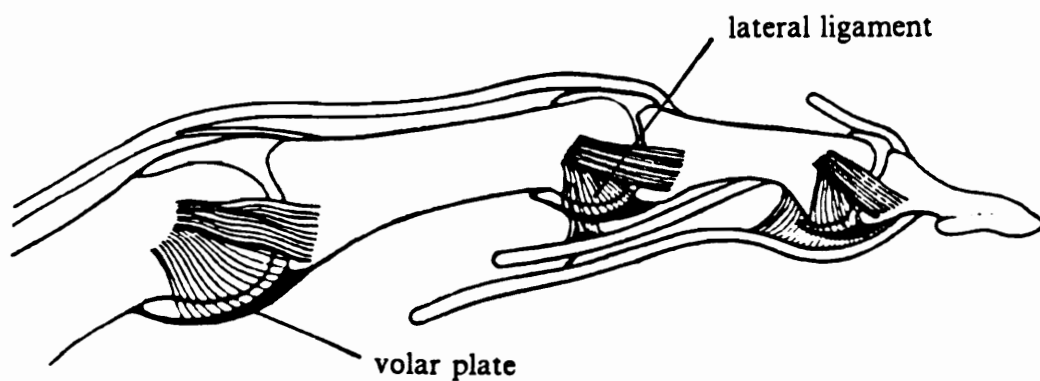
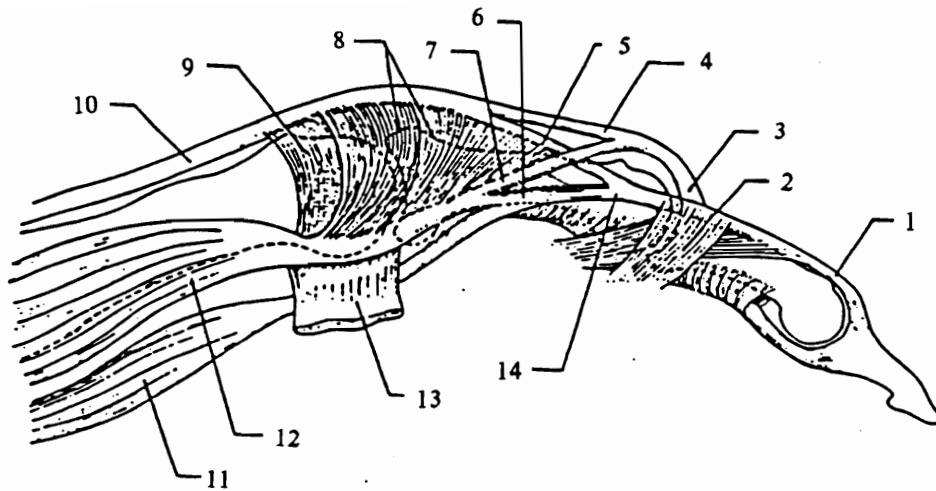


Figure 2.2 Volar plates and lateral ligaments in finger joints.

(from Tubiana, 1981)



**Figure 2.3 Extensor tendons and other parts of the fibrous skeleton of the finger.**

1. Terminal extensor tendon; 2. Retinacular ligament; 3. Central (middle) extensor tendon; 4. Middle band of the common extensor tendon; 5. Lateral band of the common extensor tendon; 6. Lateral band of the interossei; 7. Middle band of the interossei; 8. Dorsum of the interossei; 9. Sagittal band; 10. Common extensor tendon; 11. Lumbrical muscle; 12. Interosseous muscle; 13. transverse intermetacarpal ligament; 14. Lateral extensor tendon.

(from Tubiana, 1981)

The tendons of flexors pass through the carpal tunnel at the wrist. The carpal tunnel is a groove formed by the anterior cavity of the carpal bones and is divided into two parts by a sagittal septum. The carpal canal proper is situated medially and contains the tendons of the flexor digitorum superficialis and profundus, the median nerve, and blood vessels. The lateral tunnel contains the tendon of the flexor carpi radialis. Since the carpal tunnel is narrow and the median nerve is more superficial than the tendons, the nerve is compressed by the tendons when the wrist is in the flexed position (Clemente, 1985; Tubiana, 1981).

In the hand, the tendons of the flexors digitorum superficialis and profundus are held in position along the digits by strong fibrous sheaths. These fibrous tunnels or canals are formed by the palmar surfaces of the phalanges and by strong collagenous bands that arch over the tendons and are attached to the margins of the phalanges on both sides.

## ***2.3 Muscular System of the Hand***

### **2.3.1 Muscles of the Hand**

Two groups of muscles are in charge of hand movements: intrinsic and extrinsic muscles. The intrinsic muscles are located entirely in the hand while the extrinsic muscles are in the forearm but extend their tendons across the wrist into the hand. Muscles in the forearm are divided into two groups by their functions: flexors and extensors.

Each group of muscles is divided again into three subgroups depending upon layers in which they are located.

The flexor compartment in the forearm consists of three layers: the superficial, the second, and the deep layer. Muscles in the superficial layer are related to wrist movements. The second layer contains the flexor digitorum superficialis (FDS). The flexor digitorum profundus (FDP) and flexor pollicis longus (FPL) are in deep layer of the flexor compartment.

The extensor compartment also consists of three parts: the superficial, the deep, and the lateral. The extensor digitorum communis (EDC) is in the superficial layer. In the deep layer, muscles which move the wrist and the thumb are located. The extensor digitorum indicis, which reinforces the action of the extensor digitorum communis, is also in this deep layer. Muscles in the lateral compartment are related to the movements of wrist and forearm.

The intrinsic muscles consist of two groups, the interossei and lumbricals. The interosseous muscles are divided into palmar and dorsal interossei. There are three palmar interossei and four dorsal interossei in the hand. The major function of the interossei is to flex the proximal phalanges and extend the middle and distal phalanges. The lumbricals are the only skeletal muscles that have no direct bony attachments. They originate from the tendons of the flexor digitorum profundus at the palm and insert on the bases of the distal phalanges. There are four lumbricals in the hand. Generally, the lumbricals extend the interphalangeal joint but their activities are not clearly understood because they are inconsistent and depend on finger positions.

### 2.3.2 Muscular Activities in the Finger

Muscular activities during finger movements have been studied by electromyographic (EMG) recordings as well as by direct observation of muscles. Backhouse and Catton (1954) examined the activity of lumbrical muscles by recording EMGs during electrical stimulation. Firm extension of the interphalangeal (IP) joints produced a high level of activity in the lumbrical muscles. Relaxation of IP extension produced an immediate reduction in the electrical activity in the lumbrical muscles. Flexion at the MCP joint with IP extension appeared to give a slightly higher level of lumbrical electrical activity than in MCP extension. They thus concluded that the function of lumbrical muscle was extension of the IP joints.

Long, Brown, and Weiss (1960 and 1961) and Long and Brown (1962 and 1964) investigated the activation of muscles during finger motion using EMG, cinematography, and an electrogoniometer. The extrinsic extensor was active when the MCP joint was extending or held extended. The dorsal interosseous was usually active when the IP joints were being extended regardless of the position or direction of movement of the MP joint. The flexor digitorum profundus was extremely active whenever the DIP joints were flexing. The lumbricalis was consistently used to keep the fingers straight or to extended the IP joints. The lumbricalis and the extensor digitorum formed a synergistic pair during extension of the whole finger, or during extension with the MCP joint held extended. In addition, Long, Brown, and Weiss (1960 and 1961) and Long and Brown (1962 and 1964) found that the electromyographic activity of the flexor digitorum superficialis varied with wrist position, being least in the extended and greatest in the flexed position.

Stack (1962 and 1963) studied the location and functions of tendons of the fingers and found that the prime action of the lumbricalis, and also of the distal interosseous, was IP extension.

Smith, Juvinal, Bender, and Pearson (1964) reported that the interossei on the radial and ulnar side had approximately equal moment arms about the flexion-extension axes of the MCP joint, so that the sum of the interosseus forces can be treated as a single force. Only half of the total interosseous force reaches the insertion beyond the PIP joint. Therefore, interosseous forces act at the both the PIP and DIP joints.

Muscular activities in various finger movements are summarized in Table 2.1.

## ***2.4 Mechanisms of Finger Movements***

The finger is a multiarticular system. Extrinsic muscles act across two or more joints, usually by having their tendons cross a joint or joints without attachment to bony elements. The tendon of the flexor digitorum profundus runs through the MCP and PIP joints and inserts into the base of the distal phalanx. It involves in movements of the PIP and DIP joints, but does not act in MCP joint movement. The tendons of the extensor digitorum have three insertions: the bases of the proximal, middle, and distal phalanges. To extend the PIP joint, the force exerted by the extensor digitorum is used to pull the middle band of the tendon, but does not act on the MCP joint.

Movement of the finger (in the absence of external resistance) is the result of two opposite forces: the active forces of muscular contraction and the passive forces (viscoelastic forces of tissues and antagonistic muscular forces) which slow down or stop the opposing movement.

Table 2.1 Roles of the muscles in finger joint movements.

Muscle	MCP		PIP		DIP		Other Movements
	Flex.	Ext.	Flex.	Ext.	Flex.	Ext.	
<b>EDC</b>		X		X		X	
<b>FDS</b>	X	(X)	X				
<b>FDP</b>			X		X		
<b>Interossei</b>	X			X		X	abduct & adduct fingers
<b>Lumbricals</b>	(X)			X		X	rotate fingers
<b>Flexor Carpi Radialis</b>							flex the wrist
<b>Extensor Digiti Minimi</b>		X		X		X	extend the little finger
<b>Extensor Indicis</b>		X		X		X	extend the index finger

legend (X) : inconsistent activation

EDC : Extensor Digitorum Communis

FDS : Flexor Digitorum Superficialis

FDP : Flexor Digitorum Profundus



Simplifying the human finger to a biarticular system allows to explain why it is impossible to control the finger joints independently of each other by only two muscles, flexor and extensor. Loading the opposing tendons will result in collapse of the system, with one joint going into flexion and the other into extension. To avoid this collapse, another force must be added to oppose the direction of collapse. The most economical unit would be one that is oblique, thus opposing extension in one joint and flexion in the other. This role of the oblique third force is well fulfilled by the intrinsic muscles (Figures 2.4 and 2.5).

### **2.4.1 Mechanisms of Finger Flexion**

Two flexor muscles and the palmar interossei are in charge of finger flexion. When all joints are flexed synchronously, the flexor digitorum profundus (FDP) is the major flexor of the fingers. It always activates when the distal phalanx is flexed, but remains inactive when the MCP joint flexes while the IP joints are extended. It is also inactive after the PIP joint is flexed.

The flexor digitorum superficialis (FDS) flexes the PIP and MCP joints. The interossei are active when the interphalangeal joints are in extension as the MCP joints are flexing. The interossei thus work for MCP joint flexion.

The extensor digitorum communis (EDC) is a major extensor but also acts as a synergistic antagonist during finger flexion.

DIP flexion is simplest to explain. The flexor digitorum profundus acts as a flexor while the extensor digitorum communis plays the role of antagonist. Because the forces from the extensor digitorum communis act through the two lateral tendons, the DIP joint is stable during flexion. Contraction of the flexor digitorum profundus, however,

affects the tendon of flexor digitorum superficialis. (The tendon of the flexor digitorum profundus runs through the tendon of flexor digitorum superficialis.) Therefore flexion of the PIP joint is accompanied by the DIP flexion and vice versa.

The flexor digitorum superficialis plays a major role in PIP flexion. In PIP flexion, the flexor digitorum profundus is also activated and the extensor digitorum communis acts as an antagonist.

Flexion of MCP joint is performed by contraction of the flexor digitorum superficialis and palmar interossei. No flexor muscle inserts at the base of proximal phalanx. The flexor digitorum superficialis thus provides the force for flexing the MCP joint while the extensor digitorum communis acts as antagonist. Simultaneously, interossei activate for aiding to flex as well as to stabilize the MCP joint during flexion. Sometimes, but not consistently, lumbricals are activated in MCP flexion.

In general, finger flexion is a sequential and combined movement of three finger joints. Finger flexion begins normally at the PIP joint, followed by the MCP and DIP joints. At the beginning of finger flexion, the flexor digitorum profundus and extensor digitorum communis contract simultaneously. The oblique retinacular ligament, which is put under tension by the flexion of the distal phalanx, acts as an active tenodesis (tendon fixation) to initiate flexion of the PIP joint. As the PIP joint flexes, the tension in the oblique retinacular ligament decreases, thereby allowing more flexion at the DIP joint. Flexion of the PIP joint puts the lumbrical and interosseous tendons under tension, and this initiates flexion of the MCP joint. Without the contraction of the lumbrical and interosseous muscles, the extrinsic muscles can not flex the MCP joint; they only cause a hyperextension of the MCP joint and a clawlike flexion of the finger. Flexion of the MCP joint displaces the interosseous hood distally making it act as a flexor of the proximal phalanx. This sequence of finger flexion was shown in Figure 2.4.

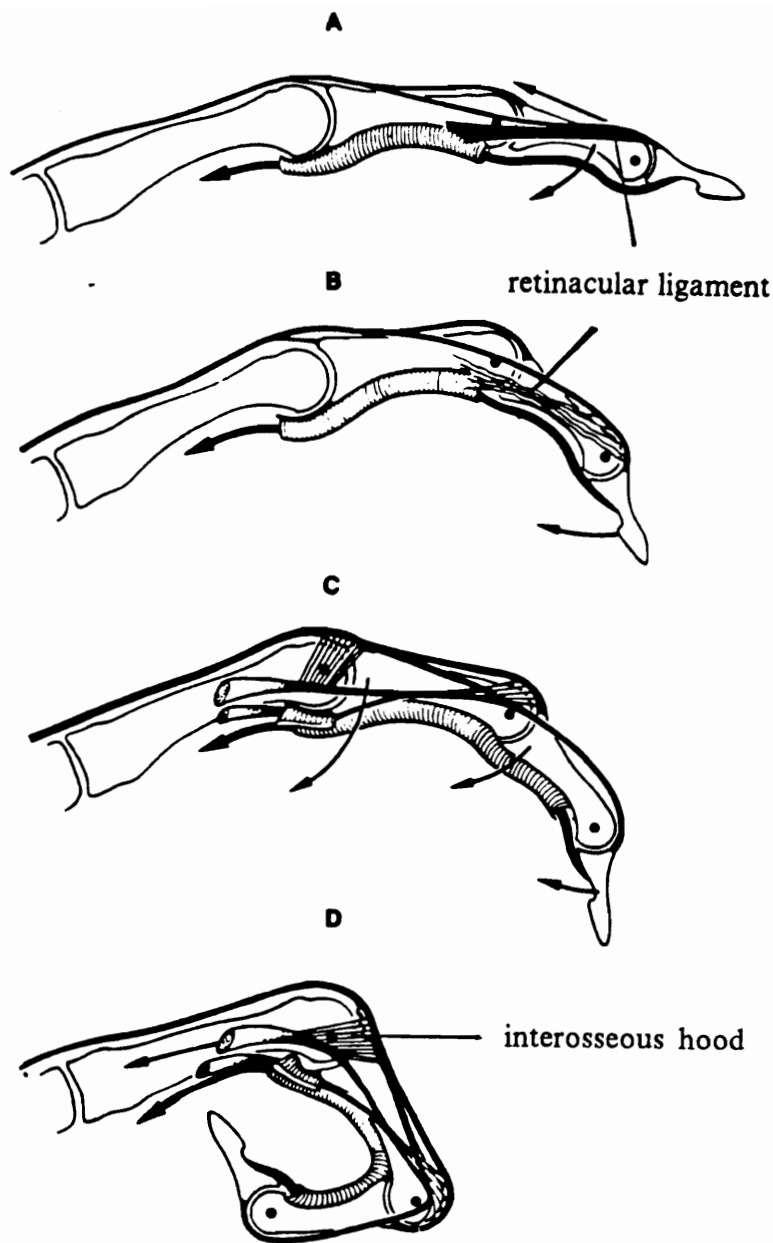


Figure 2.4 Sequence of finger flexion.

A. The flexor profundus and extensor digitorum contract simultaneously at the beginning of the flexion. The retinacular ligament is taut with the PIP joint in extension, preventing DIP joint flexion; B. Release of the retinacular ligament allows DIP joint flexion; C. Flexion of the PIP joint puts the lumbrical and interosseous tendons under tension, and this initiates flexion of the MCP joint; D. Flexion of the MCP joint displaces the interosseous hood distally; once distal to the joint, it can act as a flexor of the proximal phalanx.

(from Tubiana, 1981)

## 2.4.2 Mechanisms of Finger Extension

The extensor digitorum communis plays a major role in finger extension. Since the finger is a multiarticular system, and the extensor tendon inserts at three phalanges, to extend each phalanx independently and to stabilize the joints during finger extension other forces must be added to the force exerted by the extensor communis. Intrinsic muscles and the flexor digitorum superficialis provide these forces.

On the whole, the proximal phalanx behaves like a link in articulated chain and is submitted to the forces exerted by adjacent links. Extension in the MCP joint is brought about by two forces: one is direct and the other is indirect. The direct force comes from the extensor digitorum communis. This force acts directly on the proximal phalanx through the tendon inserted at the base of the phalanx. The indirect force, more important in MCP extension than in IP extension, is exerted by the head of the proximal phalanx on the base of the middle phalanx. It is generated by activation of the flexor digitorum superficialis and the extensor digitorum communis inserted at the base of the middle phalanx.

The two forces, direct and indirect, are activated in succession during extension of MCP joint. Extension of MCP joint is brought about in the early stage by the force that acts on the middle phalanx through the middle tendon. In the later stage of MCP extension, the tendon of the extensor digitorum communis inserted into the middle phalanx plays a major role. The sequence of finger extension is represented in Figure 2.5.

The action of the flexor is essential for MCP extension especially when the other two joints remain flexed. It restricts extension of the PIP joint and generates MCP extension. Simultaneous activation of both the extensor digitorum communis and the flexor digitorum superficialis brings about a tendency of hyperextension in the MCP joint (with

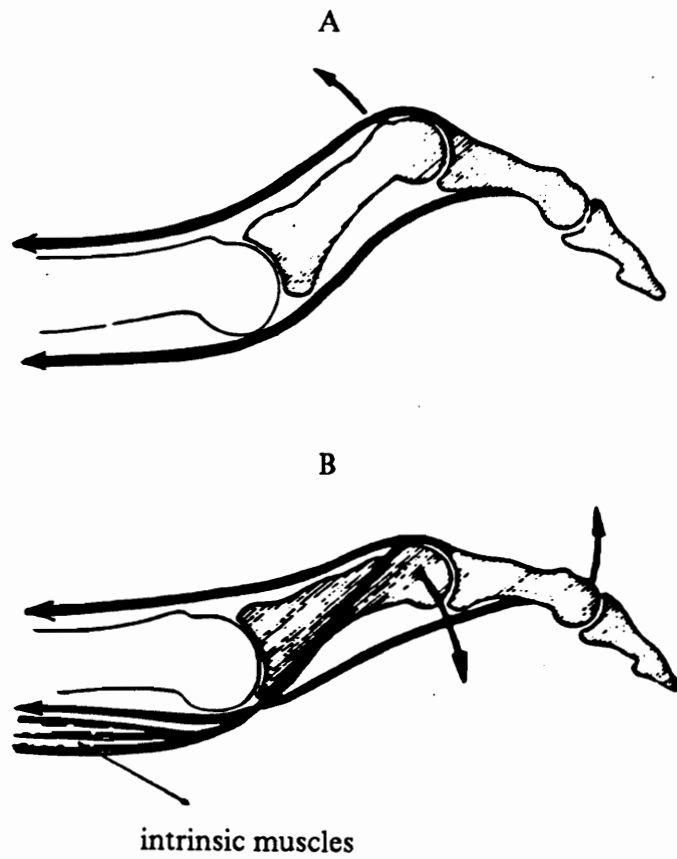


Figure 2.5 Sequence of finger extension.

A. When the extensor contracts for extending the MCP joint, the flexor acts as an antagonist; B. The intrinsic muscles act to extend the PIP and DIP joints.

(from Tubiana, 1981)

PIP flexion). It thus necessary to pull down the PIP joint to restore the equilibrium of the articulated chain. A flexor "pull-down" is believed to be provided by the intrinsic muscles. Long (1968) reported that contraction of the lumbricals was synchronous with that of the extensor digitorum communis.

Extension of the PIP joint is produced by excursion of the tendons inserted at the middle phalanx itself, i.e., of the middle extensor tendon and the tendons of the flexor digitorum superficialis.

Extension of the DIP joint is usually coupled with that of the middle phalanx. Extension is initiated in the retinacular ligament by extension of the proximal interphalangeal joint. This triggers extension of the proximal phalanx. Then follows a combined action of the extensor communis tendon and of the tendons of the intrinsic muscles.

If the MCP joint is in extension, the contraction of the interossei is transmitted directly to the lateral bands, which extend the proximal and distal phalanges. If the proximal phalanx is flexed to 90 degrees, the hood of the interossei on the head of the proximal phalanx absorbs all the force of the interossei, which reinforces the flexion; no traction is transmitted to the lateral extensor tendon (Figure 2.6). In the intermediate positions, the interossei contribute at the same time to flexion on the proximal phalanx and to extension of the distal phalanx.

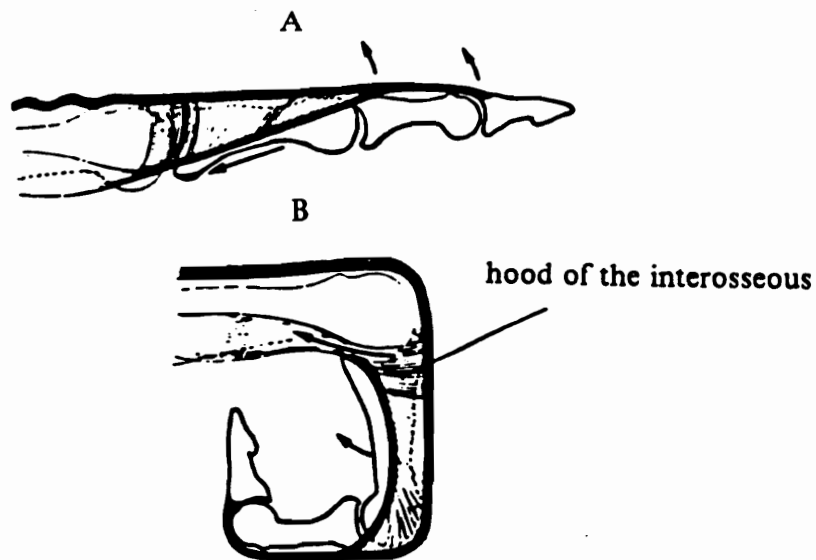


Figure 2.6 Role of the interossei in MCP extension.

A. When the MCP joint is in extension, the force of the interossei can be transmitted by the lateral band for extending the PIP and DIP joints; B. When the MCP joint is in flexion, the force of the interossei cannot be transmitted to the PIP and DIP joints.

(from Tubiana, 1981)

## *2.5 Discussion and Summary*

The hand is a multiarticular system. Its bony skeleton consists of carpals, metacarpals, and phalanges. The major mobile parts of the hand, phalanges, are moved by tendon excursions which are results of muscle contractions.

Muscles of the hand are divided into two groups by their locations: intrinsic and extrinsic muscles. Intrinsic muscles are the interossei and lumbricals. Extrinsic muscles are divided again into two groups by their functions: flexors and extensors. The flexors consist of the flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS). The extensor digitorum communis (EDC) is the major extensor.

The EDC extends the MCP, PIP, and DIP joints. The FDS flexes the MCP and PIP joints and the FDP flexes the PIP and DIP joints. The interossei participate in extension of the PIP and DIP joints and in flexion of the MCP joint. The lumbricals are activated when the PIP and DIP joints extend. However, activities of the intrinsic muscles are not consistent.

The complexity of finger movements results from the structure of the finger: each finger has three articulations, and the tendons of the muscles have multiple insertions, running across two or three joints. Tendons of the interossei and lumbricals merge into the tendon of the EDC and are connected with each other. The lumbricals arise from the tendons of the FDP. Therefore, the force generated by one muscle may act on several joints; conversely, forces from several muscles may act on one joint. Forces from the intrinsic muscles act obliquely. This complexity causes many arguments about the functions of the hand muscles. Although some uncertainties still exist,



electromyography has helped much to understand the muscular functions of finger movements.

## **III. Definitions of Finger Positions and Movements**

### ***3.1 Overview***

Since the finger is a tri-articular system, a large number of finger positions are possible by combining three joint angles. To describe these finger positions, definitions of some fundamental finger positions are needed. Four basic finger positions are explained followed by definition of the "resting position" of the finger. Then, two basic finger movements, which are important for this study, are explained.

### ***3.2 Four Basic Finger Positions***

Four basic finger positions were defined by Stack (1962) to study muscular functions in different finger positions; Landsmeer and Long (1965) used these four positions in their study on finger control using electromyography. They are

“Full extension” -- MCP extension and IP extension,

“Lumbrical position” -- Full MCP flexion and IP extension,

“Hook grip position” -- MCP extension and full IP flexion, and

“Full flexion” -- Full MCP flexion and full IP flexion.

These four basic finger positions have been used to study muscular functions (Landsmeer and Long, 1965; Stack, 1962). However, since these positions consist of only fully flexed or extended finger joints, they do not describe intermediate joint positions which are frequently used in control or force exertions. In order to study mechanical efficiencies of different finger positions in force exertions, it is necessary to define finger positions between the extremely flexed and extended finger positions.

Three angles of finger joints are defined :

Angle of the MCP joint -- Flexion angle of the proximal phalanx from its extended position at which the metacarpal and proximal phalanx are in a line.

Angle of the PIP joint -- Flexion angle of the middle phalanx from its extended position at which the proximal and middle phalanges are in a line.

Angle of the DIP joint -- Flexion angle of the distal phalanx from its extended position at which the middle and distal phalanges are in a line.

The angles of finger joints are illustrated in Figure 3.1.

In this study, four finger positions are defined based on the angle of each finger joint.

"Position 1" has angles of 15, 15, and 15 degrees at the MCP, PIP, and DIP joints, respectively.

"Position 2" has angles of 15, 30, and 15 degrees at the MCP, PIP, and DIP joints, respectively.

"Position 3" has angles of 30, 15, and 15 degrees at the MCP, PIP, and DIP joints, respectively.

"Position 4" has angles of 30, 30, and 15 degrees at the MCP, PIP, and DIP joints, respectively.

The angle of the DIP joint is kept constant.

### ***3.3 Resting Position of the Finger***

The resting position of the finger is defined as a position in which there are no activities in both the intrinsic and extrinsic muscles (Roberts, 1975). For the purpose of

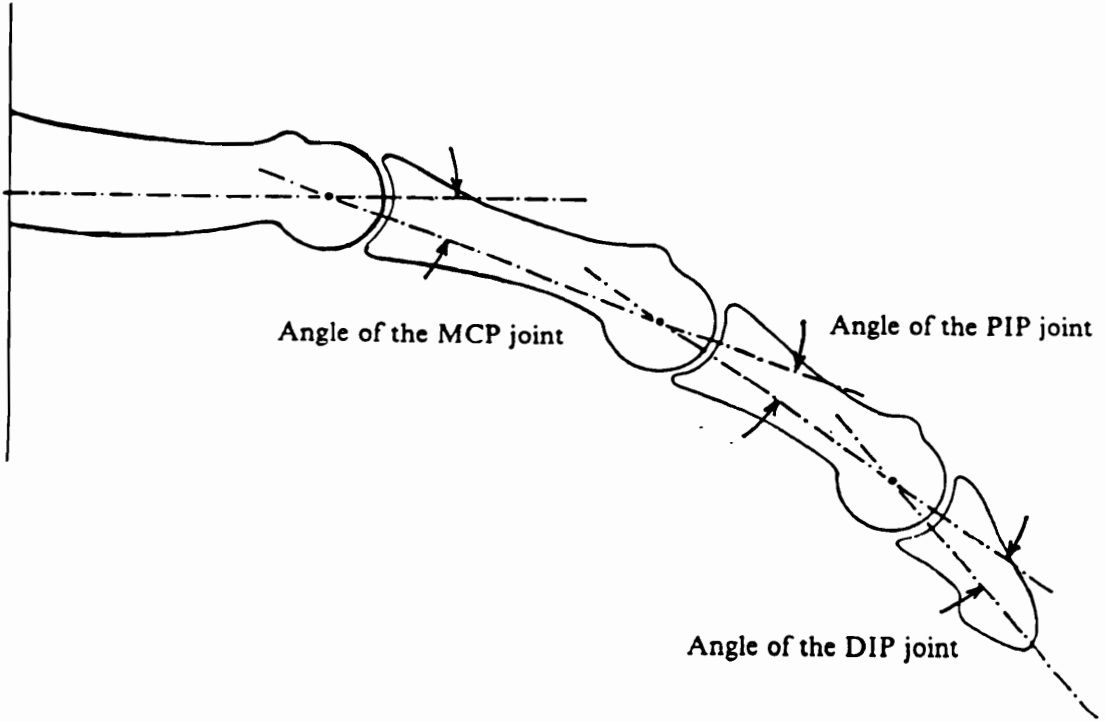


Figure 3.1 Definition of three finger joint angles.

this study, it is postulated that the finger muscles are at their resting lengths (Vander, Sherman, and Luciano, 1985). In this resting position, the finger is slightly flexed by the viscoelastic forces of tissues in the finger (Napier, 1980).

It is assumed that the resting muscle length is the middle of the muscle's range of contraction and extension which corresponds to the range of motion of the joint (Wilkie, 1976). Therefore, if the range of motion of a finger joint is known, the resting position of the finger can be quantitatively defined as being at the middle of the range of motion of the joint.

### ***3.4 Finger Movements about the MCP Joint ("Tapping")***

If the PIP and DIP joints are fixed, the finger can be considered a rigid body moving about the MCP joint. Finger movement about the MCP joint in the sagittal plane is named "tapping". Finger tapping is divided into two motion elements; "downward" movement of the finger is made by flexion of the proximal phalanx, and "upward" movement of the finger is made by extension of the proximal phalanx.

### ***3.5 Finger Movements about the PIP Joint ("Rocking")***

If the MCP joint is fixed, finger movements occur at the PIP and DIP joints. As discussed earlier, movement of the distal phalanx is dependent upon the movement of the middle phalanx. Finger movement about the PIP joint in the sagittal plane is named

“rocking”. Finger rocking is divided into two motion elements: “forward” pushing movement of the finger from its resting position is made by extension of the middle and distal phalanges; “aft” pulling movement of the finger from the resting position is made by flexion of the middle and distal phalanges. (In reality, finger rocking also involves minor movements in the MCP and DIP joints.)

### ***3.6 Muscles in Finger Tapping and Rocking***

Muscular activities involved in finger motions were investigated by many researchers (Backhouse, 1966; Backhouse and Catton, 1954; Close and Kidd, 1969; Harris and Rutledge, 1972; Ketchum, Funderburk, Essen, and Lind, 1975; Landsmeer, 1961, 1962, 1963; Landsmeer and Long, 1965; Long, Brown, and Weiss, 1960 and 1961; Long, Conrad, Hall, and Furler, 1970; Spoor, 1983; Spoor and Landsmeer, 1976; Stack, 1962; Storace, 1977; Thomas, 1965; Thomas, Long, and Landsmeer, 1968; Wells, Ranney, and Keeler, 1985). As gleaned from their studies, the muscles activated in finger tapping and rocking are as follows:

#### **1. Tapping**

(a) Flexion of the proximal phalanx: The flexor digitorum profundus plays a major role and the intrinsic muscles are also activated. Interossei are always activated when the MCP joint is flexed. Activation of the lumbricals in this motion is not consistent.

(b) Extension of the proximal phalanx: Only the extensor muscle is activated. There is no activity in the intrinsic muscles. The flexor digitorum profundus may act as an internal antagonistic force.

## 2. Rocking

- (a) Extension of the middle phalanx: The extensor, interossei, and lumbricals are simultaneously activated.
- (b) Flexion of the middle phalanx: Both the flexor digitorum profundus and the flexor digitorum superficialis are activated.

The muscular activities for each simplified finger movement in tapping and rocking are listed in Table 3.1. Muscular involvements in finger movements, however, are variable depending on the finger positions and existence of external load. Especially, the roles of the FDS in MCP joint extension and of the lumbricals in MCP joint flexion are not clear (Eyler and Markee, 1954; Hall and Long, 1968; Long and Brown, 1964; Long, Brown, and Weiss, 1961; Youm, Gillespie, Flatt, and Sprague, 1978). It is necessary to investigate the functions of muscles as the finger positions are changing and with and without an external load.

### *3.7 Discussion and Summary*

Stack's (1962) definitions of four basic finger positions are used to discuss joint angles and to establish the four finger positions to be investigated in this study.

The resting position of the finger is qualitatively defined. (It will be re-defined quantitatively in the Chapter 7 using information on ranges of motions of finger joints and muscle length-tension relationships.)



Table 3.1 Muscular activities in finger tapping and rocking.

Muscle \ Movem't	Tapping		Rocking	
	Upward	Downward	Forward	Backward
EDC	X		X	
FDS	(X)	X		X
FDP				X
Interossei		X	X	
Lumbricals		(X)	X	

**legend** (X) : inconsistent activation

EDC : Extensor Digitorum Communis

FDS : Flexor Digotorum Superficialis

FDP : Flexor Digitorum Profundus

Finger tapping is defined as finger movements about the MCP joint in the sagittal plane. It consists of downward and upward movements. Finger rocking is defined as finger movements about the PIP joint. It consists of backward and forward movements. In finger tapping the PIP and DIP joints are assumed to be fixed while in finger rocking the MCP joint is fixed. Muscles involved in tapping and rocking are identified.

# **IV. Literature Review of Biomechanical Finger Models**

## ***4.1 Overview***

Kinematic and static models of the finger have been developed using Landsmeer's tendon excursion models. In this chapter, Landsmeer's three tendon excursion models are reviewed first. Then, explanations of static and kinematic finger models are provided. Two approaches for establishing equilibrium equations are compared.

## 4.2 Tendon Excursion Models

The functional anatomy and the spatial relationships between the tendons and muscles and their associated joints were extensively studied by Landsmeer (1961 and 1962). Landsmeer also proposed a series of models to represent the various manners in which tendons bridge associated joints.

Landsmeer's first model (Model I) is for a joint in which the bridging tendon runs straight over a trochlea, which is the anatomical equivalent of a mechanical pulley. In this joint system, there is a simple relationship between the change of angle of the joint and the concomitant excursion of the tendon. The relationship can be expressed by

$$X = r \theta, \quad (4.1)$$

where  $X$  is the length of tendon excursion,  $r$  is the radius of the trochlea, and  $\theta$  is the change of angle of the joint in radians (Figure 4.1).

Landsmeer's second model (Model II) is for a joint in which the tendon runs through an imaginary loop which is freely movable round the axis of joint. The tendon runs parallel with the long axes of the adjacent bones. The loop then takes up a position along the bissectrix of the joint angle. The amount of tendon excursion,  $X$ , is

$$X = 2r \sin \left( \frac{\theta}{2} \right), \quad (4.2)$$

in which  $r$  stands for the radius of the imaginary circle through which the tendon runs, and  $\theta$  stands for the angle of rotation (Figure 4.2). For limited changes of angle,

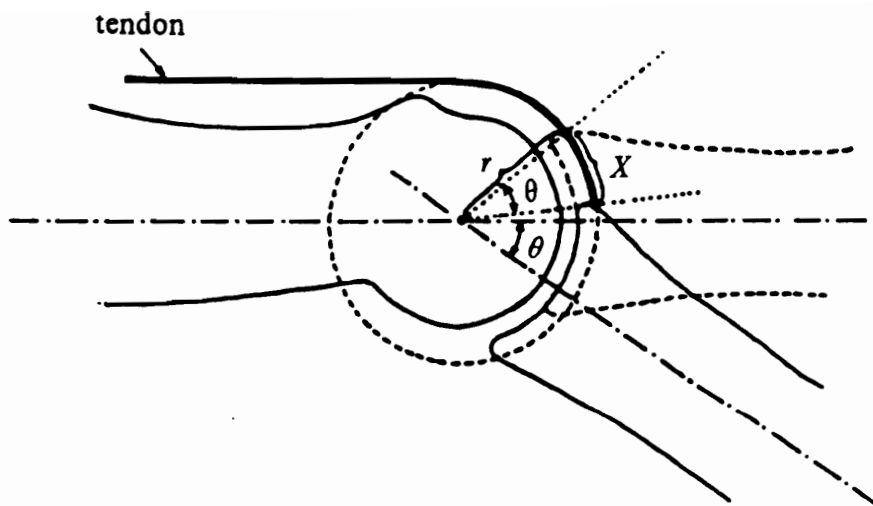


Figure 4.1 Schematic diagram of tendon excursion in Landsmeer's first model.

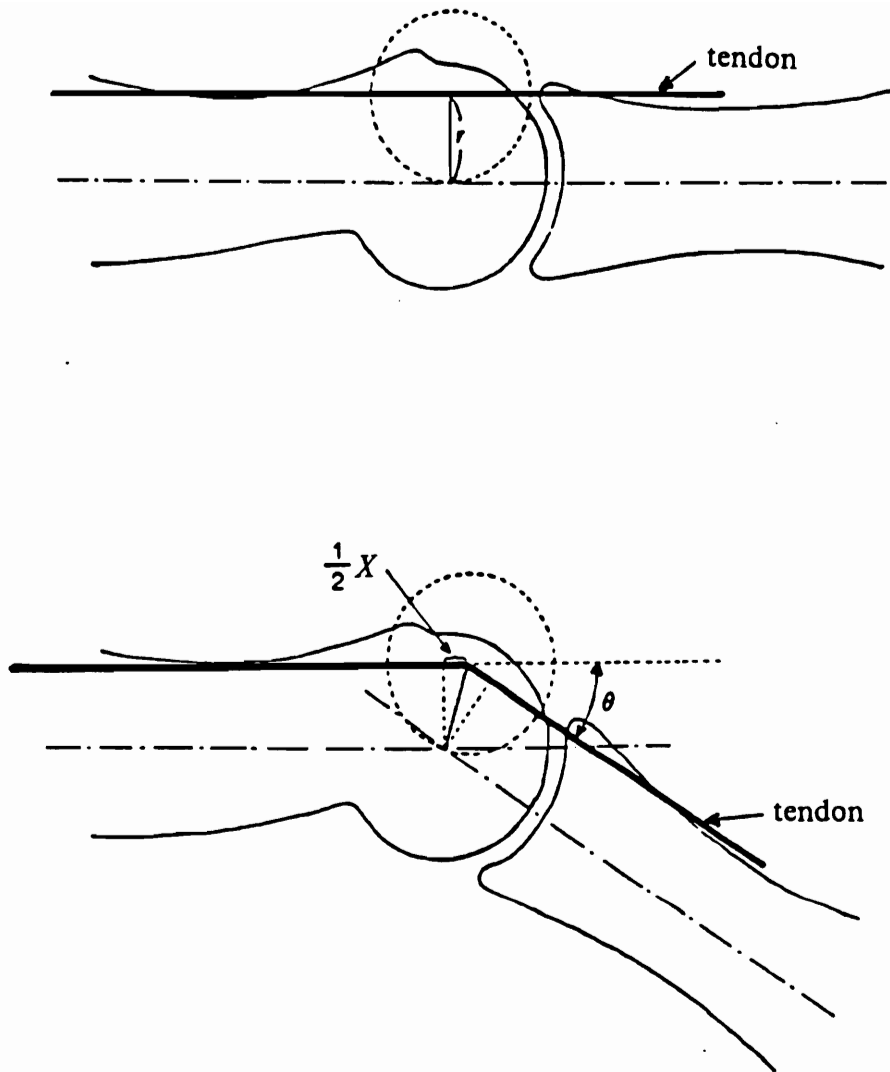


Figure 4.2 Schematic diagram of tendon excursion in Landsmeer's second model.

$\theta < 0.5 \pi$  radians, this formula can be written as  $X = 2r(\theta/2)$ . For large angles,  $\theta > 0.5 \pi$  radians, the formula  $X = r\theta$  provides a reasonable approximation.

Landsmeer's third model (Model III) represents a situation in which the tendon runs in a tendon-sheath which holds it firmly in a constant position against the shaft of the bones. The tendon sheath, however, allows the tendon to curve smoothly instead of bending like the joint. When the joint flexes from the extended position to a value  $\theta$ , each bone is assumed to have passed through an angle of  $\frac{\theta}{2}$ . The excursion of the tendon,  $X$ , can be expressed as

$$X = 2 \left[ y + \frac{\theta}{2} \left\{ d - \frac{y}{\tan\left(\frac{\theta}{2}\right)} \right\} \right], \quad (4.3)$$

where  $y$  is the distance from the straight part of the tendon or the rigid part of the sheath to the joint axis, measured along the axis of the bone, and  $d$  stands for the distance of that particular part of the tendon to the long axis of the bone (Figure 4.3).

Landsmeer's first model is well suited for describing extensor tendon excursion in the finger. Some investigators reported that Landsmeer's first model may also appropriately describe the displacement of flexor tendons (Armstrong and Chaffin, 1978; Brand, Cranor, and Ellis, 1975; Fischer, 1969). Landsmeer's third model is suitable for describing the displacement of the flexor tendons, while the tendon excursion of the interosseous muscle is described by the Landsmeer's second model.

An, Ueba, Chao, Cooney, and Lindscheid (1983) investigated the relationship between joint displacement, tendon excursion, and moment arm in the index finger. They performed finger joint excursion experiments and compared tendon excursions and moment arms with those of Landsmeer's three models. They found that the flexion-extension moment arms of the extrinsic muscles were fairly constant at the PIP and DIP

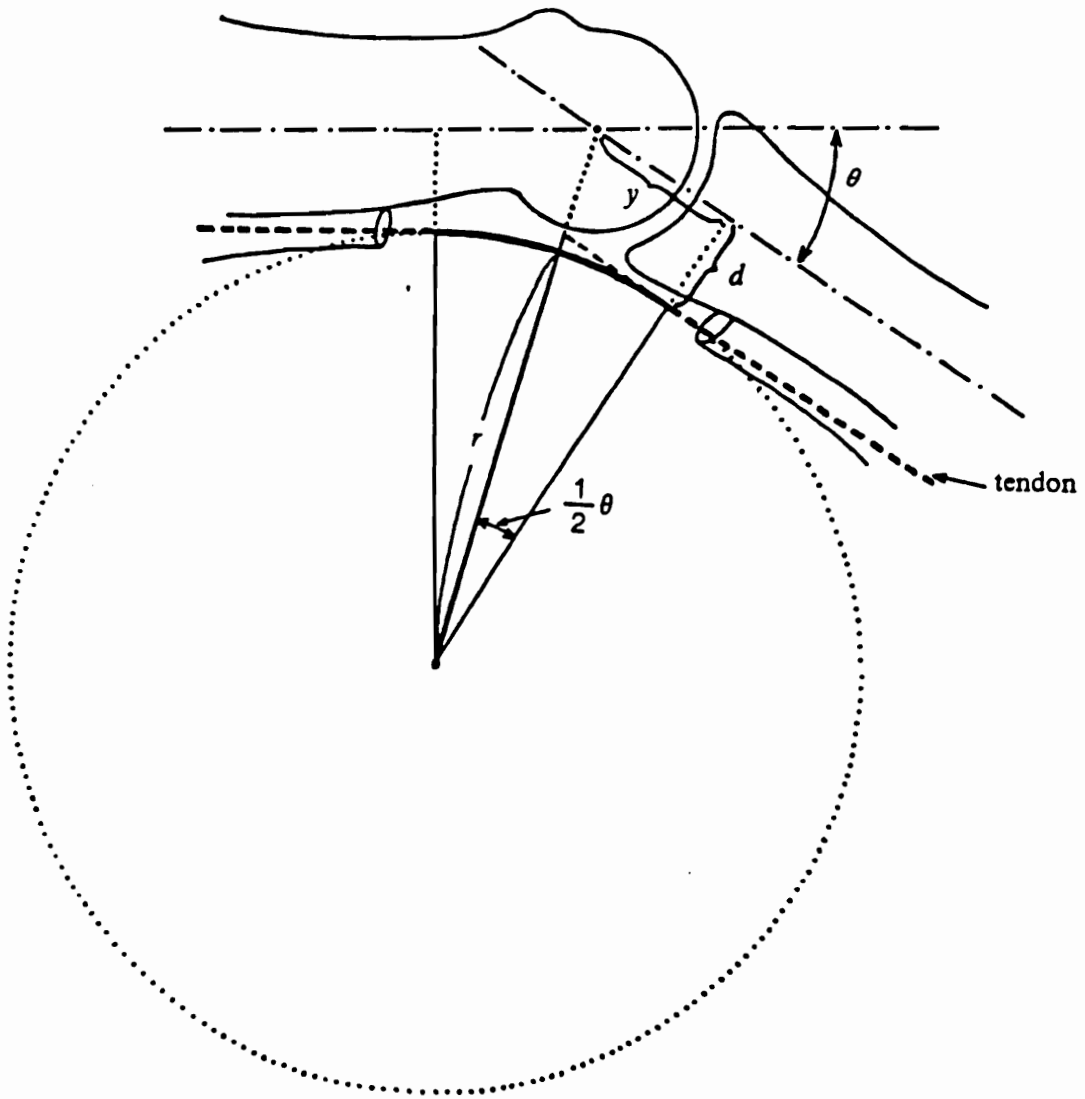


Figure 4.3 Schematic diagram of tendon excursion in Landsmeer's third model.



joints, but tended to increase slightly (3.8 mm/radian) toward the flexed position. In addition, the extension moment arms of the extensor and intrinsic muscles at the PIP joint were fairly constant near the extended position, but constantly increased in the flexed position.

Fischer (1969) derived an approximation of Landsmeer's first model of tendon excursion, assuming that flexor tendon moment arms increase linearly during finger flexion. Since the tendon moment arm is a function of finger position,  $\theta$ , the tendon excursion can be expressed as

$$\begin{aligned}
 X &= \int_{\theta_0}^{\theta} r(\theta) d\theta \\
 &= \int_{\theta_0}^{\theta} (r_0 + b \theta) d\theta \\
 &= \left\{ r_0 + \frac{b}{2} (\theta + \theta_0) \right\} (\theta - \theta_0),
 \end{aligned} \tag{4.4}$$

where  $r_0$  denotes the moment arm of the tendon when the joint angle is  $\theta_0$ , and  $b$  is a constant. Joint angles are in radians. If  $\theta_0 = 0$ , the tendon excursion becomes

$$X = \left( r_0 + \frac{b}{2} \theta \right) \theta. \tag{4.5}$$

This expression of tendon excursion has the same form as the equation derived by Thomas (1965). Thomas also reported that "some bone heads have radii of curvature which increase about 15 percent per radian of rotation from the extended position into flexion"(pp. 39). This means that "b" in equation (4.5) equals  $0.15 r_0$ . As An et al. (1983)

showed, equation (4.5) can be used to compute tendon excursions of the flexor digitorum profundus and superficialis muscles when the tendon moment arms increase in finger flexion.

### ***4.3 Static and Kinematic Models of The Finger***

Mechanical modeling of finger motion relies on force analyses. External forces may cause motion of the body which may change body geometry. Kinematics is the study of this geometry of body motion.

As the finger and hand are complex in anatomy and functions of muscles, tendons, ligaments, and sheaths, simplification and assumptions have been made for modeling the motion of finger. Spoor (1983) developed a two-dimensional model of a slightly flexed middle finger with the following assumptions:

- 1) No joint is in an extreme position of flexion or extension.
- 2) The intrinsic muscles inserting into the proximal phalanx are slack.
- 3) The interossei and the lumbricals are represented by only one intrinsic muscle.
- 4) The extensor tendon branches into three bundles at the proximal phalanx.
- 5) The intrinsic muscles insert into the three bundles.

With these assumptions, Spoor derived the equilibrium equation for each finger joint (Figure 4.4). The equations of moment equilibrium with respect to the flexion axes of the joints are as follows:

$$F_P r_{P1} + F_S r_{S1} + F_I r_{I1} - F_E r_{E1} - T r_{K1} = 0 \quad (4.6)$$

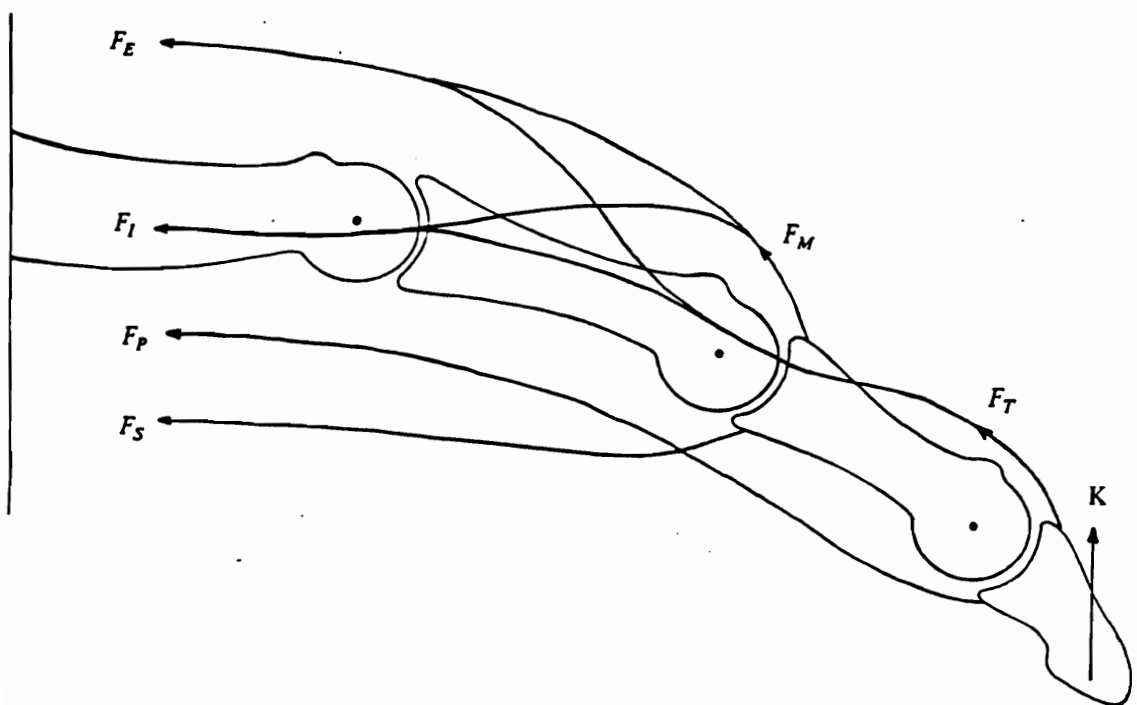


Figure 4.4 Forces in Spoor's finger model.

$$F_P r_{P2} + F_S r_{S2} - F_M r_{M2} - F_T r_{T2} - T r_{K2} = 0 \quad (4.7)$$

$$F_P r_{P3} - F_T r_{T3} - T r_{K3} = 0 \quad (4.8)$$

$$F_I + F_E = F_M + F_T, \quad (4.9)$$

where  $F_P$  stands for the force in the tendon of the flexor profundus muscle,  $F_S$  stands for the force in the flexor superficialis tendon,  $F_E$  stands for the force in the extensor tendon,  $F_M$  stands for the force in the medial extensor slip,  $F_T$  stands for the force in the terminal extensor slip,  $F_I$  stands for the force in the intrinsics, and  $T$  stands for the external force on the fingertip. The letter  $r$  stands for the distance from a tendon (or the line of action of a force) to a joint axis. Its first index indicates the tendon (T, M, I, E, P, and S) and the external force (K) and the second index indicates the joint of finger (1 = MCP, 2 = PIP, and 3 = DIP joints, respectively).

Storace and Wolf (1979) developed a two-joint model of finger extension and flexion. They considered only the MP and PIP joints because the movement of the DIP joint is dependent on the movement of the PIP joint. Extensor, flexor profundus, and interosseous muscles were used for modeling the finger. Landsmeer's first model of tendon excursion was applied to the movements of three muscles. Tendon excursions of three muscles are expressed as

$$X_E = a_1 \theta_1 + a_2 \theta_2 \quad (4.10)$$

$$X_P = - b_1 \theta_1 - b_2 \theta_2 \quad (4.11)$$

$$X_I = - c_1 \theta_1 + c_2 \theta_2, \quad (4.12)$$

where  $X_E$ ,  $X_P$ , and  $X_I$  represent the tendon excursions of the extensor, flexor profundus, and interosseous muscles, respectively, with distal excursions considered positive and proximal excursions negative. The angles  $\theta_1$ ,  $\theta_2$ , and  $\theta_3$  stand for the MCP, PIP, and DIP joint angles. The constants  $a_1$ ,  $a_2$ ,  $b_1$ ,  $b_2$ ,  $c_1$ , and  $c_2$  are all positive.

Using the "principle of virtual work", Storace and Wolf (1979) developed a two-tendon model and a three-tendon model based upon the moment equilibrium equation and evaluated these models with respect to the anatomy. In the two-tendon model, the force of the interosseous muscle was assumed to be zero. Therefore, the extensor and flexor profundus forces were required to maintain equilibrium of the finger when external torques were applied. The three-tendon model consisted of three unknown tendon forces, while only two equations were provided. With those equations, Storace and Wolf (1979) investigated the conditions under which the finger could be expected to support an arbitrary applied load.

Buchner, Hines, and Hemami (1988) developed excursion equations for the five muscles in the finger. They used Landsmeer's first tendon excursion model for describing the displacement of the extensor tendons, while Fischer's (1969) approximation of Landsmeer's first model was used for the flexor tendons. They made the following assumptions for their model of finger motions:

- 1) The motion of the model is restricted to the sagittal plane, since only interphalangeal movements of the finger are performed.
- 2) One finger model represents the four fingers assuming that they all perform the same movement.
- 3) The palmar and dorsal interossei are viewed as one muscle.
- 4) The insertion of the interossei into the lateral band of the extensor apparatus is ignored, which means that the interossei are considered to

insert solely into the base of the middle phalanx.

- 5) The lumbrical tendon is assumed to join together with the lateral band proceeding distally to perform the terminal tendon.

The tendon excursion models developed by Buchner, Hines, and Hemami (1988) are

$$X_E = -r_{E1}\theta_1 + \min \{ -r_{E2}\theta_2; -(r_{E2} - r_{E2}'\theta_2)\theta_2 - r_{E3}\theta_3 \} \quad (4.13)$$

$$X_P = (r_{P1} + r_{P1}'\theta_1)\theta_1 + (r_{P2} + r_{P2}'\theta_2)\theta_2 + (r_{P3} + r_{P3}'\theta_3)\theta_3 \quad (4.14)$$

$$X_S = (r_{S1} + r_{S1}'\theta_1)\theta_1 + r_{S2}\theta_2 \quad (4.15)$$

$$X_I = r_{I1}\theta_1 - r_{I2}\theta_2 \quad (4.16)$$

$$X_L = (r_{L1} - r_{P1} - r_{P1}'\theta_1)\theta_1 - (r_{L2} + r_{L2}'\theta_2 + r_{P2} + r_{P2}'\theta_2)\theta_2 - (r_{E3} + r_{P3} + r_{P3}'\theta_3)\theta_3, \quad (4.17)$$

where  $r_{ij}$  represents the moment arm of the muscle  $i$  at the joint  $j$  when the finger is extended. The first index of  $r$  indicates the muscle (E = extensor, P = flexor profundus, S = flexor superficialis, I = interosseous, and L = lumbrical muscles), and the second index of  $r$  indicates the joint (1 = MCP, 2 = PIP, and 3 = DIP joints).  $r_{ij}'$  refers to the moment arm of the muscle  $i$  at the joint  $j$  when the finger is flexed. The angles  $\theta_1$ ,  $\theta_2$ , and  $\theta_3$  refer to the MCP, PIP, and DIP joint angles, respectively.

Fischer (1969) developed a finger model using Landsmeer's tendon excursion models and his own approximation of Landsmeer's model. Fischer's tendon excursion models are

$$X_E = (r_{E1} + b_E \theta_1) \theta_1 + r_{E2} \theta_2 + r_{E3} \theta_3 \quad (4.18)$$

$$X_P = - \sum_{j=1}^3 [ 2y_{Pj} ( 1 - \frac{\frac{\theta_j}{2}}{\tan \frac{\theta_j}{2}} ) + d_{Pj} \theta_j ] \quad (4.19)$$

$$X_S = - \sum_{j=1}^2 [ 2y_{Sj} ( 1 - \frac{\frac{\theta_j}{2}}{\tan \frac{\theta_j}{2}} ) + d_{Sj} \theta_j ] \quad (4.20)$$

$$X_I = - (r_{I1} + b_I \theta_1) \theta_1 + \int_0^{\theta_2} r_{12}(\theta) d\theta + r_{E3} \theta_3 \quad (4.21)$$

$$X_L = - (r_{L1} + b_L \theta_1) \theta_1 - X_P + \int_0^{\theta_2} r_{12}(\theta) d\theta + r_{L3} \theta_3, \quad (4.22)$$

where  $r_{E1}$ ,  $r_{E2}$ , and  $r_{E3}$  are the moment arms of the extensor at MCP, PIP, and DIP joint, respectively;  $r_{I1}$  is the moment arm of the interossei at MCP joint;  $r_{L1}$  and  $r_{L3}$  are the moment arms of the lumbricals at the MCP and DIP joint, respectively;  $y_{Pj}$  and  $y_{Sj}$  are the distances from the joint axis to the straight part of the flexor profundus and superficialis tendon at joint j, respectively;  $d_{Pj}$  and  $d_{Sj}$  are the distances from the longitudinal axis of the bone to the flexor profundus and superficialis tendon at joint j, respectively;  $b_E$ ,  $b_L$ , and  $b_I$  are the changes of  $r_{E1}$ ,  $r_{L1}$ , and  $r_{I1}$  per radian of flexion, respectively;  $X_P$  is the total proximal displacement of the flexor profundus tendon;  $r_{12}(\theta)$  corresponds to the moment arm of the lateral band.

Fischer also derived the equations of static equilibrium. They are

$$\begin{aligned}
F_L(r_{P1} - r_{L1}) - F_{I_R}r_{I_{R1}} - F_{I_U}r_{I_{U1}} - F_P r_{P1} \\
- F_S r_{S1} + F_E r_{E1} - TR_1 = 0
\end{aligned} \tag{4.23}$$

$$\begin{aligned}
F_M r_{E2} + F_T r_{E12} + F_L r_{P2} - F_P r_{P2} \\
- F_S r_{S2} - F_R r_{R2} - TR_2 = 0
\end{aligned} \tag{4.24}$$

$$F_T r_{E3} + F_L r_{P3} - F_P r_{P3} + F_R r_{E3} - TR_3 = 0 \tag{4.25}$$

$$F_M + F_T - F_E - F_{I_U} - F_{I_R} + F_R = 0 \tag{4.26}$$

$$F_L + F_{I_R} - F_{I_U} + TR_R = 0 \tag{4.27}$$

In these equations,  $F_E$ ,  $F_M$ , and  $F_T$  denote the tensions applied to extensor tendon at the MCP joint, median tendon at the PIP joint, and terminal tendon at the DIP joint, respectively.  $F_P$ ,  $F_S$ ,  $F_I$ , and  $F_L$  are the tensions applied to the flexor profundus, flexor superficialis, interosseous, and lumbrical muscles, respectively.  $F_R$  represents the tension acting on oblique portion of retinacular ligament.  $F_{I_R}$  and  $F_{I_U}$  are radial and ulnar components of interosseous tension  $F_I$ . The letter "r" represents the moment arms: thus,  $r_{P1}$  denotes the moment arm of flexor profundus at MCP joint.  $r_{E12}$  is the moment arm of the lateral band at the PIP joint.  $TR_1$ ,  $TR_2$ , and  $TR_3$  are external torques applied to the MCP, PIP, and DIP joints, respectively.  $TR_R$  is a force that accounts for a radial or ulnar imbalance in the intrinsic loads in Fischer's models.

Thomas (1965) modified Landsmeer's tendon excursion models and developed a finger model in which finger movements about the dorsal-volar axis (adduction-abduction) are included as well as finger flexion-extension. For the extensor muscle whose tendon



moment arms varies linearly with the angular rotation,  $\theta$ , the tendon excursion is expressed (like in equation (4.5)) as

$$X = (r_o + \frac{b}{2} \theta) \theta. \quad (4.28)$$

When the finger flexes from the extended position by  $\theta$  about a radial-ulnar axis (axis of flexion-extension) and by  $\psi$  about a dorsal-volar axis (axis of adduction-abduction), total tendon excursion of the extensor (for combined flexion/extension and abduction/adduction) is expressed as

$$X_E = [r_E (1 + 0.15 \theta) + \frac{t_E}{2}] \theta - 2y_E [1 - \frac{\frac{\psi}{2}}{\tan \frac{\psi}{2}}], \quad (4.29)$$

where  $y_E$  denotes the axial distance from the axis of flexion to the point where the wing tendon inserts into the extensor tendon on the dorsum of the proximal phalanx, and  $d_E$  is the perpendicular distance from the longitudinal axis of the proximal phalanx to the tendon;  $r_E$  is the moment arm of the extensor tendon;  $t_E$  is the thickness of the tendon.

For flexors, Thomas (1965) derived the following equations of tendon excursions:

$$X_S = -[(2y_F - 0.15 r_E \theta) (1 - \frac{\frac{\theta}{2}}{\tan \frac{\theta}{2}}) + d_{F_S} \theta + 2y_F (1 - \frac{\frac{\psi}{2}}{\tan \frac{\psi}{2}})] \quad (4.30)$$

$$X_P = -[(2y_F - 0.15 r_E \theta) (1 - \frac{\frac{\theta}{2}}{\tan \frac{\theta}{2}}) + d_{F_P} \theta] - 2y_F (1 - \frac{\frac{\psi}{2}}{\tan \frac{\psi}{2}}), \quad (4.31)$$

where  $r_E$  and  $r_F$  are the moment arms of the extensor and flexor profundus, respectively;  $d_{FS}$  and  $d_{FP}$  are the perpendicular distances from the longitudinal axis to the edge of the flexor superficialis and profundus tendons, respectively, at the opening of the tendon sheath;  $y_F$  is the axial distance to the opening of the tendon sheath.

Tendon excursion of the lumbrical muscle is expressed as

$$X_L = r_{L\psi} \psi - \left( r_{L\theta} + \frac{b_{L\theta}}{2} \theta \right) \theta, \quad (4.32)$$

where  $r_{L\psi}$  refers to the tendon moment arm measured perpendicular to the  $\psi$  -axis;  $r_{L\theta}$  is the tendon moment arm measured perpendicular to the  $\theta$  -axis when the finger is extended;  $b_{L\theta}$  is the change in the tendon moment arm per radian of finger flexion.

For the interosseous muscles, Thomas assumed that the ulnar and radial interossei are mutually independent muscles. The ulnar interossei have only a tendinous insertion while the radial interossei have both bony and tendinous insertions. The bony insertion of the radial interossei is on the radial side of the base of the proximal phalanx and the tendinous insertion is into the wing tendon. These two segments have slightly different radii at the MCP joint. Thomas described tendon excursions for these three different insertions of the interossei.

Tendon excursion of the radial interossei inserted into the base of the proximal phalanx is described by

$$X_{RI_B} = - \left[ r_{\psi_B} \psi + \left( r_{\theta_B} + \frac{b_{\theta_B}}{2} \theta \right) \theta \right], \quad (4.33)$$

where  $r_{\psi_B}$  and  $r_{\theta_B}$  are the moment arms to the segment with the bony insertions from the  $\psi$  -axis and  $\theta$  - axis, respectively;  $b_{\theta_B}$  is the change in  $r_{\theta_B}$  per radian of flexion.

Tendon excursion of the radial interossei inserted into the wing tendon is expressed as

$$X_{RI_T} = - \left[ r_{\psi T} \psi + \left( r_{\theta T} + \frac{b_{\theta T}}{2} \theta \right) \theta \right], \quad (4.34)$$

where  $r_{\psi T}$  and  $r_{\theta T}$  are the moment arms to the segment with the tendinous insertion from the  $\psi$  -axis and  $\theta$  -axis, respectively;  $b_{\theta T}$  is the change in  $r_{\theta T}$  per radian of flexion.

Tendon excursion of the ulnar interossei is expressed as

$$X_{UI} = r_{\psi U} \psi - \left( r_{\theta U} + \frac{b_{\theta U}}{2} \theta \right) \theta, \quad (4.35)$$

where  $r_{\psi U}$  and  $r_{\theta U}$  are the tendon moment arms from  $\psi$  -axis and  $\theta$  -axis, respectively, when the finger is extended;  $b_{\theta U}$  is the change in  $r_{\theta U}$  per radian of flexion.

Most of the mechanical models for the finger motion have been made in the sagittal plane only, thus they are two-dimensional models. Chao, Opgrande, and Axmear (1976), however, performed three-dimensional force analysis of the finger. Six Cartesian coordinate systems were established to facilitate the location and orientation of the tendons and applied forces in pinch and grasp. Two coordinate systems were used for both the middle and proximal phalanges. The first coordinate system was located at the approximate center of rotation of the phalangeal head, and the second system was a translation of the first system to the center of the concave articular surface at the proximal end. The x-axis of the system was projected along the phalangeal shaft, while the y-axis was projected dorsally and the z-axis was projected radially for the right hand.

Eulerian angles for rigid-body motion were used to express the local coordinates. Free-body analyses were performed on all three finger joints. There were 19 independent

equations, but the unknown joint-constraint forces and tendon-muscle forces in the equations totaled 23. To solve that problem, Chao, Opgrande, and Axmear (1976) assumed that four tendons carried no force, thus making the system statically determinate. Linear programming technique was used to solve the problem.

An and coworkers published extensively on their three-dimensional model of the finger (An, Chao, Cooney, and Lindscheid, 1979; An, Chao, Cooney, and Lindscheid, 1985; An, Ueba, Chao, Cooney, and Lindscheid, 1983; Chao, Opgrande, and Axmear, 1976; Cooney and Chao, 1977). Their studies provide three-dimensional force analyses of the finger and thumb joints. Fingers and thumb were considered as linkage systems of intercalated bony segments. Six Cartesian coordinate systems at each finger and thumb were defined to express the location and orientations of tendons and to describe joint configurations. Using these coordinate systems, they computed the tendon locations and excursions for various configurations of the finger.

#### ***4.4 Methods for Establishing the Equilibrium Equations***

For biomechanical modeling of the finger, one needs to describe muscular forces which act on the joints in various finger positions. Equilibrium equations are generally used to compute muscular forces. There are two ways to obtain equilibrium equations. One is development of moment and force equilibrium equations for all joints via free body analysis. These equations may have the following forms:

$$\sum force = 0 \tag{4.36}$$

$$\sum \text{moment} = 0. \quad (4.37)$$

If this problem is statically determinate, solutions can be obtained by solving these simultaneous equations for muscular forces. Fischer (1969), Spoor (1983), and Thomas (1965) used this approach.

The other approach consists of two stages: development of tendon excursion equations for all muscles, and of moment equilibrium equations based on the principle of virtual work (Beer and Johnston, 1987; Buchner, 1983; Storage and Wolf, 1979). If there is no external load, this problem has the following forms:

$$X_i = (\text{total tendon excursion in muscle } i) \quad (4.38)$$

$$\sum F_i \delta X_i = 0, \quad (4.39)$$

where  $X_i$  stands for tendon excursion in muscle  $i$ , and  $F_i$  stands for the force exerted by muscle  $i$ . To solve this problem for muscular forces  $F_i$ , the concept of partial derivatives can be used (Storage and Wolf, 1979).

Buchner (1983) compared the method of virtual work to the free body analysis regarding derivation of equations of muscular-skeletal dynamics. He explained that the Newton-Euler approach required qualitative knowledge about the origin and insertion of the muscles. Information about the points of the origins and insertions of the muscles and tendons must be acquired. In addition, a large amount of computational work is required in this approach. During the numerical analysis, every location of the connection points and the directional sines and cosines of all muscular forces must be computed. The torques about the center of mass of each link also have to be calculated.

This is a laborious procedure even though the number of computations may be reduced by simplifying the analytical expression.

Buchner (1983) showed that the method of virtual work is identical with free body analysis when the connection constraint forces between the links are eliminated. Buchner reported that the method of virtual work was a convenient approach to implement muscles into a skeletal assemblage:

- 1) The implementation of muscles or tendons may be accomplished after the dynamic equations have been derived.
- 2) The mathematical expression is in general easy to simplify.
- 3) The locations of muscle origin or insertion are superfluous if the displacement of the muscle can be expressed as a function of the joint angle.

In summary, the free body analysis requires many values of direction and magnitude of forces (vector quantities) acting on the point of tendon insertion. It is difficult or even impossible to define all forces in the joints. The method of virtual work requires relatively fewer data to solve the problem. In addition, the required data, which are scalar quantities, can be easily obtained.

## ***4.5 Discussion and Summary***

Tendon excursions at the finger joints were modeled by Landsmeer (1961 and 1962). Landsmeer's first model is well suited for extensor tendon excursion. It is also applicable to flexor tendons. Landsmeer's third model is suitable for flexor tendons. Landsmeer's second model was developed for tendon excursions of the interossei but is rarely used:

since the interossei run obliquely over the joint, Landsmeer's first model can be used to describe their tendon excursions.

Many biomechanical finger models have been developed. These finger models generally have two forms: tendon excursion equations and/or force (moment) equilibrium equations. The tendon excursion equations (kinematic models) use Landsmeer's models and/or modified Landsmeer's equations. The force equilibrium equations are made by free body analysis. Free body analysis based on the Newton-Euler approach is easy to understand but requires exact knowledge of magnitudes and directions of forces. It also requires a large amount of computational work.

A new approach to develop equilibrium equations has two stages: development of tendon excursion equations for all muscles and of moment equilibrium equations using the principle of virtual work. This method requires somewhat complex steps to develop equilibrium equations. However, it does not require exact information about the directions of the forces, and uses scalar quantities instead of vectors in free body analysis. This method requires fewer data and is useful when the exact directions of the forces can not be identified.

## **V. Muscular Force and Electromyography**

### ***5.1 Overview***

Muscular strength is defined as the maximal voluntary force that muscle(s) can develop under prescribed conditions. In muscular strength assessment, major issues are how a true maximal exertion can be made by the subject and whether the exerted force is a true maximal force or not. Several techniques for making the subject exert the maximal voluntary contraction (MVC) are reviewed. Applications of electromyograms (EMGs) for assessing a true maximal exertion are explained. Finally, relationships between exerted muscular forces and EMGs are explained.



## *5.2 Assessment of Maximal Voluntary Contraction*

Isometric voluntary muscular strength, static strength in short, is operationally defined as the maximal force or torque that muscle(s) can exert isometrically in a single voluntary effort. The force or torque measured is the result of complex interactions of internal functions of the musculo-skeletal system which involves different types of motor units, mechanical advantages and feedback control by nerves. In a test situation, however, even a cooperative subject exerts a muscular output that is below the structural strength limit by a substantial yet unspecified safety margin. This submaximal exertion of muscle(s) is called "maximum voluntary contraction" (MVC) (Kroemer and Howard, 1970).

Static strength testing has several advantages over dynamic strength testing:

1. The test is relatively simple.
2. Subjects are at minimal risk of injuring themselves during test since the exertion is isometric.
3. The measurement is repeatable with a high degree of reliability (NIOSH, 1981).

Assessment of MVC is of much practical importance and yet a difficult problem. Various techniques may be applied to make a subject exert a true "maximal" effort.

A standard test procedure was proposed for static MVC tests (Caldwell, Chaffin, Dukes-Dobos, Kroemer, Laubach, Snook, and Wasserman, 1974). The so-called "Caldwell Regimen" consists of two stages of force exertion. First, subjects increase the force exertion to maximal level in about one second. Then they maintain the maximal exertion for four seconds. The average force over three of the four seconds is the MVC.

The length of force build-up time is important for achieving the maximum voluntary contraction (Newell and Carlton, 1985). Muscle fibers require time to produce a maximal output. This muscular force-to-time relationship was studied by Miller and Nelson (1976) and modeled by Kroemer and Marras (1981). Kroemer and Marras fitted a linear line to the force-to-time relationship and determined the slope of the line for various single joint actions such as finger flexion, elbow flexion, and knee flexion and extension. The results showed that maximal strength was reached in less than one second. Kroemer and Marras (1981) also reported that the shorter the build-up time, the higher the probability that an MVC was performed.

Viitasalo and Komi (1981) investigated the rate of force development by sampling the force-time curve at 5 ms intervals establishing a tangent on the slope, and finding the highest value of the slope coefficient. They reported that the highest rate of force development represented the point where the firing rate and number of active Type F motor units was maximal, i.e., the point of MVC.

Electromyography (EMG) is often used to check whether or not a maximal exertion of muscle is present. Chaffin, Lee, and Freivalds (1980) used rectified EMG amplitudes to detect sincere and faking subjects in isometric contraction. The sincere subjects group was told to exert maximal strength, while the "fakers" were told to exert about 50 to 75% MVC of their assumed maximum strength. Chaffin et al. compared the rectified EMG amplitudes at the chosen force levels and at the beginning and end of endurance static exertions. The rectified EMG amplitude increased as the exerted force increased, and also increased in continuous static exertions. The EMG amplitudes themselves and their increase rates between the sincere and fakers showed significant differences. Chaffin et al. thus could identify all 10 fakers and 11 of 12 sincere subjects.

The rectified EMG amplitudes, which are associated with the numbers of recruited motor units, increase as the exerted force increases to the maximum level (Bouisset, 1973; Bouisset and Maton, 1972; Bronks and Brown, 1987; Ericson and Hagberg, 1981; Jonsson, 1981; Komi and Viitasalo, 1976; Lawrence and De Luca, 1983; Lee, 1979; Lee, 1981; Lee and Lee, 1982; Milner-Brown, Stein, and Yemm, 1973). The high correlation between EMG amplitude and exerted muscular force makes EMG a useful tool in MVC assessment.

### *5.3 Electromyography and Muscular Force*

Muscle fibers are basic elements in muscle contraction. Human muscles mainly consist of two types of muscle fibers. Type S, slow-twitch, fatigue-resistant, high-oxidative, red muscle fibers are small in diameter. Type F, fast-twitch, fast-fatigue, high-glycolytic, white muscle fibers have relatively large diameter. The Type S muscle fibers exert small force and are associated with low action potentials. The Type F muscle fibers exert large force and require a high action potential to be recruited.

A motoneuron and all its target muscle fibers together are called a motor unit. Numbers of muscle fibers in a motor unit vary while the type of muscle fiber is same. Each motoneuron innervates a few to thousands of muscle fibers. Large motor units generally involve Type F muscle fiber, and smaller motor units involve Type S muscle fibers (McMahon, 1984). Therefore motor units can be grouped into Type S and Type F by not only the morphological and biochemical characteristics of muscle fibers but also by the required action potential levels (Vander, Sherman, and Luciano, 1985).

The "size principle" determines the order of recruitment of motor units into activity (Henneman, Somjien, and Carpenter, 1965) from smallest to largest diameter motoneurons. Since the number of muscle fibers innervated by a motoneuron is proportional to its size, smaller motor units are recruited first and larger motor units last.

During a constant-force isometric exertion, a motor unit that becomes active at the beginning of contraction remains active throughout the contraction (Grimby and Hannerz, 1977).

In isometric contractions, recruitment of motor units and firing rate interplay for force generation. At the beginning of a contraction, recruitment is dominant factor for force generation. Up to 30 percent MVC, recruitment remains the dominant factor, with progressively large motor units being recruited as the force increases. The firing rate also increases as a secondary factor. For force levels ranging from 30 to 75 percent MVC, the dominant factor is the increase in the firing rate. Some recruitment of large motor units also occurs, but plays a secondary role. At force levels above 75 percent MVC, the increase in the firing rate continues to be the dominant factor (De Luca, 1979).

Synchronization of the discharges of motor units has been observed when a muscle becomes fatigued, after exercise, and during relatively high force exertion (Lippold, Redfearn, and Vuvo, 1970; Milner-Brown, Stein, and Lee, 1975).

EMG is the superposition of the motor unit action potential trains (MUAPTs) (Brown and Milner-Brown, 1976; De Luca, 1979). Signal characteristics of the EMG thus reflect the principles and procedures of muscle contraction (Hagberg, 1981; Karlsson, Funderburk, Essen, and Lind, 1975; Komi, 1973; Lam, Morgan, and Lampard, 1979; Maton, 1976; Sale, 1988; Yemm, 1977).

The amplitude of EMG (generally, the integral of the mean rectified value or the root-mean-squared (RMS) value is used) is proportional to the number of recruited motor units. It also relates to muscle fiber composition in a muscle. The action potential of a muscle fiber is proportional to the fiber diameter which is large in F-type fibers and small in S-type fibers. A high amplitude of motor unit action potentials results in a high EMG amplitude. EMG amplitude, however, is a function of the distance between the muscle fibers and the electrodes: the greater the distance, the smaller the amplitude (Basmajian and De Luca, 1985).

Relationships between exerted muscular force and EMG amplitude have been a controversial issue: it remains difficult to quantitatively document their relationship. Bigland-Ritchie (1974), Hagberg (1979), Komi and Buskirk (1970), Komi (1973), Lippold (1952), and Milner-Brown and Stein (1975) reported a linear relationship while Bronk and Brown (1987) Chaffin, Lee, and Freivalds (1980), Ericson and Hagberg (1981), Jonsson (1981), Komi and Karlsson (1978), Komi and Viitasalo (1976), Lee (1979), Lee (1981), Milner-Brown and Stein (1975), Thorstensson, Hulten, von Döbeln, and Karlsson (1976), and Vredenburg and Rau (1973) reported a non-linear relationship. Lawrence and De Luca (1983) showed that the relationship between force and EMG amplitude was linear in the first dorsal interosseous but non-linear in the biceps brachii and deltoid. Comparisons of force-EMG amplitude relationships in small and large muscles were performed by Clamann and Broecker (1979) and Woods and Bigland-Ritchie (1983). Although there were some differences in the methodology in these two studies, they showed the same conclusion: in small muscles, the first dorsal interosseous and adductor pollicis, the relationship was quasilinear whereas in the large muscles, the biceps brachii, triceps brachii, deltoid, and soleus, the relationship was non-linear. Basmajian and De Luca (1985) summarized the studies relating to this issue, and associated the findings with variability in the examined muscles, the types of muscle con-

tractions, the quantities derived from the raw data to represent the amplitude of the EMG signal.

While inconsistencies in the literature make it difficult to derive conclusions regarding force-EMG amplitude relationship, a possible conclusion at this time is that the EMG amplitude increases monotonically as exerted muscular force increases. For a certain force range, the relationship is linear, but for another range, it may be non-linear.

Theoretically, patterns of EMG amplitude variations with respect to exerted muscular force depend on the muscles and ranges of force exertions. If a muscle includes at least two types of muscle fibers, and force exertions range from low to high levels, the EMG amplitudes with respect to the force exertion levels increase non-linearly. If a muscle is homogeneous, the EMG amplitude increases linearly as the force increases (Clamann and Broeker, 1979; Lee, 1979; Lee, 1981; Lee and Lee, 1982; Woods and Bigland-Ritchie, 1983). The "size principle" (Henneman, Somjien, and Carpenter, 1965) explains these variations of EMG amplitude. Consequently, to use the EMG amplitude for predicting muscular force, it is necessary to calibrate the force-EMG amplitude relationship of the muscle (Woldstad, 1989).

Relationships between exerted muscular force and EMG amplitude are generally studied under the assumption that no muscular fatigue exists. If muscular fatigue occurs, the EMG amplitude tends to increase. However, it is difficult to quantitatively document the muscular fatigue-EMG amplitude relationship (Edwards, 1981; Hason, Signorile, and Williams, 1987; Kondraske, Carmichael, Mayer, and Mooney, 1987; Lee, 1985; Lippold, 1981; Valenica, 1986). It has been shown that a continuous isometric submaximal exertion, EMG amplitude increases non-linearly as the exertion time goes on (Jonsson, 1981; Lee, 1981).

Figure 5.1 and 5.2 show a force-EMG amplitude relationship and changes of EMG amplitudes in continuous exertions on different force levels.

## *5.4 Discussion and Summary*

Muscular strength, MVC, is defined as the maximal force or torque that muscle(s) can exert isometrically in a voluntary effort. The "Caldwell regimen" is widely used for MVC assessment. There is relationships between force build-up time and exerted muscular force: the shorter the build-up time, the higher the probability that an MVC is performed.

EMG analysis is often used to validate whether a true MVC is performed or not.

The relationship between exerted muscular force and EMG amplitude has been a controversial issue. Some investigators reported a linear relationship while others reported non-linear relations. A possible conclusion at this time is that, under the condition of no muscular fatigue, the EMG amplitude increases monotonically as exerted muscular force increases. It is difficult to quantitatively document the relationships between muscular force and EMG amplitude when muscular fatigue exists. Therefore, conditions possibly leading to muscular fatigue must be avoided. This allows to use the EMG amplitude for predicting muscular force after calibrating the muscular force-EMG amplitude relationship of the muscle.

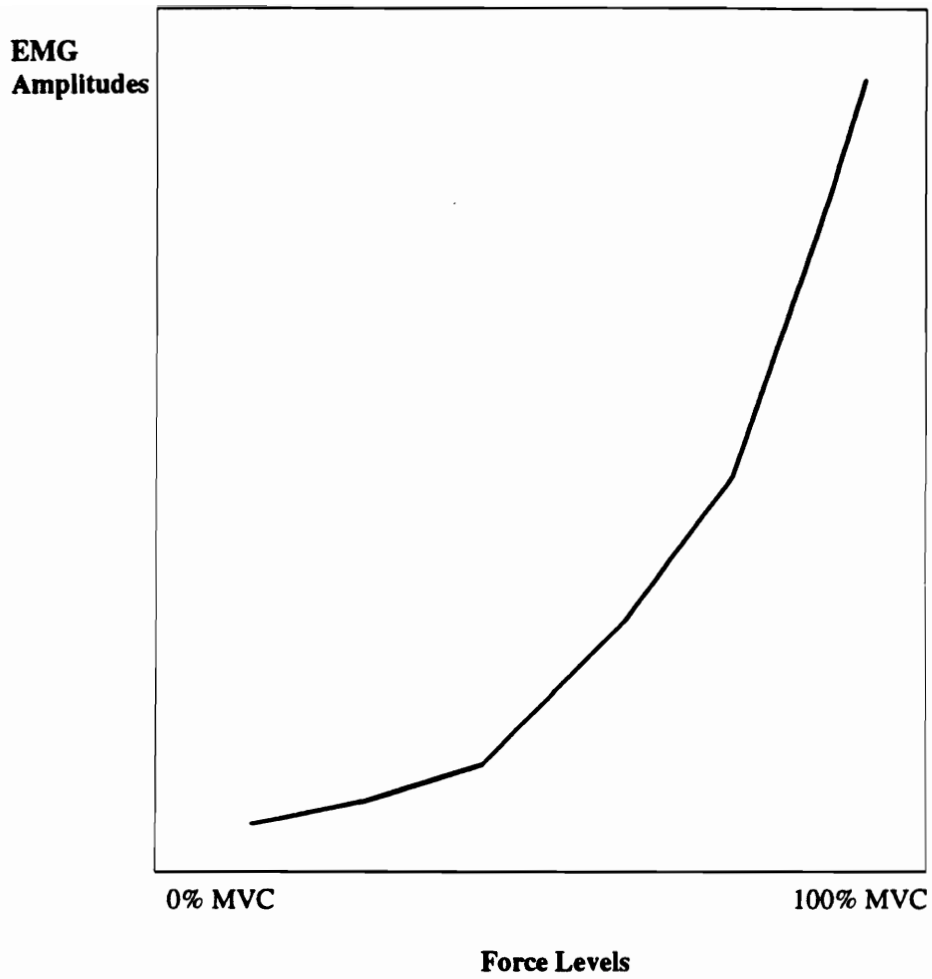


Figure 5.1 A typical relation between exerted force and EMG amplitude.

(from Lee, 1981)



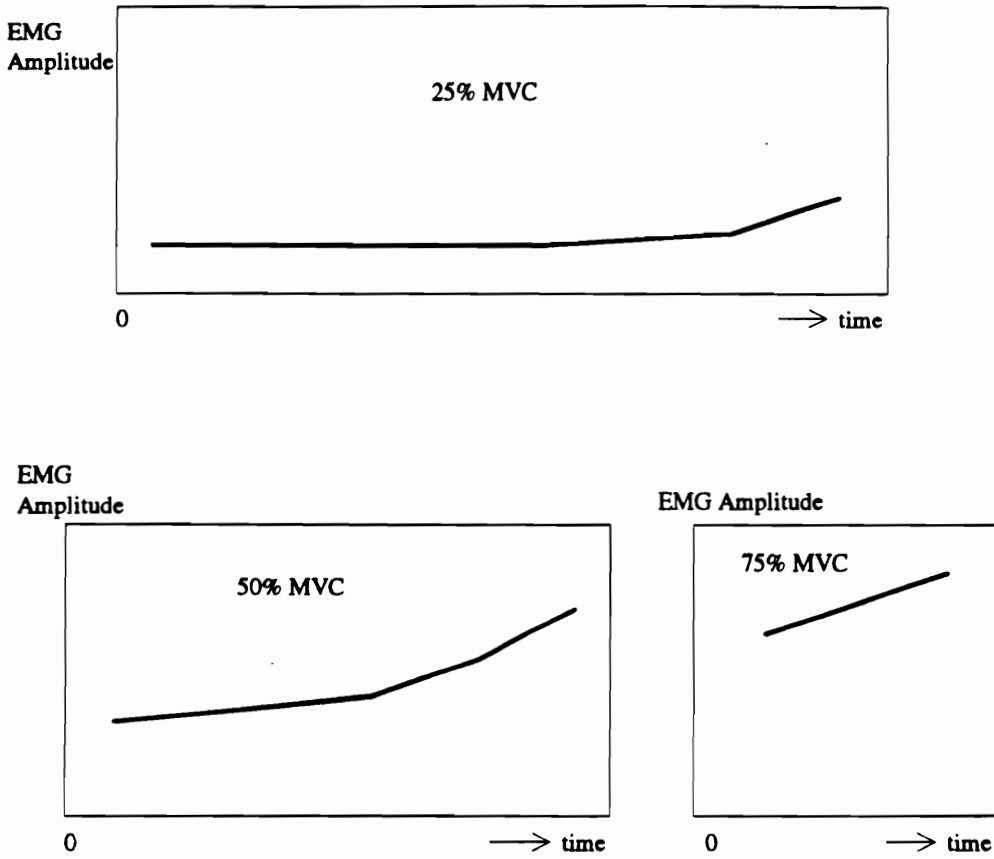


Figure 5.2 Typical Variations of EMG amplitudes at different force levels in continuous isometric contractions.

(from Lee, 1981)

## **VI. Biomechanical Models of the Finger**

### ***6.1 Overview***

Two “biomechanical models” of the finger are developed based upon finger anatomy and physiology of finger movements. The first model relies on the assumption of constant moment arms of the tendons at the joints, while the second model is based on the assumption of non-constant tendon moment arms. Equilibrium equations are derived using the principle of virtual work. Finally, equations of muscular forces in static exertions against an external load are established.

## ***6.2 Basic Assumptions of the Finger Models***

The finger model shown in Figure 6.1 was developed based upon the functional anatomy and physiology of hand and finger movements covered in Chapter II. The finger model reflects the anatomical structure of the finger and includes all activities of the muscles in flexion and extension of the finger joints with the assumptions listed below. When muscles are inconsistently activated in joint movement, their roles are neglected. By this principle, the lumbricals are considered not to act about the MCP joint. The activations of the muscles used in the finger model are summarized in Table 6.1.

The finger model has the following features:

- 1) The finger movements are performed in the sagittal plane.
- 2) The finger joints are pin joints.
- 3) Five muscles are involved in the finger flexion and extension: the EDC, FDP, FDS, interossei, and lumbricals. The extensor digitorum communis and the extensor indicis are treated as one muscle which extends the index finger. The palmar and dorsal interossei are treated as one muscle which flexes the MCP joint and extends the PIP and DIP joints.
- 4) The combined extensor muscle inserts into the bases of the proximal, middle, and distal phalanges.
- 5) The flexor digitorum profundus inserts into the base of the distal phalanx.
- 6) The flexor digitorum superficialis inserts into the body of the middle phalanx.
- 7) The combined interosseous muscle inserts into the bases of the proximal and middle phalanges and the lateral band. (In reality, there is no physical insertion of the interosseous muscle into the proximal phalanx. In this study, however, an imaginary insertion of the interosseous muscle into the base of the proximal phalanx is installed to reflect the contribution of the interosseous muscle to flexing the MCP joint.)
- 8) The lumbrical muscle inserts into the base of the middle phalanx and the lateral band.

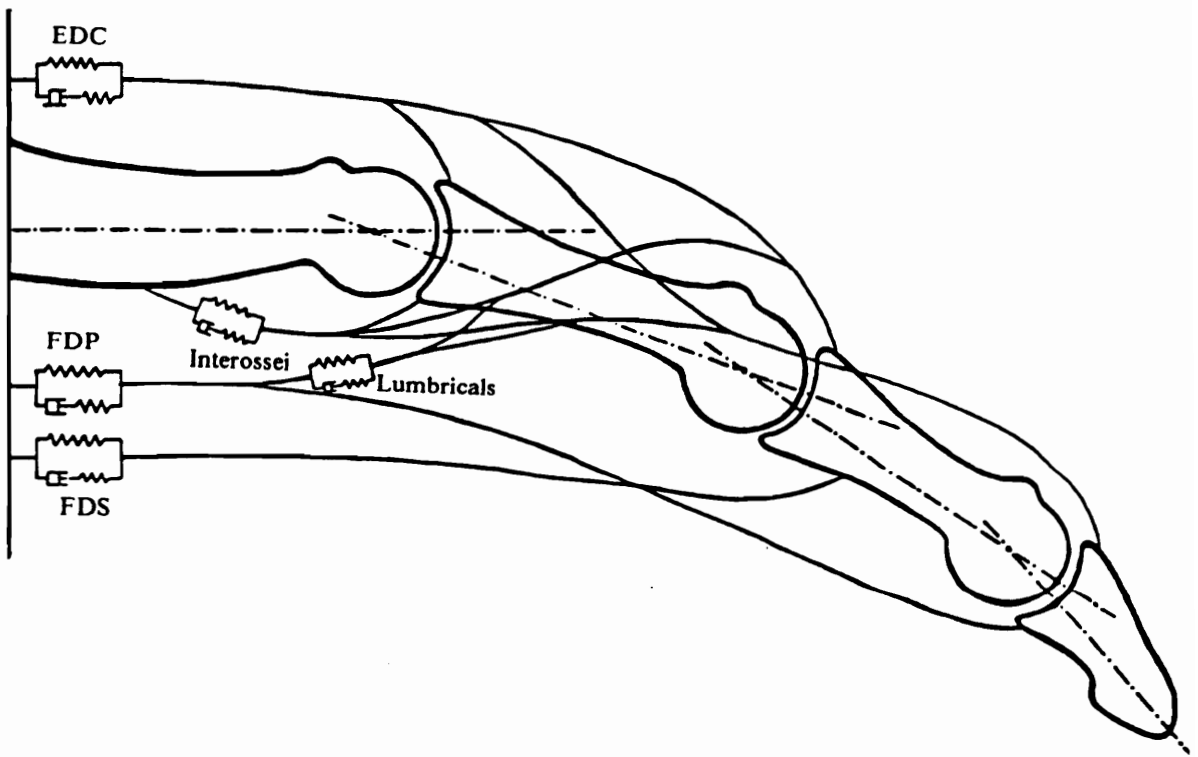


Figure 6.1 Schematic diagram of muscles and tendons in the index finger model.

EDC: Extensor Digitorum Communis, FDP: Flexor Digitorum Profundus,

FDS: Flexor Digitorum Superficialis.

Table 6.1 Activations of the muscles in finger joint movements as considered in the index finger model.

Joint Movem't Muscle	MCP		PIP		DIP	
	Flex.	Ext.	Flex.	Ext.	Flex.	Ext.
<b>EDC</b>		<b>X</b>		<b>X</b>		<b>X</b>
<b>FDS</b>	<b>X</b>		<b>X</b>			
<b>FDP</b>			<b>X</b>		<b>X</b>	
<b>Interossei</b>	<b>X</b>			<b>X</b>		<b>X</b>
<b>Lumbricals</b>				<b>X</b>		<b>X</b>

**legend**      **EDC : Extensor Digitorum Communis**  
**FDS : Flexor Digitorum Superficialis**  
**FDP : Flexor Digitorum Profundus**

### 6.3 Biomechanical Finger Models

Biomechanical models of the index finger are developed based upon the basic assumptions described in the previous section. Since movements of the phalanges are performed by excursions of the tendons, tendon excursions of muscles are mathematically formulated. In the development of the mathematical models, two cases are considered: either moment arms of the tendons remain constant during finger flexion and extension, or tendon moment arms of the flexors and lumbricals increase linearly as the finger flexes from the extended position.

In the case of constant tendon moment arms, Landsmeer's first model of tendon excursion is used to express the relationships between tendon excursions and joint angles. In the case of non-constant tendon moment arms, an approximation of Landsmeer's first model (Fischer, 1969; Thomas, 1965) is used to describe the tendon excursion of the flexors and lumbricals.

Landsmeer's first model may be expressed as

$$X = (r + r' \theta) \theta, \quad (6.1)$$

where  $X$  is the tendon excursion;  $\theta$  is the change of joint angle in radians;  $r$  is the tendon moment arm when the finger is in extended position; and  $r'$  is the moment arm when the finger is in flexed position. With Thomas' (1965) finding of  $r' = \frac{0.15}{2} r$ , this equation becomes (like in equation (4.5))

$$X = \left( r + \frac{0.15}{2} r \theta \right) \theta. \quad (6.2)$$

The following notations are used in developing the mathematical model of the finger:

$\theta_1$  = angle of MCP joint (angle between the MC and proximal phalanx)

$\theta_2$  = angle of PIP joint (angle between the proximal and middle phalanges)

$\theta_3$  = angle of DIP joint (angle between the middle and distal phalanges)

$\phi$  = angle between the external load and vertical line in the sagittal plane

$l_1$  = length of the proximal phalanx

$l_2$  = length of the middle phalanx

$l_3$  = length of the distal phalanx

$X_E$  = excursion of extensor tendon

$X_P$  = excursion of flexor profundus tendon

$X_S$  = excursion of flexor superficialis tendon

$X_I$  = excursion of interossei tendon

$X_L$  = excursion of lumbricalis tendon

$F_E$  = force exerted by extensor

$F_P$  = force exerted by flexor profundus

$F_S$  = force exerted by flexor superficialis

$F_I$  = force exerted by interossei

$F_L$  = force exerted by lumbricalis

$T$  = external torque acting on the fingertip and joints

$r$  = moment arm of the tendon. Indices are used to identify the moment arm

of the specified tendon and the location of joint. First index refers to the

muscle (E = extensor, P = flexor profundus, S = flexor superficialis,

I = interossei, and L = lumbricalis) and the second index refers to the joint

(1 = MCP, 2 = PIP, 3 = DIP joints). For example,  $r_{E1}$  is the moment arm

of the extensor at the MCP joint.

$r'$  = moment arm of a tendon at the final position of finger movement.

The direction of finger extension is designated positive.

### 6.3.1 Finger Model for Constant Tendon Moment Arms

The first model of the finger is based upon the assumption that moment arms of tendons are constant during finger movements (i.e.,  $r = r'$ ). In this case, tendon excursion is expressed as a linear function of joint angle.

The extensor digitorum communis has three insertions: the bases of the proximal, middle, and distal phalanges. The extensor tendon splits into three parts halfway down the phalanx: an extensor medial band and two lateral bands. The extensor medial band is inserted into the base of the middle phalanx. Each lateral band runs along one side of the proximal phalanx. They unite on the back of the middle phalanx and insert into the base of the distal phalanx. When the finger flexes the lateral bands move palmwards. Therefore the tendon excursion of the extensor by DIP joint flexion can not be added directly to the total tendon excursion of the extensor (Buchner, Hines, and Hemami, 1988). In this study, however, the total tendon excursion of the extensor digitorum communis is assumed to be a summation of the tendon excursions by three finger joints.

The flexor digitorum profundus runs through the MCP, PIP, and DIP joints within the tendon sheath and is inserted in the base of the distal phalanx. Therefore the total tendon excursion of the flexor profundus can be expressed as the summation of the tendon excursions by flexion of the three finger joints. Since the direction of finger



flexion is designated negative, the tendon excursions of the flexor profundus have negative signs.

The flexor digitorum superficialis runs through the MCP and PIP joints and inserts in the border of the middle phalanx. The total tendon excursion of the flexor superficialis is expressed as the summation of the tendon excursions by the MCP and PIP joint flexions. Tendon excursions are negative since they are brought about by finger flexion.

The interossei are considered to have three insertions: an imaginary insertion in the base of the proximal phalanx, an insertion into the lateral band, and an insertion into the base of the distal phalanx. Excursion of the imaginary tendon is assumed to occur when the MCP joint flexes. Excursions of both tendons inserted into the lateral band and the distal phalanx occur when the PIP and DIP joints extend. The total tendon excursion of the interossei is expressed as the summation of the tendon excursions by MCP joint flexion and by extension of the PIP and DIP joints. Tendon excursion by MCP joint flexion is negative while tendon excursions by PIP and DIP joint extension have positive signs.

The lumbricals originate from the tendons of the flexor digitorum profundus and insert into the lateral band and the terminal tendon of the extensor. Tendon excursion of the lumbricals occurs when the PIP and DIP joints extend. Tendon excursion also occurs passively at the MCP joint when the MCP joint is flexed. Therefore the total tendon excursion can be expressed as the sum of the tendon excursions by extensions of the PIP and DIP joints and by flexion of the MCP joint. Tendon excursions of the lumbricals have positive signs in extension and negative signs in flexion.

The tendon excursions can be described mathematically as follows:

Extensor Digitorum Communis

$$X_E = r_{E1} \theta_1 + r_{E2} \theta_2 + r_{E3} \theta_3 \quad (6.3)$$

Flexor Digitorum Profundus

$$X_P = - r_{P1} \theta_1 - r_{P2} \theta_2 - r_{P3} \theta_3 \quad (6.4)$$

Flexor Digitorum Superficialis

$$X_S = - r_{S1} \theta_1 - r_{S2} \theta_2 \quad (6.5)$$

Interossei

$$X_I = - r_{I1} \theta_1 + r_{I2} \theta_2 + r_{I3} \theta_3 \quad (6.6)$$

Lumbricals

$$X_L = - r_{L1} \theta_1 + r_{L2} \theta_2 + r_{L3} \theta_3 \quad (6.7)$$

### 6.3.2 Finger Model for Non-Constant Tendon Moment Arms

The second model of the finger is based upon Landsmeer's first tendon excursion model and Fischer's approximation. Landsmeer's first model is used to describe the tendon excursions of the extensor and interossei as well as the tendon excursion of the flexor digitorum profundus at the DIP joint. Application of the approximation of Landsmeer's model is based upon the experimental results of An et al. (1983), which

showed that tendon moment arms of the flexors increased as the finger flexed. Fischer's approximation is used to describe the tendon excursions of flexor muscles at the joints where the tendons run in a tendon-sheath: the flexor profundus and superficialis at the MCP and PIP joints. It is also applied to the lumbricals at the MCP joint. Assumptions and procedures for development the model with non-constant tendon moment arms are same to those for the constant tendon moment arms model.

The tendon excursions in the model for non-constant moment arms are expressed as follows:

#### Extensor Digitorum Communis

$$X_E = r_{E1} \theta_1 + r_{E2} \theta_2 + r_{E3} \theta_3 \quad (6.8)$$

#### Flexor Digitorum Profundus

$$X_P = - (r_{P1} + r_{P1}' \theta_1) \theta_1 - (r_{P2} + r_{P2}' \theta_2) \theta_2 - r_{P3} \theta_3 \quad (6.9)$$

#### Flexor Digitorum Superficialis

$$X_S = - (r_{S1} + r_{S1}' \theta_1) \theta_1 - (r_{S2} + r_{S2}' \theta_2) \theta_2 \quad (6.10)$$

#### Interossei

$$X_I = - r_{I1} \theta_1 + r_{I2} \theta_2 + r_{I3} \theta_3 \quad (6.11)$$

#### Lumbricalis

$$X_L = - (r_{L1} + r_{L1}' \theta_1) \theta_1 + r_{L2} \theta_2 + r_{L3} \theta_3 \quad (6.12)$$

### 6.3.3 Comparison of the Models

The biomechanical models of the finger developed in this study can be compared to other finger models. The models in this study are expanded from the model of Storage and Wolf (1979), which dealt with only three muscles and two joints. The models in this study are different from those of Thomas (1965), Fischer (1969), and Buchner, Hines, and Hemami (1988) in the following respects:

Thomas (1965) applied the approximation of Landsmeer's first model and Landsmeer's third model to develop a tendon excursion model in which he considered the tendon excursions in finger adduction and abduction as well as in flexion and extension.

Fischer (1969) applied the approximation of Landsmeer's first model to describe the tendon excursions of the extensor and intrinsic muscles, but he used Landsmeer's third model to describe the tendon excursions of the flexors.

Buchner, Hines, and Hemami (1988) applied both Landsmeer's first model and its approximation. They used the approximation model to describe the tendon excursions of the lateral band, flexor profundus at all three joints, flexor superficialis at the MCP joint, and lumbrical muscle at three joints.

In this study, for the finger model with constant tendon moment arms, Landsmeer's first model is applied to the all tendons at all joints. In the model with non-constant tendon moment arms, the approximation model is applied to the tendons of flexor profundus and superficialis at the MCP and PIP joints and to the tendon of lumbricalis at the MCP joint. For all other tendons Landsmeer's first model is applied as in the case of constant tendon moment arms.

The tendon excursion models in this study have forms similar to the models developed by other researchers. However, they differ in the number of muscles and joints involved from the models of Storaas and Wolf (1979). They are also distinguished from the models of Fischer (1969), Buchner et al. (1988), and Thomas (1965) in such that they include only Landsmeer's first model of tendon excursion and its approximation while the models of Fischer, Buchner et al., and Thomas use Landsmeer's first and third models of tendon excursion.

A list of the features of the various finger models is provided in Table 6.2.

## *6.4 Equilibrium Equations*

If there is an external load acting on the fingertip, the external load can be divided into three torques which act at the DIP joint ( $T_3$ ), at the PIP joint ( $T_2$ ), and at the MCP joint ( $T_1$ ). If the finger is assumed to be in static equilibrium, the amount of work done by all muscles and the external load becomes zero. Thus,

$$\begin{aligned}
 &F_E \delta X_E + F_P \delta X_P + F_S \delta X_S + F_I \delta X_I + F_L \delta X_L \\
 &+ (T_1 + T_2 + T_3) \delta \theta_1 + (T_2 + T_3) \delta \theta_2 + T_3 \delta \theta_3 = 0,
 \end{aligned} \tag{6.13}$$

where  $\delta X$  stands for the increment of tendon excursion,  $X$ , and  $\delta \theta$  stands for the increment of joint angle.

Tendon excursions of extensor, flexor digitorum profundus, and interossei are a function of finger joint angles,  $\theta_1$ ,  $\theta_2$ , and  $\theta_3$ , since these three muscles are related to the movements of three joints. Tendon excursion of the flexor digitorum superficialis is a

Table 6.2 Comparison of finger models.

Researcher	Muscle	EDC			FDP			FDS		Interossei			Lumbricals		
		MCP	PIP	DIP	MCP	PIP	DIP	MCP	PIP	MCP	PIP	DIP	MCP	PIP	DIP
Thomas		(Im)*			(III)*			(III)*		(Im)*			(Im)*		
Fischer		Im	I	I	III	III	III	III	III	Im	n/a	I	Im	n/a	I
Srorace & Wolf		I	I	n/a	I	I	n/a	n/a	n/a	I	I	n/a	n/a	n/a	n/a
Buchner et al.		I	Im	I	Im	Im	Im	Im	I	I	I	n/a	Im	Im	Im
Lee (Const.)		I	I	I	I	I	I	I	I	I	I	I	I	I	I
Lee (N-Const.)		I	I	I	Im	Im	I	Im	Im	I	I	I	Im	I	I

**legend**

EDC : Extensor Digitorum Communis  
 FDP : Flexor Digitorum Profundus  
 FDS : Flexor Digitorum Superficialis

Lee (Const.) : Finger model developed in this study with constant tendon moment arms.

Lee (N-Const.) : Finger model developed in this study with non-constant tendon moment arms.

I : Landsmeer's first model

Im : Approximation of Landsmeer's first model

III : Landsmeer's third model

(Im)\* : Approximation of Landsmeer's first model in modified form

(III)\* : Landsmeer's third model in modified form

note : Finger models of Thomas include the tendon excursions by adduction and abduction of the MCP joint

function of  $\theta_1$  and  $\theta_2$ , since this muscle is related to the movements of the MCP and PIP joints. Tendon excursion of the lumbricalis is a function of  $\theta_2$  and  $\theta_3$ , since the lumbricalis is related to the movements of the PIP and DIP joints. These relationships can be expressed as follows:

$$X_E = f(\theta_1, \theta_2, \theta_3) \quad (6.14)$$

$$X_P = f(\theta_1, \theta_2, \theta_3) \quad (6.15)$$

$$X_S = f(\theta_1, \theta_2) \quad (6.16)$$

$$X_I = f(\theta_1, \theta_2, \theta_3) \quad (6.17)$$

$$X_L = f(\theta_1, \theta_2, \theta_3). \quad (6.18)$$

Then

$$\delta X_E = \frac{\partial X_E}{\partial \theta_1} \delta \theta_1 + \frac{\partial X_E}{\partial \theta_2} \delta \theta_2 + \frac{\partial X_E}{\partial \theta_3} \delta \theta_3 \quad (6.19)$$

$$\delta X_P = \frac{\partial X_P}{\partial \theta_1} \delta \theta_1 + \frac{\partial X_P}{\partial \theta_2} \delta \theta_2 + \frac{\partial X_P}{\partial \theta_3} \delta \theta_3 \quad (6.20)$$

$$\delta X_S = \frac{\partial X_S}{\partial \theta_1} \delta \theta_1 + \frac{\partial X_S}{\partial \theta_2} \delta \theta_2 \quad (6.21)$$

$$\delta X_I = \frac{\partial X_I}{\partial \theta_1} \delta \theta_1 + \frac{\partial X_I}{\partial \theta_2} \delta \theta_2 + \frac{\partial X_I}{\partial \theta_3} \delta \theta_3 \quad (6.22)$$

$$\delta X_L = \frac{\partial X_L}{\partial \theta_1} \delta \theta_1 + \frac{\partial X_L}{\partial \theta_2} \delta \theta_2 + \frac{\partial X_L}{\partial \theta_3} \delta \theta_3. \quad (6.23)$$

Substituting  $\delta X_E, \delta X_P, \delta X_S, \delta X_I,$  and  $\delta X_L$  in equations (6.19) through (6.23) into equation (6.13), equation (6.13) becomes

$$\begin{aligned} & \delta\theta_1 \left( F_E \frac{\partial X_E}{\partial \theta_1} + F_P \frac{\partial X_P}{\partial \theta_1} + F_S \frac{\partial X_S}{\partial \theta_1} + F_I \frac{\partial X_I}{\partial \theta_1} + F_L \frac{\partial X_L}{\partial \theta_1} + T_1 + T_2 + T_3 \right) \\ & + \delta\theta_2 \left( F_E \frac{\partial X_E}{\partial \theta_2} + F_P \frac{\partial X_P}{\partial \theta_2} + F_S \frac{\partial X_S}{\partial \theta_2} + F_I \frac{\partial X_I}{\partial \theta_2} + F_L \frac{\partial X_L}{\partial \theta_2} + T_2 + T_3 \right) \\ & + \delta\theta_3 \left( F_E \frac{\partial X_E}{\partial \theta_3} + F_P \frac{\partial X_P}{\partial \theta_3} + F_I \frac{\partial X_I}{\partial \theta_3} + F_L \frac{\partial X_L}{\partial \theta_3} + T_3 \right) = 0. \end{aligned} \quad (6.24)$$

For the constant tendon moment arms model, from equations (6.3) through (6.7) and (6.24), the following simultaneous equations are obtained:

$$F_E r_{E1} - F_P r_{P1} - F_S r_{S1} - F_I r_{I1} - F_L r_{L1} + T_1 + T_2 + T_3 = 0 \quad (6.25)$$

$$F_E r_{E2} - F_P r_{P2} - F_S r_{S2} + F_I r_{I2} + F_L r_{L2} + T_2 + T_3 = 0 \quad (6.26)$$

$$F_E r_{E3} - F_P r_{P3} + F_I r_{I3} + F_L r_{L3} + T_3 = 0. \quad (6.27)$$

For the non-constant tendon moment arms model, equations (6.8) through (6.12) and (6.24) yield

$$\begin{aligned} & F_E r_{E1} - F_P (r_{P1} + 2 r_{P1}' \theta_1) - F_S (r_{S1} + 2 r_{S1}' \theta_1) \\ & - F_I r_{I1} - F_L (r_{L1} + r_{L1}' \theta_1) + T_1 + T_2 + T_3 = 0 \end{aligned} \quad (6.28)$$

$$\begin{aligned} & F_E r_{E2} - F_P (r_{P2} + 2 r_{P2}' \theta_2) - F_S (r_{S2} + 2 r_{S2}' \theta_2) \\ & + F_I r_{I2} + F_L r_{L2} + T_2 + T_3 = 0 \end{aligned} \quad (6.29)$$



$$F_E r_{E3} - F_P r_{P3} + F_I r_{I3} + F_L r_{L3} + T_3 = 0. \quad (6.30)$$

Even with known values for the tendon moment arm,  $r$  and  $r'$ , and for the external torque,  $T$ , there are still five unknown muscular forces in each set of three equations. There are several ways to solve this problem. One is to use a mathematical technique which utilizes linear programming (An, Kwak, Chao, and Morrey, 1984; Penrod, Davy, and Singh, 1974). Another is to use the results of EMG studies, which provide information of muscle activations for a specific finger movement. The latter solution is used in this study.

## ***6.5 Muscular Forces for Static Exertions***

### **6.5.1 Directions of Force Exertions and External Load**

To find the relations between external load and internal muscular forces, it is necessary to solve the equilibrium equations derived in the prior section. If the number of variables is reduced sufficiently, muscular forces can be expressed as functions of external load and finger positions. Four directions of external load and force exertions are defined to compare muscular forces in static exertions about the MCP and PIP joints.

A "standard hand position" is defined in order to designate the directions of forces. In the standard hand position, the forearm is horizontally positioned and the hand is aligned with the forearm, the palm facing the floor. The four directions of external load

and force exertions in this standard hand position are named "downward", "upward", "backward", and "forward".

Figure 6.2 shows the standard hand position and four directions of external load and force exertions.

### 6.5.2 Muscular Forces in the Constant Tendon Moment Arms Model

When the finger is in static equilibrium against an external load acting upward, muscles associated with flexion of the MCP, PIP, and DIP joints must be working. This involves the activations of flexor digitorum profundus and superficialis and interossei. The major torque is at the MCP joint. This case is thus named "static finger flexion exertion about the MCP joint".

Since the extensor digitorum and lumbricals are silent during finger flexion, muscular forces of these muscles are assumed to be zero:

$$F_E = 0$$

$$F_L = 0.$$

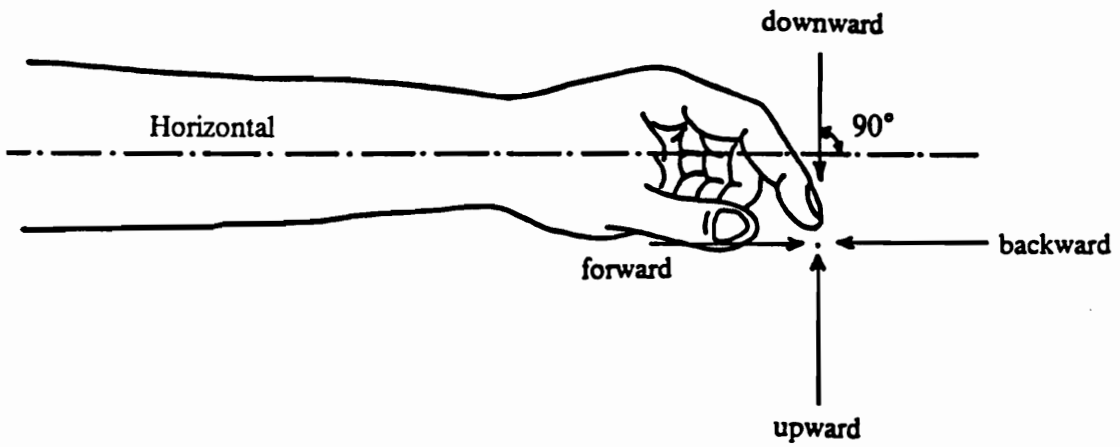
If  $F_E$  and  $F_L$  become zeros in equilibrium equations (6.25), (6.26), and (6.27), three unknown variables remain in three equations. It means that these equations can be mathematically solved. The equations to be solved become

$$- F_P r_{P1} - F_S r_{S1} - F_I r_{I1} + T_1 + T_2 + T_3 = 0 \quad (6.31)$$

$$- F_P r_{P2} - F_S r_{S2} + F_I r_{I2} + T_2 + T_3 = 0 \quad (6.32)$$

$$- F_P r_{P3} + F_I r_{I3} + T_3 = 0. \quad (6.33)$$

directions of external loads



directions of force exertions

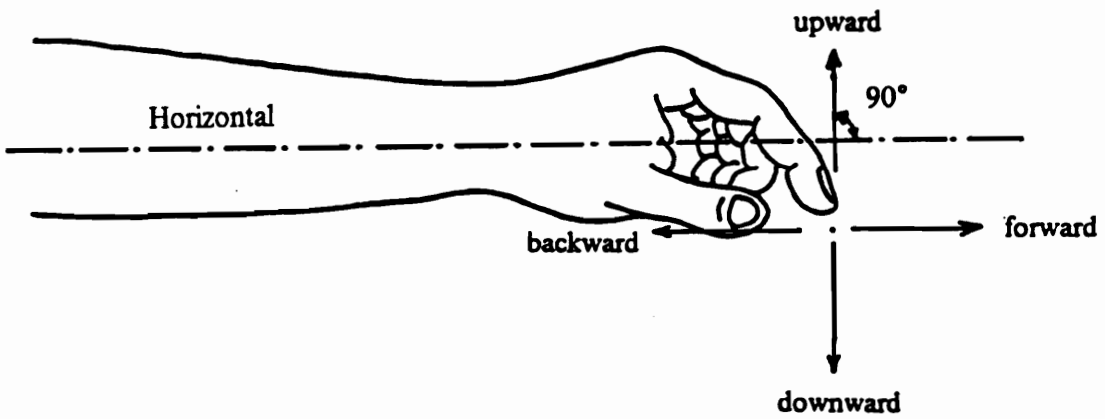


Figure 6.2. Four directions of external load and force exertions.

Solutions of these simultaneous equations are

$$F_S = \frac{T_1 k_3 + T_2 (k_2 + k_3) + T_3 (k_2 + k_3 - k_1)}{(r_{S1} k_3 + r_{S2} k_2)} \quad (6.34)$$

$$F_I = \frac{T_1 r_{P3} r_{S2} + T_2 k_5 + T_3 (k_4 + k_5)}{r_{S1} k_3 + r_{S2} k_2} \quad (6.35)$$

$$F_P = \frac{T_1 (r_{S2} r_{I3}) + T_2 r_{I3} (r_{S2} - r_{S1})}{(r_{S1} k_3 + r_{S2} k_2)} + \frac{T_3 (r_{I3} r_{S2} - r_{S1} r_{I3} + r_{S1} r_{I2} + r_{S2} r_{I1})}{(r_{S1} k_3 + r_{S2} k_2)}, \quad (6.36)$$

where  $k_1, k_2, k_3, k_4,$  and  $k_5$  have the following values:

$$k_1 = r_{P1} r_{I2} + r_{P2} r_{I1}$$

$$k_2 = r_{P1} r_{I3} + r_{P3} r_{I1}$$

$$k_3 = r_{P3} r_{I2} - r_{P2} r_{I3}$$

$$k_4 = r_{P2} r_{S1} - r_{P1} r_{S2}$$

$$k_5 = r_{P3} r_{S2} - r_{P3} r_{S1}$$

When an external load acts forward and the finger is in static equilibrium against the external load, major torque acts on the PIP joint. This is thus named "static finger flexion exertion about the PIP joint".

The equilibrium equations and their solutions for muscular forces have the same form as those in "static finger flexion exertion about the MCP joint". However, the amount of torques (  $T_1$ ,  $T_2$ , and  $T_3$  ) loading the joints have different values due to the direction of  $T$ .

When an external load is acting downward and the finger is in static equilibrium, muscles associated with extension of the MCP, PIP, and DIP joints must be working. Since major torque is at the MCP joint due to the direction of the external load, this is named "static finger extension exertion about the MCP joint". Extensor digitorum, interossei, and lumbricals are involved in this situation. Muscular forces of the flexor digitorum profundus and superficialis are assumed to be zero, thus

$$F_P = 0$$

$$F_S = 0.$$

If muscular forces of both flexors are zero in the equilibrium equations (6.25), (6.26), and (6.27), the equations to be solved become

$$F_E r_{E1} - F_I r_{I1} - F_L r_{L1} + (T_1 + T_2 + T_3) = 0 \quad (6.37)$$

$$F_E r_{E2} + F_I r_{I2} + F_L r_{L2} + (T_2 + T_3) = 0 \quad (6.38)$$

$$F_E r_{E3} + F_I r_{I3} + F_L r_{L3} + T_3 = 0. \quad (6.39)$$

Since there are three equations for three variables, these simultaneous equations can be mathematically solved. The solutions are

$$F_L = \frac{T_1 c_1 + T_2 (c_1 + c_2) + T_3 (c_1 + c_2 - c_3)}{r_{L1} c_1 - r_{L2} c_2 + r_{L3} c_3} \quad (6.40)$$

$$F_I = \frac{T_1 c_4 + T_2 (c_4 - c_5) + T_3 (c_4 - c_5 + c_6)}{r_{I1} c_4 + r_{I2} c_5 - r_{I3} c_6} \quad (6.41)$$

$$\begin{aligned} F_E = & - T_1 \frac{r_{I3} c_4 c_8 + r_{L3} c_1 c_7}{r_{E3} c_7 c_8} \\ & - T_2 \frac{r_{I3} (c_4 - c_5) c_8 + r_{L3} (c_1 + c_2) c_7}{r_{E3} c_7 c_8} \\ & - T_3 \frac{r_{I3} (c_4 - c_5 + c_6) c_8 + r_{L3} (c_1 + c_2 - c_3) c_7 + c_7 c_8}{r_{E3} c_7 c_8} \end{aligned} \quad (6.42)$$

where  $c_1, c_2, c_3, c_4, c_5, c_6, c_7$ , and  $c_8$  are

$$c_1 = r_{E3} r_{I2} - r_{E2} r_{I3}$$

$$c_2 = r_{E1} r_{I3} + r_{E3} r_{I1}$$

$$c_3 = r_{E1} r_{I2} + r_{E2} r_{I1}$$

$$c_4 = r_{E2} r_{L3} - r_{E3} r_{L2}$$

$$c_5 = r_{E1} r_{L3} + r_{E3} r_{L1}$$

$$c_6 = r_{E2} r_{L1} + r_{E1} r_{L2}$$

$$c_7 = r_{I1} c_4 + r_{I2} c_5 - r_{I3} c_6$$

$$c_8 = r_{L1} c_1 - r_{L2} c_2 + r_{L3} c_3$$

When the finger is in static equilibrium against an external load acting backward, muscles associated with extension of the finger must be working. In this case, however, the major torque is at the PIP joint. This case is named "static finger extension exertion about the PIP joint". The equilibrium equations and their solutions for muscular forces will have the same form with those in "static exertion about the MCP joint toward finger extension" except the direction of the external force.

In summary, if the tendon moment arms remain constant during finger movements, muscular forces for static equilibrium against an external load are expressed as functions of external torques and tendon moment arms on the joints. External torques are functions of finger positions, which depend on the joint angles  $\theta_1$ ,  $\theta_2$ , and  $\theta_3$ .

### 6.5.3 Muscular Forces in the Non-Constant Tendon Moment Arms Model

When the moment arms of the tendons increase as the joint angle increases, tendon excursions of the flexor digitorum profundus and superficialis and lumbricals are as expressed in equations (6.9), (6.10), and (6.12). Tendon excursions of the extensor digitorum and interossei are described the same as in the constant tendon moment arms model. The associated equilibrium equations are (6.28), (6.29), and (6.30).

Solutions for these equations can be obtained by replacing  $r_{P1}$ ,  $r_{P2}$ ,  $r_{S1}$ ,  $r_{S2}$ , and  $r_{L1}$  by  $(r_{P1} + 0.5 r_{P1}' \theta_1)$ ,  $(r_{P2} + 0.5 r_{P2}' \theta_2)$ ,  $(r_{S1} + 0.5 r_{S1}' \theta_1)$ ,  $(r_{S2} + 0.5 r_{S2}' \theta_2)$ , and  $(r_{L1} + 0.5 r_{L1}' \theta_1)$ , respectively, in the solutions of the constant tendon moment arms model.

This yields

$$R_{P1} = r_{P1} + 0.5 r_{P1}' \theta_1$$

$$R_{P2} = r_{P2} + 0.5 r_{P2}' \theta_2$$

$$R_{S1} = r_{S1} + 0.5 r_{S1}' \theta_1$$

$$R_{S2} = r_{S2} + 0.5 r_{S2}' \theta_2.$$

The forces required for "static finger flexion exertion about the MCP joint" are

$$F_S = \frac{T_1 k_3 + T_2 (k_2 + k_3) + T_3 (k_2 + k_3 - k_1)}{(R_{S1} k_3 + R_{S2} k_2)} \quad (6.43)$$

$$F_I = \frac{T_1 r_{P3} R_{S2} + T_2 k_5 + T_3 (k_4 + k_5)}{R_{S1} k_3 + R_{S2} k_2} \quad (6.44)$$

$$F_P = \frac{T_1 (R_{S2} r_{I3}) + T_2 r_{I3} (R_{S2} - R_{S1})}{(R_{S1} k_3 + R_{S2} k_2)} + \frac{T_3 (r_{I3} R_{S2} - R_{S1} r_{I3} + R_{S1} r_{I2} + R_{S2} r_{I1})}{(R_{S1} k_3 + R_{S2} k_2)}, \quad (6.45)$$

where  $k_1, k_2, k_3, k_4,$  and  $k_5$  have the following values:

$$k_1 = R_{P1} r_{I2} + R_{P2} r_{I1}$$

$$k_2 = R_{P1} r_{I3} + r_{P3} r_{I1}$$

$$k_3 = r_{P3} r_{I2} - R_{P2} r_{I3}$$

$$k_4 = R_{P2} R_{S1} - R_{P1} R_{S2}$$



$$k_5 = r_{p3} R_{S2} - r_{p3} R_{S1}$$

Required muscular forces for "static finger flexion exertion about the PIP joint" have the same forms as those in "static finger flexion exertion about the MCP joint". Only the  $T_1$ ,  $T_2$ , and  $T_3$  have different values due to the direction of external load.

Required muscular forces for "static finger extension exertion about the MCP joint" can be obtained by substituting  $(r_{L1} + 0.5 r_{L1}' \theta_1)$  for  $r_{L1}$  in equation (6.40), (6.41), and (6.42). This results in:

$$F_L = \frac{T_1 c_1 + T_2 (c_1 + c_2) + T_3 (c_1 + c_2 - c_3)}{(r_{L1} + 0.5 r_{L1}' \theta_1) c_1 - r_{L2} c_2 + r_{L3} c_3} \quad (6.46)$$

$$F_I = \frac{T_1 c_4 + T_2 (c_4 - c_5) + T_3 (c_4 - c_5 + c_6)}{r_{I1} c_4 + r_{I2} c_5 - r_{I3} c_6} \quad (6.47)$$

$$\begin{aligned} F_E = & - T_1 \frac{r_{I3} c_4 c_8 + r_{L3} c_1 c_7}{r_{E3} c_7 c_8} \\ & - T_2 \frac{r_{I3} (c_4 - c_5) c_8 + r_{L3} (c_1 + c_2) c_7}{r_{E3} c_7 c_8} \\ & - T_3 \frac{r_{I3} (c_4 - c_5 + c_6) c_8 + r_{L3} (c_1 + c_2 - c_3) c_7 + c_7 c_8}{r_{E3} c_7 c_8}, \end{aligned} \quad (6.48)$$

where  $c_1, c_2, c_3, c_4, c_5, c_6, c_7$ , and  $c_8$  stand for

$$c_1 = r_{E3} r_{I2} - r_{E2} r_{I3}$$

$$c_2 = r_{E1} r_{I3} + r_{E3} r_{I1}$$

$$c_3 = r_{E1} r_{I2} + r_{E2} r_{I1}$$

$$c_4 = r_{E2} r_{L3} - r_{E3} r_{L2}$$

$$c_5 = r_{E1} r_{L3} + r_{E3} (r_{L1} + 0.5 r_{L1}' \theta_1)$$

$$c_6 = r_{E2} r_{L3} - r_{E3} r_{L2}$$

$$c_7 = r_{I1} c_4 + r_{I2} c_5 - r_{I3} c_6$$

$$c_8 = (r_{L1} + 0.5 r_{L1}' \theta_1) c_1 - r_{L2} c_2 + r_{L3} c_3$$

Muscular forces in "static finger extension exertion about the PIP joint" for non-constant tendon moment arms have the same forms as those for constant tendon moment arms models except for the value of tendon moment arm of the lumbricals, which increases as the finger flexes.

## *6.6 Discussion and Summary*

Two biomechanical finger models are developed with five muscles and three joints. One is with the assumption that tendon moment arms at the joints are constant during finger movements. The other is with the assumption of non-constant tendon moment arms during finger movements.

In the constant tendon moment arms model, tendon excursions are expressed as a linear function of joint angles. Landsmeer's first equation is used to develop tendon

excursion model. In the non-constant tendon moment arms model, Landsmeer's first equation is applied to the tendons of the muscles when they extend the joints. Landsmeer's third equation is applied in case that the tendons of the muscles flex the joints.

These finger models are expanded from the model of Storace and Wolf (1979). There are some other finger models. However, finger models developed in this study can be distinguished by anatomical and functional considerations of the muscles and tendons as well as the number of involved muscles and joints.

From the tendon excursion equations, equilibrium equations are developed using the principle of virtual work. Three equilibrium equations include five unknown forces. Therefore, the equations are indeterminate. Two variables are eliminated by information from EMG studies about the muscular functions in finger movements. Then these equations are solved for the forces. An external load is assumed to act on the finger tip. The muscular forces are expressed as functions of tendon moment arms and torques at the joints caused by an external load.

The procedure of deriving the force equations is straightforward. Yet, special consideration is required to eliminate two variables from the equilibrium equations. Since static equilibrium is assumed in finger flexion exertions (about the MCP and PIP joints) against an external load toward finger extension, muscles should work to flex the three joints. Therefore, the FDP, FDS, and interossei are determined as the flexors of the joints. In finger extension exertions, the external load is assumed to act toward finger flexion. The interossei and lumbricals are determined as the extensors in addition to the EDC. These simplifications may induce incomplete or faulty results. However, in the current situation, they are the best possible decisions.

## **VII. Muscle Length-Tension Relationships**

### ***7.1 Overview***

Muscle length is an important factor which determines the exerted muscular force. The length-tension relationships for the five muscles of interest can be normalized. The tendon excursions are computed from the finger models developed in Chapter VI and from the range of motions of the MCP, PIP, and DIP joints. Ranges of motion of the finger joints can be obtained by direct measurements. In this study, however, data of motion ranges for computing tendon excursions of the muscles are taken from other studies.

## *7.2 Muscle Length-Tension Relationships*

A resting muscle has elasticity. It can be stretched by a force, and the greater the force, the greater the extension. The elasticity of the resting muscle arises largely from the meshwork of connective tissue within the muscle. As the muscle is stretched, muscle fibers become progressively taut (Chaffin and Andersson, 1984; Wilkie, 1976).

Muscle is thought to have three components: a contractile component (CC), a parallel elastic component (PEC), and a series elastic component (SEC) (Hatze, 1981; Jones, 1986). The muscle length-tension relationship generally includes two forces: active and passive forces. The active force comes from the contractile component and the passive force comes from the elastic components. The connective elastic tissue is mechanically parallel with the contractile component. When muscle is stimulated, the contractile component develops tension which varies according to the length of the muscle. Since the contractile and parallel elastic components are in parallel, their tensions are added together. A muscle model including the contractile and elastic components is shown in Figure 7.1. A typical muscle length-tension relationship is shown in Figure 7.2.

The muscle length-tension curves from different types of muscles have different shapes (Huijing and Woittiez, 1984; Woittiez and Huijing, 1983; Woittiez, 1984). The parallel-fibered muscles are known to have longer ranges of contraction-extension than the pennate-fibered muscles, in which muscle fibers are bilaterally arranged to a line like a feather. Woittiez, Huijing, Boom, and Rozendal (1984) reported that the normalized active length-tension curve runs from about 71% to 129% of the optimal muscle length in the parallel-fibered semimembranosus. The active length-tension curve of the pennate-fibered gastrocnemius runs from about 82% to 118% of the optimal muscle

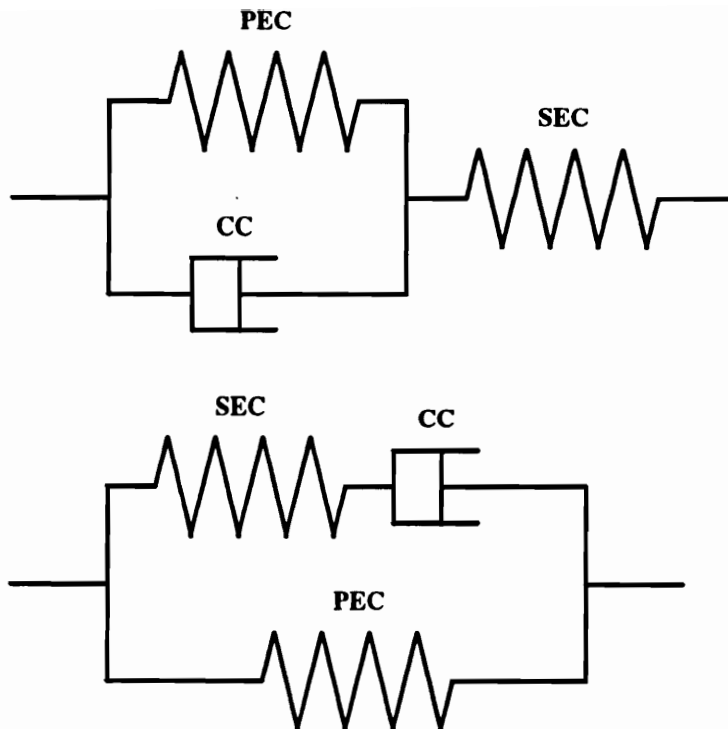


Figure 7.1. Muscle models with contractile and elastic components.

CC represents contractile component, SEC is the series elastic component, and PEC is the parallel elastic component in the muscle.

muscular tension

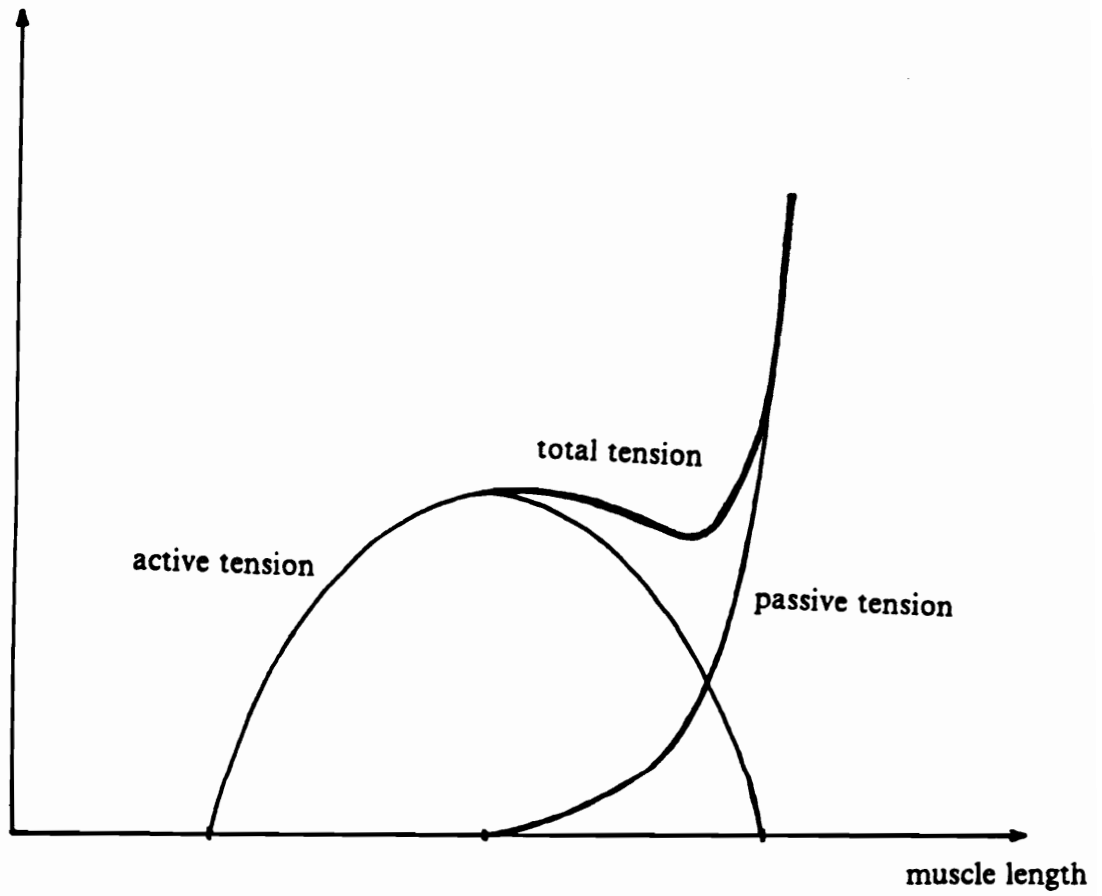


Figure 7.2. Diagram of the typical muscle length-tension relationship.

length. Woittiez et al. (1984) expressed the active and passive length-tension relationships using parabolic and exponential functions, respectively.

### *7.3 Normalized Muscle Length-Tension Curves*

The muscles associated with finger movements are pennate-fibered. The muscle length-tension curves of pennate-fibered muscles run from about 82% to 118% of their optimal muscle lengths (Woittiez et al., 1983 and 1984). For ease of computation, the length-tension relations can be approximated (except for extreme flexions and extensions, which are not used in this study) by considering only the active length-tension curves of muscles in the range from above 80% to below 120% of the resting muscle lengths. In this study, extrinsic muscle lengths are close to resting length in all finger positions. Therefore, the contribution of passive stretch (above resting length) to total muscle tension can be disregarded.

The range of muscle length corresponds to the range of motion of the finger and wrist. Tendon excursions of the muscles are computed using the finger models developed in Chapter VI and the ranges of motions of finger joints taken from the study of Brand (1985). Total tendon excursions of extrinsic muscles are the sum of tendon excursions by finger and wrist movement. Tendon excursions by wrist movements are obtained from the study of Tubiana (1981). Tendon excursions of five muscles are computed using the finger models and ranges of motions of finger joints. For the constant tendon moment arms models, equations (6.3) through (6.7) are used; for the non-constant tendon moment arms models, equations (6.8) through (6.12) are used. Tendon excursions computed from the two finger models are summarized in Tables 7.1 and 7.2.



Table 7.1. Tendon excursions in cm computed from the constant tendon moment arms model.

Joint	Muscle ROM**	EDC	FDP	FDS	Int.	Lumb.
		MCP	90.0	1.35	1.74	1.87
PIP	100.0	0.49	1.38	1.08	0.45	0.31
DIP	60.0	0.23	0.43	–	0.17	0.07
Excursion by Finger		2.07	3.55	2.96	1.66	1.84
Excursion by Wrist*		4.50	3.80	4.60	–	–
<b>Total Excursion</b>		<b>6.57</b>	<b>7.35</b>	<b>7.55</b>	<b>1.66</b>	<b>1.84</b>

**legend** EDC : Extensor Digitorum Communis  
 FDP : Flexor Digitorum Profundus  
 FDS : Flexor Digitorum Superficialis  
 Int. : Interossei  
 Lumb. : Lumbricals

\* : Tendon excursions by wrist motion are from Tubiana (1981), in cm.

\*\* : Ranges of motion are from Brand (1985), in degrees.

Table 7.2. Tendon excursions in cm computed from the non-constant tendon moment arms model.

Joint	Muscle ROM**	EDC	FDP	FDS	Int.	Lumb.
		MCP	90.0	1.35	1.95	2.09
PIP	100.0	0.49	1.56	1.22	0.45	0.31
DIP	60.0	0.23	0.43	-	0.17	0.07
Excursion by Finger		2.07	3.94	3.31	1.66	2.01
Excursion by Wrist*		4.50	3.80	4.60	-	-
Total Excursion		6.57	7.74	7.91	1.66	2.01

**legend**    EDC : Extensor Digitorum Communis  
               FDP : Flexor Digitorum Profundus  
               FDS : Flexor Digitorum Superficialis  
               Int. : Interossei  
               Lumb. : Lumbricals

\* : Tendon excursions by wrist motion are from Tubiana (1981), in cm.

\*\* : Ranges of motion are from Brand (1985), in degrees.

The active muscle length-tension relations are generally expressed as non-symmetric, polygon-like inverse-U shapes. In this study, however, they are approximated to be symmetric and continuous. The active length-tension relationships of hand and finger muscles are normalized by parabolic functions using the information in the study of Otten (1988) and Woittiez et al. (1983 and 1984). The independent variable is muscle length and the dependent variable is percentage of muscular capability. A schematic diagram of a normalized muscle length-tension curve is shown in Figure 7.3. In the diagram, range of muscle length corresponds to the range of tendon excursion developed by finger and wrist flexion and extension. Since it is assumed that the length-tension curve runs from about 80% to 120% of the resting muscle length,  $l_0$ , the range of muscle length in muscle  $i$ ,  $X_{M_i}$  is expressed as

$$X_{M_i} = 0.4 l_0.$$

Therefore, the resting muscle length is expressed as

$$l_0 = 2.5 X_{M_i}$$

Then muscle length-tension curve runs from  $2 X_{M_i}$  to  $3 X_{M_i}$ . The normalized parabolic length-tension curve for muscle  $i$  is

$$Y_{F_i} = - \frac{100}{0.25 X_{M_i}} [ L^2 - 5 X_{M_i} L + 6 X_{M_i}^2 ], \quad (7.1)$$

where  $Y_{F_i}$  is the percentage of muscular capability of muscle  $i$ , and  $L$  is the length of the muscle in cm. From this general equation, muscle length-tension relationships of five muscles are derived from their maximal tendon excursions, which are obtained by computations using the finger models developed in this study while the values of tendon moment arms are taken from An et al. (1983).

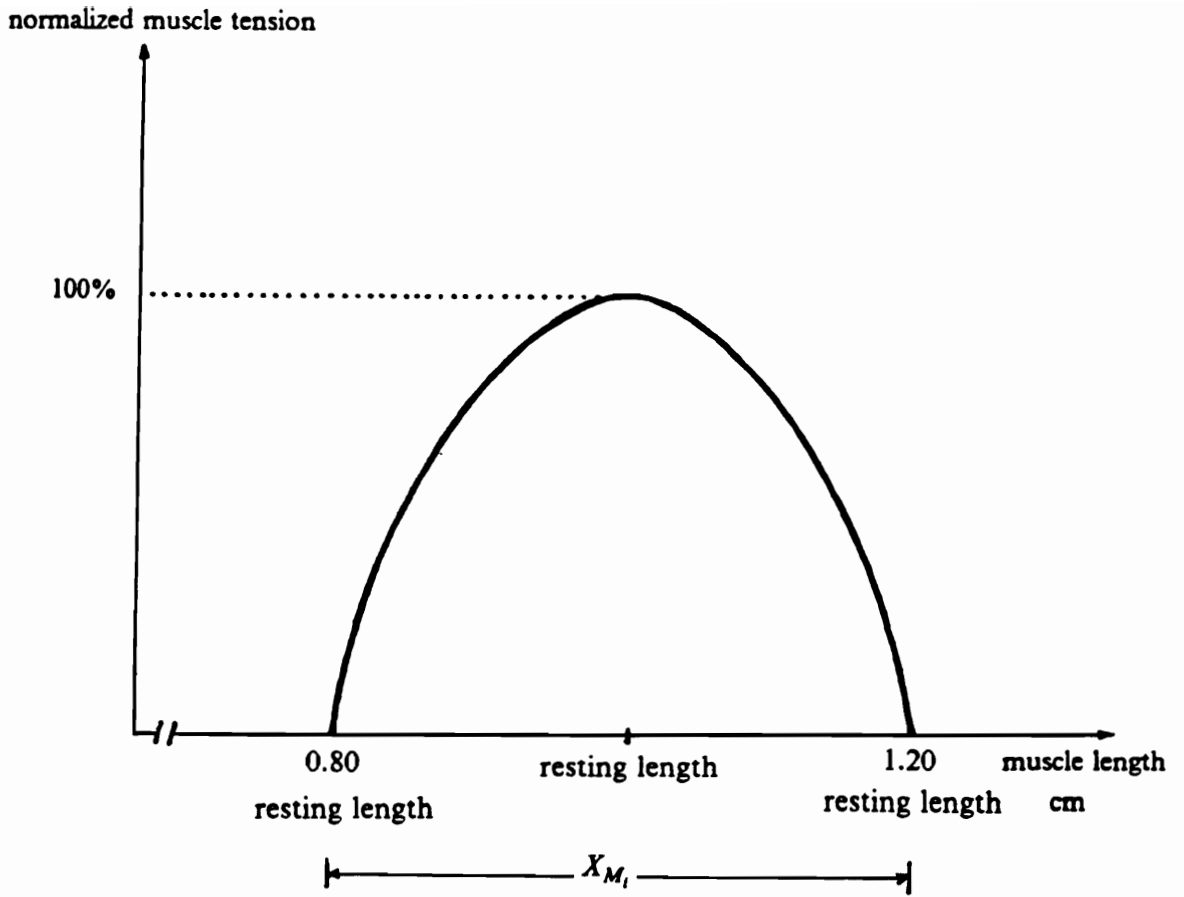


Figure 7.3. Schematic diagram of normalized muscle length-tension relationship.

Normalized muscle length-tension relationships in the finger model of constant tendon moment arms are derived using tendon excursions in Table 7.1:

Extensor Digitorum Communis

$$Y_{FE} = - 9.27 L^2 + 304.41 L - 2400.0 \quad (7.2)$$

Flexor Digitorum Profundus

$$Y_{FP} = - 7.40 L^2 + 272.11 L - 2399.9 \quad (7.3)$$

Flexor Digitorum Superficialis

$$Y_{FS} = - 7.02 L^2 + 264.90 L - 2400.0 \quad (7.4)$$

Interossei

$$Y_{FI} = - 145.16 L^2 + 1204.82 L - 2400.0 \quad (7.5)$$

Lumbricals

$$Y_{FL} = - 118.15 L^2 + 1086.96 L - 2400.0 \quad (7.6)$$

Normalized muscle length-tension relationships in the finger model of non-constant tendon moment arms are derived using tendon excursions in Table 7.2:

Extensor Digitorum Communis

$$Y_{FE} = - 9.27 L^2 + 304.41 L - 2400.0 \quad (7.7)$$

Flexor Digitorum Profundus

$$Y_{FP} = - 6.68 L^2 + 258.40 L - 2400.0 \quad (7.8)$$

Flexor Digitorum Superficialis

$$Y_{FS} = - 6.39 L^2 + 252.84 L - 2400.0 \quad (7.9)$$

Interossei

$$Y_{FI} = - 145.16 L^2 + 1204.82 L - 2400.0 \quad (7.10)$$

Lumbricals

$$Y_{FL} = - 99.01 L^2 + 995.02 L - 2400.0 \quad (7.11)$$

It is assumed that the resting muscle length is the median of its range of motion which corresponds to the range of motion of the joint. Since the range of motion of the MCP, PIP, and DIP joints are  $90^\circ$ ,  $100^\circ$ , and  $60^\circ$ , respectively, the resting position of the finger has angles of  $45^\circ$ ,  $50^\circ$ , and  $30^\circ$ , at the MCP, PIP, and DIP joints, respectively.

## ***7.4 Discussion and Summary***

Force generated by the muscle is affected by the length of the muscle. In isometric contraction, the muscle length is determined by posture or joint angles. The effect of muscle length on muscular capability is expressed as muscle length-tension relationship. Muscle length-tension curves are assumed symmetric in all muscles. For ease of computation, only the active length-tension curves of the muscles are considered and their ranges are approximated from above 80% to below 120% of the resting muscle lengths.

Normalized muscle length-tension curves are formulated with the data of maximal tendon excursions which are computed from ranges of motions of the finger joints. These computations are performed for both the constant and non-constant tendon moment arms finger models.

Normalized muscle length-tension curves in this chapter are based on the values of tendon moment arms from the literature. Therefore, they do not reflect individual results. If personal data of tendon moment arms are obtained, these equations can be personalized to precise data of finger strengths.

## VIII. Applications of Biomechanical Finger Models

### *8.1 Overview*

From the equations in Chapter VI and VII, finger strengths in different finger positions and directions of force exertions are computed. For these predictions, finger joint angles, lengths of phalanges, tendon moment arms, and individual muscular capabilities must be known.

An inverse procedure of finger strength computation makes it possible to estimate individual muscular force required to maintain static equilibrium against a submaximal external load to the finger tip. In this computation, the same data for finger strength computation except muscular capabilities are needed.

Predictions of finger strengths and muscular forces required for static equilibrium against an external load in various finger positions and directions of force exertions are performed using computer simulation.



## 8.2 Muscular Forces in Static Equilibrium

Muscular forces in static exertions against an external load can be directly computed using the equations obtained in Chapter VI. Muscular forces are functions of the torques about the three joints and of the tendon moment arms. Torques are dependent on finger positions. The torques acting on each finger joint can be computed by the following formulae:

$$T_1 = T \{ l_1 \cos(\phi - \theta_1) + l_2 \cos(\phi - \theta_1 - \theta_2) \} \\ + T \{ l_3 \cos(\phi - \theta_1 - \theta_2 - \theta_3) \} \quad (8.1)$$

$$T_2 = T \{ l_2 \cos(\phi - \theta_1 - \theta_2) + l_3 \cos(\phi - \theta_1 - \theta_2 - \theta_3) \} \quad (8.2)$$

$$T_3 = T \{ l_3 \cos(\phi - \theta_1 - \theta_2 - \theta_3) \}, \quad (8.3)$$

where  $T_1$ ,  $T_2$ , and  $T_3$  are torques acting on the MCP, PIP, and DIP joints, respectively.  $T$  is the external load acting vertically upward on the finger tip.  $l_1$ ,  $l_2$ , and  $l_3$  are the lengths of the proximal, middle, and distal phalanges, respectively.  $\phi$  refers to the direction of external load which is expressed by the angle between the external force vector and vertical (Figure 8.1).  $\theta_1$ ,  $\theta_2$ , and  $\theta_3$  are angles of the MCP, PIP, and DIP joints, respectively, and expressed as radians. These parameters are shown in Figure 8.1.

Muscular forces in "static finger flexion exertion about the MCP joint" can be computed using equations (6.32), (6.33), and (6.34). Since the value of  $\phi$  is zero, torques acting on three finger joints are computed as the follows:

$$T_1 = T \{ l_1 \cos(\theta_1) + l_2 \cos(\theta_1 + \theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3) \} \quad (8.4)$$

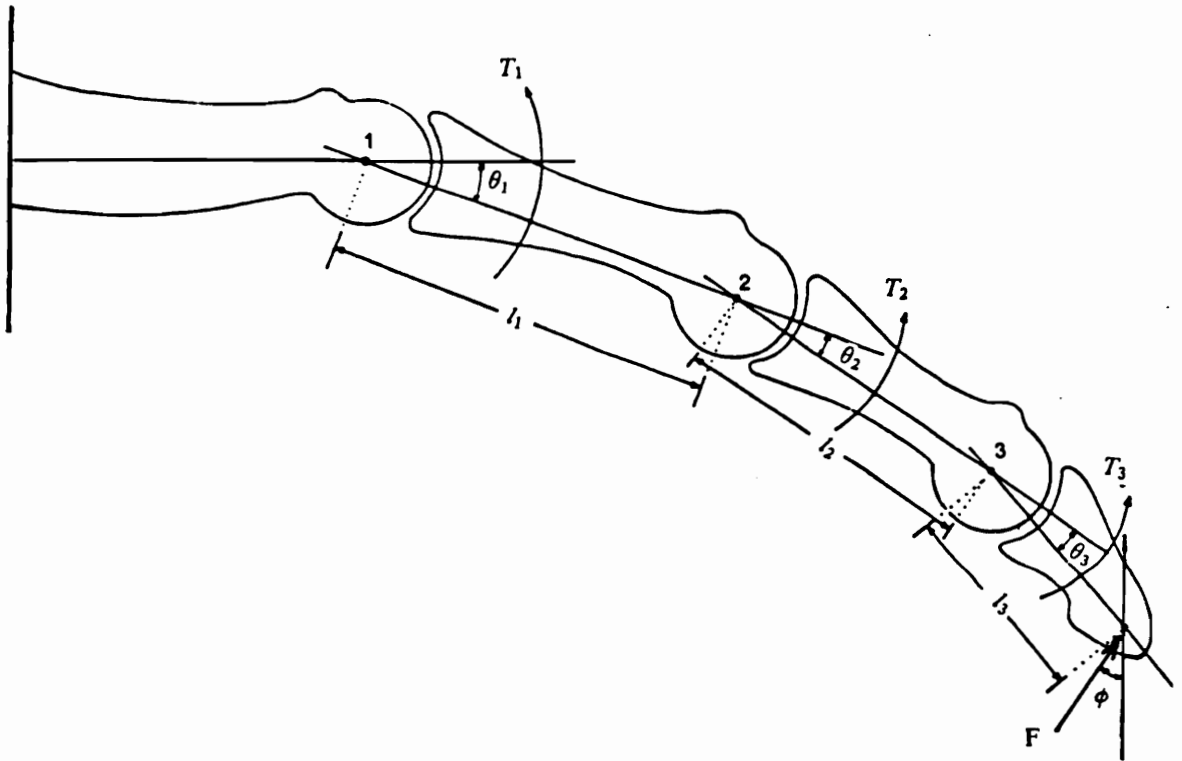


Figure 8.1 Parameters in finger models.

$$T_2 = T\{l_2 \cos(\theta_1 + \theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3)\} \quad (8.5)$$

$$T_3 = T\{l_3 \cos(\theta_1 + \theta_2 + \theta_3)\}. \quad (8.6)$$

Muscular forces required to establish equilibrium in "static finger flexion exertion about the PIP joint" against the external load acting horizontally backward on the finger tip are computed using equations (6.32), (6.33), and (6.34). Since the value of  $\phi$  is  $\frac{\pi}{2}$ , torques acting on three finger joints are computed as follows:

$$T_1 = T\{l_1 \cos(\frac{\pi}{2} - \theta_1) + l_2 \cos(\frac{\pi}{2} - \theta_1 - \theta_2)\} \\ + T\{l_3 \cos(\frac{\pi}{2} - \theta_1 - \theta_2 - \theta_3)\} \quad (8.7)$$

$$T_2 = T\{l_2 \cos(\frac{\pi}{2} - \theta_1 - \theta_2) + l_3 \cos(\frac{\pi}{2} - \theta_1 - \theta_2 - \theta_3)\} \quad (8.8)$$

$$T_3 = T\{l_3 \cos(\frac{\pi}{2} - \theta_1 - \theta_2 - \theta_3)\}. \quad (8.9)$$

Muscular forces in "static finger extension exertion about the MCP joint" are computed using equations (6.38), (6.38), and (6.40). In this case, the value of  $\phi$  is  $\pi$ . Therefore, torques resulted from the external load and acting on three finger joints are:

$$T_1 = - T\{l_1 \cos(\theta_1) + l_2 \cos(\theta_1 + \theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3)\} \quad (8.10)$$

$$T_2 = - T\{l_2 \cos(\theta_1 + \theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3)\} \quad (8.11)$$

$$T_3 = - T\{l_3 \cos(\theta_1 + \theta_2 + \theta_3)\}, \quad (8.12)$$

Muscular forces in "static finger extension exertion about the PIP joint" are computed using the equations (6.38), (6.39), and (6.40). Since the value of  $\phi$  is  $\frac{3}{2} \pi$ , torques acting on three finger joints are computed as follows:

$$T_1 = T \{ l_1 \cos(1.5 \pi - \theta_1) + l_2 \cos(1.5 \pi - \theta_1 - \theta_2) \} \\ + T \{ l_3 \cos(1.5 \pi - \theta_1 - \theta_2 - \theta_3) \} \quad (8.13)$$

$$T_2 = T \{ l_2 \cos(1.5 \pi - \theta_1 - \theta_2) + l_3 \cos(1.5 \pi - \theta_1 - \theta_2 - \theta_3) \} \quad (8.14)$$

$$T_3 = T \{ l_3 \cos(1.5 \pi - \theta_1 - \theta_2 - \theta_3) \}. \quad (8.15)$$

Muscular forces required for static equilibrium against the external load can be computed using the values of torques in equations (8.4) to (8.15). The torques acting on the joints have the same values for the constant and the non-constant tendon moment arms models.

### ***8.3 Finger Strengths in Various Finger Positions***

The other application of the finger model is estimation of finger strength in various finger positions. For this, the force capability of each muscle must be known. Muscular force capability is largely dependent upon the number of muscle fibers and upon the angle of insertion into the tendon (Zachary, 1946: cited by Tubiana, 1981). Determination of human muscular force capability, however, is difficult and various investigators

have shown much varying values (Brand, 1985; Ketchum, Thompson, Pocock, and Willingsford, 1978; Tubiana, 1981).

A method used to estimate muscular tension capability was developed by Fick (1911) in his anatomical studies (cited by Tubiana, 1981). Accordingly, the muscular tension capability is computed by multiplying the surface area of the muscle in cross section expressed in ( $cm^2$ ) by a coefficient of  $10.0 \text{ kg}/cm^2$ . The force capabilities of the extrinsic muscles of the hand were computed by Lanz and Wachsmuth (1959: cited by Tubiana, 1981), who used Fick's coefficient. The force capabilities of the extrinsic muscles computed by Lanz and Waschsmuth are expressed by Boyes (1962) using a so-called unit "working power":

Extensor Digitorum Communis -- 1.7 kg-m

Extensor Indicis -- 0.5 kg-m

Flexor Digitorum Profundus -- 4.5 kg-m

Flexor Digitorum Superficialis -- 4.8 kg-m.

There are some problems with these data. First, the unit of muscular force is N not kg. "Working power" was defined as the force of a muscle expressed in kg multiplied by the distance in m. This unit appears not to be suitable to express the muscular capability since, by definition, the unit "force times displacement" is not "power".

Second, it is not assured that the force per cross-section unit is constant. While Fick found  $10 \text{ kg}/cm^2$ , Recklinghausen reported  $3.6 \text{ kg}/cm^2$  in 1920, which coincides with the finding of Arkin (1938, cited by Steindler, 1955). Åstrand and Rodahl (1986) state that the maximal muscular tension is roughly constant in different muscles, being on the or-

der of  $60 \text{ N/cm}^2$  in an isometric contraction. Hettinger (1972) also found constant tension values in the biceps muscle.

Third, the muscle size is highly variable: Fahrer and Pineau (1976) reported that the cross-section of the flexor digitorum superficialis was  $12 \text{ cm}^2$  on one cadaver, but Fick found  $21 \text{ cm}^2$ .

Brand (1985) and Brand, Beach, and Thompson (1981) reported relative tension capabilities of the muscles in the forearm and hand. They described the mechanical characteristics of a muscle as:

- (1) Mass or volume of muscle fibers is proportional to tension capacity of a muscle.
- (2) Average fiber length is proportional to potential excursion of a muscle.
- (3) Cross-sectional area of all fibers is proportional to tension capacity of a muscle.

Assuming that the total tension generated by muscles in the forearm and hand is 100%, Brand et al. (1975 and 1981) computed the tension fraction of every muscle based on the resting fiber length and mass fraction of the muscle. The tension fractions of the muscles associated with the index finger are

Extensor Digitorum Communis -- 1.0 %

Flexor Digitorum Profundus -- 2.7 %

Flexor Digitorum Superficialis -- 2.0 %

Palmar Interossei -- 1.3 %

Dorsal Interossei -- 3.2 %

Lumbricals -- 0.2 %.

Ketchum, Thompson, Pocock, and Willingford (1978) computed forces generated by the muscles in the forearm and hand. They selectively measured the intrinsic and extrinsic muscle forces by local anesthesia and using strain gauges and amplifiers. According to Ketchum et al., force capabilities of the muscles were expressed in kg, which is not a correct unit of force. For this study, force capabilities of the muscles in the index finger measured by Ketchum et al. are expressed in N:

Extensor Digitorum Communis -- 58.60 N (S.D. = 28.03)

Flexor Digitorum Profundus -- 60.56 N (S.D. = 25.87)

Flexor Digitorum Superficialis -- 67.72 N (S.D. = 23.13)

Palmar Interossei -- 27.15 N (S.D. = 11.47)

Dorsal Interossei -- 53.31 N (S.D. = 24.70)

Lumbricals -- 19.89 N (S.D. = 8.82)

In this study, Ketchum et al.'s (1978) data of force capabilities are used to predict finger strength at various finger positions and in different directions of force exertions.

In static finger flexion exertion about the MCP joint, equations (6.34) through (6.36) which express muscular forces  $F_S$ ,  $F_P$ , and  $F_I$  can be re-written for torque  $T$  by substituting equations of  $T_1$ ,  $T_2$ , and  $T_3$ , equations (8.4), (8.5), and (8.6), into the equations from (6.34) to (6.36). The equations of muscular forces, (6.34), (6.35), and (6.36), can be re-written as

$$FT_S = \frac{(r_{S1} k_3 + r_{S2} k_2) F_S}{d_1 k_3 + d_2 (k_2 + k_3) + d_3 (k_2 + k_3 - k_1)} \quad (8.16)$$

$$\begin{aligned}
FT_P &= \frac{(r_{S1} k_3 + r_{S2} k_2) F_P}{d_1 r_{S2} r_{I3} + d_2 r_{I3} (r_{S2} - r_{S1})} \\
&+ \frac{(r_{S1} k_3 + r_{S2} k_2) F_P}{d_3 (r_{S2} r_{I3} - r_{S1} r_{I3} + r_{S1} r_{I2} + r_{S2} r_{I1})}
\end{aligned} \tag{8.17}$$

$$FT_I = \frac{(r_{S1} k_3 + r_{S2} k_2) F_L}{d_1 r_{P3} r_{S2} + d_2 k_5 + d_3 (k_4 + k_5)}, \tag{8.18}$$

where  $k_1$  to  $k_5$  have the same values as those in the equations of muscular forces in Chapter VI. The  $d_1$ ,  $d_2$ , and  $d_3$  stand for

$$d_1 = l_1 \cos \theta_1 + l_2 \cos(\theta_1 + \theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3)$$

$$d_2 = l_2 \cos(\theta_1 + \theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3)$$

$$d_3 = l_3 \cos(\theta_1 + \theta_2 + \theta_3).$$

These equations involve  $\theta_1$ ,  $\theta_2$ , and  $\theta_3$  as well as tendon moment arms and muscular capabilities ; thus, they are functions of finger position. Finger strength at the finger positions,  $\theta_1$ ,  $\theta_2$ , and  $\theta_3$  can be expressed as the sum of the  $FT_S$ ,  $FT_P$ , and  $FT_I$ .

Finger flexion strength about the PIP joint can be estimated by the same procedure as used for computing finger strength toward finger flexion about the MCP joint. The equations for  $FT_S$ ,  $FT_P$ , and  $FT_I$  have the same forms except that they include different cosines of force exertions shown in  $d_4$ ,  $d_5$ , and  $d_6$ . The contributions of the flexor digitorum profundus and superficialis, and of the interossei to finger strength can be expressed as



$$FT_S = \frac{(r_{S1} k_3 + r_{S2} k_2) F_S}{d_4 k_3 + d_5 (k_2 + k_3) + d_6 (k_2 + k_3 - k_1)} \quad (8.19)$$

$$FT_P = \frac{(r_{S1} k_3 + r_{S2} k_2) F_P}{d_4 r_{S2} r_{I3} + d_5 r_{I3} (r_{S2} - r_{S1})} + \frac{(r_{S1} k_3 + r_{S2} k_2) F_P}{d_6 (r_{S2} r_{I3} - r_{S1} r_{I3} + r_{S1} r_{I2} + r_{S2} r_{I1})} \quad (8.20)$$

$$FT_I = \frac{(r_{S1} k_3 + r_{S2} k_2) F_L}{d_4 r_{P3} r_{S2} + d_5 k_5 + d_6 (k_4 + k_5)}, \quad (8.21)$$

where  $d_4$ ,  $d_5$ , and  $d_6$  are

$$d_4 = l_1 \cos\left(\frac{\pi}{2} - \theta_1\right) + l_2 \cos\left(\frac{\pi}{2} - \theta_1 - \theta_2\right) + l_3 \cos\left(\frac{\pi}{2} - \theta_1 - \theta_2 - \theta_3\right)$$

$$d_5 = l_2 \cos\left(\frac{\pi}{2} - \theta_1 - \theta_2\right) + l_3 \cos\left(\frac{\pi}{2} - \theta_1 - \theta_2 - \theta_3\right)$$

$$d_6 = l_3 \cos\left(\frac{\pi}{2} - \theta_1 - \theta_2 - \theta_3\right).$$

Finger extension strength about the MCP joint can be computed from modified equations (6.40), (6.41), and (6.42). In this case, the extensor, interossei, and lumbricals contribute to finger strength as follows:

$$FT_E = - \frac{(r_{E3} c_7 c_8) F_E}{d_7 (r_{I3} c_4 c_8 + r_{L3} c_1 c_7) + d_8 \{r_{I3} (c_4 - c_5) c_8 + r_{L3} (c_1 + c_2) c_7\}} - \frac{(r_{E3} c_7 c_8) F_E}{d_9 \{r_{I3} (c_4 - c_5 + c_6) c_8 + r_{L3} (c_1 + c_2 - c_3) c_7 + c_7 c_8\}} \quad (8.22)$$

$$FT_I = \frac{(r_{I1} c_4 + r_{I2} c_5 - r_{I3} c_6) F_I}{d_7 c_4 + d_8 (c_4 - c_5) + d_9 (c_4 - c_5 + c_6)} \quad (8.23)$$

$$FT_L = \frac{(r_{L1} c_1 - r_{L2} c_2 + r_{L3} c_3) F_L}{d_7 c_1 + d_8 (c_1 + c_2) + d_9 (c_1 + c_2 - c_3)}, \quad (8.24)$$

where  $c_1$  to  $c_8$  are same as in equations of muscular forces in Chapter VI, and the  $d_7$ ,  $d_8$ , and  $d_9$  are

$$d_7 = l_1 \cos(\pi - \theta_1) + l_2 \cos(\pi - \theta_1 - \theta_2) + l_3 \cos(\pi - \theta_1 - \theta_2 - \theta_3)$$

$$d_8 = l_2 \cos(\pi - \theta_1 - \theta_2) + l_3 \cos(\pi - \theta_1 - \theta_2 - \theta_3)$$

$$d_9 = l_3 \cos(\pi - \theta_1 - \theta_2 - \theta_3).$$

Contributions by the extensor, interossei, and lumbricals to finger extension strength about the PIP joint can be derived by the same way and have the same forms as those of finger extension strength about the MCP joint except that they include different values of cosines. The equations are

$$FT_E = - \frac{(r_{E3} c_7 c_8) F_E}{d_{10} (r_{I3} c_4 c_8 + r_{L3} c_1 c_7) + d_{11} \{ r_{I3} (c_4 - c_5) c_8 + r_{L3} (c_1 + c_2) c_7 \}} - \frac{(r_{E3} c_7 c_8) F_E}{d_{12} \{ r_{I3} (c_4 - c_5 + c_6) c_8 + r_{L3} (c_1 + c_2 - c_3) c_7 + c_7 c_8 \}} \quad (8.25)$$

$$FT_I = \frac{(r_{I1} c_4 + r_{I2} c_5 - r_{I3} c_6) F_I}{d_{10} c_4 + d_{11} (c_4 - c_5) + d_{12} (c_4 - c_5 + c_6)} \quad (8.26)$$

$$FT_L = \frac{(r_{L1} c_1 - r_{L2} c_2 + r_{L3} c_3) F_L}{d_{10} c_1 + d_{11} (c_1 + c_2) + d_{12} (c_1 + c_2 - c_3)}. \quad (8.27)$$

The  $d_{10}$ ,  $d_{11}$ , and  $d_{12}$  stand for

$$d_{10} = l_1 \cos\left(\frac{3}{2}\pi - \theta_1\right) + l_2 \cos\left(\frac{3}{2}\pi - \theta_1 - \theta_2\right) + l_3 \cos\left(\frac{3}{2}\pi - \theta_1 - \theta_2 - \theta_3\right)$$

$$d_{11} = l_2 \cos\left(\frac{3}{2}\pi - \theta_1 - \theta_2\right) + l_3 \cos\left(\frac{3}{2}\pi - \theta_1 - \theta_2 - \theta_3\right)$$

$$d_{12} = l_3 \cos\left(\frac{3}{2}\pi - \theta_1 - \theta_2 - \theta_3\right).$$

Finger extension strength is sum of these  $FT_E$ ,  $FT_I$ , and  $FT_L$ .

Accordingly, when an external static load is given, muscular forces to maintain the finger position can be computed. Inversely, when muscular capabilities are known, finger strength can be predicted.

## 8.4 Computer Simulation

Muscular forces for static exertions about the MCP and PIP joints were computed for various finger positions. Equations of muscular forces derived in Chapter VI and muscle length-tension relationships derived in Chapter VII were used. Anatomical data of tendon moment arms were obtained from the literature. Four different directions of external load were considered.

Finger strengths about the MCP and PIP joints were also estimated for various finger positions. Equations of torques derived in prior section and muscle length-tension

relationships derived in Chapter VII were used. Data of muscular capabilities were obtained from the literature. Four directions of force exertions were considered.

Computer programs were written for the constant and non-constant tendon moment arms models, respectively, using Turbo Pascal. A 80386-based IBM PC was used to run these programs.

#### **8.4.1 Data for Simulation**

Required data for computing finger strength are tendon moment arms, lengths of phalanges, finger positions, and individual muscular capabilities. For computing muscular forces, data on magnitude and direction of external load are needed instead of muscular capabilities.

Among the required data, tendon moment arms of five muscles on each finger joint were taken from the study of Brand (1985); muscular force capabilities were adopted from Ketchum, Thompson, Pocock, and Willingford (1978). Lengths of phalanges can be obtained from An et al. (1983). However, in this study, phalangeal lengths were measured on the six subjects who participated in the experiments of finger strength tests and of submaximal contractions. Mean values of measured phalangeal lengths were used when the trends of finger strengths and muscular forces were investigated with respect to finger positions and directions of force exertions. To compute individual's finger strengths and muscular forces, personal data of phalangeal lengths were used.

Finger positions were determined by the combinations of angles in three finger joints. The angle of each finger joint was determined under the condition that the summed value of three joint angles ( $\theta_1 + \theta_2 + \theta_3$ ) was not greater than 90 degrees. Since the

directions of force exertions were vertically upward or downward or horizontally forward or backward, the finger positions with greater than 90 degrees of summed angles might involve undefined forces and make the interpretation of results difficult. Two angles were considered for every joint : 15 and 30 degrees. This resulted in eight finger positions. The results for these eight finger positions were practically applicable for force measurements in finger flexion and extension exertions.

The magnitude of external load was set to 5.0 newtons. Force exertions for finger strength and external load were assumed to have four directions: upward, downward, forward, and backward. Data for computing finger strength and muscular forces in static exertions are summarized in Table 8.1.

#### **8.4.2 Methods and Procedures of Simulation**

The computer simulation consisted of two parts: 1) computations of muscular forces for a given set of data which includes tendon moment arms, lengths of phalanges, finger positions, and external load, and 2) computations of finger strengths in specific directions of force exertions for a given data set of muscular tension capabilities, tendon moment arms, lengths of phalanges, and finger positions. These computations were performed for both the constant and non-constant tendon moment arms models.

Two computer programs were written: one was for the constant tendon moment arms model and the other was for the non-constant tendon moment arms model. Computer programs were written in Pascal and were run on a 80386-based IBM personal computer. Source lists of these programs are in Appendix D.

Torques on finger joints and tendon excursions of the muscles were computed first. Then muscular forces for static equilibrium and finger strength were computed using

Table 8.1 Data for computing finger strength and muscular forces.

**Tendon Moment Arms in cm (from Brand, 1985)**

Joint \ Muscle	EDC	FDP	FDS	Interossei	Lumbricals
MCP	0.97	1.01	1.21	0.85	1.14
PIP	0.58	0.98	0.83	0.50	0.36
DIP	0.35	0.65	-	0.30	0.30

**Individual Muscular Capability in N (from Ketchum et al., 1978)**

Muscle	EDC	FDP	FDS	Interossei		Lumbricals
				Palmar	Dorsal	
Force capability	58.60	60.56	67.72	27.15	53.31	19.89

**Length of Phalanges in cm (measured from subjects)**

Phalanx	Proximal	Middle	Distal
Length	4.08	2.25	1.90

these values. Exertable muscular capabilities were computed next using the equations of muscle length-tension relationships. Exertable muscular capabilities were expressed as percent values of maximal muscular capabilities. Finally, finger strength and muscular forces in static exertions were modified by introducing percent values of exertable muscular capabilities to the original muscular forces and finger strength.

Computations of finger strengths and muscular forces were performed two times. First, mean values of measured phalangeal lengths were used to compute the finger strengths and muscular forces. This was to investigate the trends of finger strengths and muscular forces with respect to finger positions and directions of force exertions. Second, individual's finger strengths and muscular forces were computed with individual data of phalangeal lengths. This was to compare the computed results to the measured data. The flow diagram of these procedures is shown in Figure 8.2.

### **8.4.3 Results**

Numerical values of finger strength and muscular forces in static exertions were obtained for eight finger positions and four directions of force exertions. Finger strengths and muscular forces computed by computer simulations with mean values of tendon moment arms, muscular capabilities, and phalangeal lengths are summarized in Tables 8.2, 8.3, and 8.4, and graphically presented in Figures 8.3 and 8.4. These figures contain eight finger positions: the least flexed finger position has 45 degrees of total angle of finger flexion while the most flexed position has 90 degrees of total angle of flexion. The other finger positions are between these extremes. Three finger positions have 60 degrees of total angle of finger flexion and another three have 75 degrees of total flexion angle. When there is an external load on the fingertip, a larger torque acts on the MCP joint

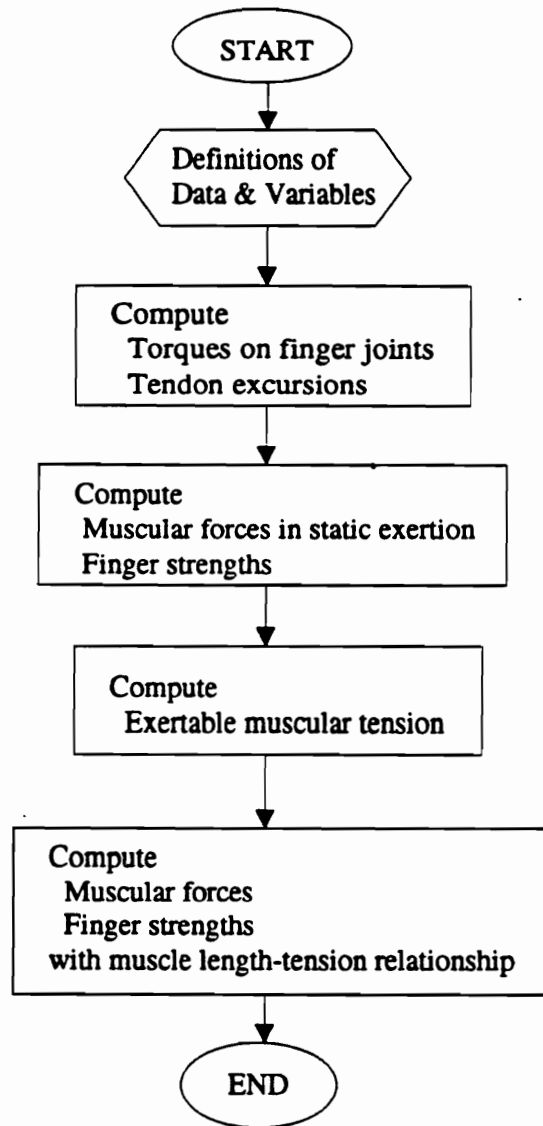


Figure 8.2 Flow diagram of the computer program.



Table 8.2 Computed finger strengths in N in the constant and non-constant tendon moment arms models.

Directions	Models	Angles of MCP		15				30			
		PIP	DIP	15		30		15		30	
				15	30	15	30	15	30	15	30
Downward	Constant	24.22	25.79	29.76	32.54	30.85	34.39	43.98	51.83		
	Non-constant	21.64	22.96	28.01	30.41	28.74	31.89	43.23	50.31		
Upward	Constant	12.19	14.86	15.45	20.53	15.98	21.92	23.68	38.90		
	Non-constant	12.35	14.87	15.77	20.49	15.37	20.35	23.23	35.80		
Backward	Constant	41.09	37.63	32.29	30.41	29.68	28.86	26.52	26.22		
	Non-constant	36.94	33.86	29.80	28.11	27.85	27.13	25.71	25.43		
Forward	Constant	16.47	14.23	13.67	12.58	12.69	11.93	11.72	11.52		
	Non-constant	16.86	14.82	13.89	12.94	12.37	11.80	11.36	11.26		

Table 8.3 Computed muscular forces in N in the constant tendon moment arms model  
(in static exertion against an external load of 5.0 N).

Directions	Muscles	Angles of MCP		15				30			
		PIP	DIP	15		30		15		30	
				15	30	15	30	15	30	15	30
Downward	FDS	15.26	14.16	12.61	11.28	12.69	11.35	8.85	7.37		
	FDP	18.04	15.44	15.37	11.86	14.76	11.22	10.94	6.81		
	Interosseus	21.44	19.95	18.77	16.64	17.66	16.98	16.22	14.90		
Upward	EDC	24.69	20.36	20.62	15.25	19.96	14.46	14.64	8.52		
	Interosseus	76.46	69.48	55.52	46.84	57.58	54.06	36.81	30.05		
	Lumbrical*	77.13	67.73	56.13	46.50	68.61	62.55	45.89	39.95		
Backward	FDS	10.18	11.02	14.07	14.62	14.45	15.00	17.46	17.66		
	FDP	13.10	16.03	16.67	18.72	18.22	20.32	20.85	21.80		
	Interosseus	9.49	10.04	10.64	10.50	14.24	15.14	15.97	16.11		
Forward	EDC	18.17	22.12	22.26	24.91	24.96	27.63	27.75	28.81		
	Interosseus	55.37	58.09	72.43	70.71	70.88	75.50	88.98	89.68		
	Lumbrical*	50.67	50.19	62.93	58.47	77.01	78.75	91.93	89.61		

\* : Muscular forces of the lumbrical have negative signs.

Table 8.4 Computed muscular forces in N in the non-constant tendon moment arms model (in static exertion against an external load of 5.0 N).

Directions	Muscles	Angles of MCP		15				30			
		PIP	DIP	15		30		15		30	
				15	30	15	30	15	30	15	30
Downward	FDS	11.92	11.09	9.74	8.79	10.44	9.38	7.15	6.05		
	FDP	13.02	11.61	11.96	9.56	11.18	8.79	8.85	5.68		
	Interosseus	21.56	20.04	19.38	17.11	17.32	16.69	16.35	14.98		
Upward	EDC	25.74	21.52	21.47	16.21	21.68	16.41	15.75	9.87		
	Interosseus	75.08	68.03	54.51	45.77	55.51	50.67	35.45	28.42		
	Lumbrical*	40.02	27.99	21.84	11.55	55.59	46.39	33.39	25.49		
Backward	FDS	7.93	8.56	10.89	11.28	11.86	12.29	14.15	14.30		
	FDP	9.46	12.06	12.97	15.07	13.82	15.94	16.87	18.17		
	Interosseus	9.85	10.14	11.32	11.18	13.84	14.71	16.23	16.37		
Forward	EDC	18.78	22.67	23.25	25.86	26.67	29.27	30.06	31.11		
	Interosseus	54.58	57.41	71.24	69.64	68.81	73.47	86.13	86.88		
	Lumbrical*	26.29	20.74	24.49	14.52	62.40	58.41	66.31	58.64		

\* : Muscular forces of the lumbrical have negative signs.

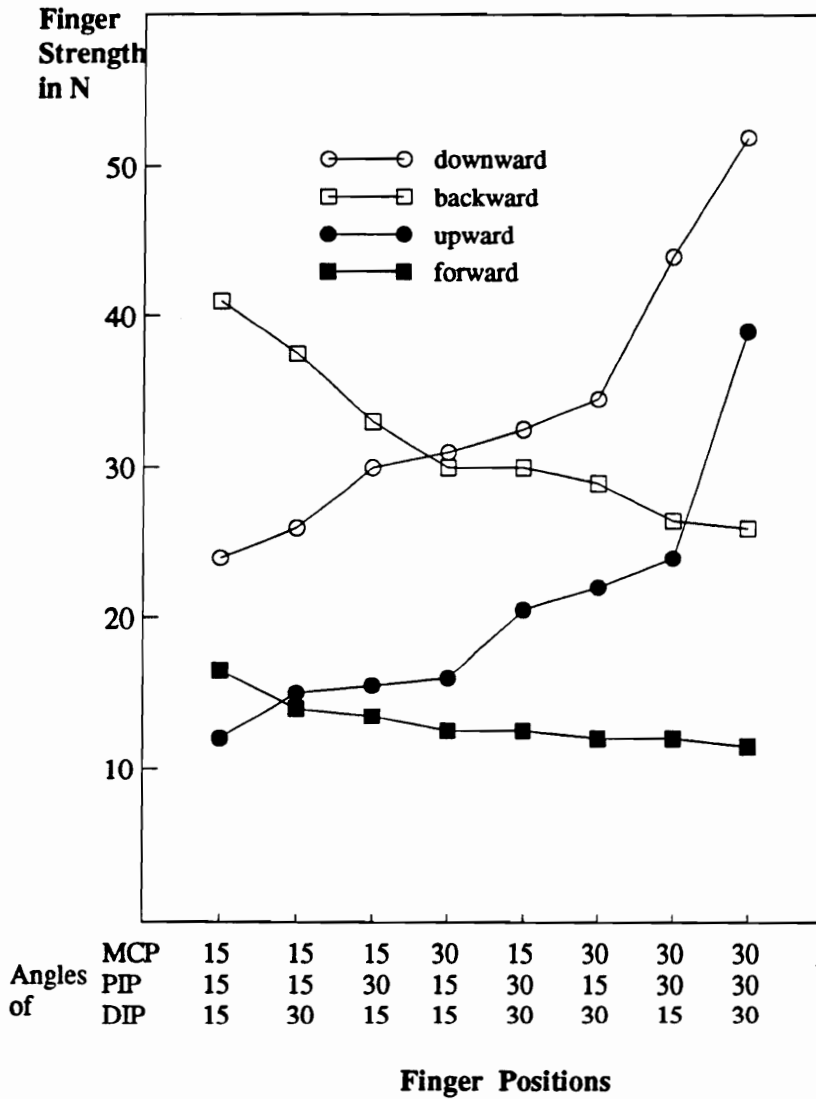


Figure 8.3 Finger strengths predicted from the constant tendon moment arms model.

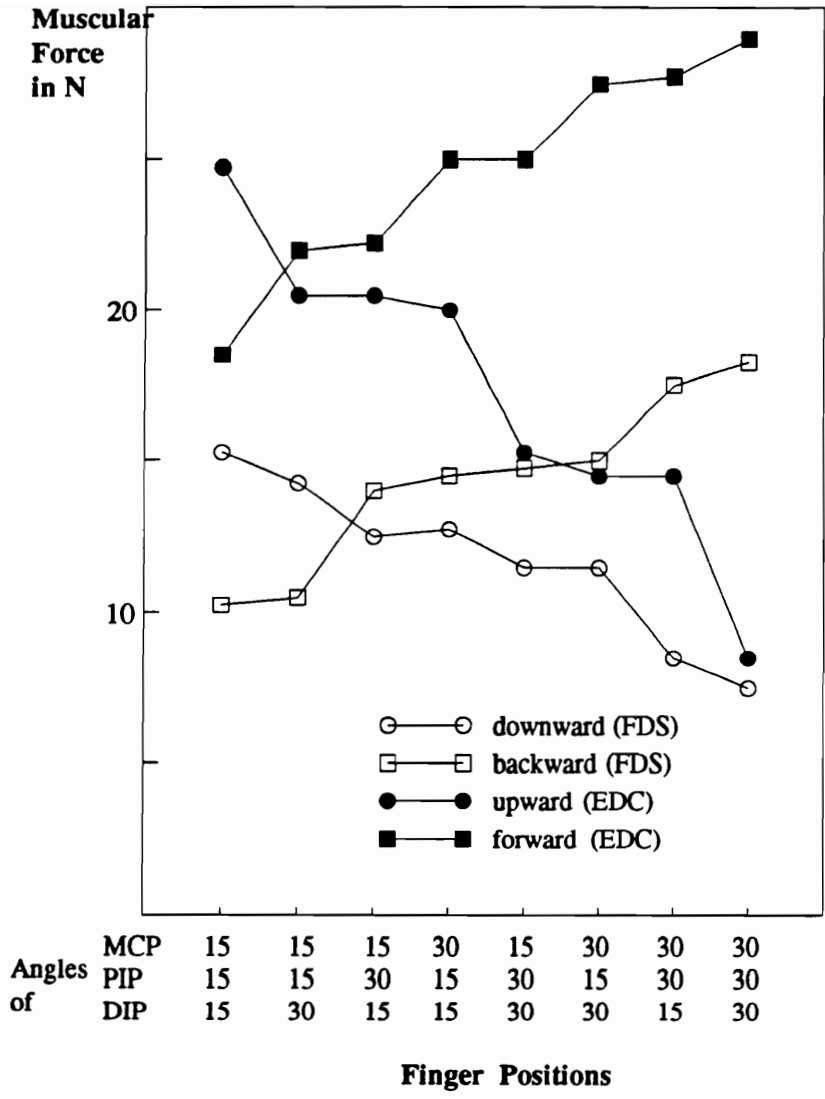


Figure 8.4 Muscular forces required against an external load.

than on the PIP joint; in turn, the torque on the PIP joint is larger than that on the DIP joint. This indicates that the angle of MCP joint is more important to finger strength and muscular force than the angles of the PIP and DIP joints. Therefore, of the finger positions with the same total angle of flexion, the position with the more flexed MCP joint was located to the right of the finger position with less flexed MCP joint. If two positions have the same angle of the MCP joint, the position with more flexed PIP joint was located to the right of the position with less flexed PIP joint.

Predicted finger strengths in MCP exertions (downward and upward exertions) increased as the finger flexes while predicted finger strengths in PIP exertions (backward and forward exertions) decreased as the finger flexed. The downward and backward force exertions involved the same group of muscles. However, the downward finger strengths increased while the backward finger strengths decreased as the finger flexed. The two strength curves with respect to finger positions crossed over between finger Positions 2 and 3. Similarly, the two strength curves of the upward and forward exertions crossed over between finger Positions 1 and 2 although both exertions involved the same muscle.

Finger strengths in the constant tendon moment arms model were generally larger than those in the non-constant tendon moment arms model, but the differences were small (less than 10%) and statistically nonsignificant (Table 8.5).

Muscular forces required to exert five newtons at the fingertip varied depending on the finger positions and directions of force exertions. Muscular forces in downward and upward exertions (force exertions about the MCP joint) decreased as the finger flexed. In contrast, muscular forces in backward and forward exertions (force exertions about the PIP joint) increased as the finger flexed. These results imply that, in force exertions

Table 8.5 ANOVA for predicted finger strengths.

Source	SS	df	F	p
Direction(D)	4142.557	3	36.60	0.001
Position(P)	578.350	7	2.19	0.050
Model(M)	23.438	1	0.62	0.434
Error	1962.045	52		
Total	6706.390	63		

about the MCP joint, more muscular force was required at the extended finger positions than at the flexed positions. In force exertions about the PIP joint, however, more muscular force was required at the flexed finger positions than at the extended positions.

The crossovers of the force curves in the downward and backward exertions between finger Positions 1 and 2, and in the upward and forward exertions between Positions 1 and 2, indicate that the backward and forward force exertions (about the PIP joint) in extended finger positions were more "efficient" than the downward and upward force exertions (about the MCP joint) (meaning that less muscular force was required to maintain static equilibrium against an external load: the smaller the muscular force the larger the efficiency). In the flexed finger positions, the downward and upward force exertions (about the MCP joint) were more efficient than the backward and forward force exertions: muscular forces required to maintain static equilibrium against an external load in force exertions about the MCP joint were smaller than those about the PIP joint.

Comparing the constant tendon moment arms model and the non-constant tendon moment arms model, one finds that the computed muscular forces were generally larger in the constant tendon moment arms model. This was especially apparent for the lumbrical forces required for finger extension exertions (upward and forward exertions). In downward force exertions, however, the forces computed for the FDP and FDS, using either model became closer as the finger flexed: in the most extended finger position, differences between the forces computed using either model were 5.02 N in the FDP and 3.34 N in the FDS; in the most flexed finger position, they were 1.13 N and 1.32 N in the FDP and FDS, respectively. In backward force exertions, however, the difference in muscular force of the FDS between the two models increased with finger flexion:



from 2.25 N in the most extended finger position to 3.36 N in the most flexed finger position. The interossei and EDC forces computed with either model were fairly similar.

Forces of the lumbricals showed negative signs, indicating that the lumbrical force was toward finger flexion. The lumbricals were activated when the PIP and DIP joints extended. However, since the lumbricals are located in the palm, direction of lumbrical force is downward or backward. This made the sign of lumbrical force negative.

Finger strengths and muscular forces of the subjects are tabulated in Appendix C. In these tables, results are shown only for four finger positions in order to compare the measured finger strengths and muscular activity levels. Since the trends of finger strengths and muscular forces with respect to finger positions and directions of force exertions are the same in both the constant and non-constant tendon moment arms models, only the results computed in the constant tendon moment arms model are given.

An individual's finger strengths and muscular forces were computed with the data of the person's phalangeal lengths. However, data of tendon moment arms and muscular capabilities were the same for all subjects. Finger strengths and muscular forces, thus, were functions of phalangeal lengths. A person with short phalangeal lengths was expected to have large finger strength. Trends of individual's finger strengths and muscular forces with respect to finger positions and force directions were the same as those computed with mean phalangeal lengths.

## *8.5 Discussion and Summary*

Force equations in Chapter VI showed that muscular forces are functions of tendon moment arms and external torques. The external torques were determined by the magnitude and directions of external load, lengths of phalanges, and angles of the finger joints. In this chapter, the external torques were computed for four directions of external loads. This made it possible to predict the numerical values of muscular forces.

The inverse procedure was to predict the maximally exertable force by the finger, i.e., finger strength with assumed muscular capabilities.

In both cases, angles of joints and directions of forces acted as independent variables while tendon moment arms, lengths of phalanges, external load, and muscular capabilities were parameters. These parameters can be measured or assumed.

Computer simulations were performed to predict finger strengths and muscular forces using the measured lengths of phalanges and data from the literature. Results showed that the finger strengths in MCP exertions increased as the finger flexed while those in PIP exertions decreased as the finger flexed. Muscular forces required for sub-maximal contractions decreased in force exertions about the MCP joint and increased in force exertions about the PIP joint as the finger flexed.

Both the curves of finger strengths and muscular forces with respect to finger positions crossed over between the finger Positions 1 and 2 or Positions 2 and 3. This implies that the efficiencies of the muscles were different at the flexed and extended finger positions depending on the directions of force exertions. Force exertions about the MCP joint were most efficient at the flexed finger positions while force exertions about the PIP joint were most efficient at the extended finger positions.

# **IX. Experiments: Finger Strength Tests and EMG Recordings**

## ***9.1 Overview***

Experiments were performed to validate the biomechanical finger models developed in this study. Index finger strengths were measured for the combinations of four finger positions and four directions of force exertions. Surface EMGs were recorded for sub-maximal force exertions of 25%, 50%, and 75% MVC. EMG recordings were also performed for all combinations of finger positions and directions of force exertions. RMS EMG amplitudes were computed from the digitized EMG signals. Then, EMG amplitude/force ratios were computed to compare muscular activity levels among different finger positions and directions of force exertions.

## *9.2 Hypotheses to Be Tested*

Force equations in Chapter VIII, which are the solutions of the equilibrium equations established from finger models, showed that muscular forces were functions of the mechanical leverages of the finger (tendon moment arms, lengths of phalanges, finger positions, and directions of force exertions) and of the external load. Modifications of these equations expressed the finger strength as a function of the mechanical leverages of the finger and the physiological capabilities of muscles.

In Chapter VIII, finger strengths and muscular forces in a submaximal contraction were numerically computed with data of tendon moment arms, lengths of phalanges, muscular capabilities, and external load. The results of those computations showed that finger strengths and muscular forces varied with finger positions and directions of force exertions.

If finger models are well developed and the data are correct, those predictions of finger strengths and muscular forces should be the same as or close to the actually measured finger strengths and muscular forces.

Results of computer simulations led to the following hypotheses to be tested through experiments:

Hypothesis I. Finger strengths in force exertions about the MCP joint (downward or upward force exertions about the MCP joints) increase as the finger flexes. Conversely, finger strengths in force exertions about the PIP joint (forward and backward force exertions about the PIP joint) decrease as the finger flexes.

Hypothesis II. Finger strengths in finger extension exertions are smaller than those in finger flexion.

Hypothesis III. Muscular activities required to exert a constant amount of force (measured by EMG amplitude), increase in force exertions about the PIP joint as the finger flexes, and decrease in force exertions about the MCP joint as the finger flexes.

These hypotheses are illustrated in the diagrams of Figures 9.1 and 9.2.

To test the hypotheses it is necessary to measure finger strength at various finger positions and to measure muscular forces during static exertion against an external load. Measurement of finger strengths at various finger positions is relatively easy. Direct measurement of force of an individual muscle in static exertion, however, is difficult and imprecise, if possible at all. To find an alternate measure of muscular force, the following rationale was developed based on relationships between muscular force and EMG amplitudes (which had been reviewed in Chapter V):

When a task requires muscular force, motor units are recruited. As the force increases the number of recruited motor units and the firing rate increase. These increase the amplitude of surface EMG. As the exerted muscular force increases the EMG amplitude also increases monotonically.

Based on this rationale, surface EMG amplitudes were used in this study to investigate muscular activity levels for submaximal force exertions.

### ***9.3 Subjects***

Six paid volunteers (three males and three females) participated in the experiments. Their ages ranged from 23 to 34 years (mean : 29.3 years). They were healthy and had no musculo-neurological disfunctions, nor anatomical anomalies in the hand and

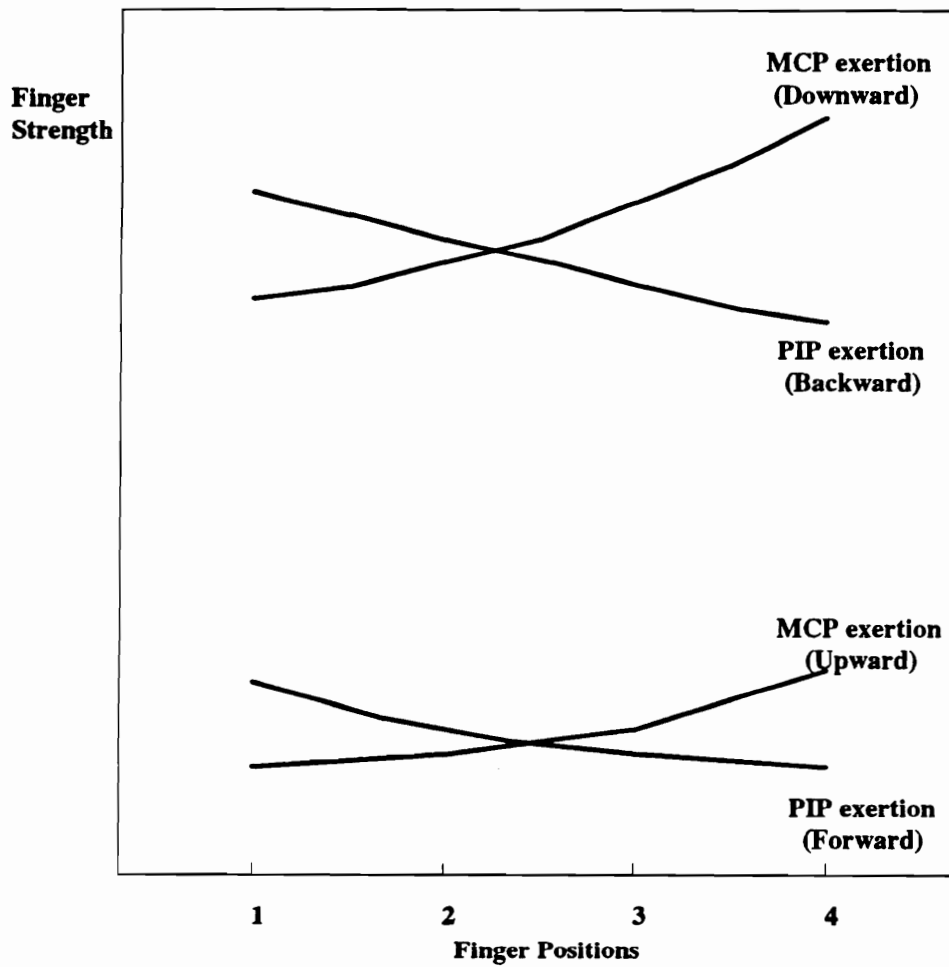


Figure 9.1 Schematic diagram of Hypotheses I and II.

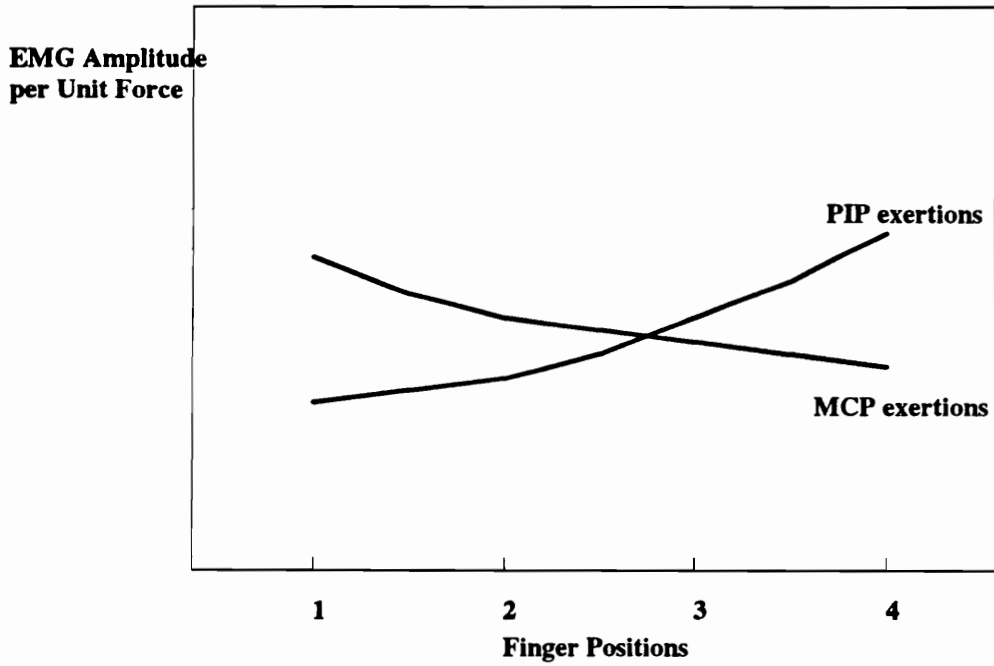


Figure 9.2 Schematic diagram of Hypothesis III.

fingers (as ascertained by questioning and appearance). Each subject participated in tests lasting two and half hours a day, on four days. The subjects were asked not to do strenuous work with the hand during the four day period. Personal and anthropometric data of the subjects are shown in Table 9.1.

## ***9.4 Equipment***

For the purpose of recording the MVC and the surface EMG, the following equipment was used:

- Micro-computer and A/D board
- Load cell and bridge amplifier
- Strip chart (thermal array) recorder
- Electromyographic measurement system
- Arm and wrist fixture
- Finger splints
- Anthropometer.

### Micro-computer and A/D board

An IBM PC/AT computer with hard disk and an A/D board (DASH-8, MetraByte) were used for collecting and analyzing surface EMG signals. Range of input signal to the A/D board was plus and minus five volts, and the sampling rate was 1000 Hz. Interactive computer programs were written using BASIC and compiler. Computer programs provided a start signal for force exertion to the subject, performed A/D conversions, gave a stop signal, and stored the digitized EMG amplitudes on the hard disk.



Table 9.1 Personal and anthropometric data of the subjects.

		Subject A	Subject B	Subject C	Subject D	Subject E	Subject F
Age (yrs.)		34	34	26	34	23	25
Sex		male	male	male	female	female	female
Height (cm)		170	178	170	161	172	159
Weight (kg)		65.0	74.3	73.9	77.8	62.3	51.8
Forearm length (cm)		25.5	26.2	25.0	23.3	26.0	22.8
Circumference of forearm (cm)	relaxed	28.4	28.7	28.0	26.8	25.7	22.5
	flexed	28.9	29.2	28.5	27.4	26.5	23.8
Length of phalanges (cm)	Metacarpal	7.6	7.8	7.1	7.2	8.8	7.6
	Proximal	4.1	4.2	4.2	3.9	4.0	4.1
	Middle	2.3	2.3	2.2	2.1	2.3	2.3
	Distal	2.1	2.1	1.9	1.8	1.8	1.7
Thickness of joints (cm)	MCP	2.6	2.9	2.5	2.4	2.6	2.2
	PIP	1.7	1.8	1.6	1.6	1.6	1.4
	DIP	1.3	1.3	1.2	1.2	1.1	1.0

### Load cell and bridge amplifier

A strain gauge load cell (Lebow #3397, Eaton) was used to measure the exerted forces. Its capacity was 25 lbs. A bridge amplifier within a thermal array strip chart recorder (TA 600, Gould) was used as the source of bridge excitation and signal amplification. The input voltage for load cell was set to 10 volts DC. Output from the bridge amplifier was directly connected to the chart recorder. A L-shaped iron beam was made to hold the load cell, and to change its location to measure the force output in four directions. Locations of L-shaped beam and load cell are shown in Figure 9.3.

### Strip chart recorder

The thermal array recorder was used to continuously record the signal output (force) from the load cell and surface EMG. A DC amplifier and a bridge amplifier were used to amplify the signals from electromyograph and load cell, respectively. The high-cut filter of the amplifier was set to 200 Hz. Paper sweep speed was set to 10 mm per second. These recordings were used for providing feedback to subjects during experiments and as backup data carrier for analyzing the test results.

### Electromyographic Measurement System

An electromyographic measurement system was used for recording surface EMGs from the extensor digitorum communis and flexor digitorum superficialis. The pre-amplifier of this electromyograph has a fixed gain of 200 times; the total gain was adjusted to 5000 and 10000 times. Disposable silver-to-silver chloride surface electrodes (40493A, Hewlett Packard) were used in a bipolar configuration (Basmajian and De Luca, 1985; Woldstad, 1989). Two types of output were provided by this electromyograph : raw EMG and RMS (time constant 55ms) EMG. The raw EMG signals were sent to the the A/D board to be digitized and stored on the hard disk of the computer; the RMS EMG signals were sent to the strip chart recorder.

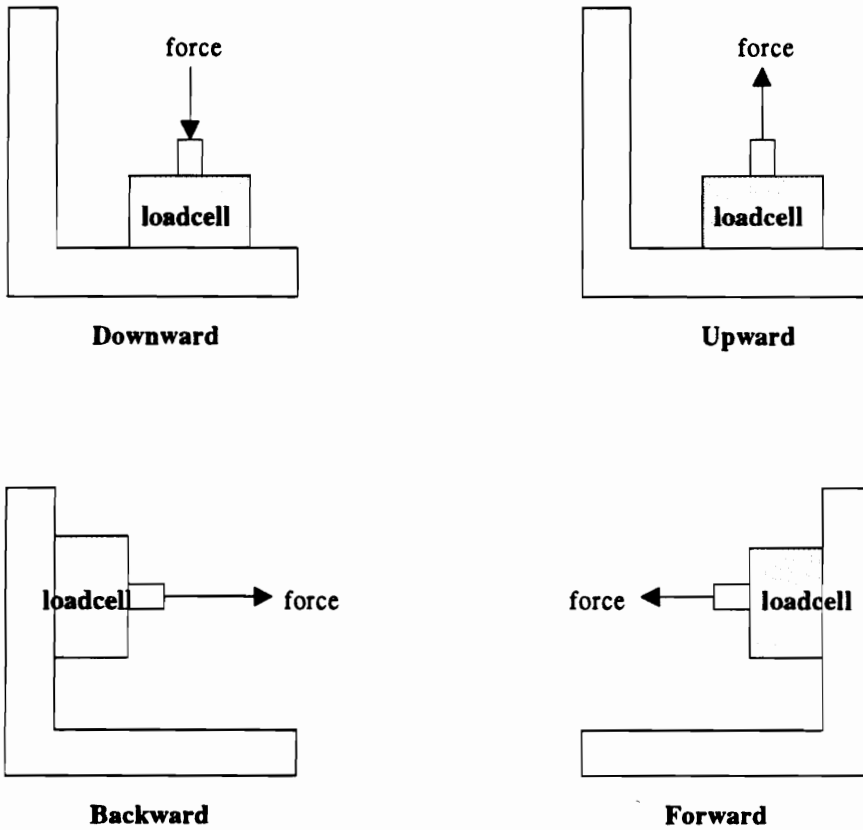


Figure 9.3 Positions of L-shape beam and load cell and force directions.

### Digital Multimeter

A digital multimeter (Model 4700, DANA) showing five and half digits was used to calibrate the load cell and to provide visual feedback of exerted force to the subject. In submaximal force exertions, target force level was given to the subject in form of a digital voltage value on the display of the multimeter.

### Oscilloscope

A two-channel oscilloscope (2215A, Tektronix) was used to monitor the EMG signal during force exertions. The oscilloscope was also used for calibrations of the strip chart recorder and the electromyograph.

### Arm and Wrist Fixture

An arm and wrist fixture, needed to keep the forearm in position during force exertions, was made by installing an iron beam and upper arm rest of the chair.

### Finger Splints

Two sets of finger splints were made of orthopedic plastic following the curvature of the finger : one was for fixing both the PIP and DIP joints, and the other was for fixing the DIP joint only. Finger splints were customized for every subject based on the lengths of phalanges.

### Function Generator

A Function generator (TM 503, Tektronix) was used to calibrate the A/D board. It consisted of three modules (FG 502, function generator; PS 503, dual power supply; DC 504, counter/timer). Sine waves with various amplitudes and frequencies were generated and supplied to the A/D board. A voltage standard (Model 741B AC-DC, Hewlett-Packard) was also used to provide a constant voltage signal. With signals of constant amplitudes and frequencies, the sampling rate of the A/D board was calibrated and the gain of the EMG amplifier determined.

A schematic diagram of equipment configuration is shown in Figure 9.4.

## *9.5 Experimental Variables*

Finger strengths were tested for four directions of force exertions in four finger positions. Finger strength may vary depending upon individual muscular capability, finger positions, lengths of phalanges and forearm, and training, which can be considered the independent variables of finger strength. Among these variables, directions of force exertions and finger positions can be controlled in the experiments. Lengths of forearm and phalanges are measurable. The most important factor in finger strength, force capability of muscles, however, cannot be directly measured. Since force capability of the muscle is proportional to the volume of the muscle, volume of the forearm can be used as index of muscular capability. The volume of the forearm can be estimated from the circumference and length of the forearm.

In this study, only the finger positions and directions of force exertions were considered independent variables for finger strengths and muscular forces. Finger strengths and muscular force levels were measured for the combinations of four finger positions and four directions of force exertions. The angles of the MCP/PIP/DIP joints of four finger positions were 15/15/15, 15/30/15, 30/15/15, and 30/30/15, respectively (Figure 3.1). Directions of force exertions were downward, upward, backward, and forward. Other factors were treated as parameters whose values could be determined as constants.

The amplitude of surface EMG varied as the exerted force varies. EMG amplitude was also affected by the muscles involved, characteristics of skin tissue, locations of electrodes, muscular fatigue, etc. : all with large individual variations (Basmajian and

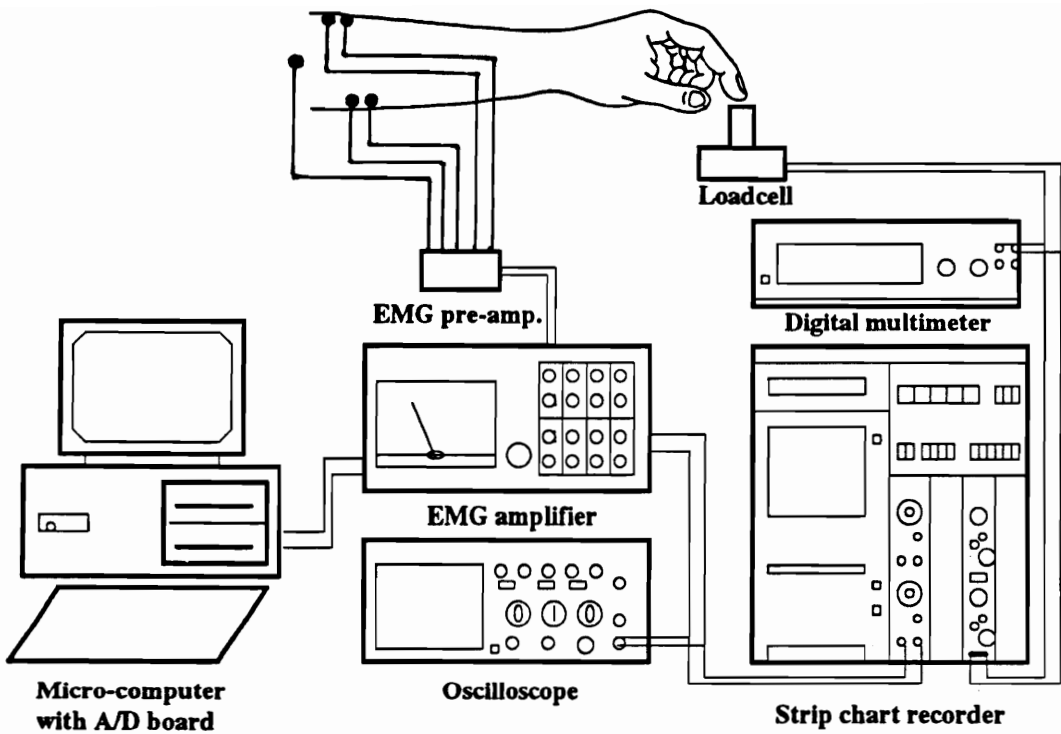


Figure 9.4 Schematic diagram of equipment configuration.

De Luca, 1985; De Luca, 1979; Lee, 1981). In this study, however, only the exerted force levels were considered independent variables for EMG amplitudes. Root-mean-squared (RMS) values of EMG amplitudes were used to estimate the levels of muscular activities in exerted force levels of 25%, 50%, 75%, and 100% MVC.

## *9.6 Experimental Design*

Finger strengths and surface EMGs were recorded for the combinations of four finger positions and four directions of force exertions. Six subjects were tested for all test cells. Therefore, this experiment was in a 4x4 factorial within-subjects design as represented in Table 9.2.

There were sixteen test conditions. In each condition finger strength (maximal voluntary contraction) was measured first, then three submaximal contractions (25%, 50%, and 75% MVC) were performed for recording EMGs. Four tests were performed a day for a subject. Therefore four days were taken to complete the total of sixteen test conditions.

Test sequences for subjects were determined as follows: Downward and backward force exertions require the same muscle group (flexors), and upward and forward force exertions require the same muscle group (extensors). To prevent accumulated muscular fatigue, consequent use of the same muscle group was to be avoided. These considerations resulted in eight test combinations. From them, the sequence of six directions of force exertions were randomly chosen. In each direction of force exertion, test sequences for the four finger positions were randomly determined. For each test cell,

Table 9.2 Experimental 4x4 factorial within-subject design.

<b>Direction Finger position</b>	<b>Downward</b>	<b>Upward</b>	<b>Backward</b>	<b>Forward</b>
<b>1</b>	S1 S2 . . . S6	S1 S2 . . . S6	S1 S2 . . . S6	S1 S2 . . . S6
<b>2</b>	S1 S2 . . . S6	S1 S2 . . . S6	S1 S2 . . . S6	S1 S2 . . . S6
<b>3</b>	S1 S2 . . . S6	S1 S2 . . . S6	S1 S2 . . . S6	S1 S2 . . . S6
<b>4</b>	S1 S2 . . . S6	S1 S2 . . . S6	S1 S2 . . . S6	S1 S2 . . . S6



sequences of three submaximal contractions were also randomly determined. The test sequences for six subjects are shown in Table 9.3.

## ***9.7 Methods and Procedures***

The experiments were in three parts: 1) collection of anthropometric data from the forearm, hand, and index finger, 2) tests of finger strength, and 3) EMG recordings for submaximal contractions. It took four days per subject to complete all test sessions. On the first test day, collection of anthropometric data was performed as well as measurements of finger strengths and EMG amplitudes. On the other three days, finger strengths and EMG amplitudes were measured by predetermined test sequences. There were sixteen test sessions per subject. Four test sessions were performed a day.

### **9.7.1 Anthropometric Data Collection**

Finger strength and muscular activity depended on individual muscular capabilities and on biomechanical efficiency of the musculo-skeletal system of the hand and finger. To predict individual muscular capabilities and mechanical efficiency, anthropometric data of the forearm, hand, and index finger were needed. The following personal and anthropometric data were obtained:

**Age**

**Sex**

**Height**

Table 9.3 Test sequences for the subjects.

Subject A

direction position	U	B	F	D
1	3, E	2, C	4, D	3, C
2	1, D	3, B	3, B	1, D
3	4, A	4, A	1, E	2, E
4	2, F	1, F	2, C	4, A

Subject D

direction position	F	D	U	B
1	2, E	4, D	1, E	1, A
2	3, A	1, B	4, F	2, E
3	1, C	3, E	3, C	4, B
4	4, F	2, A	2, B	3, D

Subject B

direction position	D	F	B	U
1	3, F	4, A	4, B	2, A
2	2, B	3, E	1, D	4, D
3	4, C	1, F	2, A	1, B
4	1, D	2, C	3, E	3, E

Subject E

direction position	B	U	D	F
1	4, B	2, A	1, D	4, E
2	2, D	3, E	3, E	1, B
3	3, F	1, D	2, B	3, A
4	1, C	4, C	4, F	2, C

Subject C

direction position	D	U	B	F
1	1, A	4, F	4, D	1, F
2	4, B	2, D	3, C	3, E
3	2, C	1, E	2, A	4, B
4	3, E	3, B	1, F	2, C

Subject F

direction position	U	D	F	B
1	3, D	2, A	4, D	1, F
2	1, E	3, C	3, B	4, C
3	2, F	4, B	1, C	2, E
4	4, B	1, F	2, E	3, A

note : numbers indicate the test days, and alphabets indicate test sequences of submaximal contractions, which represent

A : 25% - 50% - 75% MVC

B : 25% - 75% - 50% MVC

C : 50% - 25% - 75% MVC

D : 50% - 75% - 25% MVC

E : 75% - 25% - 50% MVC

F : 75% - 50% - 25% MVC.

## Weight

Length of the forearm (distance from elbow to the wrist)

Length of the carpometacarpal of the index finger

Length of the proximal phalanx of the index finger

Length of the middle phalanx of the index finger

Length of the distal phalanx of the index finger

Circumference of the forearm, relaxed and flexed

Thickness of the MCP joint

Thickness of the PIP joint

Thickness of the DIP joint.

Length of the forearm was measured with an anthropometer. Circumference of the forearm was measured using a steel tape measure. Lengths of CM and phalanges, and thickness of joints were measured with a caliper (Garrett, 1970 and 1971; NASA, 1978). The results are listed in Table 9.1.

### **9.7.2 Finger Strength Test**

Finger strengths were tested for the index finger in four directions of force exertions at four finger positions. Directions of force exertions were downward, upward, forward, and backward. The four finger positions were distinguished by the degree of finger flexion. The "Position 1" had angles of 15, 15, and 15 degrees at the MCP, PIP, and DIP joints, respectively. Positions 2, 3, and 4 had finger joint angles of 15/30/15, 30/15/15, and 30/30/15 degrees, respectively.

Finger strengths were measured using a load cell which was located perpendicular to the directions of force exertions. Finger splints were used to fix the joint angles for a finger position. The upper arm was fixed on the arm rest. The hand and wrist were fixed so that the carpometacarpals and the ulna were parallel.

Finger flexion strengths about the MCP joint were measured when the finger exerted the force vertically downward.

Finger flexion strengths about the PIP joint were measured when the finger exerted the force horizontally backward.

Finger extension strengths about the MCP joint were measured when the finger exerted the force vertically upward.

Finger extension strengths about the PIP joint were measured when the finger exerted the force horizontally forward.

Locations of the load cell and directions of force exertions are shown in Figure 9.3.

### **9.7.3 EMG Recordings during Submaximal Contractions**

Surface electrodes were attached on the skin above the extensor digitorum communis and flexor digitorum superficialis. (The skin was cleaned with alcohol and dried before the electrodes were attached.) A pair of electrodes was attached over the belly of the muscle. The distance between electrodes was 2.5 cm and the two electrodes were parallel to the muscle fiber direction. A reference electrode was attached on the ligament area of the medial epicondyle (Delagi, Perotto, Iazzetti, and Morrison, 1975). After the electrodes were attached, about 5 minutes of "aging" was allowed. During that time,

noise in the EMG was checked using the oscilloscope and removed if it existed. Then the subject was seated with the upper arm strapped in the fixture. Appropriate finger splints were attached with bands on the palm and back sides of finger joints depending upon test requirements. Finger splints for fixing the PIP and DIP joints were attached when force exertions about the MCP joint (downward and upward) were performed. Splints for fixing the DIP joint were attached only when force exertions about the PIP joint (backward and forward) were performed.

Three submaximal force levels (25%, 50%, and 75% MVC) were computed from the measured finger strength in every combinations of finger positions and directions of force exertions. Surface EMGs were recorded from the flexor digitorum superficialis when the force was exerted by finger flexion. They were recorded from the extensor digitorum communis when the force was exerted by finger extension. Submaximal force levels were represented with digital values of voltage output from the load cell. These values were given to the subject, and the subject was instructed to exert the force as quickly as possible to the given force level, then to maintain the force level until the stop signal. Force exertions lasted for five seconds.

#### **9.7.4 Experimental Procedure**

Tests were performed in the Industrial Ergonomics Lab., Virginia Polytechnic Institute and State University, where temperature and noise are controlled. All test equipment were calibrated when the subject arrived in the test room. On the first day of the test, the purpose of experiment and the test procedures were explained to the subject who then signed a consent form.

Anthropometric data were collected first. Next, finger strength tests and EMG recordings for submaximal force exertions in a combination of finger positions and directions of force exertions were performed consecutively.

Before and after the daily tests, in each subject, MVCs and corresponding EMGs were recorded for four directions of force exertions at the Finger Position 3. EMG amplitudes of maximal exertions before daily tests were used to standardize the EMG amplitudes of submaximal contractions. MVCs and EMG amplitudes after daily tests were used to investigate muscular fatigue development during the tests.

Finger strength was tested using the Caldwell regimen (Caldwell, Chaffin, Dukes-Dobos, Kroemer, Laubach, Snook, and Wasserman, 1974). Three MVCs were recorded at each combination of finger positions and directions of force exertions with interspaced three-minute rest periods. The highest value among the three test results was selected as finger strength at that finger position. Exerted force and RMS EMG signals were recorded on the strip chart. Simultaneously, raw EMG signals were digitized using the A/D converter and stored on the hard disk of the computer.

The finger strength tests were conducted by running the computer program which provided a "start" signal (beep sound) of force exertions, collected digitized EMG signals, and gave a "stop" signal (beep sound). Storing the data on the hard disk was performed by real-time processing. The strip chart recorder was activated before force exertion started and stopped after force exertion.

After the finger strength tests, five minutes of rest were given to the subject before starting the submaximal exertions for EMG recordings. The subject was instructed to exert force as quickly as possible to the given force level after the start signal, and to maintain the exertion level till the stop signal sounded. When the subject was ready to exert force, digital value of a submaximal force level was given. Then the strip chart was

activated with 5 mm per second of paper sweep speed. The computer program for providing the "start" and "stop" signals and collecting digitized EMG signals was run. Exerted force and RMS EMG signal were recorded on the strip chart, while raw EMG signals were digitized at the 1000 Hz sampling rate and stored in the computer (Hason, Signorile, and Williams, 1987; Nornam, Nelson, and Cavanagh, 1978). Two minutes of rest followed before the next submaximal force exertion.

There were sixteen test cells with maximal exertions for finger strength test and three submaximal exertions for EMG recording. Only four test cells (four finger strength tests and twelve submaximal force exertions) were performed a day. The test for each subject was performed by predetermined test sequences shown in Table 9.3.

## ***9.8 Data Analysis***

Finger strengths were measured for 16 combinations of finger positions and directions of force exertions. In each test cell, surface EMGs were recorded at the force levels of 25%, 50%, 75%, and 100% MVC.

Finger strengths were measured from strip chart recordings. RMS EMG amplitudes were computed from digitized EMGs with 250 msec time constant. RMS EMG amplitudes of submaximal contractions were standardized using the values of RMS EMG amplitudes of maximal contractions which were measured before the daily tests. RMS EMG amplitudes of submaximal contractions in a direction of force exertion were divided by the RMS EMG amplitude of maximal contraction in the same direction of force exertion at Finger Position 3. Then, to investigate muscular activity levels for a fixed amount of muscular force, those ratios of RMS EMG amplitudes were divided by

the exerted muscular forces. Those ratios of standardized RMS EMG amplitude/muscular force were used to test Hypothesis III.

ANOVAs and linear regressions were performed for finger strengths and ratios of standardized RMS EMG amplitude/muscular force. Newman-Keuls multiple comparison test (Winer, 1971) was used for post-hoc test. SAS programs were written for these ANOVA and linear regression and were run on IBM 3090 computer.

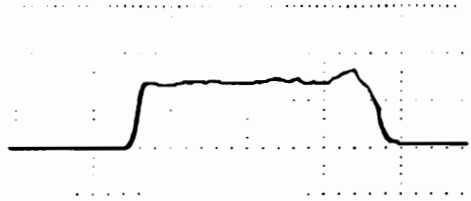
## *9.9 Experimental Results*

Typical curves of exerted forces and corresponding RMS EMGs are shown in Figure 9.5.

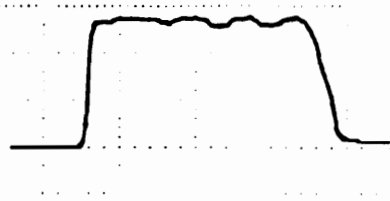
Individual test results are in tables in Appendix C: finger strengths, submaximal exertion levels, and corresponding RMS EMG amplitudes in Tables C.2; MVCs and RMS EMG amplitudes at Finger Position 3 in Tables C.3; ratios of EMG amplitude/force in Tables C.4.

To test hypotheses I and II, finger strengths at different finger positions in different directions of force exertions were analyzed. To test hypothesis III, ratios of EMG amplitude/force at different finger positions in different directions of force exertions were analyzed.

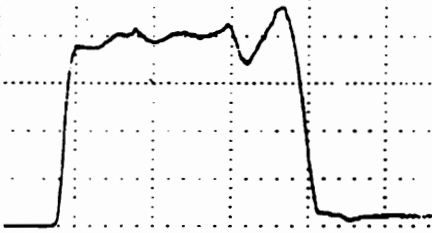
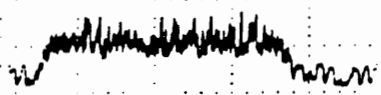




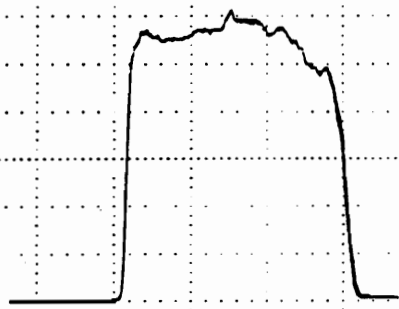
25% MVC



50% MVC



75% MVC



100% MVC

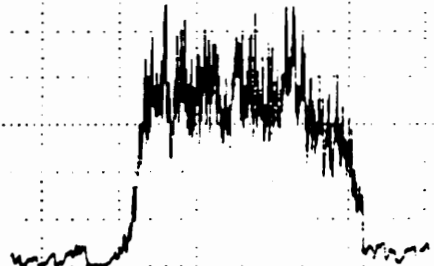
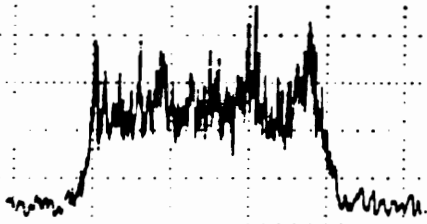


Figure 9.5 Typical curves of exerted muscular forces and RMS EMSs.

### 9.9.1 Finger Strengths

Means and standard deviations of finger strengths with respect to finger positions and directions of force exertions are presented in Table 9.4 and illustrated in Figure 9.6.

Results of ANOVA (Table 9.5) for the measured finger strengths show that there were significant differences of finger strengths among directions of force exertions ( $p < 0.01$ ). Finger strengths among finger positions were different at  $p < 0.05$ . Interactions of finger positions and directions of force exertions were significant ( $p < 0.01$ ).

Results of Newman-Keuls tests for directions of force exertions demonstrated that finger strengths in downward exertions differed from those in backward, upward, and forward exertions. Finger strengths in backward exertions also differed from those in upward and forward exertions ( $p < 0.05$ ). Finger strengths in upward and forward exertions were not significantly different. Newman-Keuls tests for finger positions showed that finger strengths at Finger Positions 2, 3, and 4 could be separated ( $p < 0.05$ ) while those at Finger Positions 3, 4, and 1 did not differ from each other. These results of Newman-Keuls tests are presented in Table 9.6.

Finger strengths in four directions of force exertions were compared at each finger positions. Newman-Keuls comparisons demonstrated that downward and backward finger strengths were not different at extended finger positions (Positions 1 and 2). Difference between downward and backward finger strengths became significant ( $p < 0.05$ ) as the finger flexed. Finger strengths in upward and forward exertions were not different in all finger positions, and they were smaller than downward and backward finger strengths. These results are presented in Table 9.7.

To investigate variations of finger strengths with respect to finger positions, linear regressions were performed for each direction of force exertion. Finger Positions 2 and

Table 9.4 Means and standard deviations of measured finger strengths (in N).

Direction Position	Downward	Upward	Backward	Forward
1	38.57 (8.91)	7.31 (2.68)	36.13 (3.42)	7.63 (2.27)
2	45.67 (8.32)	7.52 (2.94)	40.47 (5.36)	7.31 (2.26)
3	46.51 (9.17)	8.47 (2.74)	35.81 (6.30)	6.46 (2.11)
4	50.43 (8.72)	10.17 (3.43)	29.77 (5.59)	5.83 (1.99)

mean  
(S.D.)

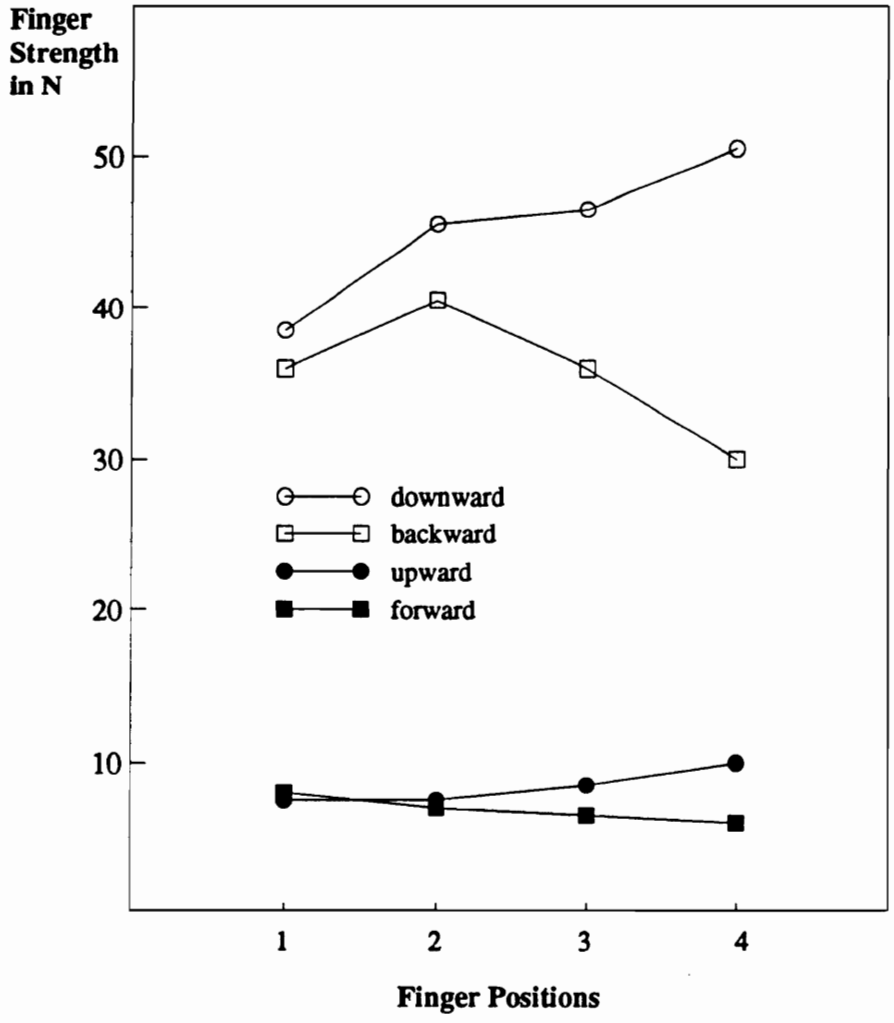


Figure 9.6 Measured finger strengths.

Table 9.5 ANOVA for measured finger strengths.

Source	SS	df	F	p
Position(P)	27039.045	3	120.47	0.001
Direction(D)	100.299	3	4.77	0.016
Subject(S)	898.277	5		
D x P	729.880	9	14.94	0.001
D x S	105.187	15		
P x S	1122.257	15		
D x P x S	244.198	45		
Total	30239.143	95		

Table 9.6 Newman-Keuls comparisons for measured finger strengths.

**Finger Positions**

2	25.24		
3	24.32		
4	24.05		
1	22.41		

**Directions of Force Exertions**

Downward	Backward	Upward	Forward
<u>45.29</u>	<u>35.55</u>	<u>8.37</u>	<u>6.81</u>

Table 9.7 Newman-Keuls comparisons of finger strengths with respect to finger positions.

Position	Direction			
	Downward	Backward	Upward	Forward
1	<u>38.57</u>	<u>36.13</u>	<u>7.31</u>	<u>7.63</u>
2	<u>45.67</u>	<u>40.47</u>	<u>7.52</u>	<u>7.31</u>
3	<u>46.51</u>	<u>35.81</u>	<u>8.48</u>	<u>6.46</u>
4	<u>50.43</u>	<u>29.77</u>	<u>10.17</u>	<u>5.83</u>

3 have the same total finger flexion (60 degrees), but only one position should be used. Since Finger Position 3 was used as a reference position in the experiments, it was selected. This leaves Finger Positions 1, 3, and 4 to be considered in linear regressions. The total angles of finger flexion in Positions 1, 3, and 4 were 45, 60, and 75 degrees, respectively. For convenience, the ratios of the angles were used as independent variables in the linear regressions. Dividing the total flexion angles by 15 yielded the numbers 3, 4, and 5, respectively. Results of linear regressions for these three finger position ratios in four directions of force exertions are shown in Table 9.8.

The slopes of downward and backward finger strengths were significantly different ( $p < 0.05$ ) from the zero slope assumption while those of upward and forward finger strengths did not show statistical significances. This means that increases in downward finger strength and decreases in backward finger strength were apparent. However, finger strengths in upward and forward force exertions did not change with finger positions.

These results support Hypothesis I which stated that finger strengths in force exertions about the MCP joint should increase as the finger flexes while finger strengths in force exertions about the PIP joint should decrease as the finger flexes.

Results of ANOVA and post-hoc tests also support Hypothesis II. Finger strengths in downward and backward exertions (finger flexion exertions) were significantly higher than those in upward and forward exertions (finger extension exertions).

In finger flexion exertions, it was expected that downward finger strengths would be smaller than backward finger strengths when the finger was in extended position (Position 1). As the finger flexed, downward finger strengths were expected to increase while the backward finger strengths were expected to decrease. In the flexed finger position (Position 4), downward finger strengths should be larger than backward finger strengths. The two regression lines of finger strengths were expected to cross over around Position



Table 9.8 Parameters of linear regression for measured finger strengths.

Regression parameter Direction	slope	p*	intercept
Downward	5.93	0.03	21.44
Upward	1.43	0.11	2.93
Backward	- 3.18	0.05	46.62
Forward	- 0.90	0.15	10.24

\* : level of significance that rejects the hypothesis in which slope of regression line is zero.

2. The measured downward finger strengths, however, are larger than the backward finger strengths at all finger positions. Therefore, no crossover occurred.

It was also expected that, for the extended finger, upward finger strength would be smaller than forward finger strength. Upward finger strength of the flexed finger should increase as the finger flexed more while forward finger strength should decrease. At flexed finger position (Position 4), upward finger strengths were expected to be larger than forward finger strengths. Accordingly, the two regression lines of upward and forward finger strengths should cross over around Position 2. This crossover did occur.

### **9.9.2 Muscular Activity Levels in Submaximal Contractions**

Means and standard deviations of RMS EMG amplitudes at 25%, 50%, 100% MVC with respect to finger positions and directions of force exertions are presented in Table 9.9.

RMS EMG amplitudes were measured in order to investigate and compare muscular activity levels at various finger positions and directions of force exertions. It is well known that there are large individual differences in EMG amplitudes and that EMG amplitudes of similar force exertions might vary from day to day. Finger strengths varied as finger positions and directions of force exertions changed. Therefore, it was necessary to standardize EMG amplitudes to compensate for personal and daily variations. RMS EMG amplitudes of submaximal contractions were divided by those measured with maximal contractions at Finger Position 3 (which were measured before daily tests as references). Then these ratios of RMS EMG amplitudes were divided by exerted muscular forces. The standardized ratio of EMG amplitude/force thus represents muscular activity level for a unit muscular force. Means and standard deviations

Table 9.9 Means and standard deviations of RMS EMG amplitudes (in mV).

Finger Position	Direction	Downward	Upward	Backward	Forward
	Force Level				
1	25%	0.06 (0.02)	0.03 (0.01)	0.04 (0.01)	0.04 (0.01)
	50%	0.09 (0.03)	0.04 (0.02)	0.05 (0.01)	0.05 (0.01)
	75%	0.11 (0.03)	0.07 (0.03)	0.07 (0.02)	0.07 (0.02)
	100%	0.16 (0.06)	0.12 (0.03)	0.12 (0.04)	0.13 (0.03)
2	25%	0.06 (0.02)	0.03 (0.01)	0.04 (0.01)	0.04 (0.01)
	50%	0.09 (0.03)	0.04 (0.01)	0.05 (0.02)	0.05 (0.02)
	75%	0.12 (0.04)	0.07 (0.02)	0.08 (0.03)	0.07 (0.02)
	100%	0.17 (0.06)	0.13 (0.03)	0.12 (0.04)	0.12 (0.03)
3	25%	0.06 (0.02)	0.03 (0.01)	0.04 (0.01)	0.03 (0.01)
	50%	0.09 (0.02)	0.05 (0.02)	0.05 (0.02)	0.05 (0.01)
	75%	0.13 (0.03)	0.08 (0.02)	0.07 (0.03)	0.07 (0.02)
	100%	0.17 (0.05)	0.12 (0.02)	0.11 (0.04)	0.13 (0.03)
4	25%	0.06 (0.02)	0.03 (0.01)	0.04 (0.01)	0.03 (0.01)
	50%	0.09 (0.02)	0.05 (0.02)	0.05 (0.02)	0.05 (0.01)
	75%	0.12 (0.04)	0.08 (0.02)	0.07 (0.02)	0.07 (0.02)
	100%	0.17 (0.05)	0.13 (0.03)	0.12 (0.05)	0.12 (0.03)

mean (S.D.)

of the standardized ratios of EMG amplitude/force are presented in Table 9.10, and are graphically represented with respect to finger positions in Figure 9.7.

Relationships between standardized ratios of EMG amplitude/force and finger positions were analyzed using linear regressions which were calculated for each direction of force exertions. Three finger positions (Positions 1, 3, and 4) were considered since Finger Positions 2 and 3 had the same degrees (60 degrees) of finger flexion. Results of linear regressions are summarized in Table 9.11.

Although statistical significance was not attained, there are apparent trends indicating that at all exertion levels, standardized ratios of EMG amplitude/force decrease in downward and upward exertions (about the MCP joint) as the finger flexes, and that they increase in backward and forward exertions (about the PIP joint) as the finger flexes. If these trends could be verified, they would support Hypothesis III which stated that muscular activities, required to exert a constant amount of force, increase in force exertions about the PIP joint and decrease in force exertions about the MCP joint as the finger flexes.

## *9.10 Discussion and Summary*

Experiments were conducted on the combinations of four finger positions and four directions of force exertions. Measurements of finger strengths and EMG amplitudes were performed to validate the predictions from the finger models. Finger strengths were measured first, and then the 25%, 50%, and 75% MVC levels were computed. Surface EMGs were recorded during these submaximal contractions. RMS EMG amplitudes were measured as indices of muscular activity levels.

Table 9.10 Means and standard deviations of standardized ratios of EMG amplitude/force (in arbitrary unit).

Finger Position	Direction	Downward	Upward	Backward	Forward
	Force Level				
1	25%	0.36 (0.04)	1.47 (0.57)	0.37 (0.17)	1.53 (0.54)
	50%	0.29 (0.07)	1.10 (0.39)	0.24 (0.09)	1.03 (0.32)
	75%	0.25 (0.05)	1.14 (0.39)	0.24 (0.04)	1.09 (0.39)
	100%	0.26 (0.07)	1.53 (0.50)	0.28 (0.03)	1.40 (0.40)
2	25%	0.32 (0.12)	1.45 (0.49)	0.31 (0.12)	1.67 (0.43)
	50%	0.24 (0.09)	1.05 (0.36)	0.23 (0.06)	1.14 (0.25)
	75%	0.21 (0.07)	1.17 (0.35)	0.21 (0.05)	1.13 (0.25)
	100%	0.22 (0.05)	1.55 (0.61)	0.25 (0.05)	1.50 (0.48)
3	25%	0.34 (0.14)	1.36 (0.56)	0.38 (0.11)	1.76 (0.70)
	50%	0.25 (0.09)	1.08 (0.38)	0.27 (0.10)	1.31 (0.51)
	75%	0.23 (0.07)	1.13 (0.22)	0.25 (0.07)	1.45 (0.29)
	100%	0.22 (0.06)	1.29 (0.42)	0.28 (0.05)	1.69 (0.44)
4	25%	0.30 (0.12)	1.14 (0.49)	0.44 (0.10)	2.06 (0.98)
	50%	0.23 (0.07)	0.82 (0.27)	0.32 (0.06)	1.45 (0.53)
	75%	0.19 (0.05)	0.87 (0.29)	0.29 (0.06)	1.47 (0.39)
	100%	0.20 (0.05)	1.08 (0.35)	0.34 (0.06)	1.88 (0.55)

mean (S.D.)

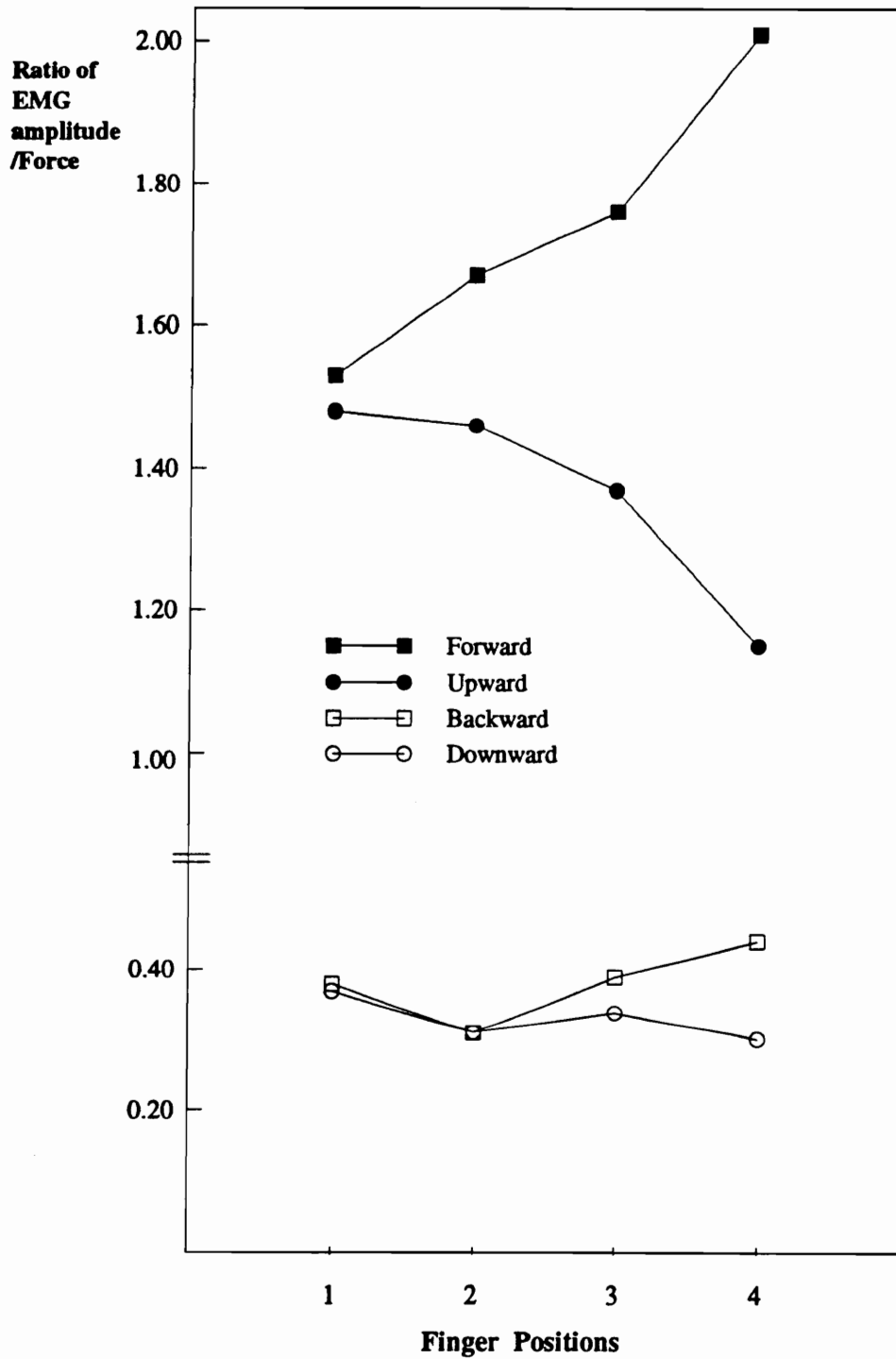


Figure 9.7(a) Ratios of EMG amplitude/force (25% MVC).

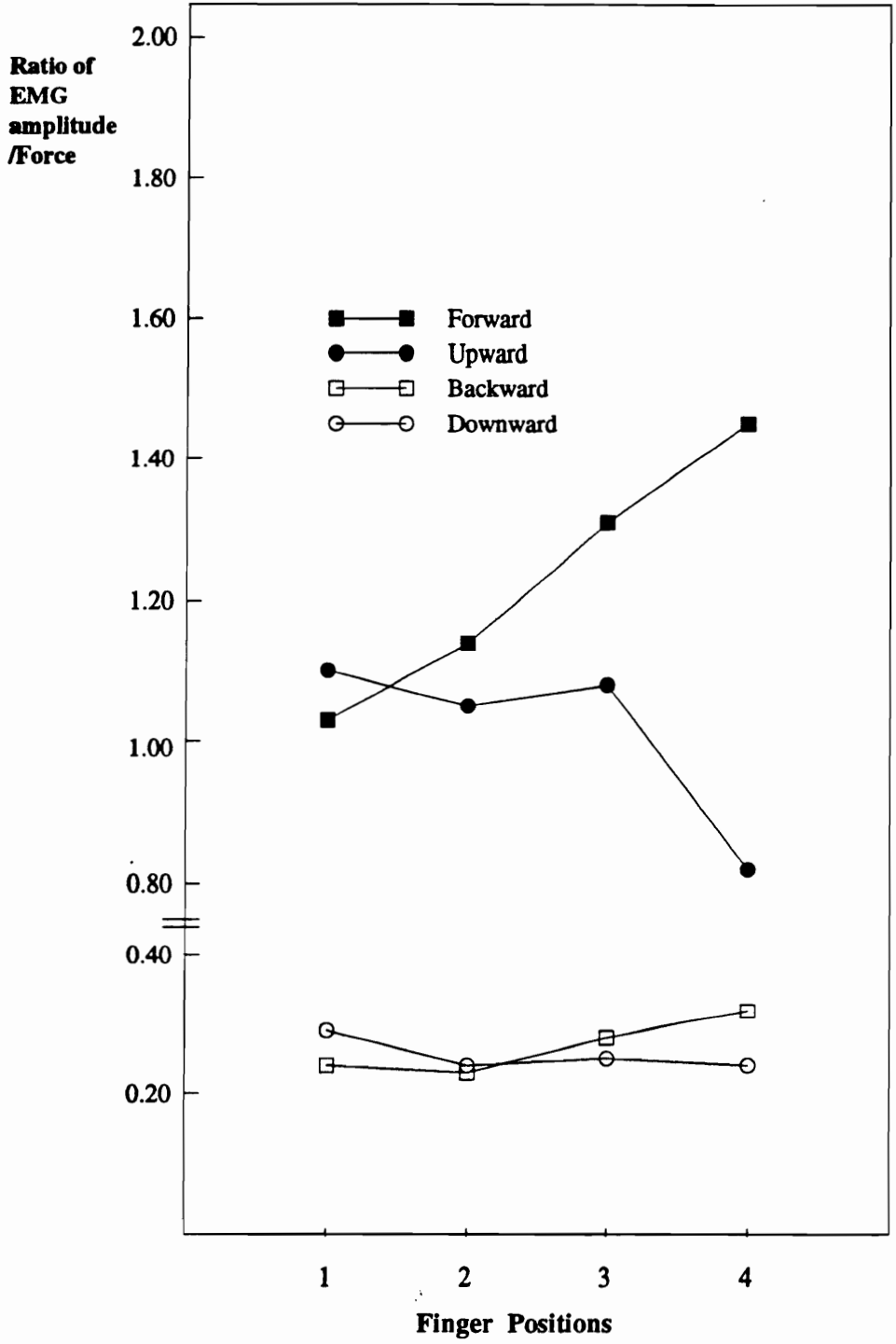


Figure 9.7(b) Ratios of EMG amplitude/force (50% MVC).

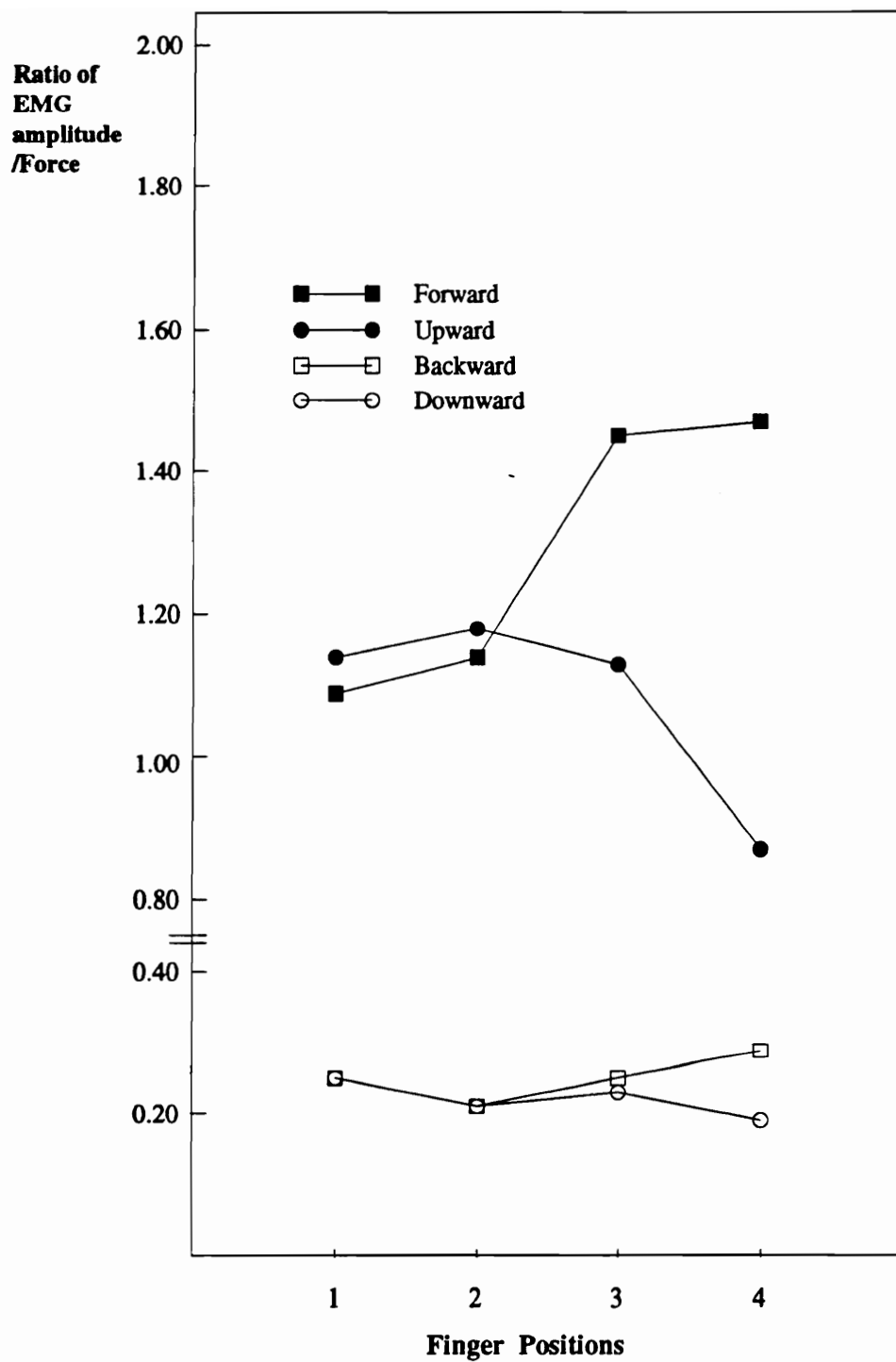


Figure 9.7(c) Ratios of EMG amplitude/force (75% MVC).



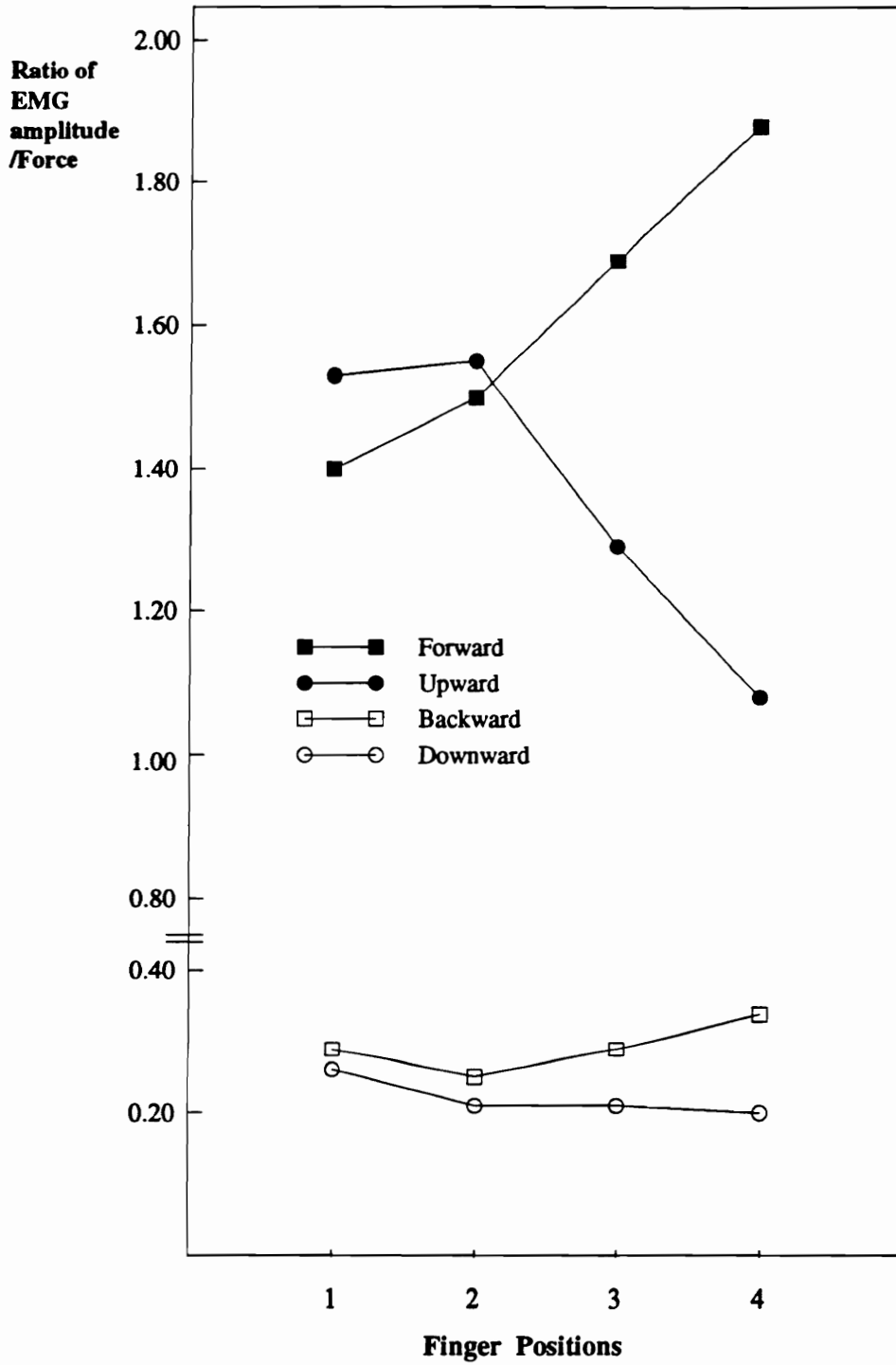


Figure 9.7(d) Ratios of EMG amplitude/force (100% MVC).

Table 9.11 Parameters of linear regressions for ratios of EMG amplitude/force.

Force level	Direction	Regression parameter	slope	p*	intercept
25%	downward		- 0.03	0.32	0.46
	upward		- 0.17	0.29	1.99
	backward		0.03	0.42	0.27
	forward		0.26	0.24	0.73
50%	downward		- 0.03	0.19	0.38
	upward		- 0.14	0.17	1.57
	backward		0.04	0.11	0.12
	forward		0.21	0.12	0.42
75%	downward		- 0.03	0.07	0.34
	upward		- 0.13	0.15	1.57
	backward		0.02	0.18	0.17
	forward		0.19	0.09	0.58
100%	downward		- 0.03	0.09	0.35
	upward		- 0.23	0.08	2.21
	backward		0.03	0.08	0.19
	forward		0.24	0.09	0.70

\* : level of significance that rejects the hypothesis in which the slope of regression line is zero.

The directions of the forces were horizontally backward and forward, and vertically downward and upward. Joint angles of the MCP and PIP joints were fixed by finger splints at 15 or 30 degrees depending on the finger position.

Variations in EMGs were of concern since each subject was tested for four days. Therefore, MVC and RMS EMG amplitude at a reference finger position (Position 3) were measured before and after daily tests. Both the MVC and EMG amplitude showed large personal variations. However, little variations occurred in the results among daily tests and between before and after tests (Table 9.12). It means that muscular fatigue was not present in the tests. RMS EMG amplitudes recorded before the tests were used to standardize the EMG amplitudes of submaximal contractions.

Finger strengths showed large personal variations. Yet, finger strengths with respect to the finger positions showed the same trends in all subjects. As predicted, finger strengths in MCP exertions increased as the finger flexed. Those in PIP exertions decreased as the finger flexed.

One exception was at the finger Position 1 in backward force exertion. Backward and forward force exertions (about the PIP joint) at the extended finger positions were uncomfortable. Similarly, downward and upward force exertions (about the MCP joint) at the flexed finger positions were uncomfortable. In these cases, it was also difficult to maintain the exact directions of force exertions. Experimental results showed that the measured forces were relatively small in these cases, especially finger strengths in Position 1 in the backward direction.

While statistical significance was not attained, trends were apparent. This seems to indicate that ratios of EMG amplitude/force in force exertions about the MCP joint decrease as the finger flexes while the ratios in force exertions about the PIP joint increase as the finger flexes. This implies that the muscles were more efficiently used at

Table 9.12 ANOVA for ratios of EMG amplitude/MVC measured before and after daily tests.

Source	SS	df	F	p
Day(D)	0.045	3	0.04	0.988
Direction(R)	94.172	3	31.50	0.001
Before/After(T)	0.019	1	0.03	0.872
D x R	0.182	9	9999.99	0.001
D x T	0.002	3	9999.99	0.001
R x T	0.008	3	9999.99	0.001
D x R x T	0.163	9	0.13	0.999
D x S	7.122	20		
R x S	19.933	20		
T x S	6.850	10		
D x R x S	0.0	40		
D x T x S	0.0	10		
R x T x S	0.0	10		
D x R x T x S	7.090	50		
Total	116.242	191		

the flexed finger positions in the downward and upward force exertions. In the backward and forward force exertions, the muscles were more efficiently used at the extended finger positions.

The one exception to these statement is backward force exertion in Finger Position 1 where the finger is extremely weak.

## **X. Validation of Finger Models**

### ***10.1 Overview***

Finger strengths and muscular activity levels for submaximal exertions measured in experiments were compared to those predicted by biomechanical finger model and computer simulations.

Normalized EMG amplitude/force ratios were compared to the normalized muscular forces against an external load.

## *10.2 Comparisons of Finger Strengths*

ANOVA for overall data of predicted and measured finger strengths was performed first. Since the measured and predicted data were combined, there were four factors: finger position, direction of force exertion, finger strength (predicted and measured), and subject. Of those factors, subject was treated as a random factor while the others were treated as fixed factors. Predicted finger strengths were from the constant tendon moment arms model.

Result of ANOVA (Table 10.1) showed that there were significant effects of finger position and direction of force exertion on finger strength ( $p < 0.01$ ). Predicted and measured finger strengths were not significantly different. Significant interactions of finger position and direction of force exertion, finger position and measure, direction of force exertion and measure, and of three factors on the finger strength were found ( $p < 0.01$ ). Newman-Keuls comparisons for these three factors were performed and are summarized in Table 10.2.

Finger strengths in Finger Position 4 differed from those at other finger positions ( $p < 0.05$ ). Finger strengths in Finger Positions 2 and 3 could be grouped together, and those in Positions 1 and 3 could be grouped together. Finger strengths in Position 2 differed from those in Position 1 ( $p < 0.05$ ).

To investigate the differences between the predicted and measured finger strengths in the same directions of force exertions, ANOVAs and post-hoc tests were performed for finger strengths in each direction of force exertion. Results of these ANOVAs and Newman-Keuls tests are presented in Tables 10.3 through 10.6. In all four directions of force exertions, finger position showed significant effect on finger strength ( $p < 0.01$ ). Predicted and measured finger strengths were different ( $p < 0.05$ ) in downward, upward,

Table 10.1 ANOVA for overall data of predicted and measured finger strengths.

Source	SS	df	F	p
Position(P)	149.21	3	13.54	0.001
Direction(D)	30432.85	3	244.71	0.001
Measure(M)	5.83	1	0.05	0.840
Subject(S)	362.87	5		
P x D	2516.55	9	96.17	0.001
P x M	201.64	3	19.93	0.001
D x M	3630.18	3	35.37	0.001
P x S	55.09	15		
D x S	621.82	15		
M x S	625.29	5		
P x D x M	407.76	9	17.48	0.001
P x D x S	130.84	45		
P x M x S	50.60	15		
D x M x S	513.20	15		
P x D x M x S	116.64	45		
Total	39820.36	191		



Table 10.2 Results of Newmal-Keuls comparisons for overall data of predicted and measured finger strengths.

**Position**

4	25.20	
2	23.97	
3	23.26	
1	22.90	

**Direction**

Downward	Backward	Upward	Forward
38.67	33.89	12.57	10.20
_____	_____	_____	_____

**Measure**

Predicted	Measured
23.66	24.01
_____	_____

Table 10.3 ANOVA and Newman-Keuls tests for downward finger strengths.

**Result of ANOVA**

Source	SS	df	F	p
Position(P)	1510.73	3	55.50	0.001
Measure(M)	2106.35	1	14.20	0.013
Subject(S)	590.47	5		
P x M	177.79	3	8.15	0.002
P x S	136.10	15		
M x S	741.46	5		
P x M x S	109.05	15		
<b>Total</b>	<b>5371.95</b>	<b>47</b>		

**Result of Newman-Keuls Comparison**

<u>Position</u>		<u>Measure</u>	
		Predicted	Measured
4	47.10		
3	38.60	32.05	45.29
2	37.64	_____	_____
1	31.34		

Table 10.4 ANOVA and Newman-Keuls tests for upward finger strengths.

**Result of ANOVA**

Source	SS	df	F	p
Position(P)	336.76	3	667.70	0.001
Measure(M)	845.46	1	33.17	0.002
Subject(S)	55.65	5		
P x M	117.58	3	152.10	0.001
P x S	2.52	15		
M x S	127.45	5		
P x M x S	3.87	15		
<b>Total</b>	<b>1489.28</b>	<b>47</b>		

**Result of Newman-Keuls Comparison**

<u>Position</u>			<u>Measure</u>	
4	16.88		Predicted	Measured
3	12.20		16.76	8.37
2	11.46		_____	_____
1	9.73			

Table 10.5 ANOVA and Newman-Keuls tests for backward finger strengths.

**Result of ANOVA**

Source	SS	df	F	p
Position(P)	747.74	3	81.86	0.001
Measure(M)	132.30	1	3.52	0.120
Subject(S)	312.79	5		
P x M	297.79	3	28.21	0.001
P x S	45.67	15		
M x S	188.12	5		
P x M x S	52.78	15		
Total	1777.18	47		

**Result of Newman-Keuls Comparison**

<u>Position</u>			<u>Measure</u>	
1	38.50		Predicted	Measured
2	36.30		32.23	35.55
3	32.67			
4	28.08			

Table 10.6 ANOVA and Newman-Keuls tests for forward finger strengths.

<b>Result of ANOVA</b>				
Source	SS	df	F	p
Position(P)	70.54	3	215.23	0.001
Measure(M)	551.89	1	33.88	0.002
Subject(S)	25.78	5		
P x M	16.25	3	52.79	0.001
P x S	1.64	15		
M x S	81.46	5		
P x M x S	1.54	15		
Total	749.10	47		

**Result of Newman-Keuls Comparison**

<u>Position</u>			<u>Measure</u>	
1	12.02		Predicted	Measured
2	10.47		13.59	6.81
3	9.56		_____	_____
4	8.76			

and forward force exertions. Only in backward exertions, predicted finger strengths were not different from measured finger strengths.

Predicted finger strengths had been computed with mean values of muscular capabilities and phalangeal lengths. To investigate the ranges of finger strengths depending on personal variations of muscular capabilities and phalangeal lengths, predicted finger strengths were re-computed with means plus and minus one and two standard deviations of muscular capabilities and phalangeal lengths. Ranges of predicted finger strengths and measured ones are graphically presented in Figure 10.1 through 10.4.

Measured finger strengths were larger than predicted ones in downward and backward force exertions (finger flexion exertions). In contrast, measured finger strengths in upward and forward exertions (finger extension exertions) were smaller than predicted finger strengths. Although there were significant differences between predicted and measured finger strengths, measured finger strengths were within the ranges of plus and minus one standard deviation of the predicted finger strengths.

To test whether trends of measured finger strengths with respect to finger positions followed the trends of predicted finger strengths, linear regressions were performed for both data in every direction of force exertion. The parameters of linear regressions are presented in Table 10.7. In downward and upward exertions (about the MCP joint), both the predicted and measured finger strengths had positive slopes: finger strengths increased as the finger flexed. In backward and forward exertions (about the PIP joint), the predicted and measured finger strengths had negative slopes: finger strengths decreased as the finger flexed.

To test whether the slopes of measured finger strengths were the same to those of predicted ones, confidence intervals of the slopes of the predicted finger strengths were

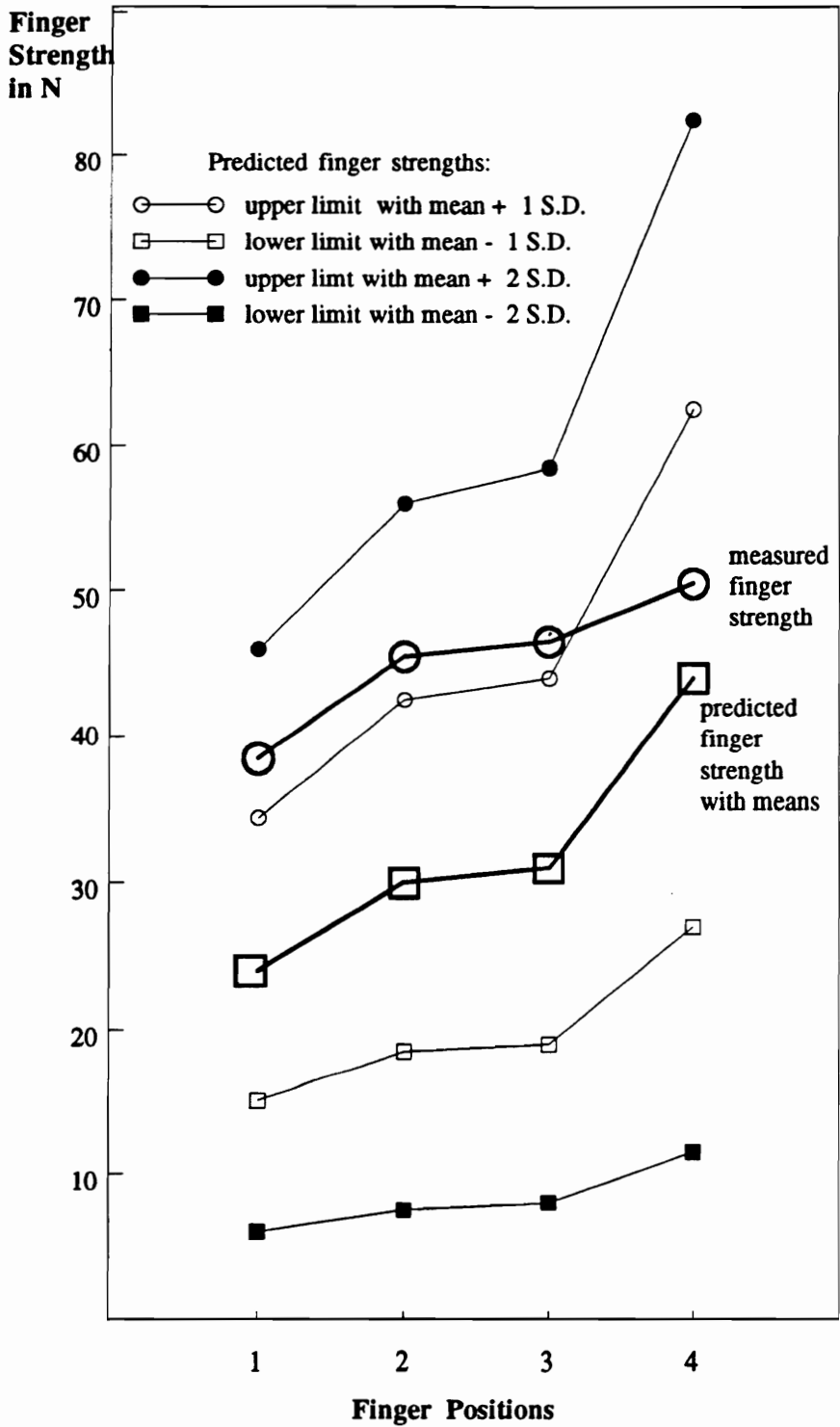


Figure 10.1 Predicted and measured finger strengths in downward force exertions.

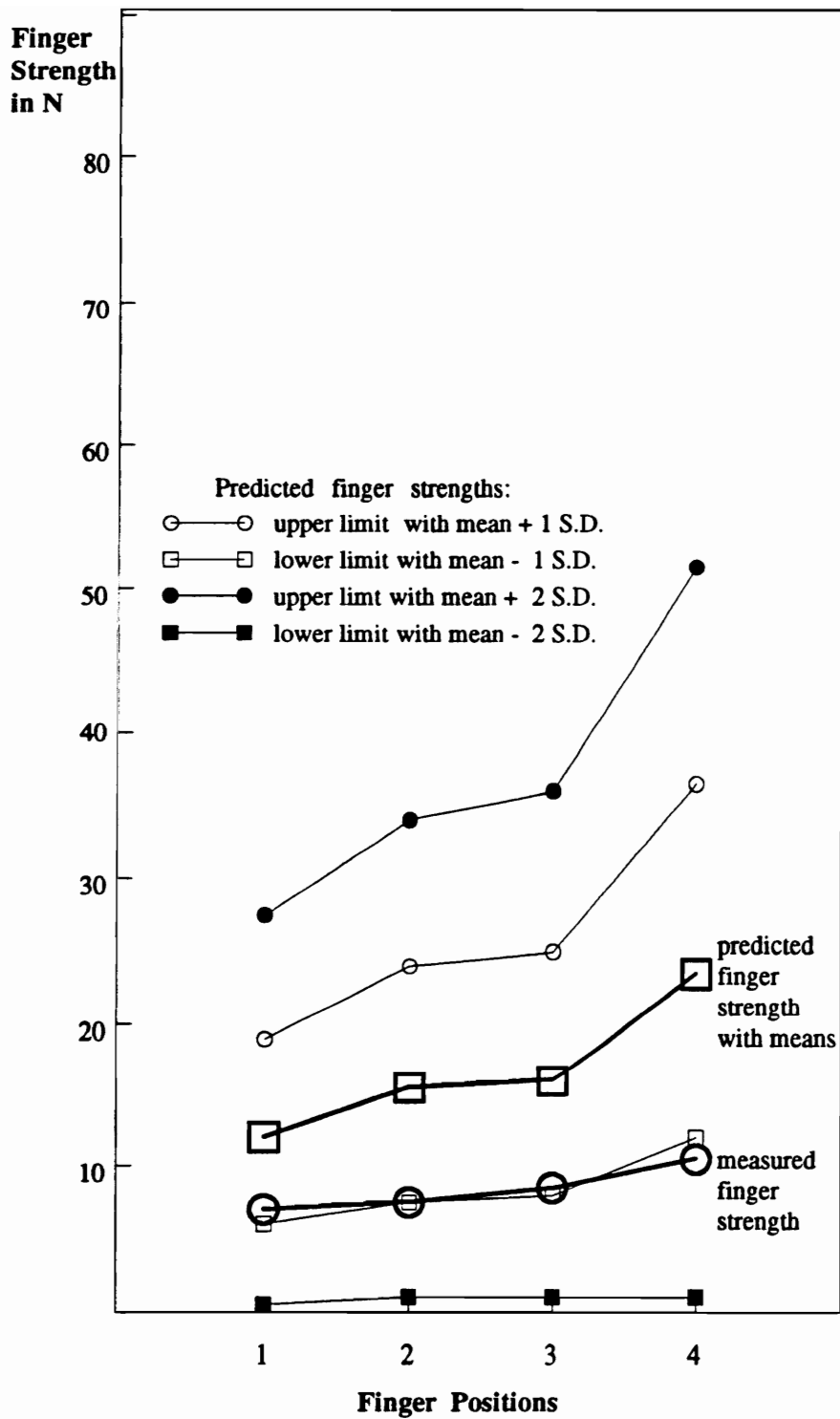


Figure 10.2 Predicted and measured finger strengths in upward force exertions.



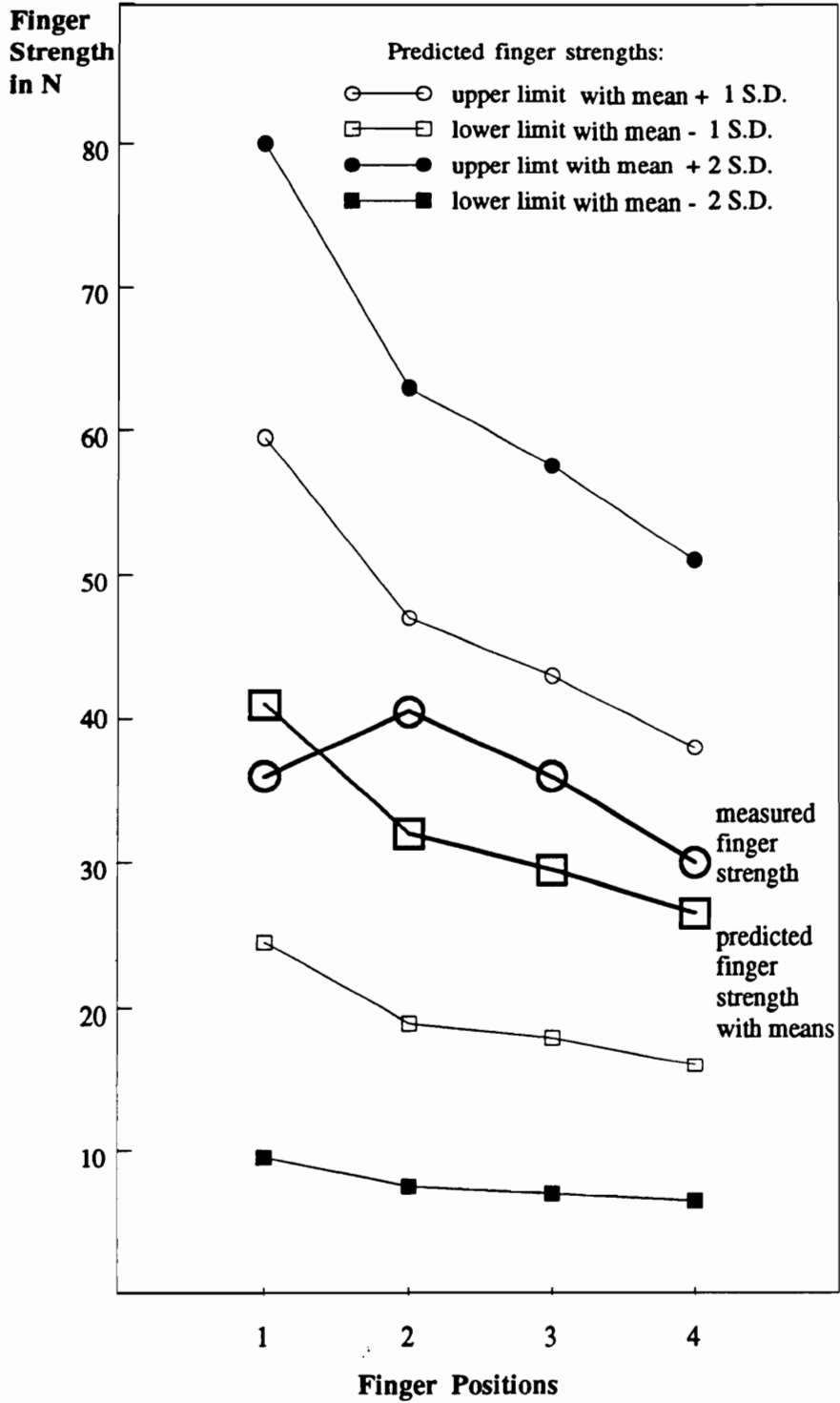


Figure 10.3 Predicted and measured finger strengths in backward force exertions.

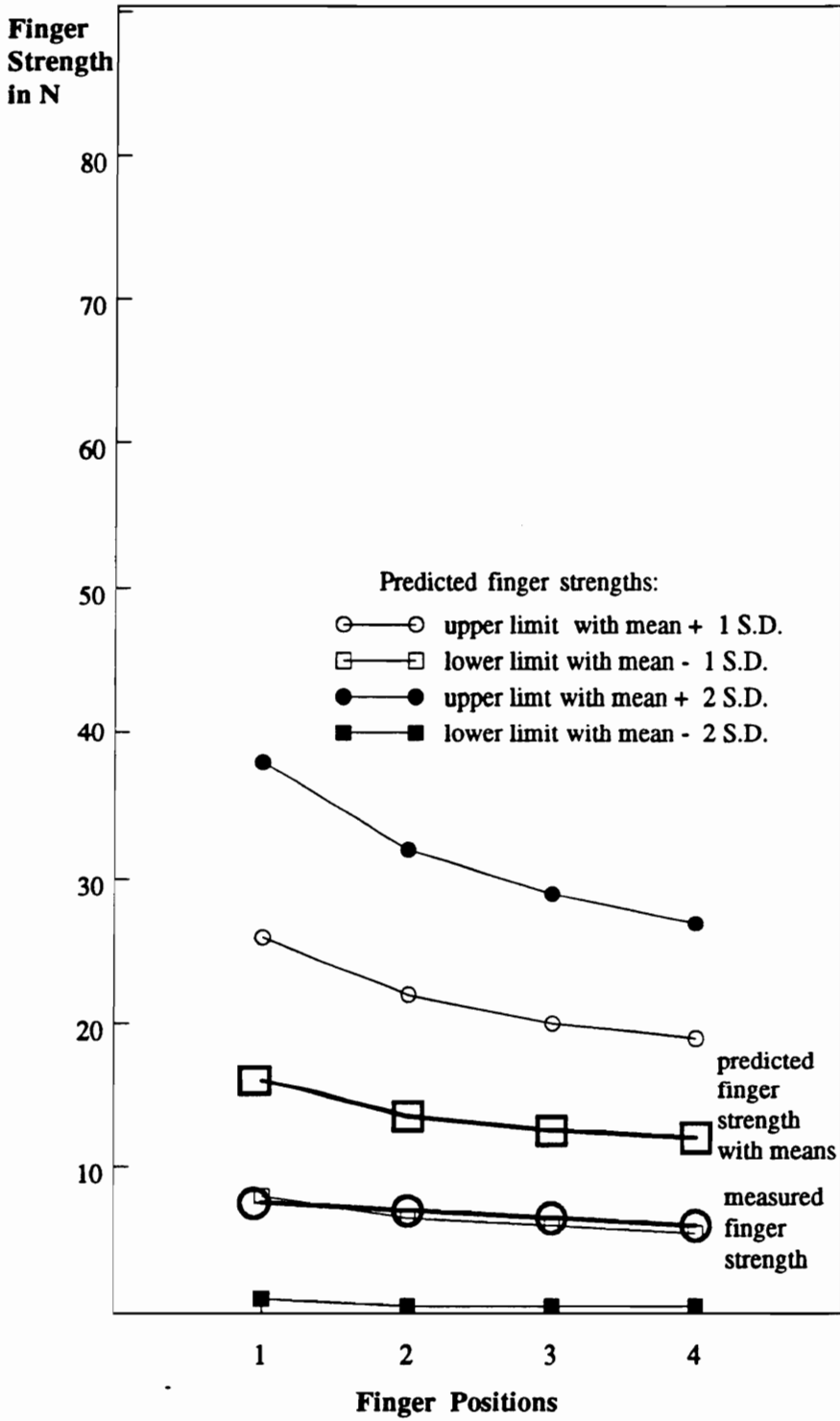


Figure 10.4 Predicted and measured finger strengths in forward force exertions.

Table 10.7 Parameters of linear regressions for predicted and measured finger strengths.

Direction \ Regression parameter		Intercept	Slope	p*
Downward	Predicted	- 6.47	9.83	0.01
	Measured	21.44	5.93	0.03
Upward	Predicted	- 5.69	5.73	0.01
	Measured	2.93	1.43	0.11
Backward	Predicted	61.25	- 7.25	0.01
	Measured	46.62	- 3.18	0.05
Forward	Predicted	23.03	- 2.36	0.01
	Measured	10.24	- 0.90	0.15

**note : Predicted values are for the constant tendon moment arms model**

**\* : level of significance that rejects the hypothesis in which the slope of regression line is zero.**

computed (at  $p = 0.05$ ) in each direction of force exertion (Table 10.8). Slopes of measured finger strengths in downward, backward, and forward exertions were within the confidence intervals of those of predicted finger strengths. Only the slope of measured upward finger strengths was outside the confidence interval.

### *10.3 Comparisons of Muscular Activity Levels*

Computer simulations calculated the muscular forces required to maintain static equilibrium against an external load. For finger flexion (downward and backward) force exertions, muscular forces of the FDS, FDP, and interossei were computed; for finger extension (upward and forward) force exertions, muscular forces of the EDC, interossei, and lumbricals were computed.

In experiments, RMS EMG amplitudes in submaximal force exertions at 25%, 50%, and 75% MVC were measured from the FDS and EDC, and were standardized by the RMS EMG amplitudes of maximal exertions at Finger Position 3.

Results of computer simulations demonstrated that the muscular forces changed as the finger positions and directions of force exertions changed because torques acting on the finger joints were determined by the mechanical leverages (Cromer, 1977; Chaffin and Andersson, 1984). The same results were expected in experiments in which changes of muscular forces were assessed by EMG amplitudes since direct measurements of muscular forces were not possible.

As EMG amplitude is sensitive to exerted muscular force, it was expected that large muscular force would induce a high EMG amplitude (Basmajian and De Luca, 1985; Ericson and Hagberg, 1978; Lee, 1981; Woods and Bigland-Richie, 1983).

Table 10.8 Confidence limits of the slopes of predicted finger strengths.

regression parameter direction	Slope of predicted finger strength		Slope of measured finger strength
	Lower limit	Upper limit	
Downward	4.67	15.00	5.93
Upward	2.55	8.91	1.43
Backward	- 13.47	- 1.02	- 3.18
Forward	- 5.18	0.46	- 0.90

The effect of finger position and direction of force exertion on muscular activity level are of major interest in this study. In computer simulation, muscular activity levels were represented by the muscular forces against a fixed external load (5 N). In experiments, they were measured by standardized RMS EMG amplitudes in submaximal exertions at 25%, 50%, and 75% MVC. Since these two measures had different units, normalization of data was required to compare one to the other.

Predicted muscular activity levels were represented by muscular forces against a fixed external load. In this case, the ratios of these muscular forces would hold the characteristics of the measure. RMS EMG amplitudes, however, were measured in exertions of different percentages of MVC levels. MVC varied as the finger positions and directions of force exertions changed. Exerted forces at the same percentage of a MVC level thus showed large variation. Normalization of EMG amplitudes were performed in two steps. First, the standardized RMS EMG amplitude was divided by the amount of exerted muscular force. Then ratios of these standardized RMS EMG amplitude/force were computed for the four finger positions. Values of standardized EMG amplitude/force at Finger Position 3 were used as the references since EMG amplitudes were standardized by the EMG amplitudes at Finger Position 3. Relative ratios of predicted muscular forces for finger positions were also computed with the muscular forces at Finger Position 3. Normalized muscular forces and EMG amplitude/force, which represented predicted and measured muscular activity levels, are shown in Tables 10.9 and 10.10, respectively. Predicted muscular activity levels and measured muscular activity levels in submaximal force exertions are graphically presented in Figures 10.5 through 10.8.

Linear regressions were performed for the ratios of muscular forces and standardized EMG amplitude/force. Three finger positions (Positions 1, 3, and 4) were considered and values of finger positions were given to 3, 4, and 5, respectively, based on the flexed

Table 10.9 Normalized muscular forces (predicted muscular activity levels).

Directions Positions	Downward	Upward	Backward	Forward
1	1.20	1.24	0.71	0.73
2	0.99	1.03	0.97	0.90
3	1.00	1.00	1.00	1.00
4	0.69	0.72	1.21	1.11

Table 10.10 Normalized EMG amplitude/force (measured muscular activity levels).

Force Level	Direction	Downward	Upward	Backward	Forward
	Finger Position				
25%	1	1.06	1.08	0.97	0.87
	2	0.94	1.07	0.82	0.95
	3	1.00	1.00	1.00	1.00
	4	0.88	0.84	1.16	1.17
50%	1	1.16	1.02	0.89	0.79
	2	0.96	0.97	0.85	0.87
	3	1.00	1.00	1.00	1.00
	4	0.92	0.76	1.19	1.11
75%	1	1.09	1.01	0.96	0.75
	2	0.91	1.04	0.84	0.78
	3	1.00	1.00	1.00	1.00
	4	0.83	0.77	1.16	1.01
100%	1	1.18	1.19	1.00	0.83
	2	1.00	1.20	0.89	0.89
	3	1.00	1.00	1.00	1.00
	4	0.91	0.84	1.21	1.11



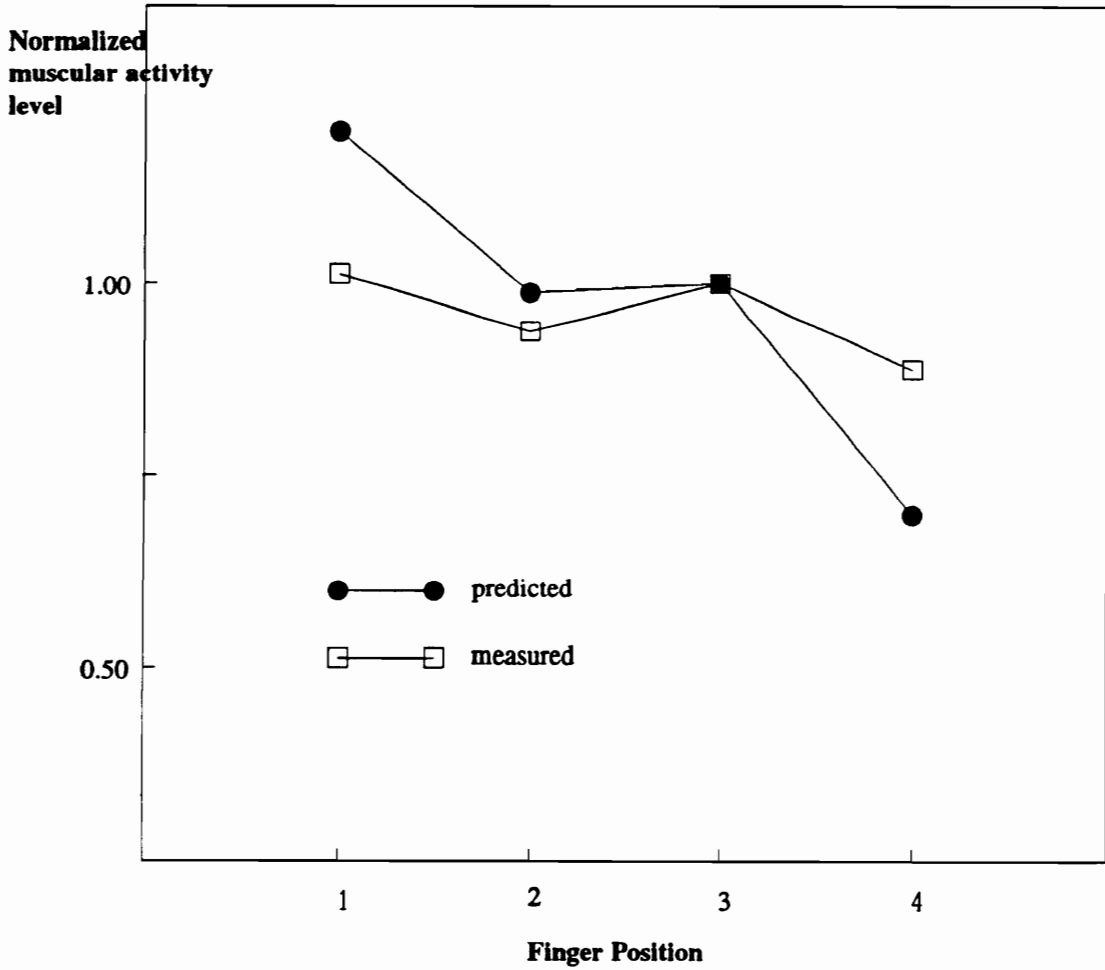


Figure 10.5(a) Predicted and measured muscular activity levels in downward force exertions (25%MVC).

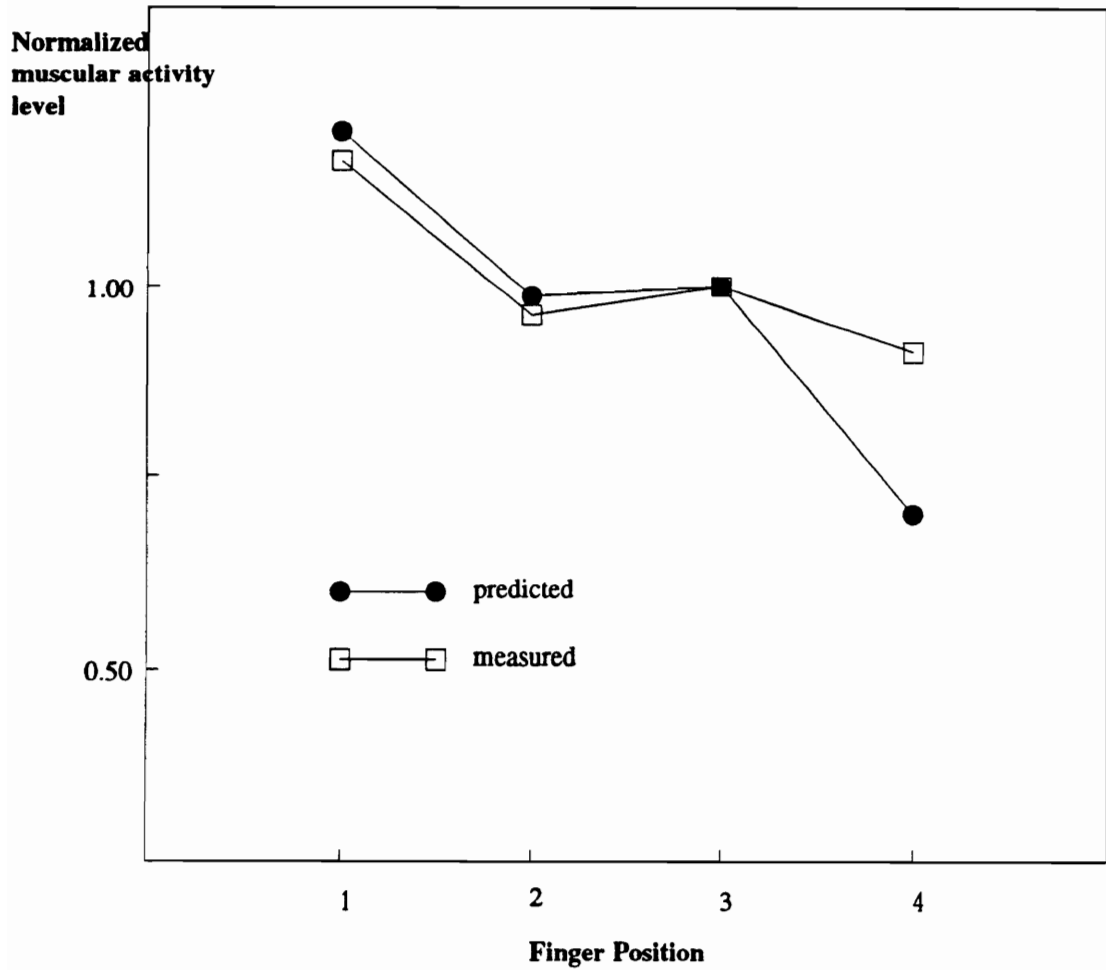


Figure 10.5(b) Predicted and measured muscular activity levels in downward force exertions (50%MVC).

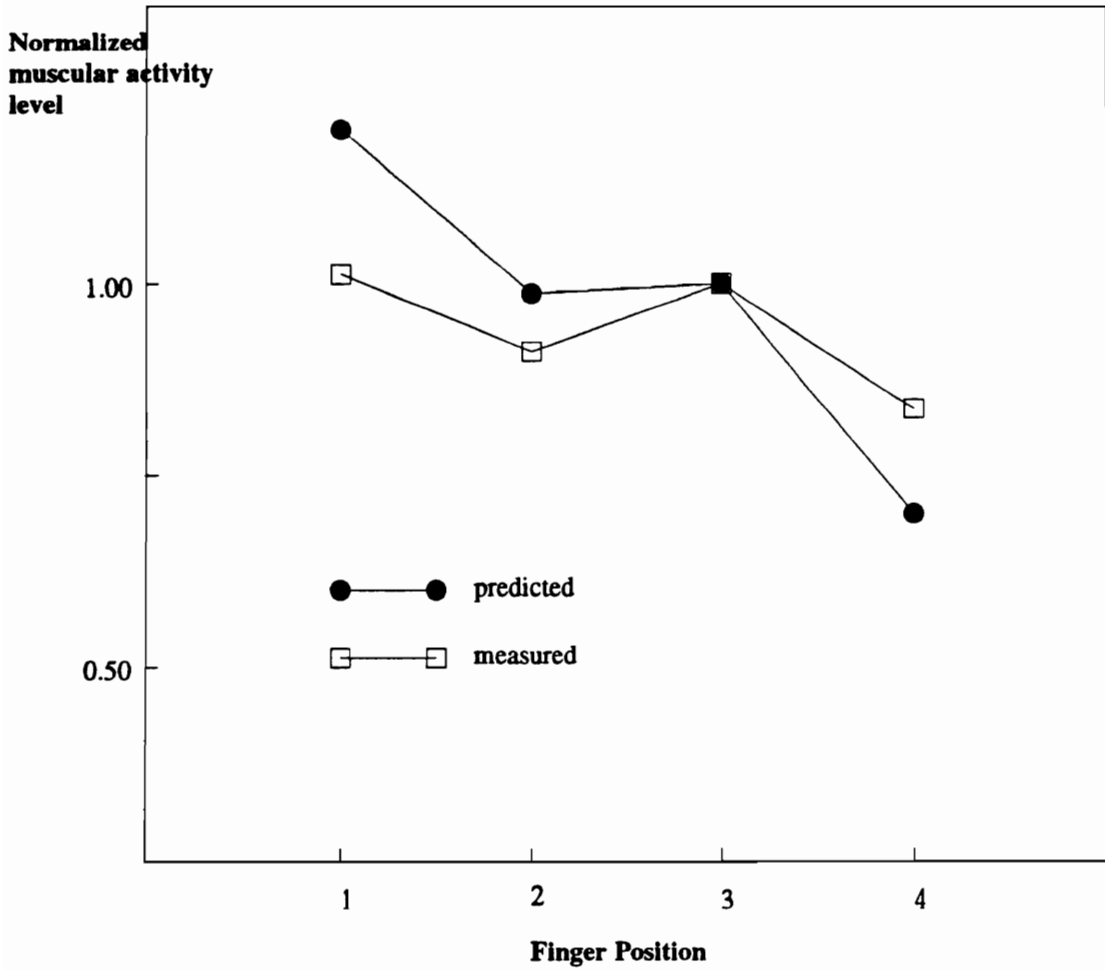


Figure 10.5(c) Predicted and measured muscular activity levels in downward force exertions (75%MVC).

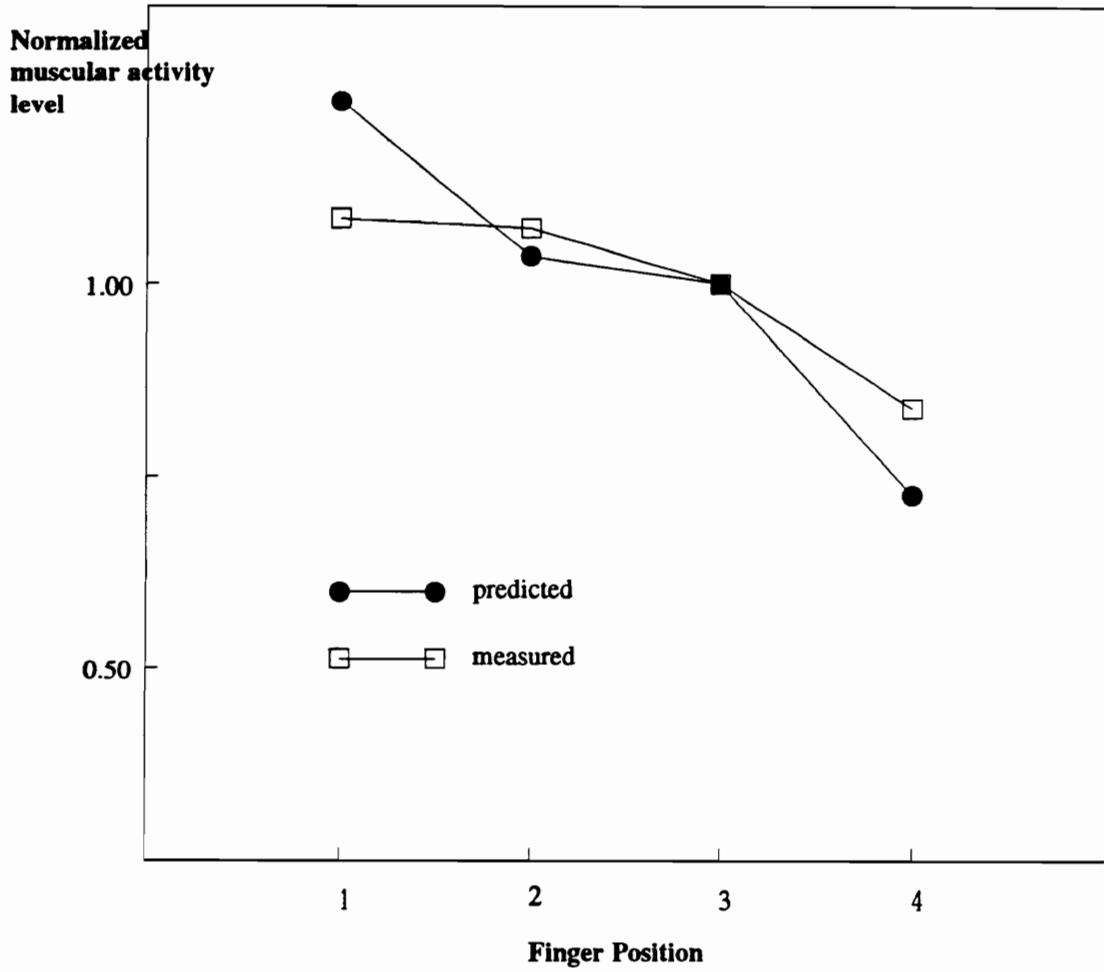


Figure 10.6(a) Predicted and measured muscular activity levels in upward force exertions (25%MVC).

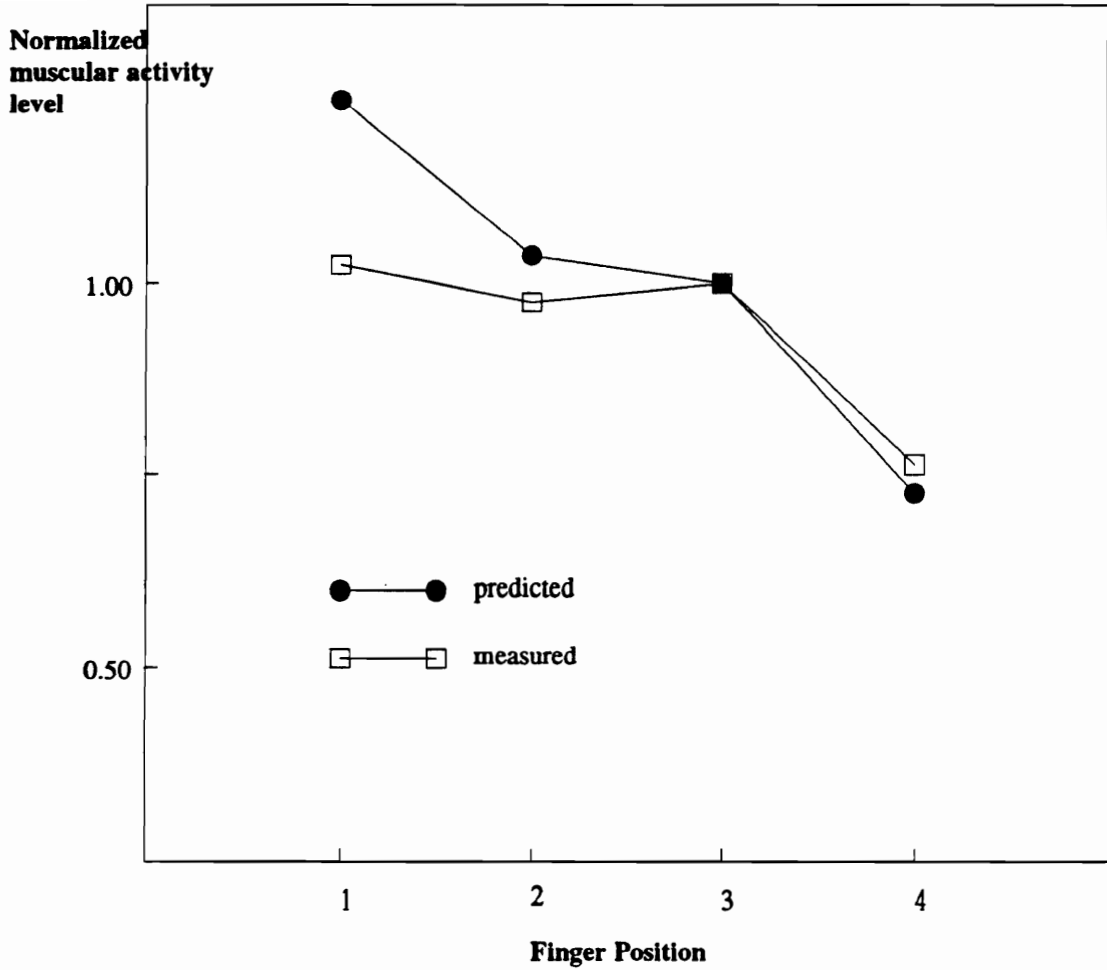


Figure 10.6(b) Predicted and measured muscular activity levels in upward force exertions (50% MVC).

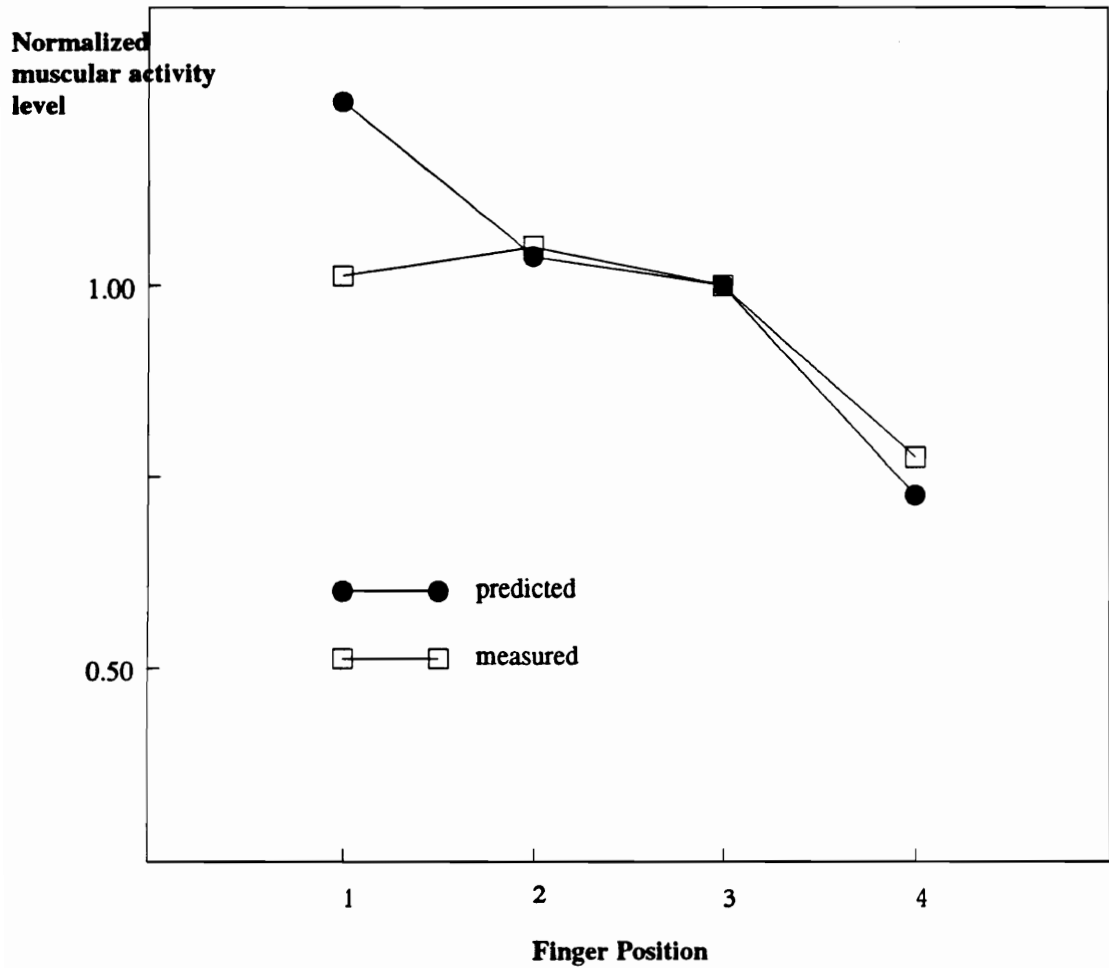


Figure 10.6(c) Predicted and measured muscular activity levels in upward force exertions (75%MVC).

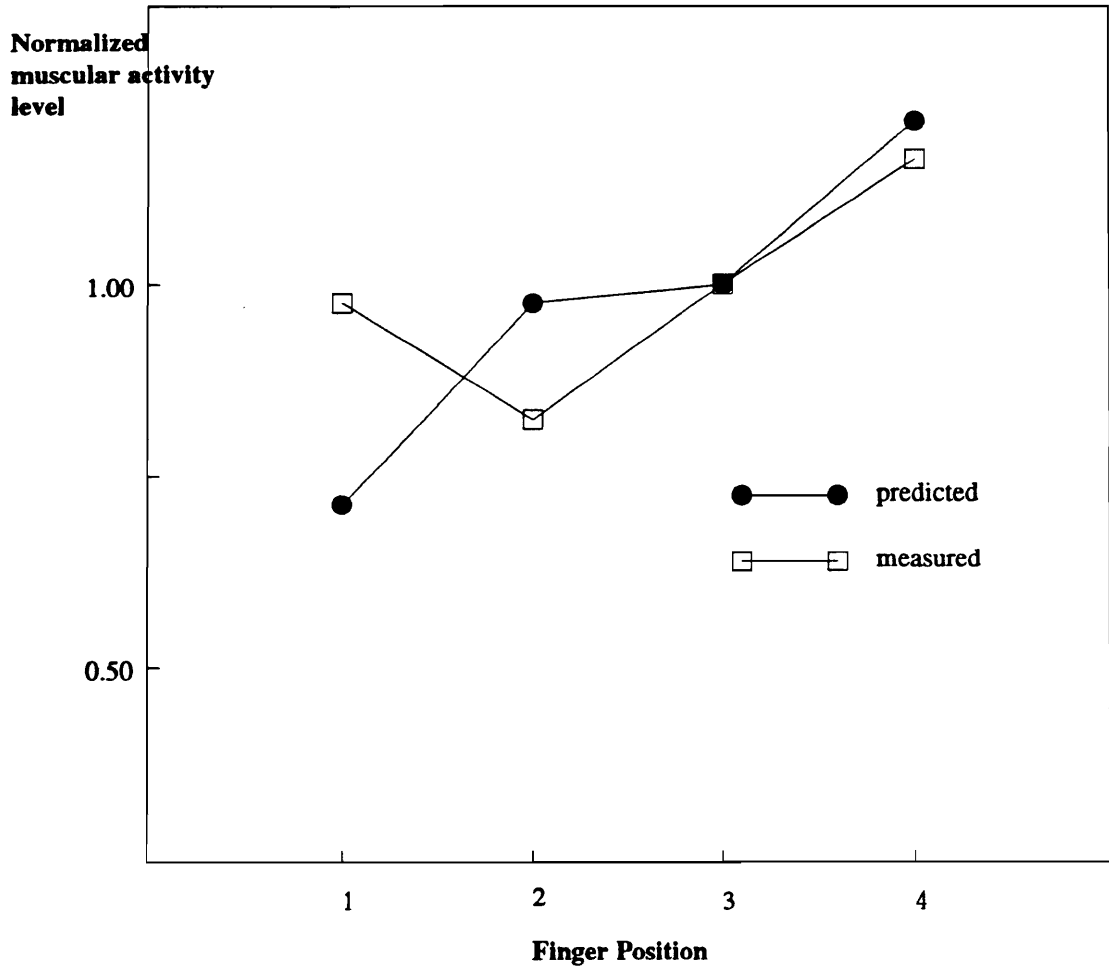


Figure 10.7(a) Predicted and measured muscular activity levels in backward force exertions (25%MVC).

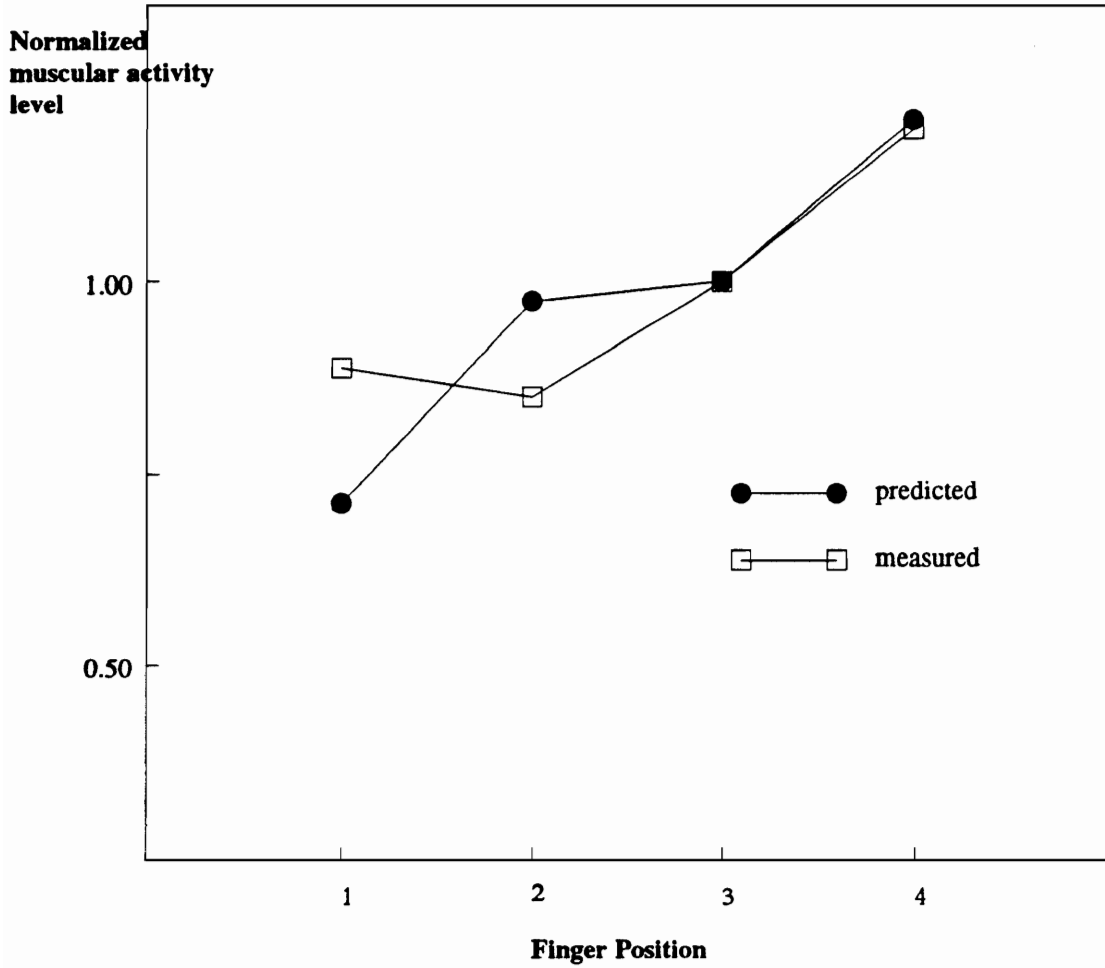


Figure 10.7(b) Predicted and measured muscular activity levels in backward force exertions (50% MVC).



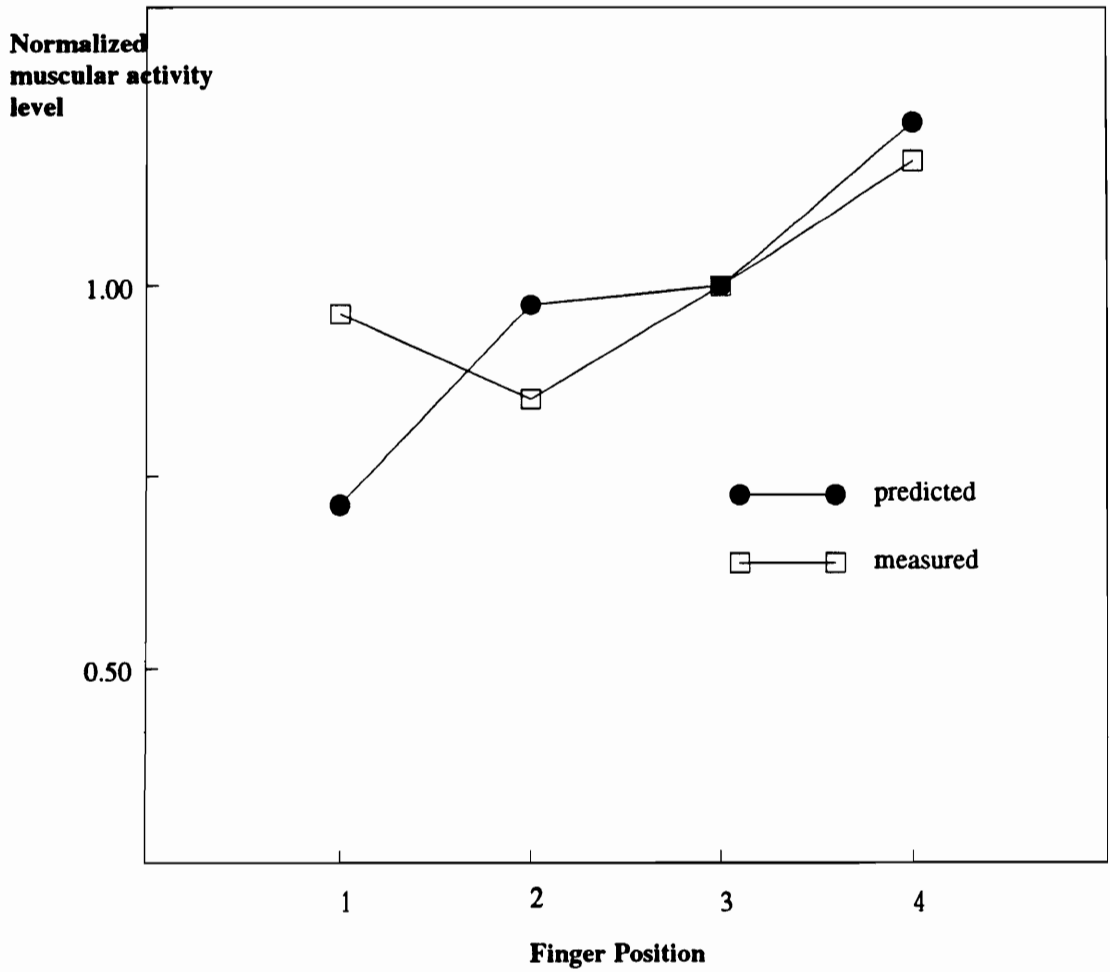


Figure 10.7(c) Predicted and measured muscular activity levels in backward force exertions (75% MVC).

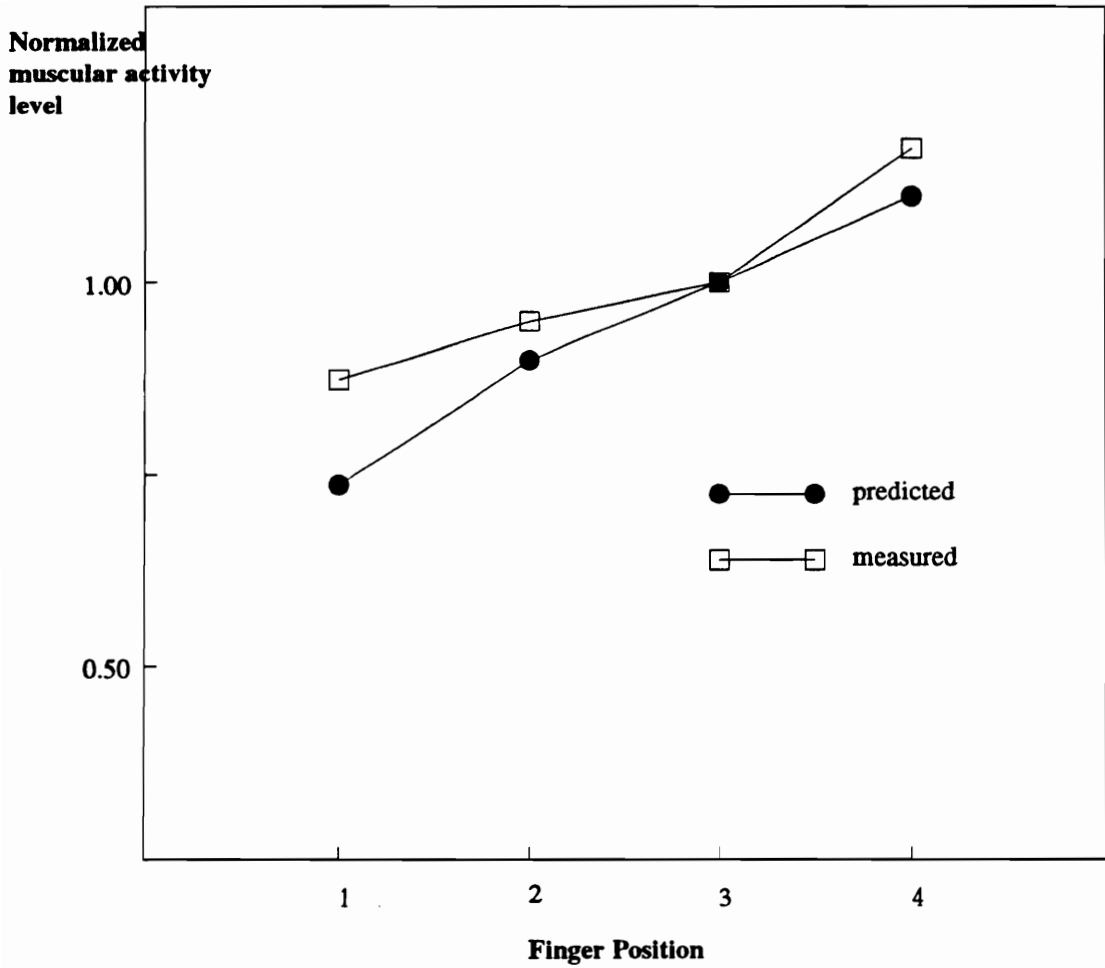


Figure 10.8(a) Predicted and measured muscular activity levels in forward force exertions (25%MVC).

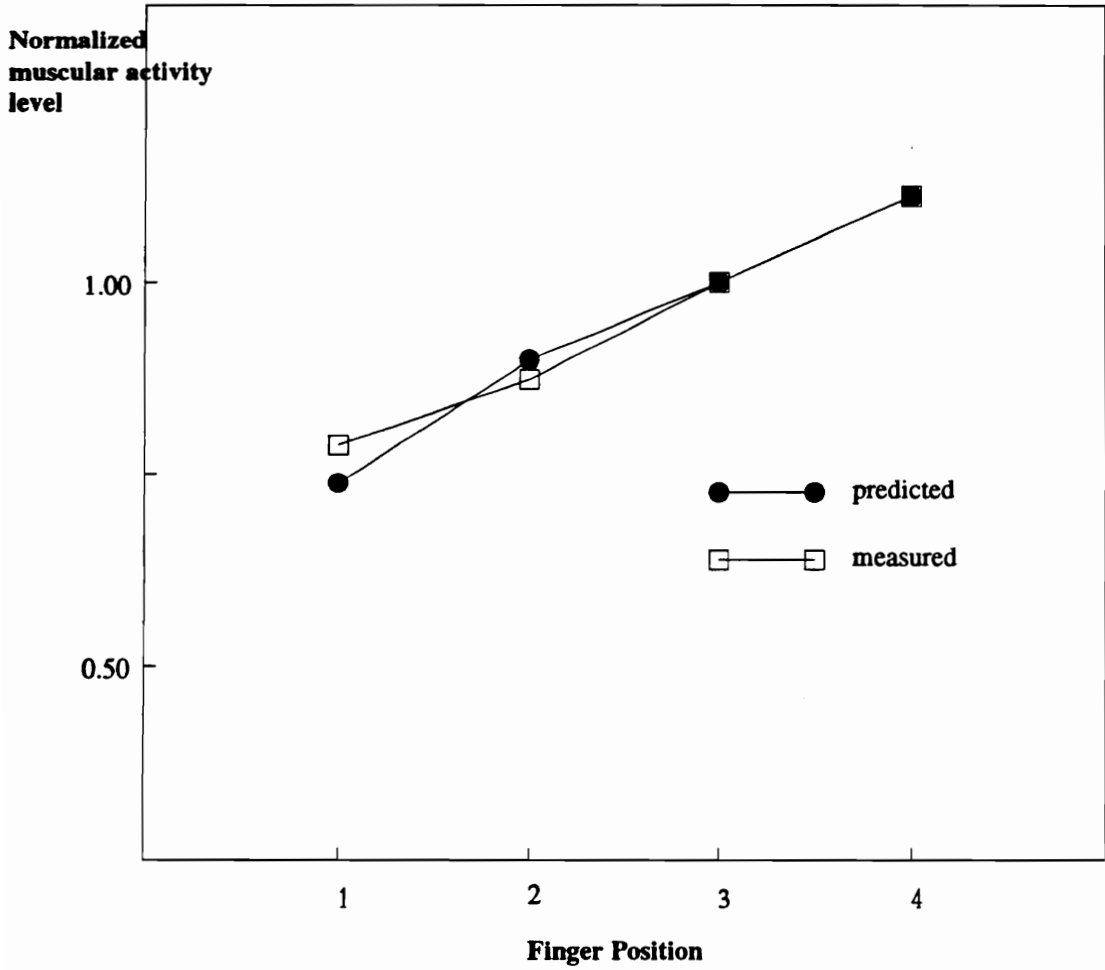


Figure 10.8(b) Predicted and measured muscular activity levels in forward force exertions (50%MVC).

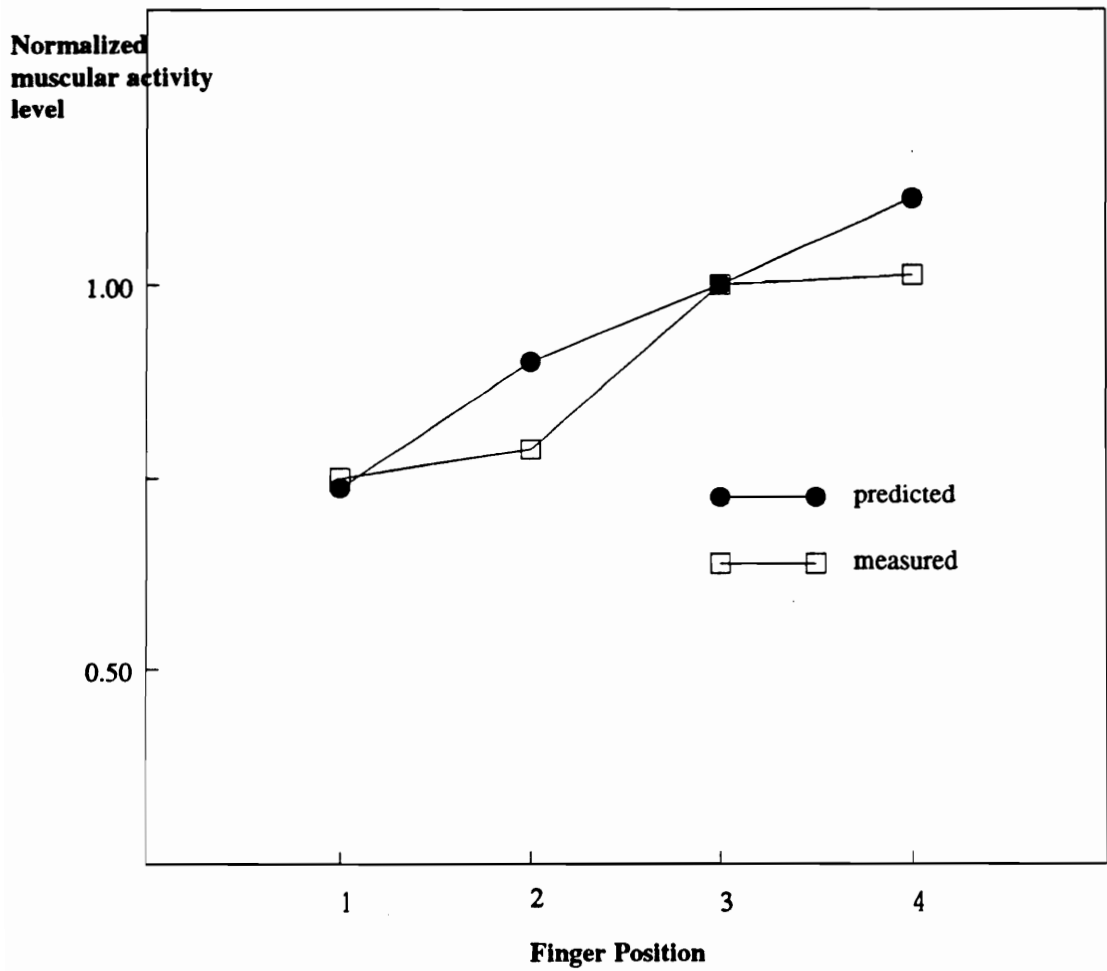


Figure 10.8(c) Predicted and measured muscular activity levels in forward force exertions (75%MVC).

angles of the finger. Results of linear regressions for predicted and measured muscular activity levels are summarized in Tables 10.11 and 10.12, respectively.

In both the predicted and measured data, muscular activity levels in downward and upward force exertions (about the MCP joint) had positive slopes while those in backward and forward force exertions (about the PIP joint) had negative slopes. To investigate whether the trends of measured muscular activity levels were as predicted, t-tests were performed on the differences between the slopes of the predicted and measured muscular activity levels at  $\alpha = 0.05$  (Neter and Wasserman, 1974). Results (Table 10.13) show that, in downward force exertions, there were no significant differences between the slopes of measured muscular activity and those predicted at 25% and 50% MVC levels. In upward force exertions, the measured and predicted slopes were not different at 50% and 100% MVC. In backward force exertions, the slopes were not different at levels of 25% and 50% MVC. In forward force exertions, there were no significant differences between the slopes. This means that, in ten out of sixteen force exertions, the slopes of measured muscular activity levels were not significantly different from the slopes of predicted muscular activities.

## *10.4 Discussion and Summary*

Measured finger strengths were statistically different from predicted finger strengths. This result might be due to limitations in the data used for predicting finger strengths. Individual finger strengths were determined by tendon moment arms, phalangeal lengths, muscular capabilities, finger positions, and directions of force exertions. Individual data of tendon moment arms and muscular capabilities could not be measured. Instead, a set

Table 10.11 Results of linear regression for predicted muscular activity levels.

<b>Direction</b> \ <b>Regression parameter</b>	<b>Intercept</b>	<b>Slope</b>	<b>p*</b>
<b>Downward</b>	1.98	- 0.26	0.01
<b>Upward</b>	2.03	- 0.26	0.01
<b>Backward</b>	- 0.03	0.25	0.01
<b>Forward</b>	0.19	0.19	0.01

\* : level of significance that rejects the hypothesis in which the slope of regression line is zero.

Table 10.12 Results of linear regression for measured muscular activity levels.

Force level	Direction	Regression parameter	slope	p*	intercept
25%	downward		- 0.14	0.05	1.58
	upward		- 0.12	0.02	1.47
	backward		0.10	0.19	0.66
	forward		0.12	0.02	0.53
50%	downward		- 0.15	0.03	1.65
	upward		- 0.13	0.03	1.45
	backward		0.17	0.02	0.38
	forward		0.15	0.01	0.40
75%	downward		- 0.14	0.01	1.57
	upward		- 0.12	0.02	1.39
	backward		0.09	0.07	0.71
	forward		0.13	0.11	0.40
100%	downward		- 0.14	0.01	1.58
	upward		- 0.18	0.01	1.72
	backward		0.09	0.01	0.71
	forward		0.14	0.01	0.44

\* : level of significance that rejects the hypothesis in which the slope of regression line is zero.

Table 10.13 Results of t-tests for comparing the slopes between the predicted and measured muscular activity levels.

Regression parameter Direction	Slope of predicted muscular activity level	Slope of measured muscular activity levels			
		25% MVC	50% MVC	75% MVC	100% MVC
<b>Downward</b>	- 0.26	- 0.14	- 0.15	- 0.14*	- 0.14*
<b>Upward</b>	- 0.26	- 0.12*	- 0.13	- 0.12*	- 0.18
<b>Backward</b>	0.25	0.10	0.17	0.09*	0.09*
<b>Forward</b>	0.19	0.12	0.16	0.13	0.14

\* : significantly different from the predicted ( $p < 0.05$ )



of data from the literature was used to compute individual's finger strengths. As a result, in the predicted finger strengths, personal variations were very small. These small variations might affect the results of statistical significance tests.

Predicted downward and backward (finger flexion exertion) finger strengths were smaller than measured finger strengths. These underestimations of finger strengths might be caused by the assumption that contribution of the FDP was zero. The DIP joint was assumed to be fixed in force exertions about the PIP and MCP joints. Since the FDP is in charge of flexing the DIP joint, the FDP was assumed not to contribute to flex the PIP and MCP joints. However, in reality, the FDP contributes to flexing the PIP and MCP joints (Ketchum et al., 1978; Long and Brown, 1962 and 1964; Tubiana, 1981). Unfortunately, the amount of contribution was not known. To investigate the effect of additional muscular force of the FDP on finger strengths, finger strengths were re-computed with one third and two third of muscular capability of the FDP. Results showed that the measured finger strengths were located between the newly predicted two finger strengths (Figure 10.9).

Although measured finger strengths were statistically different from predicted ones, they were within the range of predicted finger strengths computed with means plus and minus on standard deviation of muscular capabilities and phalangeal lengths. In addition, trends of variations of measured finger strengths were the same as those of predicted finger strengths in three of four directions of force exertions. If complete data (on muscular capabilities and tendon moment arms) were available, predictions of muscular strengths should be closer to the measured muscular strengths.

Muscular activity levels were defined by normalizing predicted muscular forces and measured ratios of EMG amplitude/force. Trends of measured muscular activity levels appear to be similar to the trends of predicted muscular activities since there were no

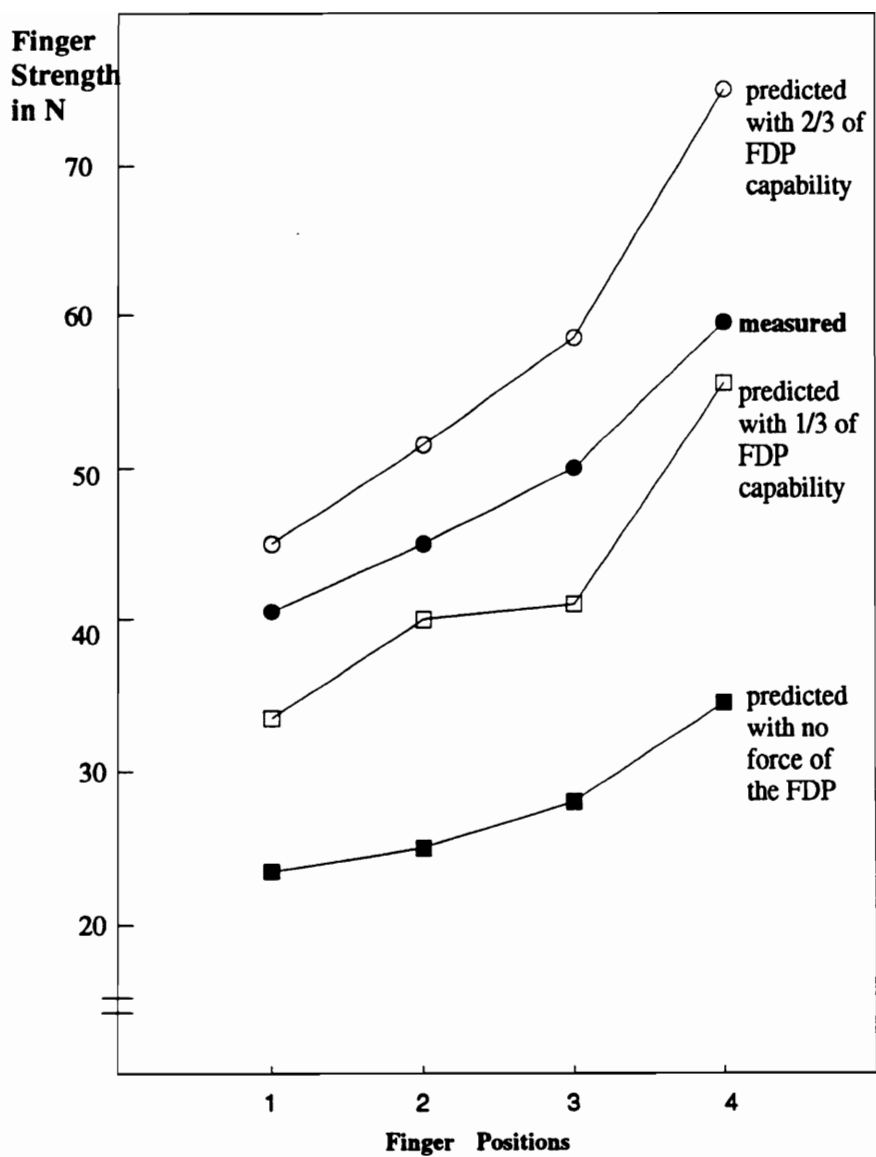


Figure 10.9 Predicted finger strengths with additional FDP capabilities.

significant differences between the slopes of predicted muscular activity levels and those measured at two of the four force exertion levels in downward, upward, and backward force exertions and at all four force exertion levels in forward exertions.

It was found that force exertions about the MCP joint were more efficient at flexed finger positions than at extended positions. In contrast, force exertions about the PIP joint were more efficient at extended finger positions than at flexed positions. This result may be applied to finger tapping and rocking. Finger tapping, downward and upward finger movements about the MCP joint, may be more efficient when the finger is in flexed position than in extended position. Conversely, finger rocking, i.e., backward and forward movements about the PIP joint, may be performed more efficiently at extended finger position than at flexed position.

## XI. CONCLUSIONS

### *11.1 Biomechanical Finger Models and Equilibrium Equations*

Two kinematic finger models have been developed based on the anatomical and functional aspects of the finger. One was with the assumption that tendon moment arms at the joints did not change during finger movements. The other was with the assumption that tendon moment arms changed during finger movements.

The finger models contained five muscles and three joints. Landsmeer's (1961 and 1962) tendon excursion equations were used to construct the models. To use Landsmeer's equations, the anatomical structure of the finger joints and muscular activities in finger movements were carefully studied. Simplifications were made in structure and functions of the finger, but important aspects were preserved.

The finger models developed in this study were distinguished from other finger models of Buchner (1983), Fischer (1969), Storace and Wolf (1979), and Thomas (1965). They were simpler than the models of Buchner (1983), Fischer (1969), and Thomas (1965). However, they included major functions of the finger.

Validation of finger model could be done in two ways. One method consists of direct measurement of tendon excursions (An et al., 1979, 1983, and 1985; Armstrong and

Chaffin, 1978). The other method includes force analyses by developing force or moment equilibrium equations (Buchner, Hines, and Hemami, 1988; Spoor, 1983; Storace and Wolf, 1979). This method, however, is not well established.

In this study, to validate the finger models, force equilibrium equations were derived from the kinematic finger models using the principle of virtual work (Beer and Johnston, 1987; Storace and Wolf, 1979). The force equilibrium equations were indeterminate. The number of variables was reduced using the information on muscular activities in finger movements. The equations were solved for muscular forces which were expressed as functions of mechanical leverages and physiological capabilities of the muscles. Tendon moment arms, phalangeal lengths, and muscular capabilities were treated as parameters whose values could be measured (An et al., 1979, 1983, and 1985; Brand, 1985; Ketchum et al., 1978). Therefore, muscular forces were expressed as functions of finger positions and torques acting on the finger joints. The torques on the finger joints were determined by the magnitude and directions of an external load and phalangeal lengths. Since phalangeal lengths were treated as parameters, muscular forces were functions of finger positions and directions of force. If data of tendon moment arms, phalangeal lengths, and muscular capabilities were known, maximally exertable muscular forces could be computed for finger positions and directions of force exertions. Conversely, if an external load were given instead of muscular capabilities, muscular forces required to maintain static equilibrium could be computed. In this study, muscle length-tension relationships were additionally considered to muscular capabilities.

The procedures to validate finger models are straightforward. Many variations of the finger models can be made by changing the assumptions or simplifications. In this study, computer simulations were performed to compute finger strengths and muscular forces at various finger positions and directions of force exertions.

## *11.2 Evaluation of Finger Models*

From solutions of equilibrium equations and data collected from literature and measurement, finger strengths and muscular forces in a submaximal exertion were computed at various finger positions and directions of force exertions. To validate the finger models and procedures to derive the solutions of equilibrium equations, finger strengths and EMG amplitudes of submaximal exertions were measured for combinations of four finger positions and four directions of force exertions.

Significant differences were found between the predicted and measured finger strengths. Finger strengths in finger flexion exertions were underestimated by computer simulation while those in finger extension exertions were overestimated. To predict individuals' finger strengths and muscular forces, their phalangeal lengths were measured. However, data of tendon moment arms and muscular capabilities were adopted from Brand (1985) and Ketchum et al. (1978), respectively. These data were used to compute individuals' finger strengths and muscular forces. Measured finger strengths were within the ranges plus and minus one standard deviation about the means of predicted finger strengths.

Although there were differences in the values of finger strengths, trends of finger strength variations with respect to finger positions and directions of force exertions were similar in the predicted and measured values. Magnitudes of finger strengths were determined by the anthropometric and physiological data while the trends of variations were determined by the finger model itself. If personal data of tendon moment arms and muscular capabilities were available, validation of finger models could be focussed on the finger models themselves.

Since the predicted muscular forces and the measured RMS EMG amplitudes are in different units, normalization of data was needed to compare these two values. In both the predicted and measured data, muscular activity levels (which were represented by normalized muscular forces and EMG amplitude/force) in downward and upward force exertions (about the MCP joint) decreased as the finger flexed while those in backward and forward force exertions (about the PIP joint) increased as the finger flexed. These results imply that downward and upward force exertions were more efficient in flexed finger position than in extended position; backward and forward force exertions were more efficient in extended finger position than in flexed position. Results of linear regressions showed that slopes of measured muscular activities were statistically significant. In addition, slopes of measured muscular activities appear similar to the slopes of predicted muscular activity levels.

Although relationships between predicted and measured finger strengths were not supported by statistical significance, trends of variations of finger strengths and muscular activity levels were similar in both the predicted and measured data. This seems to indicate that the finger models in this study are correctly developed.

### ***11.3 Recommendations for Future Studies***

The biomechanical finger models in this study consisted of five muscles and three joints. They were developed for the index finger and were based upon many simplifications, although these were carefully made not to lose the basic characteristics of the finger and its functions. Finger models developed in this study for the index finger can

be applied to other fingers since muscles and tendons in these models are common to the other fingers. In this study, adduction and abduction of the finger were not considered. If these finger movements were considered, more muscles and tendons must be involved (Thomas, 1965).

Current finger models are basically static in nature. Finger movements were described by kinematic variables, i.e., tendon excursions (Chaffin and Andersson, 1984). Kinetic models (force equilibrium equations) were derived from these kinematic models using the principle of virtual work (Beer and Johnston, 1987). If the time histories of finger movements are known, equilibrium equations can be solved dynamically (Beer and Johnston, 1987). A dynamic approach should be advantageous for explaining finger movements.

In this study, personal data of tendon moment arms and muscular capabilities were not measured but taken from the literature (Brand, 1985; Ketchum et al., 1978). However, the values of these data are different depending on the investigators and measurement conditions (An et al., 1979, 1983 and 1985; Brand, 1985; Brand et al., 1981; Hettinger, 1972; Ketchum et al., 1978; Tubiana, 1981). A set of data from Brand and Ketchum et al. was used to compute individuals' finger strengths and muscular forces. As a result, personal characteristics were not reflected in the computed finger strengths and muscular forces. To validate the finger models properly, those data should be measured. Tendon moment arms change as the finger position changes. Fischer (1969) modified Landsmeer's tendon excursion equations to describe these changes of tendon moment arms. However, this modification has not been experimentally evaluated. If non-invasive methods for measuring tendon moment arms were available, mechanisms of finger movements could be precisely analyzed.



Predictions of finger strengths were made with the assumption that the FDP does not contribute to MCP and PIP flexions. This assumption is not correct. However, there is no information about the amount of contribution that the FDP makes in MCP and PIP flexions. Computations with one third and two thirds of muscular capability of the FDP showed that the measured finger strengths were located between these two predictions. If it is possible to measure the amount of contribution of the FDP in MCP and PIP exertions, validation of the finger models will be more reliable.

Tendon excursions were not of major interest in this study. However, since the finger models consisted of tendon excursion equations, investigating the relationships between the changes in finger joint angles and the amount of tendon excursions would be helpful to validate the models (An et al., 1979, 1983, and 1985; Armstrong and Chaffin, 1978).

There is much room to expand and generalize the finger models developed in this study. Only if all essential characteristics of the structures and functions of the finger are included, the expansion of the finger models is expected to show good results.

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## **Appendix A. Glossary of Terms and Abbreviations**

## *Terms*

Abduction -- movement of a finger away from the median axis of the body.

Adduction -- movement of a finger toward the median axis of the body.

Aponeurosis -- a flattened or ribbon-like tendinous expansion which serves  
to connect a muscle with the parts that it moves.

Articulation -- joint.

Bi-articular system -- skeletal system with a chain of two joints.

Circumduction -- circular movement of a limb.

Digit -- a finger or thumb of the hand.

Distal -- away from the body.

Extension -- movement of phalanges toward the back (dorsum) of the hand.

Extrinsic muscles -- muscles in the forearm, which move the digits.

Fascia -- a sheet or band of fibrous tissue which covers a structure beneath the skin.

Fibrous skeleton -- ligaments and tendons

Finger -- digits except the thumb

Finger strength -- exerted force by isometric contractions of the muscles involved  
in finger movements.

Flexion -- movement of the phalanges toward palm of the hand.

Intrinsic muscles -- muscles located in the hand.

Joint -- the junction between two or more bones; an articulation.

Kinematics -- the study of the geometry of motion; to relate displacement,  
velocity, acceleration, and time, without reference to the  
cause of the motion.

Kinetics -- the study of the relation between the forces acting on a body; to predict the motion caused by given forces or determine the forces required to produce a given motion.

Ligament -- a tough, fibrous band which connects bones with bone with bone, supports organs, or connects bone with a tendon.

Multi-articular system -- skeletal system with a chain of multiple joints.

Muscular capability -- maximal force that a muscle can exert.

Muscular force -- force which is generated by a muscle and can be measured by strain gauge.

Phalanx (phalanges) -- bone(s) of the finger.

Proximal -- toward the body.

Ray -- a line extended from a metacarpal to the connected phalanges.

Rocking -- finger flexion and extension with the axis at the PIP joint.

Tapping -- finger flexion and extension with the axis at the MCP joint.

Tendon -- a fibrous cord of connective tissue in which the fibers of a muscle end and by which a muscle is attached to a bone.

Tendon sheath -- an annular ligament surrounding a tendon.

Trochlea -- a pulley-shaped structure.

Volar -- pertaining to the palm or sole; indicating the flexor surface of the hand and wrist.

## *Abbreviations*

CC -- Contractile Component  
CM -- Carpal Metacarpals  
DIP -- Distal Interphalangeal  
EDC -- Extensor Digitorum Communis  
EMG -- Electromyography  
FDP -- Flexor Digitorum Profundus  
FDS -- Flexor Digitorum Superficialis  
Int. -- Interosseous or Interossei  
IP -- Interphalangeal  
Lumb. -- Lumbricalis or Lumbricals  
MCP -- Metacarpo-phalangeal  
MUAPT -- Motor Unit Action Potential Train  
MVC -- Maximal Voluntary Contraction  
PIP -- Proximal Interphalangeal  
PEC -- Parallel Elastic Component  
RMS -- Root Mean Square  
SEC -- Series Elastic Component



## **Appendix B. Muscles of the Hand**

## *Muscles of the Hand*

Muscles that move the fingers are divided into two groups based upon their location: the extrinsic muscles in the forearm, and the intrinsic muscles in the hand. Some muscles in the forearm are in charge of wrist movement while others relate to the movements of the thumb and fingers.

### *B.1. Muscles of the Forearm (Extrinsic Muscles)*

Muscles of the forearm are grouped into flexors and extensors.

#### **B.1.1 Flexor Compartment**

The flexor muscles of the forearm are located in three layers of the flexor compartment: (1) the superficial layer, (2) the second layer, and (3) the deep layer.

##### *B.1.1.1 The Superficial Layer*

The superficial layer consists of the pronator teres and the three carpal flexors: flexor carpi radialis, palmaris longus, and flexor carpi ulnaris (Figure B.1). These muscles all originate from the medial epicondyle of the humerus by a common tendon.

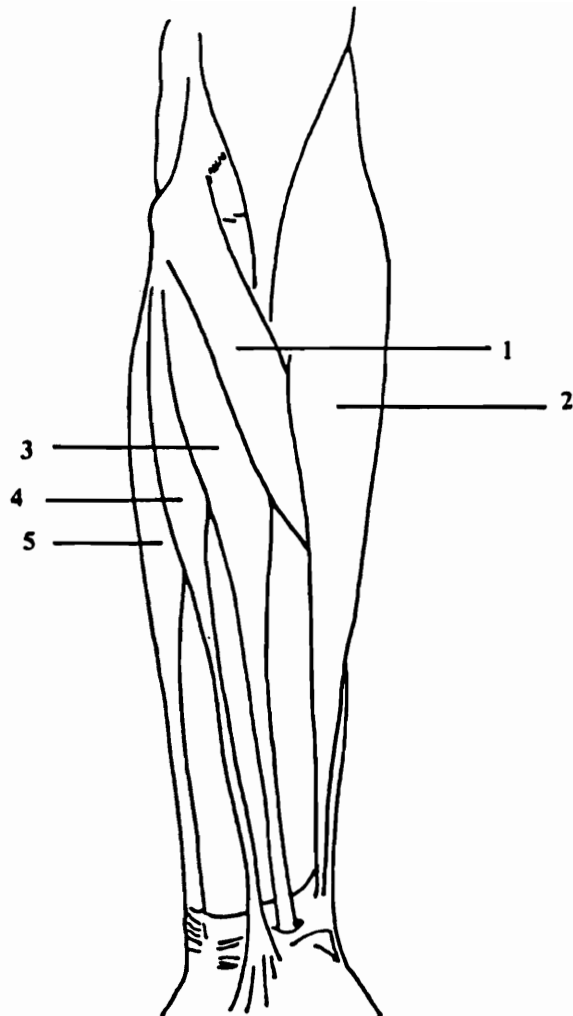


Figure B.1 Muscles of superficial layer in the flexor compartment (left arm).

1. Pronator teres; 2. Brachioradialis; 3. Flexor carpi radialis; 4. Palmaris longus; 5. Flexor carpi ulnaris.

(modified from Clemente, 1985)

<The Pronator Teres> . The pronator teres passes obliquely across the forearm and ends as a broad, flat tendon on the lateral aspect of the radius. It is supplied by the median nerve and rotates the forearm and the hand.

<The Flexor Carpi Radialis> . The flexor carpi radialis is supplied by the median nerve and flexes the wrist. The tendon of this muscle runs anterior and lateral to the median nerve, crosses the wrist within its own osteofibrous tunnel lateral to the flexor tunnel, and becomes inserted on the proximal end of the second metacarpal.

<The Palmaris Longus> . The palmaris longus is supplied by the median nerve and flexes the wrist. The tendon of this muscle fans out opposite the anterior carpal ligament and becomes continuous with the palmar aponeurosis. This muscle acts as a synergist of the extensor digitorum communis in active extension of the fingers and also an anteductor of the thumb.

<The Flexor Carpi Ulnaris> . The flexor carpi ulnaris is supplied by the ulnar nerve and acts as a carpal flexor. It ends in a thick tendon which inserts on the anterior aspect of the pisiform and gives off tendinous bands to the anterior carpal ligament and to the abductor digiti quinti. The flexor carpi ulnaris, in conjunction with extensor communis, has an important role in operating the wrist. It is also a synergist of the abductor digiti minimi.

#### ***B.1.1.2. The Second Layer***

The second layer consists of the flexor digitorum superficialis alone (Figure B.2).

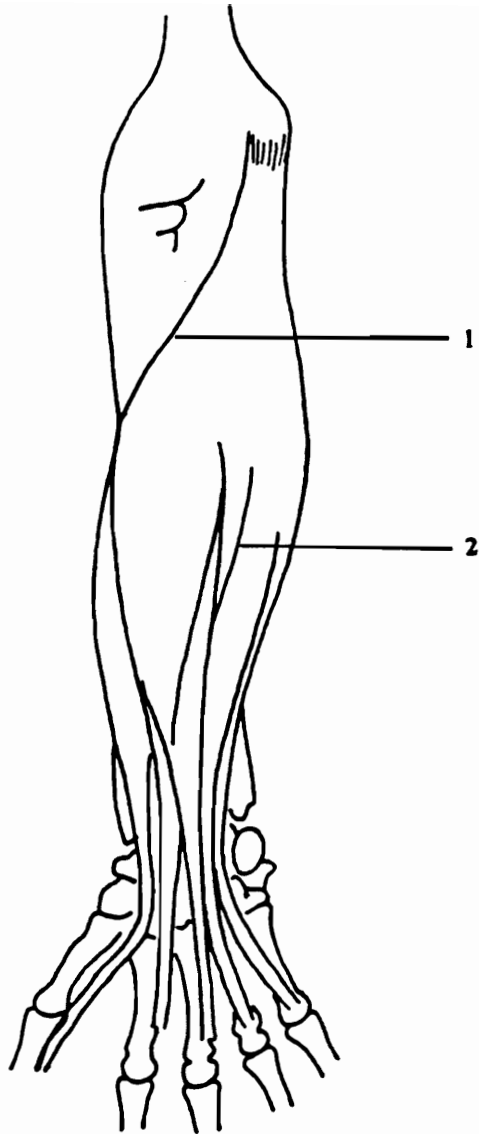


Figure B.2 Muscle of the second layer in the flexor compartment (right arm).

1. The fibrous arch of the flexor digitorum superficialis; 2. The deep digastic fascia from which the tendons of the index and ring finger arise.

(modified from Tubiana, 1981)

It also arises from the common flexor origin, the medial collateral ligament of the elbow joint, and the medial border of the coronoid process of the ulna. From the origin a fibrous arch continues to the anterior oblique line of the radius. From the belly of the muscle it splits into four parts. The two more superficial bundles give off the tendons of the middle and ring fingers, while the digastric deeper bundles develop into the tendons of the index and little fingers.

The flexor tendons cross the carpus in a common plane before diverging to reach their respective digits. At the level of the metacarpophalangeal (MCP) joints, the flexor tendons enter the digital fibrous tunnel and sink into a groove molded around the flexor profundus tendon. Half the tendon fibers then decussate (intersect in the form of the letter X) around the deep flexor tendon and become inserted behind it.

“Perforation” of the superficialis by the profundus tendon occupies the whole length of the proximal phalanx. Proximal to the profundus tendon, opposite the proximal interphalangeal (IP) joint, the decussating fibers form the chiasma tendinosum. Decussating and non-decussating fibers then reunite as they become inserted on the borders of the middle phalanx.

The flexor digitorum superficialis is supplied by the median nerve. It has an important role in the power grip and contributes to flexion of the fingers when the wrist is flexed. In other circumstances, however, this muscle is silent during digital flexion.

### ***B.1.1.3 The Plane of the Flexor Profundus***

The flexor profundus consists of the flexor digitorum profundus medially and the flexor pollicis longus laterally (Figure B.3).

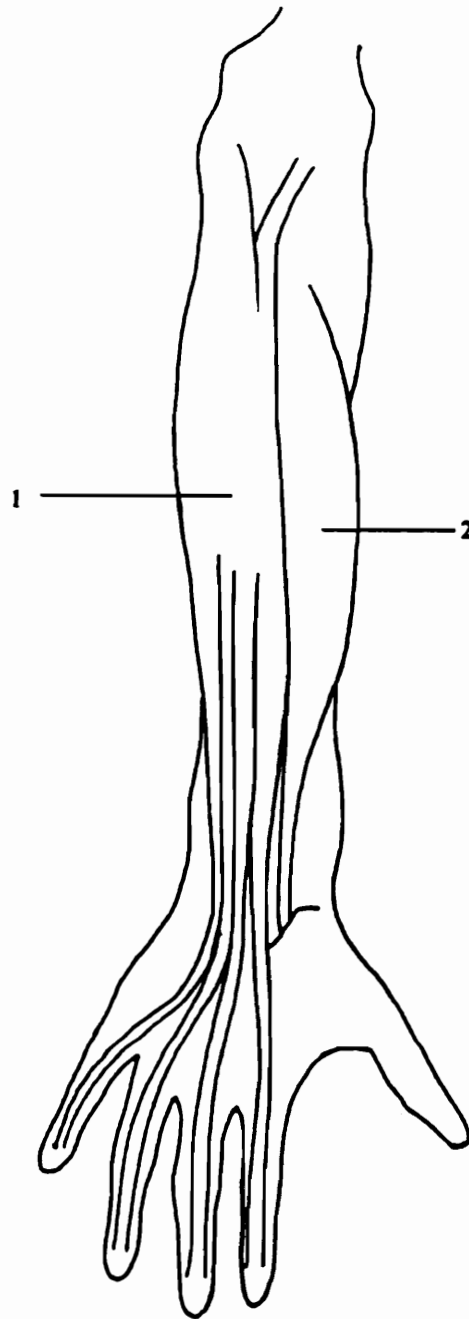


Figure B.3 Muscles of the profundus layer in the flexor compartment (left arm).

1. Flexor digitorum profundus; 2. Flexor pollicis longus.

(modified from Clemente, 1985)

<The Flexor Digitorum Profundus> . The flexor digitorum profundus (FDP) arises from the anterior surface of the ulna and from a narrow strip of interosseous membrane. It divides into four parts at the middle of the forearm, each part giving off one tendon. The four terminal tendons pass through the flexor tunnel in the same plane before diverging in the palm toward the corresponding digits. The radial component to the index finger is the most independent, so that the index finger has a special independence. Like the tendons of the flexor digitorum superficialis, the tendons of the flexor digitorum profundus travel over the wrist to the fingers within individual synovial sheaths.

The four lumbricalis take their origin from the flexor profundus tendons as it crosses the palm. These then enter the osteofibrous digital tunnel by perforating the flexor superficialis tendon, and insert on the base of the distal phalanx.

The flexor digitorum profundus is supplied by two nerves. The median nerve supplies the two lateral heads of the flexor profundus, running into the index and middle fingers. The ulnar nerve supplies the two medial heads for the ring and little fingers.

The flexor digitorum profundus exerts about 12% of the tension capability of all the muscles in the forearm and hand. It is 50% stronger than the flexor digitorum superficialis, although in the middle finger both muscles exert about equal tension. The flexor digitorum profundus to the little finger is three times as strong as the flexor digitorum superficialis (Brand et al., 1981; Brand, 1985).

The flexor digitorum profundus is the only flexor of the distal interphalangeal joints. It is also known from electromyographic (EMG) recordings (Long, Conrad, Hall, and Furler, 1970) that this muscle acts as a flexor of the proximal interphalangeal, metacarpophalangeal, and wrist joints. Long et al. (1970) have shown that the flexor digitorum profundus performs most of the unloaded flexion movement of the fingers while the flexor digitorum superficialis comes in when more strength is needed.



< The Flexor Pollicis Longus > . The flexor pollicis longus originates from the anterior surface of the radius. The tendon of the flexor pollicis longus runs immediately lateral to the tendons of the flexor digitorum profundus, crosses through the carpal canal, bends around the trapezium, runs along the medial border of the thenar in a groove formed by the two heads of the flexor pollicis brevis and then inserts into the distal phalanx of the thumb.

## **B.1.2 Extensor Compartment**

The extensor muscles of the forearm are located in the superficial and deep layers and lateral compartment of the forearm.

### ***B.1.2.1 The Superficial Layer***

The superficial layer consists of four muscles which arise from the common extensor origin on the lateral supracondylar ridge. They are the extensor digitorum communis, the extensor digitorum minimi, the extensor carpi ulnaris, and the anconeus (Figure B.4).

< The Extensor Digitorum Communis > . The extensor digitorum divides into four parts, from which four tendons emerge in the distal forearm. Then the tendons pass through an osteofibrous tunnel on the back of the wrist before diverging toward the fingers. On the dorsum of the hand, they are interconnected by transverse or oblique fibrous bands - the juncturae tendinum or conexi intertendinei.

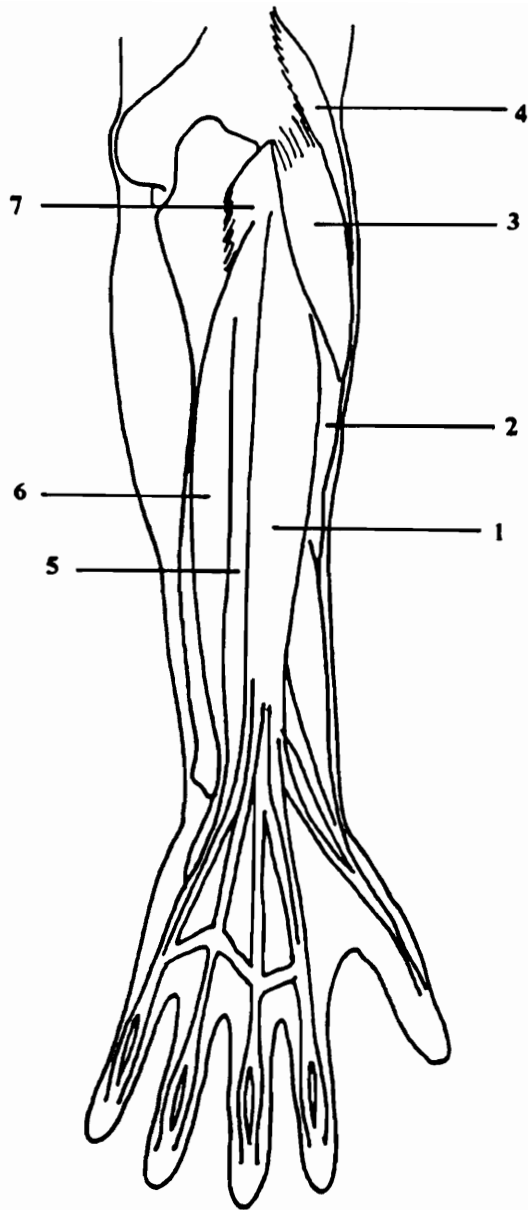


Figure B.4 Muscles of the superficial layer of the extensor compartment (right arm).

1. Extensor digitorum communis; 2. Extensor carpi radialis brevis; 3. Extensor carpi radialis longus; 4. Brachioradialis; 5. Extensor digiti minimi proprius; 6. Extensor carpi ulnaris; 7. Anconeus.

(modified from Tubiana, 1981)

At the base of each finger, the broad, flat tendon gives off from its deep surface, a tendinous strip of variable thickness which adheres to the distal part of the capsule of the MP joint, and inserts on the base of the proximal phalanx. Halfway down the phalanx, the tendon splits into three parts: an extensor medial band, which becomes anchored to the base of the middle phalanx, and two extensor lateral bands, which join a similar band from the interossei tendons to form the lateral extensor tendons. The two lateral extensor tendons unite on the back of the middle phalanx and find a common insertion on the base of the distal phalanx. In each finger, the extensor tendon forms the axis of the dorsal aponeurosis, which is completed by the sagittal bands, the interosseous and lumbrical expansions, and the retinacular ligament (Figure B.5). The extensor digitorum is supplied by the radial nerve. It extends the MP joint and also the IP joint in conjunction with the lumbricalis. During flexion of finger, it acts as a synergistic antagonist at all the digital joints.

< The Extensor Digiti Minimi > . The extensor digiti minimi is a small fusiform muscle which is rounded in the center and tapered at the ends. It runs from the lateral epicondyle of the humerus to the little finger. The tendon of the extensor digiti minimi passes behind the head of the ulna in a fibrous sheath of its own. It lies against the ulnar border of the communis tendon of the little finger, becoming united with it above the MP joint. The extensor digiti minimi complements the extensor digitorum communis and causes ulnar drifting of the little finger.

< The Extensor Carpi Ulnaris > . The extensor carpi ulnaris is a long fusiform muscle which arises from the common extensor origin and from the posterior aspect of the ulnar.

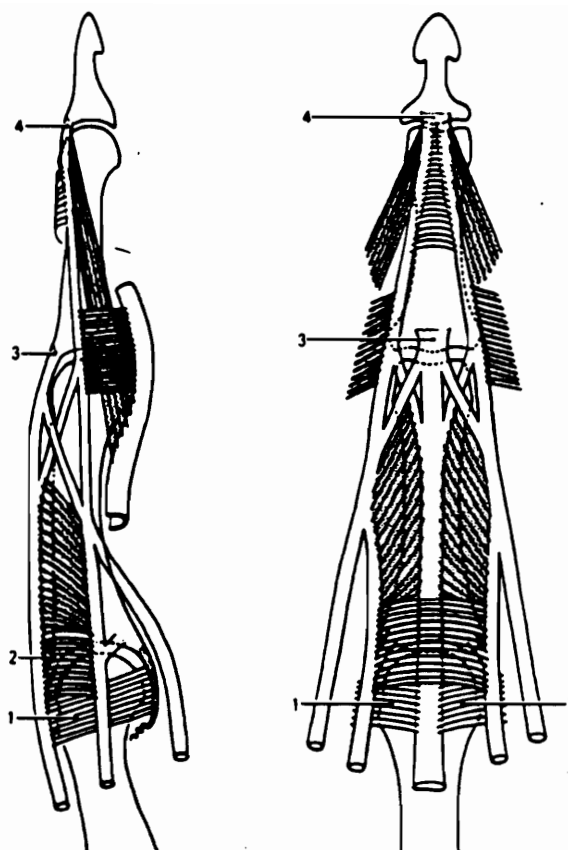


Figure B.5 Tendons of the extensor digitorum communis.

1. The sagittal bands; 2. Insertion of the extensor tendon into the base of the proximal phalanx; 3. Insertion of the middle extensor tendon into the base of the middle phalanx; 4. Insertion of the terminal extensor tendon into the distal phalanx.

(from Tubiana, 1981)

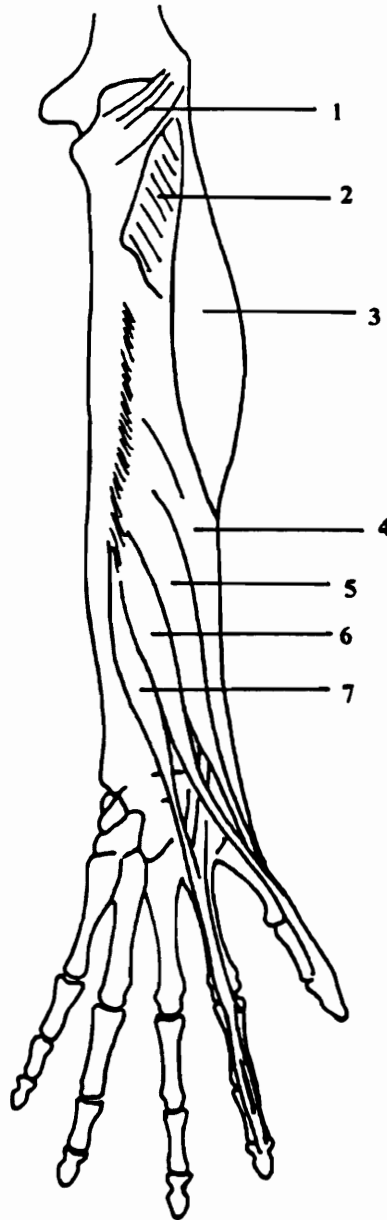
The tendon of the extensor carpi ulnaris arises superficially within the substance of the muscle and lies in the groove beside the ulnar styloid as it passes on to insert into the base of the fifth metacarpal. The extensor carpi ulnaris is supplied by the radial nerve, and extends the hand on the forearm and produces ulnar deviation. It is also a synergist of the abductor pollicis longus and the extensor pollicis brevis. It stabilizes the wrist during contraction of the thumb and finger flexors.

<The Anconeus>. The anconeus is a small triangular muscle which lies on the dorsum of the elbow joint. It arises by a separate tendon from the dorsal part of the lateral epicondyle of the humerus. It inserts into the lateral aspect of the olecranon and the dorsal surface of the ulna. The anconeus is supplied by a branch of the radial nerve, and assists the triceps brachii in extending the forearm. It has no action on the digits or the wrist.

#### ***B.1.2.2 The Deep Layer***

The deep layer consists of four muscles: the abductor pollicis longus, the extensor pollicis brevis, the extensor pollicis longus, and the extensor indicis (Figure B.6).

<The Abductor Pollicis Longus>. The abductor pollicis longus arises from the lateral part of the posterior surface of the ulna. It runs obliquely outward and gives off a tendon which spirals around the tendons of the radial extensors of the wrist just above a triangular interval, commonly referred to as the "anatomical snuff-box".



**Figure B.6 Muscles of the deep layer in the extensor compartment (right arm).**

1. Anconeus; 2. Supinator; 3. Brachioradialis; 4. Abductor pollicis longus; 5. Extensor pollicis brevis; 6. Extensor pollicis longus; 7. Extensor indicis.

(modified from Tubiana, 1981)

It passes through an osteofibrous tunnel lateral to the radial styloid and inserts at the base of the first metacarpal. The abductor pollicis longus is supplied by the radial nerve, and abducts the first metacarpal and pulls the wrist to the radial side.

< The Extensor Pollicis Brevis > . The tendon of the extensor pollicis arises from the posterior surface of the body of the radius below the abductor pollicis longus. It runs along the dorsal surface of the first metacarpal and inserts on the base of the proximal phalanx of the thumb. It shares a groove with the abductor longus, passing immediately posterior to it. The extensor pollicis brevis is supplied by the radial nerve, and extends the MP joint, abducts the first metacarpal, and produces radial deviation of the wrist.

< The Extensor Pollicis Longus > . The extensor pollicis longus arises from the middle third of the dorsolateral surface of the ulna distal to the origin of the abductor pollicis longus. The tendon of this muscle is long and runs obliquely in a groove on the dorsum of the radial styloid. It then takes a new direction and runs toward the dorsum of the thumb, where it inserts into the base of the distal phalanx of the thumb. The extensor pollicis longus is supplied by the radial nerve, and extends the interphalangeal joint, aids in the extension of the metacarpophalangeal and trapeziometacarpal joints. It is a strong adductor and supinator of the thumb.

< The Extensor Indicis > . The extensor indicis arises from the posterior surface of the body of the ulna below the origin of the extensor pollicis longus. The tendon of this muscle passes within the same synovial sheath as those of the extensor communis. It lies alongside the tendon of the extensor communis indicis with which it unites above the MP joint. The extensor indicis is supplied by the radial nerve, and reinforces the action of the extensor communis and also pulls the index finger to the ulnar side.

### ***B.1.2.3 The Lateral Compartment***

The lateral compartment consists of the brachioradials, the extensor carpi radialis longus, and the extensor carpi radialis brevis (Figure B.7).

< The Brachioradialis > . The brachioradialis arises from the upper two thirds of the lateral supracondylar ridge of the humerus. It passes along the preaxial border of the forearm, overlaying the extensor carpi radialis longus, the pronator teres, and the lateral border of the radius. It inserts at the base of the radial styloid.

The brachioradialis flexes the elbow joint and acts as a pronator or a supinator of the forearm. It has no action on the digits or the wrist.

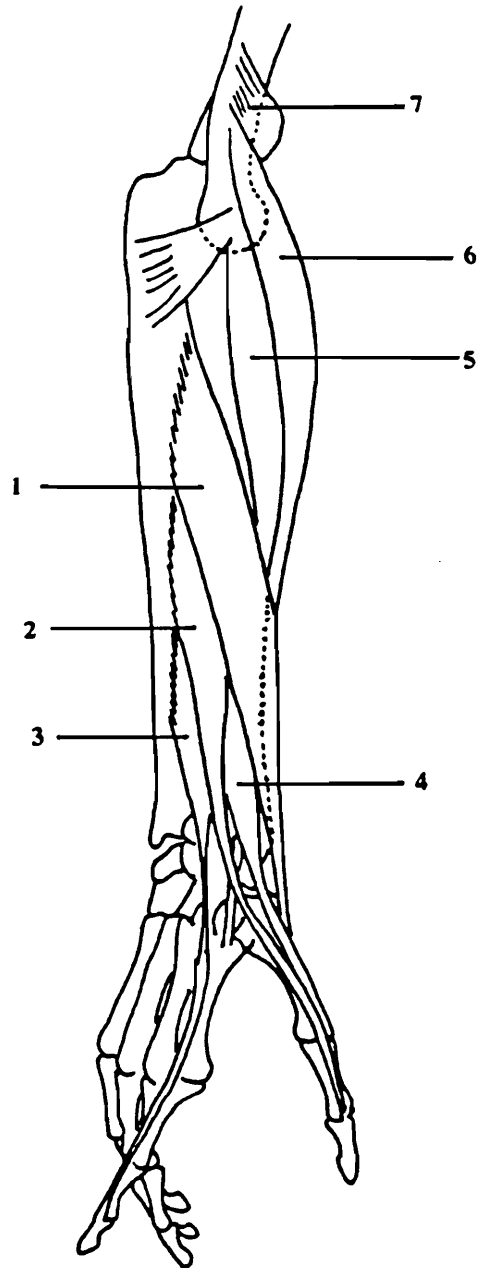
< The Extensor Carpi Radialis Longus > . The extensor carpi radialis longus arises from the upper two thirds of the lateral supracondylar ridge. The tendon of the extensor carpi radialis longus inserts into the base of the second metacarpal.

The extensor carpi radialis longus is supplied by the radial nerve, and extends the wrist and pulls the wrist radially.

< The Extensor Carpi Radialis Brevis > . The extensor carpi radialis brevis arises from the common extensor origin. Its tendon inserts on the base of the third metacarpal.

The extensor carpi radialis brevis is also supplied by the radial nerve, and it is the only extensor of the wrist which does not produce a radial or ulnar deviation. The actions of the extensor carpi radialis longus and brevis, which are synergistic with the flexor digitorum profundus, are reduced during contraction of the extensor digitorum communis.





**Figure B.7 Muscles of the lateral compartment (right arm).**

1. Abductor pollicis longus; 2. Extensor pollicis longus; 3. Extensor indicis proprius; 4. Extensor pollicis brevis; 5. Extensor carpi radialis brevis; 6. Extensor carpi radialis longus; 7. Brachioradialis.

(modified from Tubiana, 1981)

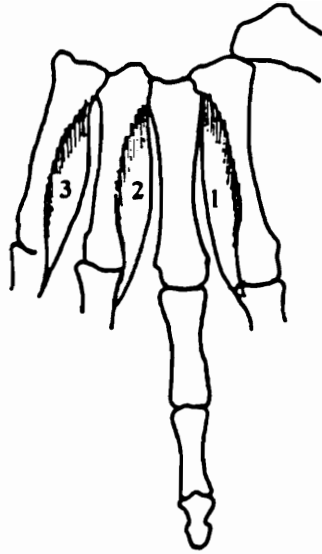
## ***B.2. Muscles in the Hand (Intrinsic Muscles)***

### **B.2.1 The Interossei**

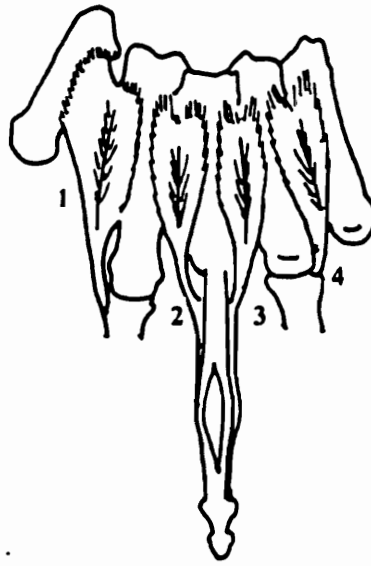
< The Palmar Interossei > . The palmar interossei originate from the entire length of the metacarpal bone of the finger. Only three palmar interossei are situated in the second, third, and fourth interosseous spaces, which insert on the ulnar border on the index and on the radial border of the ring and little fingers. There are, however, some muscle fibers that arise from the ulnar side of the first metacarpal and become inserted on the extensor aponeurosis of the thumb. Some anatomists therefore describe four palmar interossei, while others regard these fibers as part of the flexor pollicis brevis. The palmar interossei are supplied by the ulnar nerve.

< The Dorsal Interossei > . There are four dorsal interossei which occupy the four intermetacarpal spaces. Their main feature is their double origin from the two metacarpals that bound the space and their insertion on the finger corresponding to their broadest origin, which is nearer to the axis of the hand. The dorsal interossei of the first and second interspaces insert on the radial side of the index and middle finger, while those of the third and fourth interspaces insert on the ulnar sides of the middle and ring fingers, respectively. All the dorsal interossei are supplied by the ulnar nerve.

The palmar and dorsal interossei are shown in Figure B.8.



Palmar Interossei



Dorsal Interossei

Figure B.8 Interosseous muscles in the hand.  
(modified from Clemente, 1985)

The major functions of the interossei are to flex the proximal phalanx and to extend the middle and distal phalanges. In addition, the interossei generate some side-to-side movements of the finger: the dorsal interossei abduct, and the palmar interossei adduct. Finally, the interossei produce some rotation of the proximal phalanx, which, although limited, is important in prehension.

The interossei contract in extension of the digit, even if there is no resistance, if all the fingers are extended simultaneously or if the finger is extended while the wrist is flexed. Even a slight alteration in the equilibrium of the articulated digital chain can induce activation of the interossei. There is marked activity in the interossei both in the precision grip and in the power grip.

The long flexors act primarily on the middle and the distal phalanges; flexion of the proximal phalanx depends on the action of the interossei. Conversely, extension of the proximal phalanx is brought about by the extensor communis, while the middle and the distal phalanges are extended by the intrinsics.

### **B.2.2 The Lumbricals**

The lumbricals are small muscles which interconnect the deep flexors to the extensor apparatus of the fingers. They are the only skeletal muscles that have no direct bony attachments. There are four lumbricals in the hand. The first and second lumbricals are fusiform: they arise from the radial borders of the flexor profundus tendons of the index and middle fingers, overlapping their anterior aspects. The third and fourth lumbricals are penniform: they arise from the lateral borders and anterior aspects of the flexor profundus tendons between which they lie (Figure B.9).

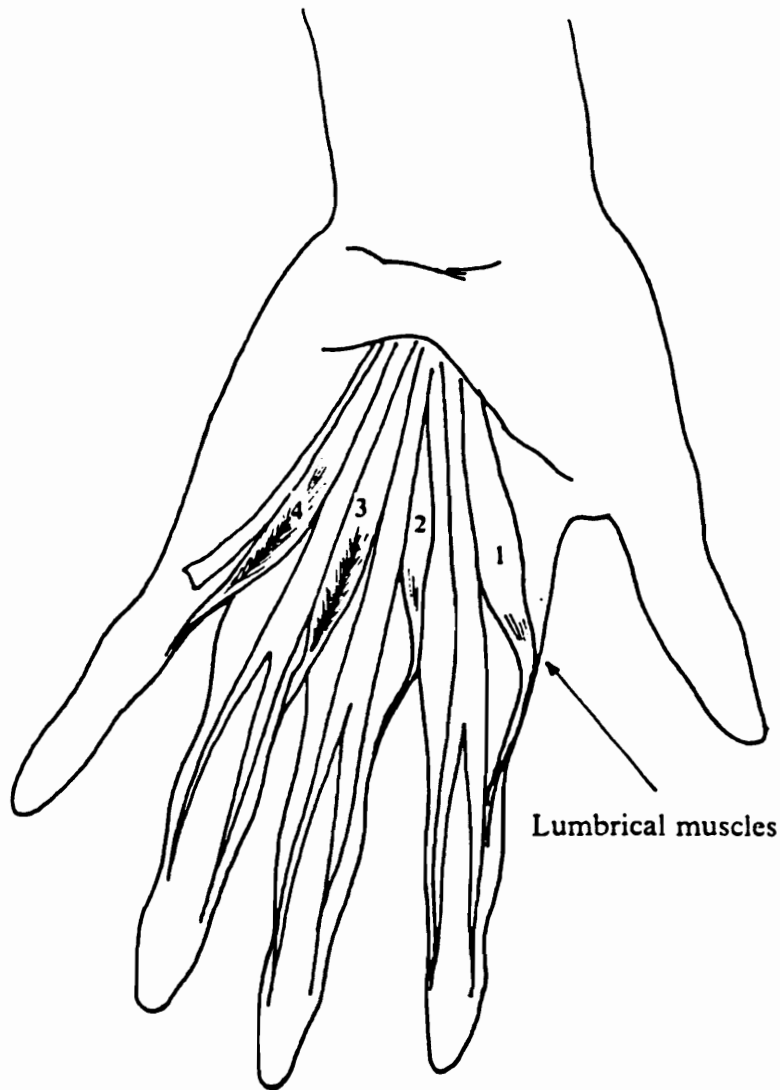


Figure B.9 Lumbrical muscles in the hand (palmar view).  
(modified from Clemente, 1985)

In the palm, the lumbrical muscles, which accompany the corresponding flexor profundus tendon on its radial side, often insinuate themselves between the superficial flexor tendons, around which they mold themselves with some overlap on the palmar aspect. Behind the deep flexors, the deep palmar fascia and the adductor pollicis muscle separate the lumbricals from the interossei. The two lateral lumbricals join the two dorsal interossei, while the two medial lumbricals join the tendons of the two palmar interossei (Figure B.8).

The two lateral lumbricals are supplied from their superficial aspect by fibers of the digital nerves of the first and second interspaces, coming from the median nerve. However, the two lateral lumbricals are supplied on their deep surface by fibers from the motor branch of the ulnar nerve. This double innervation corresponds to that of the flexor profundus communis.

The abundance of proprioceptors in the lumbricals is an indicator of their possible importance in the control of tension between the flexor and extensor systems and in the coordination of the finer and more elaborate movements of the hand. No systematic research, however, has been conducted to investigate these functions of lumbricals.

The course of the lumbricals is similar to that of the interossei. Yet, the two muscle groups differ in at least two anatomical features of functional significance: the proximal insertion of the lumbricals on the flexor profundus tendon and the fact that the lumbricals make no contribution to the formation of the interosseous hood. The lumbricals extend the IP joints whatever the position of the MP joint, but they have no part in flexion of the MP joint. The lumbricals probably play a part in side-to-side and rotation movements of the fingers.

## **Appendix C. Experimental Data**

Table C.1(a) Predicted finger strengths and muscular forces of Subject A.

Position Direction		1	2	3	4
		Downward	MVC	23.35	28.75
FDS	15.90		13.10	13.20	9.15
FDP	19.22		16.26	15.65	11.44
Int.	21.97		19.15	18.04	16.47
Upward	MVC	11.44	14.61	15.06	22.62
	EDC	26.40	21.88	21.23	15.33
	Int.	79.87	57.96	60.07	38.36
	Lumb.	80.06	58.16	71.09	47.40
Backward	MVC	39.12	30.76	28.37	25.37
	FDS	10.71	14.78	15.16	18.30
	FDP	14.25	18.15	19.71	22.58
	Int.	9.93	11.16	14.78	16.60
Forward	MVC	15.18	12.57	11.75	10.87
	EDC	19.86	24.38	27.12	30.20
	Int.	58.16	75.85	74.35	93.13
	Lumb.	53.01	65.69	80.39	94.99

Unit: N



Table C.1(b) Predicted finger strengths and muscular forces of Subject B.

Position Direction		1	2	3	4
		Downward	MVC	23.24	28.61
FDS	15.92		13.12	13.21	9.17
FDP	19.36		16.41	15.78	11.58
Int.	22.31		19.48	18.34	16.78
Upward	MVC	11.38	14.50	14.96	22.42
	EDC	26.62	22.11	21.44	15.54
	Int.	79.59	57.70	59.83	38.11
	Lumb.	80.06	58.16	71.10	47.41
Backward	MVC	38.98	30.67	28.26	25.28
	FDS	10.72	14.78	15.17	18.31
	FDP	14.29	18.19	19.79	22.66
	Int.	10.02	11.25	14.95	16.78
Forward	MVC	15.15	12.55	11.71	10.80
	EDC	19.92	24.44	27.24	30.32
	Int.	58.09	75.78	74.21	92.99
	Lumb.	53.01	65.69	80.39	94.99

Unit: N

Table C.1(c) Predicted finger strengths and muscular forces of Subject C.

Position Direction		1	2	3	4
		Downward	MVC	24.39	29.99
FDS	15.05		12.43	12.51	8.72
FDP	18.17		15.52	14.89	11.09
Int.	21.78		19.10	17.96	16.54
Upward	MVC	12.15	15.39	15.90	23.56
	EDC	24.96	20.90	20.21	14.90
	Int.	74.58	54.00	56.07	35.61
	Lumb.	75.75	55.10	67.35	45.01
Backward	MVC	41.35	32.54	29.88	26.71
	FDS	10.05	13.87	14.25	17.22
	FDP	13.13	16.69	18.29	20.91
	Int.	9.55	10.69	14.38	16.10
Forward	MVC	16.47	13.67	12.68	11.71
	EDC	18.25	22.34	25.11	27.90
	Int.	54.38	71.14	69.49	87.25
	Lumb.	49.87	61.90	75.75	89.60

Unit: N

Table C.1(d) Predicted finger strengths and muscular forces of Subject D.

Position Direction		1	2	3	4
		Downward	MVC	25.74	31.64
FDS	14.32		11.82	11.90	8.29
FDP	17.12		14.60	14.01	10.40
Int.	20.38		17.85	16.79	15.44
Upward	MVC	12.87	16.32	16.86	25.00
	EDC	23.47	19.62	18.98	13.94
	Int.	71.36	51.75	53.70	34.22
	Lumb.	72.20	52.52	64.20	42.92
Backward	MVC	43.62	34.30	31.52	28.17
	FDS	9.56	13.20	13.56	16.39
	FDP	12.42	15.79	17.27	19.76
	Int.	8.99	10.07	13.51	15.14
Forward	MVC	17.40	14.44	13.41	12.38
	EDC	17.24	21.11	23.69	26.33
	Int.	51.86	67.83	66.33	83.26
	Lumb.	47.50	58.97	72.16	85.36

Unit: N

Table C.1(e) Predicted finger strengths and muscular forces of Subject E.

Position Direction		1	2	3	4
		Downward	MVC	24.31	29.80
FDS	15.29		12.65	12.74	8.90
FDP	17.40		14.87	14.26	10.63
Int.	21.07		18.44	17.36	15.95
Upward	MVC	12.58	15.90	16.48	24.22
	EDC	23.66	19.83	19.17	14.14
	Int.	77.27	56.29	58.34	37.55
	Lumb.	77.74	56.66	69.25	46.46
Backward	MVC	41.58	32.61	29.95	26.74
	FDS	10.11	14.02	14.39	17.42
	FDP	12.53	15.95	17.47	19.99
	Int.	9.28	10.42	13.95	15.66
Forward	MVC	17.15	14.27	13.21	12.20
	EDC	17.28	21.15	23.79	26.43
	Int.	55.36	72.57	71.08	89.33
	Lumb.	50.69	63.10	77.21	91.49

Unit: N

Table C.1(f) Predicted finger strengths and muscular forces of Subject F.

Position Direction		1	2	3	4
		Downward	MVC	24.47	29.96
FDS	15.11		12.52	12.61	8.84
FDP	16.98		14.60	13.98	10.54
Int.	21.23		18.65	17.54	16.19
Upward	MVC	12.90	16.21	16.83	24.48
	EDC	23.05	19.45	18.76	14.02
	Int.	76.03	55.38	57.44	36.95
	Lumb.	76.97	56.16	68.65	46.15
Backward	MVC	42.25	33.13	30.34	27.07
	FDS	9.92	13.77	14.14	17.14
	FDP	12.01	15.27	16.83	19.24
	Int.	9.19	10.30	13.90	15.59
Forward	MVC	17.88	14.90	13.71	12.68
	EDC	16.50	20.16	22.84	25.33
	Int.	54.33	71.38	69.80	87.87
	Lumb.	49.92	62.23	76.16	90.32

Unit: N

Table C.2(a) Measured finger strengths and RMS EMG amplitudes of Subject A.

Finger Position	Direction Force Level	Downward		Upward		Backward		Forward	
		Force	EMG	Force	EMG	Force	EMG	Force	EMG
1	25%	10.81	0.06	2.07	0.02	10.01	0.05	2.23	0.04
	50%	21.62	0.08	4.13	0.03	20.03	0.06	4.45	0.06
	75%	32.43	0.12	6.21	0.07	30.04	0.08	6.68	0.08
	100%	43.23	0.15	8.26	0.14	40.05	0.11	8.90	0.12
2	25%	11.76	0.06	2.23	0.03	10.49	0.05	2.07	0.05
	50%	23.52	0.08	4.45	0.04	20.98	0.07	4.13	0.06
	75%	35.28	0.11	6.68	0.08	31.47	0.08	6.36	0.10
	100%	47.04	0.15	8.90	0.15	41.96	0.10	8.26	0.12
3	25%	12.08	0.08	2.23	0.02	10.17	0.03	1.91	0.04
	50%	24.16	0.11	4.45	0.04	20.35	0.04	3.82	0.05
	75%	36.24	0.13	6.68	0.08	30.52	0.06	5.73	0.07
	100%	48.31	0.15	8.90	0.14	40.69	0.09	7.63	0.14
4	25%	13.35	0.05	2.86	0.03	7.47	0.04	1.91	0.03
	50%	26.70	0.08	5.72	0.05	14.94	0.06	3.82	0.05
	75%	40.05	0.10	8.58	0.08	22.41	0.07	5.73	0.08
	100%	53.40	0.14	11.44	0.14	29.88	0.10	7.63	0.13

note : Unit of force is Newton, and unit of EMG is mV.

Table C.2(b) Measured finger strengths and RMS EMG amplitudes of Subject B.

Finger Position	Direction Force Level	Downward		Upward		Backward		Forward	
		Force	EMG	Force	EMG	Force	EMG	Force	EMG
1	25%	12.40	0.09	2.86	0.04	8.90	0.03	2.86	0.05
	50%	24.80	0.14	5.72	0.06	17.80	0.04	5.72	0.06
	75%	37.20	0.16	8.58	0.09	26.70	0.10	8.58	0.09
	100%	49.59	0.26	11.44	0.15	35.60	0.18	11.44	0.18
2	25%	15.35	0.10	3.02	0.04	9.85	0.04	2.86	0.05
	50%	26.70	0.14	6.04	0.06	19.71	0.07	5.72	0.07
	75%	40.05	0.19	9.06	0.09	29.56	0.14	8.58	0.10
	100%	53.40	0.27	12.08	0.15	39.41	0.18	11.44	0.17
3	25%	13.67	0.08	3.18	0.05	9.22	0.05	2.54	0.05
	50%	27.34	0.12	6.36	0.07	18.44	0.06	5.09	0.07
	75%	41.01	0.17	9.54	0.09	27.66	0.10	7.63	0.09
	100%	54.67	0.26	12.71	0.13	36.87	0.17	10.17	0.16
4	25%	14.30	0.08	3.97	0.05	7.95	0.05	2.23	0.05
	50%	28.61	0.12	7.95	0.07	15.90	0.07	4.45	0.06
	75%	42.91	0.17	11.92	0.11	23.85	0.10	6.68	0.09
	100%	57.21	0.25	15.89	0.16	31.79	0.18	8.90	0.16

note : Unit of force is Newton, and unit of EMG is mV.

Table C.2(c) Measured finger strengths and RMS EMG amplitudes of Subject C.

Finger Position	Direction Force Level	Downward		Upward		Backward		Forward	
		Force	EMG	Force	EMG	Force	EMG	Force	EMG
1	25%	10.49	0.08	2.23	0.04	9.54	0.03	1.59	0.04
	50%	20.98	0.10	4.45	0.07	19.07	0.05	3.18	0.05
	75%	31.47	0.13	6.68	0.11	28.61	0.09	4.77	0.09
	100%	41.96	0.16	8.90	0.13	38.14	0.16	6.36	0.14
2	25%	13.67	0.06	2.23	0.04	9.85	0.03	1.59	0.04
	50%	27.34	0.10	4.45	0.06	19.71	0.06	3.18	0.06
	75%	41.01	0.15	6.68	0.10	29.56	0.08	4.77	0.08
	100%	54.67	0.20	8.90	0.15	39.41	0.16	6.36	0.14
3	25%	13.99	0.06	2.54	0.05	8.27	0.05	1.43	0.03
	50%	27.97	0.10	5.09	0.08	16.53	0.08	2.86	0.05
	75%	41.96	0.13	7.63	0.10	24.80	0.11	4.29	0.08
	100%	55.94	0.20	10.17	0.14	33.06	0.17	5.72	0.16
4	25%	14.30	0.07	2.86	0.04	6.36	0.03	1.27	0.03
	50%	28.61	0.11	5.72	0.06	12.72	0.07	2.55	0.05
	75%	42.91	0.16	8.58	0.08	19.08	0.10	3.82	0.08
	100%	57.21	0.21	11.44	0.14	25.43	0.17	5.09	0.16

note : Unit of force is Newton, and unit of EMG is mV.



Table C.2(d) Measured finger strengths and RMS EMG amplitudes of Subject D.

Finger Position	Direction Force Level	Downward		Upward		Backward		Forward	
		Force	EMG	Force	EMG	Force	EMG	Force	EMG
1	25%	6.36	0.04	1.27	0.02	9.54	0.03	1.91	0.02
	50%	12.72	0.07	2.55	0.03	19.07	0.04	3.82	0.03
	75%	19.08	0.09	3.82	0.04	28.61	0.05	5.73	0.04
	100%	25.43	0.14	5.09	0.08	38.14	0.08	7.63	0.09
2	25%	11.13	0.04	1.27	0.02	12.08	0.03	1.59	0.02
	50%	22.25	0.07	2.55	0.03	24.16	0.04	3.18	0.03
	75%	33.38	0.09	3.82	0.04	36.24	0.05	4.77	0.05
	100%	44.50	0.13	5.09	0.08	48.31	0.09	6.36	0.09
3	25%	11.13	0.05	1.91	0.02	11.13	0.03	1.27	0.02
	50%	22.25	0.07	3.82	0.03	22.25	0.04	2.55	0.04
	75%	33.38	0.12	5.73	0.06	33.38	0.05	3.82	0.05
	100%	44.50	0.16	7.63	0.08	44.50	0.09	5.09	0.08
4	25%	13.35	0.04	1.91	0.02	9.85	0.03	1.11	0.02
	50%	26.70	0.08	3.82	0.03	19.71	0.04	2.23	0.03
	75%	40.05	0.11	5.73	0.06	29.56	0.05	3.34	0.05
	100%	53.40	0.15	7.63	0.08	39.41	0.08	4.45	0.08

note : Unit of force is Newton, and unit of EMG is mV.

Table C.2(e) Measured finger strengths and RMS EMG amplitudes of Subject E.

Finger Position	Direction Force Level	Downward		Upward		Backward		Forward	
		Force	EMG	Force	EMG	Force	EMG	Force	EMG
1	25%	10.17	0.05	1.11	0.02	7.63	0.02	1.27	0.02
	50%	20.35	0.07	2.23	0.03	15.26	0.03	2.55	0.03
	75%	30.52	0.10	3.34	0.06	22.89	0.05	3.82	0.07
	100%	40.69	0.13	4.45	0.09	30.51	0.08	5.09	0.11
2	25%	10.65	0.05	1.11	0.02	7.95	0.02	1.27	0.03
	50%	21.30	0.06	2.23	0.03	15.90	0.03	2.55	0.04
	75%	31.95	0.08	3.34	0.06	23.85	0.06	3.82	0.06
	100%	42.59	0.12	4.45	0.11	31.79	0.10	5.09	0.11
3	25%	11.29	0.05	1.27	0.02	6.68	0.02	1.11	0.02
	50%	22.57	0.08	2.55	0.03	13.35	0.03	2.23	0.03
	75%	33.86	0.11	3.82	0.05	20.03	0.05	3.34	0.08
	100%	45.14	0.15	5.09	0.10	26.70	0.08	4.45	0.13
4	25%	11.76	0.05	1.91	0.02	5.88	0.03	0.95	0.02
	50%	23.52	0.07	3.82	0.03	11.76	0.04	1.91	0.03
	75%	35.28	0.10	5.73	0.06	17.64	0.06	2.86	0.05
	100%	47.04	0.14	7.63	0.12	23.52	0.08	3.81	0.11

note : Unit of force is Newton, and unit of EMG is mV.

Table C.2(f) Measured finger strengths and RMS EMG amplitudes of Subject F.

Finger Position	Direction Force Level	Downward		Upward		Backward		Forward	
		Force	EMG	Force	EMG	Force	EMG	Force	EMG
		1	25%	7.63	0.03	1.43	0.03	8.56	0.05
1	50%	15.26	0.06	2.86	0.04	17.17	0.06	3.18	0.05
	75%	22.89	0.07	4.29	0.05	25.75	0.07	4.77	0.06
	100%	30.51	0.10	5.72	0.11	34.33	0.09	6.36	0.11
	2	25%	7.95	0.05	1.43	0.03	10.49	0.04	1.59
2	50%	15.90	0.08	2.86	0.04	20.98	0.05	3.18	0.04
	75%	23.85	0.10	4.29	0.05	31.47	0.06	4.77	0.05
	100%	31.79	0.12	5.72	0.11	41.96	0.08	6.36	0.09
	3	25%	7.63	0.05	1.59	0.04	8.27	0.04	1.43
3	50%	15.26	0.07	3.18	0.06	16.53	0.06	2.86	0.05
	75%	22.89	0.09	4.77	0.07	24.80	0.07	4.29	0.06
	100%	30.51	0.11	6.36	0.11	33.06	0.08	5.72	0.09
	4	25%	8.58	0.05	1.75	0.04	7.15	0.03	1.27
4	50%	17.17	0.07	3.50	0.05	14.31	0.04	2.55	0.06
	75%	25.75	0.08	5.25	0.06	21.46	0.05	3.82	0.07
	100%	34.33	0.11	6.99	0.11	28.61	0.08	5.09	0.09

note : Unit of force is Newton, and unit of EMG is mV.

Table C.3(a) Daily recorded MVCs and EMG amplitudes of Subject A.

Direction \ Day		1	2	3	4
		Downward	Before	55.94 0.15	48.30 0.16
After	55.94 0.15		47.04 0.15	50.86 0.14	54.67 0.15
Upward	Before	9.54 0.15	10.17 0.14	8.90 0.13	8.90 0.14
	After	8.90 0.13	9.54 0.13	8.90 0.14	9.54 0.15
Backward	Before	45.77 0.11	41.96 0.11	41.96 0.11	40.69 0.09
	After	41.96 0.09	39.41 0.10	36.87 0.09	41.96 0.09
Forward	Before	7.63 0.13	8.90 0.12	7.63 0.13	8.26 0.13
	After	8.26 0.13	8.90 0.13	7.63 0.11	7.63 0.12

note: Unit of MVC is Newton, and unit of EMG amplitude is mV.

Table C.3(b) Daily recorded MVCs and EMG amplitudes of Subject B.

Direction \ Day		1	2	3	4
Downward	Before	54.67 0.26	54.67 0.26	57.21 0.26	54.67 0.26
	After	47.04 0.26	57.21 0.29	58.49 0.26	57.21 0.26
Upward	Before	13.99 0.14	12.71 0.14	13.99 0.15	15.26 0.16
	After	13.35 0.13	13.35 0.12	13.35 0.15	15.26 0.15
Backward	Before	38.14 0.17	36.86 0.17	34.33 0.18	35.60 0.18
	After	36.87 0.16	33.51 0.15	33.06 0.18	35.60 0.19
Forward	Before	10.17 0.16	10.81 0.16	11.44 0.17	10.17 0.17
	After	10.17 0.16	10.17 0.16	9.64 0.19	11.44 0.18

note: Unit of MVC is Newton, and unit of EMG amplitude is mV.

Table C.3(c) Daily recorded MVCs and EMG amplitudes of Subject C.

Direction \ Day		1	2	3	4
Downward	Before	52.13 0.19	55.94 0.20	54.67 0.21	53.40 0.20
	After	53.40 0.20	53.40 0.20	53.40 0.22	53.40 0.22
Upward	Before	10.17 0.14	10.17 0.15	10.17 0.14	12.08 0.14
	After	10.17 0.15	12.08 0.17	8.90 0.14	12.08 0.14
Backward	Before	38.14 0.16	33.06 0.17	34.33 0.16	33.06 0.16
	After	36.87 0.17	34.33 0.18	34.33 0.18	34.33 0.17
Forward	Before	6.99 0.15	6.36 0.15	5.72 0.16	5.72 0.16
	After	6.36 0.15	5.72 0.15	6.36 0.16	5.72 0.16

note: Unit of MVC is Newton, and unit of EMG amplitude is mV.

Table C.3(d) Daily recorded MVCs and EMG amplitudes of Subject D.

		Day			
		1	2	3	4
Downward	Before	48.31 0.15	47.04 0.14	45.77 0.15	44.50 0.16
	After	41.96 0.13	48.31 0.15	44.50 0.15	44.50 0.17
Upward	Before	7.63 0.08	7.63 0.08	8.90 0.08	7.63 0.08
	After	6.36 0.08	6.36 0.07	7.63 0.08	6.99 0.08
Backward	Before	48.30 0.09	44.50 0.09	43.23 0.08	40.69 0.08
	After	45.80 0.09	43.23 0.08	45.80 0.10	40.69 0.08
Forward	Before	5.09 0.08	5.72 0.08	6.36 0.09	5.72 0.09
	After	5.09 0.08	5.72 0.09	6.36 0.09	5.09 0.08

note: Unit of MVC is Newton, and unit of EMG amplitude is mV.

Table C.3(e) Daily recorded MVCs and EMG amplitudes of Subject E.

Direction \ Day		1	2	3	4
Downward	Before	44.50 0.14	47.04 0.14	45.14 0.15	45.77 0.14
	After	43.23 0.15	43.23 0.14	41.96 0.13	43.23 0.13
Upward	Before	6.36 0.10	5.09 0.11	5.09 0.10	6.99 0.10
	After	5.72 0.09	6.36 0.11	5.09 0.11	6.99 0.10
Backward	Before	30.51 0.08	30.61 0.09	25.43 0.09	26.70 0.08
	After	26.70 0.08	26.70 0.08	24.16 0.09	24.16 0.08
Forward	Before	4.45 0.13	3.81 0.11	3.81 0.11	3.81 0.11
	After	4.06 0.12	3.81 0.12	3.81 0.10	3.81 0.11

note: Unit of MVC is Newton, and unit of EMG amplitude is mV.



Table C.3(f) Daily recorded MVCs and EMG amplitudes of Subject F.

Direction \ Day		1	2	3	4
Downward	Before	35.60 0.10	30.51 0.11	30.51 0.12	30.51 0.11
	After	30.51 0.11	29.24 0.09	30.51 0.12	30.51 0.11
Upward	Before	6.36 0.11	5.09 0.10	6.36 0.11	6.36 0.11
	After	6.36 0.11	5.72 0.11	6.36 0.11	5.72 0.11
Backward	Before	29.24 0.08	29.24 0.08	33.06 0.08	30.51 0.09
	After	29.24 0.08	33.06 0.09	29.24 0.08	29.24 0.10
Forward	Before	5.72 0.09	6.36 0.10	5.72 0.09	5.72 0.10
	After	5.72 0.09	5.72 0.10	5.72 0.10	6.36 0.11

note: Unit of MVC is Newton, and unit of EMG amplitude is mV.

Table C.4(a) Standardized EMG amplitude/force of Subject A.

Finger Position	Direction Force Level	Downward	Upward	Backward	Forward
	1	25%	0.37	0.72	0.46
50%		0.25	0.56	0.27	1.03
75%		0.25	0.87	0.24	0.93
100%		0.23	1.31	0.25	1.03
2	25%	0.34	0.90	0.44	1.84
	50%	0.23	0.61	0.31	1.11
	75%	0.21	0.79	0.23	0.24
	100%	0.21	1.12	0.24	1.11
3	25%	0.41	0.63	0.32	1.62
	50%	0.29	0.65	0.22	0.99
	75%	0.22	0.85	0.22	1.20
	100%	0.21	1.12	0.25	1.42
4	25%	0.27	0.73	0.48	1.31
	50%	0.21	0.63	0.37	1.10
	75%	0.18	0.66	0.29	1.27
	100%	0.19	0.87	0.30	1.42

Unit: mV/N

Table C.4(b) Standardized EMG amplitude/force of Subject B.

Finger Position	Direction	Downward	Upward	Backward	Forward
	Force Level				
1	25%	0.31	0.94	0.20	1.01
	50%	0.22	0.70	0.13	0.61
	75%	0.20	0.70	0.22	0.62
	100%	0.21	0.87	0.30	0.93
2	25%	0.23	0.96	0.22	1.01
	50%	0.17	0.71	0.20	0.72
	75%	0.16	1.06	0.19	0.69
	100%	0.19	0.89	0.25	0.87
3	25%	0.23	0.94	0.31	1.22
	50%	0.17	0.79	0.19	0.86
	75%	0.16	1.01	0.21	1.10
	100%	0.18	0.79	0.27	0.98
4	25%	0.24	0.78	0.35	1.39
	50%	0.19	0.55	0.25	0.85
	75%	0.14	0.58	0.23	0.84
	100%	0.17	0.63	0.31	1.12

Unit: mV/N

Table C.4(c) Standardized EMG amplitude/force of Subject C.

Finger Position	Direction	Downward	Upward	Backward	Forward
	Force Level				
1	25%	0.31	1.30	0.20	1.70
	50%	0.25	1.12	0.16	1.04
	75%	0.22	0.97	0.20	1.26
	100%	0.20	1.12	0.26	1.46
2	25%	0.22	1.21	0.19	1.57
	50%	0.18	0.90	0.19	1.19
	75%	0.16	1.00	0.17	1.05
	100%	0.18	1.12	0.25	1.38
3	25%	0.21	1.42	0.35	1.33
	50%	0.18	1.12	0.28	1.08
	75%	0.18	0.93	0.26	1.31
	100%	0.18	0.98	0.30	1.75
4	25%	0.23	1.01	0.30	1.57
	50%	0.18	0.75	0.35	1.29
	75%	0.18	0.66	0.33	1.39
	100%	0.17	0.81	0.42	2.10

Unit: mV/N

Table C.4(d) Standardized EMG amplitude/force of Subject D.

Finger Position	Direction	Downward	Upward	Backward	Forward
	Force Level				
1	25%	0.42	1.97	0.40	1.15
	50%	0.37	1.49	0.26	0.86
	75%	0.31	1.31	0.22	0.77
	100%	0.37	1.96	0.26	1.31
2	25%	0.26	1.97	0.27	1.38
	50%	0.22	1.49	0.18	1.04
	75%	0.19	1.31	0.15	1.17
	100%	0.21	1.96	0.21	1.57
3	25%	0.28	1.31	0.30	1.97
	50%	0.20	0.99	0.20	1.96
	75%	0.22	1.31	0.17	1.65
	100%	0.22	1.31	0.22	1.96
4	25%	0.20	1.31	0.39	2.25
	50%	0.20	0.99	0.25	1.70
	75%	0.18	1.31	0.21	1.89
	100%	0.19	1.31	0.25	2.25

Unit: mV/N

Table C.4(e) Standardized EMG amplitude/force of Subject E.

Finger Position	Direction	Downward	Upward	Backward	Forward
	Force Level				
1	25%	0.35	1.80	0.33	1.42
	50%	0.25	1.35	0.25	1.06
	75%	0.23	1.80	0.28	1.68
	100%	0.23	2.02	0.33	1.96
2	25%	0.36	1.80	0.28	2.13
	50%	0.22	1.35	0.21	1.41
	75%	0.19	1.80	0.28	1.44
	100%	0.22	2.47	0.35	1.96
3	25%	0.29	1.57	0.37	1.35
	50%	0.23	1.18	0.28	1.03
	75%	0.22	1.31	0.31	1.86
	100%	0.22	1.96	0.37	2.25
4	25%	0.31	0.94	0.56	1.89
	50%	0.21	0.71	0.37	1.41
	75%	0.20	0.96	0.38	1.57
	100%	0.21	1.43	0.38	2.62

Unit: mV/N

Table C.4(f) Standardized EMG amplitude/force of Subject F.

Finger Position	Direction	Downward	Upward	Backward	Forward
	Force Level				
1	25%	0.39	2.10	0.65	2.52
	50%	0.39	1.40	0.39	1.57
	75%	0.31	1.17	0.30	1.26
	100%	0.33	1.92	0.29	1.73
2	25%	0.53	1.89	0.48	2.08
	50%	0.42	1.26	0.30	1.38
	75%	0.35	1.05	0.24	1.17
	100%	0.31	1.75	0.24	2.10
3	25%	0.59	2.26	0.60	3.08
	50%	0.42	1.73	0.45	1.96
	75%	0.36	1.34	0.35	1.56
	100%	0.33	1.57	0.30	1.75
4	25%	0.52	2.05	0.53	3.94
	50%	0.37	1.29	0.35	2.35
	75%	0.28	1.05	0.29	1.83
	100%	0.29	1.43	0.35	1.77

Unit: mV/N

## **Appendix D. Source Lists of Computer Programs**



## PASCAL Source List for Computing Finger Strengths and Muscular Forces in the Finger Model with Constant Tendon Moment Arms

```
Program ConstMomentArm ;
{ programmed by Koo-Hyoung Lee }
{ uses finger model with constant tendon moment arms, Lee (1991) }
{ uses moment-arm data of Brand (1985) }
{ uses measured lengths of phalanges, Lee (1991) }
{ uses muscular tension capabilities from Ketchum et al.(1978) }
{ revised on 10/01/90 }
```

```
uses Crt, Graph, DOS, printer ;
```

```
const
  re1 = 0.97 ; {cm}
  re2 = 0.58 ; {cm}
  re3 = 0.35 ; {cm}
  rp1 = 1.01 ; {cm}
  rp2 = 0.98 ; {cm}
  rp3 = 0.65 ; {cm}
  rs1 = 1.21 ; {cm}
  rs2 = 0.83 ; {cm}
  ri1 = 0.85 ; {cm}
  ri2 = 0.50 ; {cm}
  ri3 = 0.30 ; {cm}
  rl1 = 1.14 ; {cm}
  rl2 = 0.36 ; {cm}
  rl3 = 0.30 ; {cm}
  l1 = 4.10 ; {cm}
  l2 = 2.30 ; {cm}
  l3 = 1.92 ; {cm}
  TQ = 5.00 ; {external load, N}
  PI = 3.141592654 ;
  mxed = 58.60 ; {N}
  mxfp = 0.0 ; {N}
  mxfs = 67.72 ; {N}
  mxpi = 27.15 ; {N}
  mxdi = 53.31 ; {N}
  mxlumb = 19.89 ; {N}
  RestMCP = 0.785398 ;
  RestPIP = 0.8726646 ;
  RestDIP = 0.5235987756 ;
```

```
type
  Result = record
    MPAngle : integer ;
    PIPAngle : integer ;
    DIPAngle : integer ;
    EDForce : real ;
    FSForce : real ;
    FPFforce : real ;
    INTForce : real ;
```

```

        LumbForce : real ;
        MVC : real
    end ; var
    OutFile : File of Result ;
    SimResult : Result ;
    TQ1, TQ2, TQ3 : real ;
    theta1, theta2, theta3 : real ;
    angle : real ;
    AA, BB, CC, DD, FF, GG : real ;
    FE, FP, FS, FI, FL : real ;
    XE, XP, XS, XI, XL : real ;
    MPCount, PIPCount, DIPCount : integer;
    GraphDriver : integer ;
    GraphMode : integer ;
    ErrorCode : integer ;
    TotalAngle, TotalForce : real ;
    FiveDegree, TenDegree, FifteenDegree : real ;
    NinetyDegree : real ;
    angleMCP, anglePIP, angleDIP : real ;
    FingerPosition, FingerPos : real ;
    RunCount : integer ;
    K1, K2, K3, K4, K5, K6, K7, K8, K9 : real ;
    M1, M2, M3, M4, M5, M6, M7, M8, M9 : real ;
    c1, c2, c3, c4, c5, c6, c7, c8, c9 : real ;
    MinTOTForce, MaxTOTForce : real ;
    MinMPAngle, MinPIPAngle, MinDIPAngle : real ;
    MaxMPAngle, MaxPIPAngle, MaxDIPAngle : real ;
    MinEDForce, MinFSForce, MinFPForce, MinFIForce, MinFLForce : real ;
    MaxEDForce, MaxFSForce, MaxFPForce, MaxFIForce, MaxFLForce : real ;
    NMCPEX, NPIPEX, NDIPPEX, NMCPEX, NPIPEX, NDIPPEX : integer ;
    PercentFE, PercentFP, PercentFS, PercentFI, PercentFL : real ;
    II, JJ, KK, LL, MM, NN : integer ;
    flname, head : string ;
    TX : text ;
    TQE, TQP, TQS, TQI, TQL, ExpMVC : real ;

```

```

PROCEDURE RawData_Print (II : integer ; flname : string) ;

```

```

BEGIN

```

```

    Assign (OutFile, flname) ;
    Reset (OutFile) ;

```

```

    For RunCount := 1 to II Do

```

```

    begin

```

```

        Read (OutFile, SimResult) ;
        TotalForce := Abs (SimResult.EDForce) + Abs (SimResult.FSForce)
            + Abs (SimResult.FPForce) + Abs (SimResult.IntForce)
            + Abs (SimResult.LumbForce) ;

```

```

        Writeln (1st) ;

```

```

        Writeln (1st, '*****', flname, '*****') ;

```

```

        Writeln (1st, 'TotalForce : ', TotalForce) ;

```

```

        Writeln (1st, 'MCP Angle : ', SimResult.MPAngle, ' PIP Angle : ',
            SimResult.PIPAngle, ' DIP Angle : ', SimResult.DIPAngle) ;

```

```

        Writeln (1st, 'ED : ', SimResult.EDForce, ' FS : ', SimResult.FSForce,
            ' FP : ', SimResult.FPForce) ;

```

```

        Writeln (1st, 'Int : ', SimResult.IntForce, ' Lumb. : ',

```

```

        SimResult.LumbForce) ;
    Writeln (lst, 'Expected MVC ', SimResult.MVC ) ;
    Writeln (lst) ;
end ;
Close (OutFile) ; END ;

```

```

PROCEDURE CompuForceMCPFlex ( var NMCPFX : integer ) ;

```

```

begin

```

```

    NMCPFX := 0 ;
    FiveDegree := PI / 36.0 ;
    TenDegree := PI / 18.0 ;
    FifteenDegree := PI / 12.0 ;
    NinetyDegree := PI / 2.0 ;
    Assign (OutFile, 'CSTMCPFX.DAT') ;
    Rewrite (OutFile) ;

```

```

    For MPCount := 1 to 2 do

```

```

        BEGIN

```

```

            theta1 := FifteenDegree * MPCount ;
            FingerPosition := theta1 ;

```

```

                For PIPCount := 1 to 2 do

```

```

                    BEGIN

```

```

                        theta2 := FifteenDegree * PIPCount ;
                        FingerPosition := theta1 + theta2 ;

```

```

                            For DIPCount := 1 to 2 do

```

```

                                BEGIN

```

```

                                    theta3 := FifteenDegree * DIPCount ;
                                    FingerPosition := theta1 + theta2 + theta3 ;

```

```

                                        angleMCP := theta1 ;
                                        anglePIP := theta1 + theta2 ;
                                        angleDIP := theta1 + theta2 + theta3 ;

```

```

                                            M1 := 13 * cos(angleDIP) + 12 * cos(anglePIP)
                                                + 11 * cos(angleMCP) ;
                                            M2 := 13 * cos(angleDIP) + 12 * cos(anglePIP) ;
                                            M3 := 13 * cos(angleDIP) ;

```

```

                                                TQ3 := TQ * 13 * cos(angleDIP) ;
                                                TQ2 := TQ * (13 * cos(angleDIP)
                                                    + 12 * cos(anglePIP)) ;
                                                TQ1 := TQ * (13 * cos(angleDIP)
                                                    + 12 * cos(anglePIP)
                                                    + 11 * cos(angleMCP)) ;

```

```

                                                    XP := ( - 1.0 ) * rp1 * ( theta1 - RestMCP )
                                                        - rp2 * ( theta2 - RestPIP )
                                                        - rp3 * ( theta3 - RestDIP ) ;
                                                    XS := ( - 1.0 ) * rs1 * ( theta1 - RestMCP )
                                                        - rs2 * ( theta2 - RestPIP ) ;

```

```

XI := ( - 1.0 ) * ri1 * ( thetal - RestMCP )
      + ri2 * ( theta2 - RestPIP )
      + ri3 * ( theta3 - RestDIP ) ;

k1 := rp1 * ri2 + rp2 * ri1 ;
k2 := rp1 * ri3 + rp3 * ri1 ;
k3 := rp3 * ri2 - rp2 * ri3 ;
k4 := rp2 * rs1 - rp1 * rs2 ;
k5 := rp3 * rs2 - rp3 * rs1 ;

FI := ( TQ1 * rp3 * rs2 + TQ2 * k5 +
      TQ3 * ( k4 + k5 ) ) / ( rs1 * k3 +
      rs2 * k2 ) ;
FS := ( TQ1 * k3 + TQ2 * ( k2 + k3 ) + TQ3 *
      ( k2 + k3 - k1 ) ) / ( rs1 * k3 + rs2 * k2 ) ;
FP := ( TQ1 * ( rs2 * ri3 ) + TQ2 * ri3 * ( rs2 -
      rs1 ) + TQ3 * ( rs2 * ri3 - rs1 * ri3 +
      rs1 * ri2 + rs2 * ri1 ) ) /
      ( rs1 * k3 + rs2 * k2 ) ;
TQI := ( mxpi * ( rs1 * k3 + rs2 * k2 ) ) /
      ( M1 * rp3 * rs2 + M2 * k5 + M3 *
      ( k4 + k5 ) ) ;
TQP := ( mxfp * ( rs1 * k3 + rs2 * k2 ) ) /
      ( M1 * rs2 * ri3 + M2 * ri3 * ( rs2 - rs1 )
      + M3 * ( rs2 * ri3 - rs1 * ri3 + rs1 * ri2
      + rs2 * ri1 ) ) ;
TQS := ( mxfs * ( rs1 * k3 + rs2 * k2 ) ) /
      ( M1 * k3 + M2 * ( k2 + k3 ) + M3 * ( k2 +
      K3 - k1 ) ) ;

XP := 18.375 - Abs ( XP ) ;
XS := 18.875 - Abs ( XS ) ;
XI := 4.15 - Abs ( XI ) ;

PercentFP := ( - 7.4 ) * XP * XP + 272.11 * XP
            - 2399.9 ;
PercentFS := ( - 7.02 ) * XS * XS + 264.9 * XS
            - 2400.0 ;
PercentFI := ( - 145.16 ) * XI * XI + 1204.82 * XI
            - 2400.0 ;

ExpMVC := ( TQP * PercentFP + TQS * PercentFS
            + TQI * PercentFI ) / 100.0 ;
FS := FS * PercentFS / 100.0 ;
FP := FP * PercentFP / 100.0 ;
FI := FI * PercentFI / 100.0 ;

NMCPCFX := NMCPCFX + 1 ;
TotalForce := Abs ( FS ) + Abs ( FI ) + Abs ( FP ) ;
FingerPos := thetal + theta2 + theta3 ;

SimResult.MPAngle := MPCCount * 15 ;
SimResult.PIPAngle := PIPCount * 15 ;
SimResult.DIPAngle := DIPCount * 15 ;
SimResult.EDForce := 0.0 ;
SimResult.FSForce := FS ;

```

```

        SimResult.FPForce := FP ;
        SimResult.IntForce := FI ;
        SimResult.LumbForce := 0.0 ;
        SimResult.MVC := ExpMVC ;

        Write (OutFile, SimResult) ;

    END ;

END ;

END ;
Close (OutFile) ; END ;

PROCEDURE CompuForcePIPFlex ( var NPIPFX : integer ) ;

BEGIN

    NPIPFX := 0 ;
    FiveDegree := PI / 36.0 ;
    TenDegree := PI / 18.0 ;
    FifteenDegree := PI / 12.0 ;
    NintyDegree := PI / 2.0 ;
    Assign (OutFile, 'CSTPIPFX.DAT') ;
    ReWrite (OutFile) ;

    For MPCount := 1 to 2 do
        BEGIN
            theta1 := FifteenDegree * MPCount ;
            FingerPosition := theta1 ;

            For PIPCount := 1 to 2 do
                BEGIN
                    theta2 := FifteenDegree * PIPCount ;
                    FingerPosition := theta1 + theta2 ;

                    For DIPCount := 1 to 2 do
                        BEGIN
                            theta3 := FifteenDegree * DIPCount ;
                            FingerPosition := theta1 + theta2 + theta3 ;

                            angleMCP := theta1 ;
                            anglePIP := theta1 + theta2 ;
                            angleDIP := theta1 + theta2 + theta3 ;

                            M1 := 13 * cos ( PI/2 - angleDIP )
                                + 12 * cos( PI/2 - anglePIP )
                                + 11 * cos( PI/2 - angleMCP ) ;
                            M2 := 13 * cos ( PI/2 - angleDIP )
                                + 12 * cos( PI/2 - anglePIP ) ;
                            M3 := 13 * cos ( PI/2 - angleDIP ) ;

                            TQ3 := TQ * 13 * cos ( PI/2 - angleDIP ) ;
                            TQ2 := TQ * ( 13 * cos ( PI/2 - angleDIP )
                                + 12 * cos( PI/2 - anglePIP ) ) ;
                            TQ1 := TQ * ( 13 * cos ( PI/2 - angleDIP )

```

```

+ 12 * cos( PI/2 - anglePIP )
+ 11 * cos ( PI/2 - angleMCP ) );

XP := ( - 1.0 ) * rp1 * ( theta1 - RestMCP )
      - rp2 * ( theta2 - RestPIP )
      - rp3 * ( theta3 - RestDIP );
XS := ( - 1.0 ) * rs1 * ( theta1 - RestMCP )
      - rs2 * ( theta2 - RestPIP );
XI := ( - 1.0 ) * ri1 * ( theta1 - RestMCP )
      + ri2 * ( theta2 - RestPIP )
      + ri3 * ( theta3 - RestDIP );

k1 := rp1 * ri2 + rp2 * ri1 ;
k2 := rp1 * ri3 + rp3 * ri1 ;
k3 := rp3 * ri2 - rp2 * ri3 ;
k4 := rp2 * rs1 - rp1 * rs2 ;
k5 := rp3 * rs2 - rp3 * rs1 ;

FI := ( TQ1 * rp3 * rs2 + TQ2 * k5 +
        TQ3 * ( k4 + k5 ) ) / ( rs1 * k3 +
        rs2 * k2 );
FS := ( TQ1 * k3 + TQ2 * ( k2 + k3 ) + TQ3 *
        ( k2 + k3 - k1 ) ) / ( rs1 * k3 + rs2 * k2 );
FP := ( TQ1 * ( rs2 * ri3 ) + TQ2 * ri3 * ( rs2 -
        rs1 ) + TQ3 * ( rs2 * ri3 - rs1 * ri3 +
        rs1 * ri2 + rs2 * ri1 ) ) /
        ( rs1 * k3 + rs2 * k2 );

TQI := ( mxpi * ( rs1 * k3 + rs2 * k2 ) ) /
        ( M1 * rp3 * rs2 + M2 * k5 + M3 *
        ( k4 + k5 ) );
TQP := ( mxfp * ( rs1 * k3 + rs2 * k2 ) ) /
        ( M1 * rs2 * ri3 + M2 * ri3 * ( rs2 - rs1 )
        + M3 * ( rs2 * ri3 - rs1 * ri3 + rs1 * ri2
        + rs2 * ri1 ) );
TQS := ( mxfs * ( rs1 * k3 + rs2 * k2 ) ) /
        ( M1 * k3 + M2 * ( k2 + k3 ) + M3 * ( k2 +
        K3 - k1 ) );

XP := 18.375 - Abs (XP) ;
XS := 18.875 - Abs (XS) ;
XI := 4.15 - Abs (XI) ;

PercentFP := ( - 7.4 ) * XP * XP + 272.11 * XP
            - 2399.9 ;
PercentFS := ( - 7.02 ) * XS * XS + 264.9 * XS
            - 2400.0 ;
PercentFI := ( - 145.16 ) * XI * XI + 1204.82 * XI
            - 2400.0 ;

ExpMVC := ( TQP * PercentFP + TQS * PercentFS
            + TQI * PercentFI ) / 100.0 ;
FP := FP * PercentFP / 100.0 ;
FS := FS * PercentFS / 100.0 ;
FI := FI * PercentFI / 100.0 ;

```

```

    NPIPFX := NPIPFX + 1 ;
    TotalForce := Abs (FP) + Abs (FS) + Abs (FI) ;

    SimResult.MPAngle := MPCount * 15 ;
    SimResult.PIPAngle := PIPCount * 15 ;
    SimResult.DIPAngle := DIPCount * 15 ;
    SimResult.EDForce := 0.0 ;
    SimResult.FSForce := FS ;
    SimResult.FPForce := FP ;
    SimResult.IntForce := FI ;
    SimResult.LumbForce := 0.0 ;
    SimResult.MVC := ExpMVC ;

    Write (OutFile, SimResult) ;

    END ;

END ;

END ;
Close (OutFile) ; END ;

PROCEDURE CompuForceMCPExt ( var NMCPEX : integer ) ;
BEGIN
    NMCPEX := 0 ;
    FiveDegree := PI / 36.0 ;
    TenDegree := PI / 18.0 ;
    FifteenDegree := PI / 12.0 ;
    NintyDegree := PI / 2.0 ;
    Assign (OutFile, 'CSTMCPExt.DAT') ;
    ReWrite (OutFile) ;

    For MPCount := 1 to 2 do
        BEGIN
            thetal := FifteenDegree * MPCount ;
            FingerPosition := thetal ;

            For PIPCount := 1 to 2 do
                BEGIN
                    theta2 := FifteenDegree * PIPCount ;
                    FingerPosition := thetal + theta2 ;

                    For DIPCount := 1 to 2 do
                        BEGIN
                            theta3 := FifteenDegree * DIPCount ;
                            FingerPosition := thetal + theta2 + theta3 ;

                            angleMCP := thetal ;
                            anglePIP := thetal + theta2 ;
                            angleDIP := thetal + theta2 + theta3 ;

                            M1 := 13 * cos( angleDIP + PI ) +
                                12 * cos( anglePIP + PI ) +

```

```

11 * cos( angleMCP + PI );
M2 := 13 * cos( angleDIP + PI ) +
12 * cos( anglePIP + PI );
M3 := 13 * cos( angleDIP + PI );

TQ3 := TQ * 13 * cos ( angleDIP + PI );
TQ2 := TQ * ( 13 * cos ( angleDIP + PI )
+ 12 * cos ( anglePIP + PI ) );
TQ1 := TQ * ( 13 * cos ( angleDIP + PI )
+ 12 * cos ( anglePIP + PI ) +
11 * cos ( angleMCP + PI ) );

XE := re1 * ( theta1 - RestMCP )
+ re2 * ( theta2 - RestPIP )
+ re3 * ( theta3 - RestDIP );
XI := ( - 1.0 ) * ri1 * ( theta1 - RestMCP )
+ ri2 * ( theta2 - RestPIP )
+ ri3 * ( theta3 - RestDIP );
XL := ( - 1.0 ) * rl1 * ( theta1 - RestMCP )
+ rl2 * ( theta2 - RestPIP )
+ rl3 * ( theta3 - RestDIP );

c1 := re3 * ri2 - re2 * ri3 ;
c2 := re1 * ri3 + re3 * ri1 ;
c3 := re1 * ri2 + re2 * ri1 ;
c4 := re2 * rl3 - re3 * rl2 ;
c5 := re1 * rl3 + re3 * rl1 ;
c6 := re2 * rl1 + re1 * rl2 ;
c7 := ri1 * c4 + ri2 * c5 - ri3 * c6 ;
c8 := rl1 * c1 - rl2 * c2 + rl3 * c3 ;

FL := ( TQ1 * c1 + TQ2 * ( c1 + c2 ) + TQ3 *
( c1 + c2 - c3 ) ) /
( rl1 * c1 - rl2 * c2 + rl3 * c3 );
FI := ( TQ1 * c4 + TQ2 * ( c4 - c5 ) + TQ3 *
( c4 - c5 + c6 ) ) /
( ri1 * c4 + ri2 * c5 - ri3 * c6 );
FE := ( - 1.0 ) * ( TQ1 * ( ri3 * c4 * c8 +
rl3 * c1 * c7 ) ) / ( re3 * c7 * c8 ) -
( TQ2 * ( ri3 * ( c4 - c5 ) * c8 + rl3 *
( c1 + c2 ) * c7 ) ) / ( re3 * c7 * c8 ) -
( TQ3 * ( ri3 * ( c4 - c5 + c6 ) * c8 +
rl3 * ( c1 + c2 - c3 ) * c7 + c7 * c8 ) ) /
( re3 * c7 * c8 );
TQL := ( mxlumb * ( rl1 * c1 - rl2 * c2 + rl3 * c3 ) )
/ ( M1 * c1 + M2 * ( c1 + c2 ) + M3 *
( c1 + c2 - c3 ) );
TQI := ( mxdi * ( ri1 * c4 + ri2 * c5 - ri3 * c6 ) ) /
( M1 * c4 + M2 * ( c4 - c5 ) + M3 *
( c4 - c5 + c6 ) );
TQE := ( mxed * ( re3 * c7 * c8 ) ) /
( ( - 1.0 ) * M1 * ( ri3 * c4 * c8 +
rl3 * c1 * c7 ) - M2 * ( ri3 * ( c4 - c5 )
* c8 + rl3 * ( c1 + c2 ) * c7 ) - M3 *
( ri3 * ( c4 - c5 + c6 ) * c8 + rl3 *
( c1 + c2 - c3 ) * c7 + c7 * c8 ) );

```



```

XE := 16.425 - Abs (XE) ;
XI := 4.15 - Abs (XI) ;
XL := 4.60 - Abs (XL) ;

PercentFE := ( - 9.27 ) * XE * XE + 304.41 * XE
            - 2400.0 ;
PercentFI := ( -145.16 ) * XI * XI
            + 1204.82 * XI - 2400.0 ;
PercentFL := ( - 118.15 ) * XL * XL
            + 1086.96 * XL - 2400.0 ;

ExpMVC := ( TQE * PercentFE + TQI * PercentFI
            + TQL * PercentFL ) / 100.0 ;

FE := FE * PercentFE / 100.0 ;
FI := FI * PercentFI / 100.0 ;
FL := FL * PercentFL / 100.0 ;

NMCPEX := NMCPEX + 1 ;
TotalForce := Abs (FE) + Abs (FI) + Abs (FL) ;

SimResult.MPAngle := MPCount * 15 ;
SimResult.PIPAngle := PIPCount * 15 ;
SimResult.DIPAngle := DIPCount * 15 ;
SimResult.EDForce := FE ;
SimResult.FSForce := 0.0 ;
SimResult.FPForce := 0.0 ;
SimResult.IntForce := FI ;
SimResult.LumbForce := FL ;
SimResult.MVC := ExpMVC ;

Write (OutFile, SimResult) ;

    END ;

END ;

END ;
Close (OutFile) ; END ;

```

```

PROCEDURE CompuForcePIPExt ( var NPIPEX : integer ) ;

```

```

BEGIN

```

```

    NPIPEX := 0 ;
    FiveDegree := PI / 36.0 ;
    TenDegree := PI / 18.0 ;
    FifteenDegree := PI / 12.0 ;
    NintyDegree := PI / 2.0 ;
    Assign (OutFile, 'CSTPIPEX.DAT') ;
    ReWrite (OutFile) ;

```

```

    For MPCount := 1 to 2 do
        BEGIN

```

```

theta1 := FifteenDegree * MPCount ;
FingerPosition := theta1 ;

For PIPCount := 1 to 2 do
BEGIN
theta2 := FifteenDegree * PIPCount ;
FingerPosition := theta1 + theta2 ;

For DIPCount := 1 to 2 do
BEGIN
theta3 := FifteenDegree * DIPCount ;
FingerPosition := theta1 + theta2 + theta3 ;

angleMCP := theta1 ;
anglePIP := theta1 + theta2 ;
angleDIP := theta1 + theta2 + theta3 ;

M1 := 13 * cos( 1.5 * PI - angleDIP ) +
12 * cos( 1.5 * PI - anglePIP ) +
11 * cos( 1.5 * PI - angleMCP ) ;
M2 := 13 * cos( 1.5 * PI - angleDIP ) +
12 * cos( 1.5 * PI - anglePIP ) ;
M3 := 13 * cos( 1.5 * PI - angleDIP ) ;

TQ3 := TQ * 13 * cos ( 1.5 * PI - angleDIP ) ;
TQ2 := TQ * ( 13 * cos ( 1.5 * PI - angleDIP )
+ 12 * cos ( 1.5 * PI - anglePIP ) ) ;
TQ1 := TQ * ( 13 * cos ( 1.5 * PI - angleDIP )
+ 12 * cos ( 1.5 * PI - anglePIP ) +
11 * cos ( 1.5 * PI - angleMCP ) ) ;

XE := re1 * ( theta1 - RestMCP )
+ re2 * ( theta2 - RestPIP )
+ re3 * ( theta3 - RestDIP ) ;
XI := ( - 1.0 ) * ri1 * ( theta1 - RestMCP )
+ ri2 * ( theta2 - RestPIP )
+ ri3 * ( theta3 - RestDIP ) ;
XL := ( - 1.0 ) * ri1 * ( theta1 - RestMCP )
+ ri2 * ( theta2 - RestPIP )
+ ri3 * ( theta3 - RestDIP ) ;

c1 := re3 * ri2 - re2 * ri3 ;
c2 := re1 * ri3 + re3 * ri1 ;
c3 := re1 * ri2 + re2 * ri1 ;
c4 := re2 * ri3 - re3 * ri2 ;
c5 := re1 * ri3 + re3 * ri1 ;
c6 := re2 * ri1 + re1 * ri2 ;
c7 := ri1 * c4 + ri2 * c5 - ri3 * c6 ;
c8 := ri1 * c1 - ri2 * c2 + ri3 * c3 ;

FL := ( TQ1 * c1 + TQ2 * ( c1 + c2 ) + TQ3 *
( c1 + c2 - c3 ) ) /
( ri1 * c1 - ri2 * c2 + ri3 * c3 ) ;
FI := ( TQ1 * c4 + TQ2 * ( c4 - c5 ) + TQ3 *
( c4 - c5 + c6 ) ) /
( ri1 * c4 + ri2 * c5 - ri3 * c6 ) ;

```

```

FE := ( - 1.0 ) * ( TQ1 * ( ri3 * c4 * c8 +
rl3 * c1 * c7 ) ) / ( re3 * c7 * c8 ) -
( TQ2 * ( ri3 * ( c4 - c5 ) * c8 + rl3 *
( c1 + c2 ) * c7 ) ) / ( re3 * c7 * c8 ) -
( TQ3 * ( ri3 * ( c4 - c5 + c6 ) * c8 +
rl3 * ( c1 + c2 - c3 ) * c7 + c7 * c8 ) ) /
( re3 * c7 * c8 );

TQL := ( mxlumb * ( rl1 * c1 - rl2 * c2 + rl3 * c3 ) )
/ ( M1 * c1 + M2 * ( c1 + c2 ) + M3 *
( c1 + c2 - c3 ) );
TQI := ( mxdi * ( ri1 * c4 + ri2 * c5 - ri3 * c6 ) ) /
( M1 * c4 + M2 * ( c4 - c5 ) + M3 *
( c4 - c5 + c6 ) );
TQE := ( mxed * ( re3 * c7 * c8 ) ) /
( ( - 1.0 ) * M1 * ( ri3 * c4 * c8 +
rl3 * c1 * c7 ) - M2 * ( ri3 * ( c4 - c5 )
* c8 + rl3 * ( c1 + c2 ) * c7 ) - M3 *
( ri3 * ( c4 - c5 + c6 ) * c8 + rl3 *
( c1 + c2 - c3 ) * c7 + c7 * c8 ) );

XE := 16.425 - Abs ( XE ) ;
XI := 4.15 - Abs ( XI ) ;
XL := 4.60 - Abs ( XL ) ;

PercentFE := ( - 9.27 ) * XE * XE + 304.41 * XE
- 2400.0 ;
PercentFI := ( - 145.16 ) * XI * XI
+ 1204.82 * XI - 2400.0 ;
PercentFL := ( - 118.15 ) * XL * XL
+ 1086.96 * XL - 2400.0 ;

ExpMVC := ( TQE * PercentFE + TQI * PercentFI
+ TQL * PercentFL ) / 100.0 ;
FE := FE * PercentFE / 100.0 ;
FI := FI * PercentFI / 100.0 ;
FL := FL * PercentFL / 100.0 ;

NPIPEX := NPIPEX + 1 ;
TotalForce := Abs ( FE ) + Abs ( FI ) + Abs ( FL ) ;

SimResult.MPAngle := MPCount * 15 ;
SimResult.PIPIAngle := PIPCount * 15 ;
SimResult.DIPAngle := DIPCount * 15 ;
SimResult.EDForce := FE ;
SimResult.FSForce := 0.0 ;
SimResult.FPForce := 0.0 ;
SimResult.IntForce := FI ;
SimResult.LumbForce := FL ;
SimResult.MVC := ExpMVC ;

Write ( OutFile, SimResult ) ;

END ;

END ;

```

```

    END ;
    Close (OutFile) ; END ;

PROCEDURE Min_Muscle_Force (KK : integer ; flname : string ; head : string);

BEGIN
    MinTOTForce := 9999999999.9 ;
    MaxTOTForce := 0.0000000001 ;
    Assign (OutFile, flname) ;
    Reset (OutFile) ;
    For RunCount := 1 to KK Do
    begin
        Read (OutFile, SimResult) ;
        TotalForce := Abs (SimResult.EDForce) + Abs (SimResult.FSForce)
            + Abs (SimResult.FPForce) + Abs (SimResult.IntForce)
            + Abs (SimResult.LumbForce) ;
        If TotalForce < MinTOTForce then
            begin
                MinTOTForce := TotalForce ;
                MinMPAngle := SimResult.MPAngle ;
                MinPIPAngle := SimResult.PIPAngle ;
                MinDIPAngle := SimResult.DIPAngle ;
                MinEDForce := SimResult.EDForce ;
                MinFSForce := SimResult.FSForce ;
                MinFPForce := SimResult.FPForce ;
                MinFIForce := SimResult.IntForce ;
                MinFLForce := SimResult.LumbForce ;
            end
        else
            begin
                If TotalForce > MaxTOTForce then
                    begin
                        MaxTOTForce := TotalForce ;
                        MaxMPAngle := SimResult.MPAngle ;
                        MaxPIPAngle := SimResult.PIPAngle ;
                        MaxDIPAngle := SimResult.DIPAngle ;
                        MaxEDForce := SimResult.EDForce ;
                        MaxFSForce := SimResult.FSForce ;
                        MaxFPForce := SimResult.FPForce ;
                        MaxFIForce := SimResult.IntForce ;
                        MaxFLForce := SimResult.LumbForce ;
                    end ;
                end ;
            end ;
        end ;
        Close (OutFile) ;

        Writeln (lst) ;
        Writeln (lst, '****', head, '****') ;
        Writeln (lst);
        Writeln (lst, 'MinTotalForce : ', MinTOTForce) ;
        Writeln (lst, 'MCP : ', MinMPAngle, ' ', 'PIP : ', MinPIPAngle, ' ',
            'DIP : ', MinDIPAngle) ;
        Writeln (lst, 'ED : ', MinEDForce, ' ', 'FS : ', MinFSForce, ' ',
            'FP : ', MinFPForce) ;
        Writeln (lst, 'Int. : ', MinFIForce, ' ', 'Lumb. : ', MinFLForce) ;
    end ;

```

```

Writeln (lst) ;

Writeln (lst) ;
Writeln (lst, 'MaxTotalForce : ', MaxTOTForce) ;
Writeln (lst, 'MCP : ', MaxMPAngle, ' ', 'PIP : ', MaxPIPAngle, ' ',
'DIP : ', MaxDIPAngle) ;
Writeln (lst, 'ED : ', MaxEDForce, ' ', 'FS : ', MaxFSForce, ' ',
'FP : ', MaxFPForce) ;
Writeln (lst, 'Int. : ', MaxFIForce, ' ', 'Lumb. : ', MaxFLForce) ;

END ;

PROCEDURE Data_To_TextFile (JJ : integer ; flname : string ; txflname : string) ;

Begin
Assign (OutFile, flname) ;
Reset (OutFile) ;
Assign (TX, txflname) ;
Rewrite (TX) ;

For RunCount := 1 to JJ Do
Begin
Read (OutFile, SimResult) ;
TotalForce := Abs (SimResult.EDForce) + Abs (SimResult.FSForce)
+ Abs (SimResult.FPForce) + Abs (SimResult.IntForce)
+ Abs (SimResult.LumbForce) ;

MaxTOTForce := TotalForce ;
MaxMPAngle := SimResult.MPAngle ;
MaxPIPAngle := SimResult.PIPAngle ;
MaxDIPAngle := SimResult.DIPAngle ;
MaxEDForce := SimResult.EDForce ;
MaxFSForce := SimResult.FSForce ;
MaxFPForce := SimResult.FPForce ;
MaxFIForce := SimResult.IntForce ;
MaxFLForce := SimResult.LumbForce ;

Writeln (TX, 'TotalForce : ', MaxTOTForce, ' ',
'MCP : ', MaxMPAngle, ' ', 'PIP : ', MaxPIPAngle, ' ',
'DIP : ', MaxDIPAngle) ;
Writeln (TX, 'ED : ', MaxEDForce, ' ', 'FS : ', MaxFSForce, ' ',
'FP : ', MaxFPForce, ' ',
'Int. : ', MaxFIForce, ' ', 'Lumb. : ', MaxFLForce) ;
end ;
Close (OutFile) ;
Close (TX) ; END ;

BEGIN

CompuForceMCPFlex (NMCPFX) ;
CompuForcePIPFlex (NPIPFIX) ;
CompuForceMCPExt (NMCPEX) ;
CompuForcePIPEExt (NPIPEX) ;

Min_Muscle_Force (NMCPFX, 'CSTMCPFX.DAT', ' Constant M-A MCP Flexion') ;
Min_Muscle_Force (NPIPFIX, 'CSTPIPFIX.DAT', ' Constant M-A PIP Flexion') ;

```

```
Min_Muscle_Force (NMCPEX, 'CSTMCPPEX.DAT', ' Constant M-A MCP Extension') ;  
Min_Muscle_Force (NPIPEX, 'CSTPIPEX.DAT', ' Constant M-A PIP Extension') ;
```

```
RawData_Print (NMCPFX , 'CSTMCPFX.DAT') ;  
RawData_Print (NPIPFX , 'CSTPIPFX.DAT') ;  
RawData_Print (NMCPEX , 'CSTMCPPEX.DAT') ;  
RawData_Print (NPIPEX , 'CSTPIPEX.DAT') ;
```

```
Data_To_TextFile (NMCPFX, 'CSTMCPFX.DAT', 'CTMFXTX.TXT') ;  
Data_To_TextFile (NPIPFX, 'CSTPIPFX.DAT', 'CTPFXTX.TXT') ;  
Data_To_TextFile (NDIPFX, 'CSTDIPFX.DAT', 'CTDFXTX.TXT') ;  
Data_To_TextFile (NMCPEX, 'CSTMCPPEX.DAT', 'CTMEXTX.TXT') ;  
Data_To_TextFile (NPIPEX, 'CSTPIPEX.DAT', 'CTPEXTX.TXT') ;  
Data_To_TextFile (NDIPEX, 'CSTDIPEX.DAT', 'CTDEXTX.TXT') ;
```

END.

## PASCAL Source List for Computing Finger Strengths and Muscular Forces in the Finger Model with Non-Constant Tendon Moment Arms

```
Program NonConstMomentArm ;
  { programmed by Koo-Hyoung Lee }
  { uses finger model with non-constant tendon moment arms, Lee (1991) }
  { uses moment-arm data of Brand (1985) }
  { uses measured lengths of phalanges, Lee (1991) }
  { uses muscular tension capabilities from Ketchum et al. (1978) }
  { revised on 10/01/90 }

uses Crt, Graph, DOS, printer ;

const
  re1 = 0.97 ; {cm}
  re2 = 0.58 ; {cm}
  re3 = 0.35 ; {cm}
  rp1 = 1.01 ; {cm}
  rp2 = 0.98 ; {cm}
  rp3 = 0.65 ; {cm}
  rs1 = 1.21 ; {cm}
  rs2 = 0.83 ; {cm}
  ri1 = 0.85 ; {cm}
  ri2 = 0.50 ; {cm}
  ri3 = 0.30 ; {cm}
  rl1 = 1.14 ; {cm}
  rl2 = 0.36 ; {cm}
  rl3 = 0.30 ; {cm}
  l1 = 4.10 ; {cm}
  l2 = 2.30 ; {cm}
  l3 = 1.92 ; {cm}
  TQ = 5.00 ; {external load, N}
  PI = 3.141592654 ;
  mxed = 58.60 ; {N}
  mxfp = 0.00 ; {N}
  mxfs = 67.72 ; {N}
  mxpi = 27.15 ; {N}
  mxdi = 53.31 ; {N}
  mxlumb = 19.89 ; {N}
  RestMCP = 0.785398 ;
  RestPIP = 0.8726646 ;
  RestDIP = 0.5235987756 ;

type
  Result = record
    MPAngle : integer ;
    PIPAngle : integer ;
    DIPAngle : integer ;
    EDForce : real ;
    FSForce : real ;
    FPForce : real ;
    INTForce : real ;
```

```

        LumbForce : real ;
        MVC : real
    end ; var
    OutFile : File of Result ;
    SimResult : Result ;
    TQ1, TQ2, TQ3 : real ;
    theta1, theta2, theta3 : real ;
    angle : real ;
    AA, BB, CC, DD, FF, GG : real ;
    FE, FP, FS, FI, FL : real ;
    XE, XP, XS, XI, XL : real ;
    RRP1, RRP2, RRS1, RRS2, RRL1 : real ;
    MPCount, PIPCount, DIPCount : integer ;
    GraphDriver : integer ;
    GraphMode : integer ;
    ErrorCode : integer ;
    TotalAngle, TotalForce : real ;
    FiveDegree, TenDegree, FifteenDegree : real ;
    NintyDegree : real ;
    angleMCP, anglePIP, angleDIP : real ;
    FingerPosition, FingerPos : real ;
    RunCount : integer ;
    K1, K2, K3, K4, K5, K6, K7, K8, K9 : real ;
    M1, M2, M3, M4, M5, M6, M7, M8, M9 : real ;
    c1, c2, c3, c4, c5, c6, c7, c8, c9 : real ;
    MinTOTForce, MaxTOTForce : real ;
    MinMPAngle, MinPIPAngle, MinDIPAngle : real ;
    MaxMPAngle, MaxPIPAngle, MaxDIPAngle : real ;
    MinEDForce, MinFSForce, MinFPForce, MinFIForce, MinFLForce : real ;
    MaxEDForce, MaxFSForce, MaxFPForce, MaxFIForce, MaxFLForce : real ;
    NMCPEX, NPIPEX, NDIPPEX, NMCPEX, NPIPEX, NDIPPEX : integer ;
    PercentFE, PercentFP, PercentFS, PercentFI, PercentFL : real ;
    II, JJ, KK, LL, MM, NN : integer ;
    flname, head : string ;
    TX : text ;
    TQE, TQP, TQS, TQI, TQL, ExpMVC : real ;

```

```
PROCEDURE RawData_Print (II : integer ; flname : string) ;
```

```
BEGIN
```

```
    Assign (OutFile, flname) ;
    Reset (OutFile) ;
```

```
    For RunCount := 1 to II Do
```

```
    begin
```

```
        Read (OutFile, SimResult) ;
        TotalForce := Abs (SimResult.EDForce) + Abs (SimResult.FSForce)
            + Abs (SimResult.FPForce) + Abs (SimResult.IntForce)
            + Abs (SimResult.LumbForce) ;
```

```
        Writeln (lst) ;
```

```
        Writeln (lst, '*****', flname, '*****') ;
```

```
        Writeln (lst, 'TotalForce : ', TotalForce) ;
```

```
        Writeln (lst, 'MCP Angle : ', SimResult.MPAngle, ' PIP Angle : ',
            SimResult.PIPAngle, ' DIP Angle : ', SimResult.DIPAngle) ;
```

```
        Writeln (lst, 'ED : ', SimResult.EDForce, ' FS : ', SimResult.FSForce,
```



```

        ' FP : ', SimResult.FPForce) ;
    Writeln (1st, 'Int : ', SimResult.IntForce, ' Lumb. : ',
        SimResult.LumbForce) ;
    Writeln (1st, 'Expected MVC ', SimResult.MVC ) ;
    Writeln (1st) ;
end ;
Close (OutFile) ; END ;

```

PROCEDURE CompuForceMCPFlex ( var NMCPFX : integer ) ;

begin

```

    NMCPFX := 0 ;
    FiveDegree := PI / 36.0 ;
    TenDegree := PI / 18.0 ;
    FifteenDegree := PI / 12.0 ;
    NintyDegree := PI / 2.0 ;
    Assign (OutFile, 'CSTMCPFX.DAT') ;
    ReWrite (OutFile) ;

    For MPCount := 1 to 2 do
        BEGIN
            theta1 := FifteenDegree * MPCount ;
            FingerPosition := theta1 ;

            For PIPCount := 1 to 2 do
                BEGIN
                    theta2 := FifteenDegree * PIPCount ;
                    FingerPosition := theta1 + theta2 ;

                    For DIPCount := 1 to 2 do
                        BEGIN
                            theta3 := FifteenDegree * DIPCount ;
                            FingerPosition := theta1 + theta2 + theta3 ;

                            angleMCP := theta1 ;
                            anglePIP := theta1 + theta2 ;
                            angleDIP := theta1 + theta2 + theta3 ;

                            RRP1 := rp1 + 0.075 * rp1 * theta1 ;
                            RRP2 := rp2 + 0.075 * rp2 * theta2 ;
                            RRS1 := rs1 + 0.075 * rs1 * theta1 ;
                            RRS2 := rs2 + 0.075 * rs2 * theta2 ;
                            RRL1 := rl1 + 0.075 * rl1 * theta1 ;

                            M1 := 13 * cos(angleDIP) + 12 * cos(anglePIP)
                                + 11 * cos(angleMCP) ;
                            M2 := 13 * cos(angleDIP) + 12 * cos(anglePIP) ;
                            M3 := 13 * cos(angleDIP) ;

                            TQ3 := TQ * 13 * cos(angleDIP) ;
                            TQ2 := TQ * (13 * cos(angleDIP)
                                + 12 * cos(anglePIP)) ;
                            TQ1 := TQ * (13 * cos(angleDIP)

```

```

+ 12 * cos(anglePIP)
+ 11 * cos(angleMCP)) ;

XP := ( - 1.0 ) * RRP1 * ( theta1 - RestMCP )
      - RRP2 * ( theta2 - RestPIP )
      - rp3 * ( theta3 - RestDIP ) ;
XS := ( - 1.0 ) * RRS1 * ( theta1 - RestMCP )
      - RRS2 * ( theta2 - RestPIP ) ;
XI := ( - 1.0 ) * ri1 * ( theta1 - RestMCP )
      + ri2 * ( theta2 - RestPIP )
      + ri3 * ( theta3 - RestDIP ) ;

k1 := RRP1 * ri2 + RRP2 * ri1 ;
k2 := RRP1 * ri3 + rp3 * ri1 ;
k3 := rp3 * ri2 - RRP2 * ri3 ;
k4 := RRP2 * RRS1 - RRP1 * RRS2 ;
k5 := rp3 * RRS2 - rp3 * RRS1 ;

FI := ( TQ1 * rp3 * RRS2 + TQ2 * k5 +
      TQ3 * ( k4 + k5 ) ) / ( RRS1 * k3 +
      RRS2 * k2 ) ;
FS := ( TQ1 * k3 + TQ2 * ( k2 + k3 ) + TQ3 *
      ( k2 + k3 - k1 ) ) /
      ( RRS1 * k3 + RRS2 * k2 ) ;
FP := ( TQ1 * ( RRS2 * ri3 ) + TQ2 * ri3 *
      ( RRS2 - RRS1 )
      + TQ3 * ( RRS2 * ri3 - RRS1 * ri3 +
      RRS1 * ri2 + RRS2 * ri1 ) ) /
      ( RRS1 * k3 + RRS2 * k2 ) ;
TQI := ( mxpi * ( rs1 * k3 + RRS2 * k2 ) ) /
      ( M1 * rp3 * RRS2 + M2 * k5 + M3 *
      ( k4 + k5 ) ) ;
TQP := ( mxfp * ( RRS1 * k3 + RRS2 * k2 ) ) /
      ( M1 * RRS2 * ri3 + M2 * ri3 * ( RRS2 - RRS1 )
      + M3 * ( RRS2 * ri3 - RRS1 * ri3 + RRS1 * ri2
      + RRS2 * ri1 ) ) ;
TQS := ( mxfs * ( RRS1 * k3 + RRS2 * k2 ) ) /
      ( M1 * k3 + M2 * ( k2 + k3 ) + M3 * ( k2 +
      K3 - k1 ) ) ;

XP := 18.375 - Abs (XP) ;
XS := 18.875 - Abs (XS) ;
XI := 4.15 - Abs (XI) ;

PercentFP := ( - 6.68 ) * XP * XP + 258.4 * XP
      - 2400.0 ;
PercentFS := ( - 6.39 ) * XS * XS + 252.84 * XS
      - 2400.0 ;
PercentFI := ( - 145.16 ) * XI * XI + 1204.82 * XI
      - 2400.0 ;

ExpMVC := ( TQP * PercentFP + TQS * PercentFS
      + TQI * PercentFI ) / 100.0 ;
FP := FP * PercentFP / 100.0 ;
FS := FS * PercentFS / 100.0 ;
FI := FI * PercentFI / 100.0 ;

```

```

NMCPFX := NMCPFX + 1 ;
TotalForce := Abs (FS) + Abs (FI) + Abs (FP) ;
FingerPos := theta1 + theta2 + theta3 ;

```

```

SimResult.MPAngle := MPCount * 15 ;
SimResult.PIPAngle := PIPCount * 15 ;
SimResult.DIPAngle := DIPCount * 15 ;
SimResult.EDForce := 0.0 ;
SimResult.FSForce := FS ;
SimResult.FPForce := FP ;
SimResult.IntForce := FI ;
SimResult.LumbForce := 0.0 ;
SimResult.MVC := ExpMVC ;

```

```

Write (OutFile, SimResult) ;

```

```

END ;

```

```

END ;

```

```

END ;
Close (OutFile) ; END ;

```

```

PROCEDURE CompuForcePIPFlex ( var NPIPFX : integer ) ;

```

```

BEGIN

```

```

NPIPFX := 0 ;
FiveDegree := PI / 36.0 ;
TenDegree := PI / 18.0 ;
FifteenDegree := PI / 12.0 ;
NintyDegree := PI / 2.0 ;
Assign (OutFile, 'CSTPIPFX.DAT') ;
ReWrite (OutFile) ;

```

```

For MPCount := 1 to 2 do

```

```

BEGIN

```

```

theta1 := FifteenDegree * MPCount ;
FingerPosition := theta1 ;

```

```

For PIPCount := 1 to 2 do

```

```

BEGIN

```

```

theta2 := FifteenDegree * PIPCount ;
FingerPosition := theta1 + theta2 ;

```

```

For DIPCount := 1 to 2 do

```

```

BEGIN

```

```

theta3 := FifteenDegree * DIPCount ;
FingerPosition := theta1 + theta2 + theta3 ;

```

```

angleMCP := theta1 ;
anglePIP := theta1 + theta2 ;
angleDIP := theta1 + theta2 + theta3 ;

```

```

RRP1 := rp1 + 0.075 * rp1 * theta1 ;

```

```

RRP2 := rp2 + 0.075 * rp2 * theta2 ;
RRS1 := rs1 + 0.075 * rs1 * theta1 ;
RRS2 := rs2 + 0.075 * rs2 * theta2 ;
RRL1 := rl1 + 0.075 * rl1 * theta1 ;

M1 := 13 * cos ( PI/2 - angleDIP )
      + 12 * cos( PI/2 - anglePIP )
      + 11 * cos( PI/2 - angleMCP ) ;
M2 := 13 * cos ( PI/2 - angleDIP )
      + 12 * cos( PI/2 - anglePIP ) ;
M3 := 13 * cos ( PI/2 - angleDIP ) ;

TQ3 := TQ * 13 * cos ( PI/2 - angleDIP ) ;
TQ2 := TQ * ( 13 * cos ( PI/2 - angleDIP )
              + 12 * cos( PI/2 - anglePIP ) ) ;
TQ1 := TQ * ( 13 * cos ( PI/2 - angleDIP )
              + 12 * cos( PI/2 - anglePIP )
              + 11 * cos ( PI/2 - angleMCP ) ) ;

XP := ( - 1.0 ) * RRP1 * ( theta1 - RestMCP )
       - RRP2 * ( theta2 - RestPIP )
       - rp3 * ( theta3 - RestDIP ) ;
XS := ( - 1.0 ) * RRS1 * ( theta1 - RestMCP )
       - RRS2 * ( theta2 - RestPIP ) ;
XI := ( - 1.0 ) * ri1 * ( theta1 - RestMCP )
       + ri2 * ( theta2 - RestPIP )
       + ri3 * ( theta3 - RestDIP ) ;

k1 := RRP1 * ri2 + RRP2 * ri1 ;
k2 := RRP1 * ri3 + rp3 * ri1 ;
k3 := rp3 * ri2 - RRP2 * ri3 ;
k4 := RRP2 * RRS1 - RRP1 * RRS2 ;
k5 := rp3 * RRS2 - rp3 * RRS1 ;

FI := ( TQ1 * rp3 * RRS2 + TQ2 * k5 +
        TQ3 * ( k4 + k5 ) ) / ( RRS1 * k3 +
        RRS2 * k2 ) ;
FS := ( TQ1 * k3 + TQ2 * ( k2 + k3 ) + TQ3 *
        ( k2 + k3 - k1 ) ) /
        ( RRS1 * k3 + RRS2 * k2 ) ;
FP := ( TQ1 * ( RRS2 * ri3 ) + TQ2 * ri3 * ( RRS2 -
        RRS1 ) + TQ3 * ( RRS2 * ri3 - RRS1 * ri3 +
        RRS1 * ri2 + RRS2 * ri1 ) ) /
        ( RRS1 * k3 + RRS2 * k2 ) ;

TQI := ( mxpi * ( RRS1 * k3 + rs2 * k2 ) ) /
        ( M1 * rp3 * RRS2 + M2 * k5 + M3 *
        ( k4 + k5 ) ) ;
TQP := ( mxfp * ( RRS1 * k3 + RRS2 * k2 ) ) /
        ( M1 * RRS2 * ri3 + M2 * ri3 * ( RRS2 - RRS1 )
        + M3 * ( RRS2 * ri3 - RRS1 * ri3 + RRS1 * ri2
        + RRS2 * ri1 ) ) ;
TQS := ( mxfs * ( RRS1 * k3 + RRS2 * k2 ) ) /
        ( M1 * k3 + M2 * ( k2 + k3 ) + M3 * ( k2 +
        K3 - k1 ) ) ;

```

```

XP := 18.375 - Abs (XP) ;
XS := 18.875 - Abs (XS) ;
XI := 4.15 - Abs (XI) ;

PercentFP := ( - 6.68 ) * XP * XP + 258.4 * XP
            - 2400.0 ;
PercentFS := ( - 6.39 ) * XS * XS + 252.84 * XS
            - 2400.0 ;
PercentFI := ( - 145.16 ) * XI * XI + 1204.82 * XI
            - 2400.0 ;

ExpMVC := ( TQP * PercentFP + TQS * PercentFS
            + TQI * PercentFI ) / 100.0 ;
FP := FP * PercentFP / 100.0 ;
FS := FS * PercentFS / 100.0 ;
FI := FI * PercentFI / 100.0 ;

NPIPFX := NPIPFX + 1 ;
TotalForce := Abs (FP) + Abs (FS) + Abs (FI) ;

SimResult.MPAngle := MPCount * 15 ;
SimResult.PIPIAngle := PIPCount * 15 ;
SimResult.DIPAngle := DIPCount * 15 ;
SimResult.EDForce := 0.0 ;
SimResult.FSForce := FS ;
SimResult.FPForce := FP ;
SimResult.IntForce := FI ;
SimResult.LumbForce := 0.0 ;
SimResult.MVC := ExpMVC ;

Write (OutFile, SimResult) ;

END ;

END ;

END ;
Close (OutFile) ; END ;

```

```

PROCEDURE CompuForceMCPEX ( var NMCPEX : integer ) ;

```

```

BEGIN

```

```

NMCPEX := 0 ;
FiveDegree := PI / 36.0 ;
TenDegree := PI / 18.0 ;
FifteenDegree := PI / 12.0 ;
NintyDegree := PI / 2.0 ;
Assign (OutFile, 'CSTMCPPEX.DAT') ;
ReWrite (OutFile) ;

```

```

For MPCount := 1 to 2 do
  BEGIN
    thetal := FifteenDegree * MPCount ;
    FingerPosition := thetal ;
  
```

```

For PIPCount := 1 to 2 do
BEGIN
theta2 := FifteenDegree * PIPCount ;
FingerPosition := theta1 + theta2 ;

For DIPCount := 1 to 2 do
BEGIN
theta3 := FifteenDegree * DIPCount ;
FingerPosition := theta1 + theta2 + theta3 ;

angleMCP := theta1 ;
anglePIP := theta1 + theta2 ;
angleDIP := theta1 + theta2 + theta3 ;

RRP1 := rp1 + 0.075 * rp1 * theta1 ;
RRP2 := rp2 + 0.075 * rp2 * theta2 ;
RRS1 := rs1 + 0.075 * rs1 * theta1 ;
RRS2 := rs2 + 0.075 * rs2 * theta2 ;
RRL1 := rl1 + 0.075 * rl1 * theta1 ;

M1 := 13 * cos( angleDIP + PI ) +
12 * cos( anglePIP + PI ) +
11 * cos( angleMCP + PI ) ;
M2 := 13 * cos( angleDIP + PI ) +
12 * cos( anglePIP + PI ) ;
M3 := 13 * cos( angleDIP + PI ) ;

TQ3 := TQ * 13 * cos ( angleDIP + PI ) ;
TQ2 := TQ * ( 13 * cos ( angleDIP + PI )
+ 12 * cos ( anglePIP + PI ) ) ;
TQ1 := TQ * ( 13 * cos ( angleDIP + PI )
+ 12 * cos ( anglePIP + PI ) +
11 * cos ( angleMCP + PI ) ) ;

XE := re1 * ( theta1 - RestMCP )
+ re2 * ( theta2 - RestPIP )
+ re3 * ( theta3 - RestDIP ) ;
XI := ( - 1.0 ) * ri1 * ( theta1 - RestMCP )
+ ri2 * ( theta2 - RestPIP )
+ ri3 * ( theta3 - RestDIP ) ;
XL := ( - 1.0 ) * RRL1 * ( theta1 - RestMCP )
+ rl2 * ( theta2 - RestPIP )
+ rl3 * ( theta3 - RestDIP ) ;

c1 := re3 * ri2 - re2 * ri3 ;
c2 := re1 * ri3 + re3 * ri1 ;
c3 := re1 * ri2 + re2 * ri1 ;
c4 := re2 * rl3 - re3 * rl2 ;
c5 := re1 * rl3 + re3 * RRL1 ;
c6 := re2 * rl1 + re1 * rl2 ;
c7 := ri1 * c4 + ri2 * c5 - ri3 * c6 ;
c8 := RRL1 * c1 - rl2 * c2 + rl3 * c3 ;

FL := ( TQ1 * c1 + TQ2 * ( c1 + c2 ) + TQ3 *
( c1 + c2 - c3 ) ) /

```

```

    ( RRL1 * c1 - r12 * c2 + r13 * c3 );
FI := ( TQ1 * c4 + TQ2 * ( c4 - c5 ) + TQ3 *
    ( c4 - c5 + c6 ) ) /
    ( r11 * c4 + r12 * c5 - r13 * c6 );
FE := ( - 1.0 ) * ( TQ1 * ( r13 * c4 * c8 +
    r13 * c1 * c7 ) ) / ( re3 * c7 * c8 ) -
    ( TQ2 * ( r13 * ( c4 - c5 ) * c8 + r13 *
    ( c1 + c2 ) * c7 ) ) / ( re3 * c7 * c8 ) -
    ( TQ3 * ( r13 * ( c4 - c5 + c6 ) * c8 +
    r13 * ( c1 + c2 - c3 ) * c7 + c7 * c8 ) ) /
    ( re3 * c7 * c8 );
TQL := ( mxlumb * ( RRL1 * c1 - r12 * c2
    + r13 * c3 ) )
    / ( M1 * c1 + M2 * ( c1 + c2 ) + M3 *
    ( c1 + c2 - c3 ) );
TQI := ( mxdi * ( r11 * c4 + r12 * c5 - r13 * c6 ) ) /
    ( M1 * c4 + M2 * ( c4 - c5 ) + M3 *
    ( c4 - c5 + c6 ) );
TQE := ( mxed * ( re3 * c7 * c8 ) ) /
    ( ( - 1.0 ) * M1 * ( r13 * c4 * c8 +
    r13 * c1 * c7 ) - M2 * ( r13 * ( c4 - c5 )
    * c8 + r13 * ( c1 + c2 ) * c7 ) - M3 *
    ( r13 * ( c4 - c5 + c6 ) * c8 + r13 *
    ( c1 + c2 - c3 ) * c7 + c7 * c8 ) );

XE := 16.425 - Abs (XE) ;
XI := 4.15 - Abs (XI) ;
XL := 4.60 - Abs (XL) ;

PercentFE := ( - 9.27 ) * XE * XE + 304.41 * XE
    - 2400.0 ;
PercentFI := ( -145.16 ) * XI * XI
    + 1204.82 * XI - 2400.0 ;
PercentFL := ( - 99.01 ) * XL * XL
    + 995.02 * XL - 2400.0 ;

ExpMVC := ( TQE * PercentFE + TQI * PercentFI
    + TQL * PercentFL ) / 100.0 ;
FE := FE * PercentFE / 100.0 ;
FI := FI * PercentFI / 100.0 ;
FL := FL * PercentFL / 100.0 ;

NMCPEX := NMCPEX + 1 ;
TotalForce := Abs (FE) + Abs (FI) + Abs (FL) ;

SimResult.MPAngle := MPCount * 15 ;
SimResult.PIPAngle := PIPCount * 15 ;
SimResult.DIPAngle := DIPCount * 15 ;
SimResult.EDForce := FE ;
SimResult.FSForce := 0.0 ;
SimResult.FPForce := 0.0 ;
SimResult.IntForce := FI ;
SimResult.LumbForce := FL ;
SimResult.MVC := ExpMVC ;

Write (OutFile, SimResult) ;

```

```

        END ;

    END ;

    END ;
    Close (OutFile) ; END ;

PROCEDURE CompuForcePIPEExt ( var NPIPEX : integer ) ;
BEGIN
    NPIPEX := 0 ;
    FiveDegree := PI / 36.0 ;
    TenDegree := PI / 18.0 ;
    FifteenDegree := PI / 12.0 ;
    NintyDegree := PI / 2.0 ;
    Assign (OutFile, 'CSTPIPEX.DAT') ;
    ReWrite (OutFile) ;

    For MPCount := 1 to 2 do
        BEGIN
            theta1 := FifteenDegree * MPCount ;
            FingerPosition := theta1 ;

            For PIPCount := 1 to 2 do
                BEGIN
                    theta2 := FifteenDegree * PIPCount ;
                    FingerPosition := theta1 + theta2 ;

                    For DIPCount := 1 to 2 do
                        BEGIN
                            theta3 := FifteenDegree * DIPCount ;
                            FingerPosition := theta1 + theta2 + theta3 ;

                            angleMCP := theta1 ;
                            anglePIP := theta1 + theta2 ;
                            angleDIP := theta1 + theta2 + theta3 ;

                            RRP1 := rp1 + 0.075 * rp1 * theta1 ;
                            RRP2 := rp2 + 0.075 * rp2 * theta2 ;
                            RRS1 := rs1 + 0.075 * rs1 * theta1 ;
                            RRS2 := rs2 + 0.075 * rs2 * theta2 ;
                            RRL1 := rl1 + 0.075 * rl1 * theta1 ;

                            M1 := 13 * cos( 1.5 * PI - angleDIP ) +
                                12 * cos( 1.5 * PI - anglePIP ) +
                                11 * cos( 1.5 * PI - angleMCP ) ;
                            M2 := 13 * cos( 1.5 * PI - angleDIP ) +
                                12 * cos( 1.5 * PI - anglePIP ) ;
                            M3 := 13 * cos( 1.5 * PI - angleDIP ) ;

                            TQ3 := TQ * 13 * cos ( 1.5 * PI - angleDIP ) ;
                            TQ2 := TQ * ( 13 * cos ( 1.5 * PI - angleDIP )
                                + 12 * cos ( 1.5 * PI - anglePIP ) ) ;

```



```

TQ1 := TQ * ( 13 * cos ( 1.5 * PI - angleDIP )
+ 12 * cos ( 1.5 * PI - anglePIP ) +
11 * cos ( 1.5 * PI - angleMCP ) );

XE := re1 * ( theta1 - RestMCP )
+ re2 * ( theta2 - RestPIP )
+ re3 * ( theta3 - RestDIP );
XI := ( - 1.0 ) * ri1 * ( theta1 - RestMCP )
+ ri2 * ( theta2 - RestPIP )
+ ri3 * ( theta3 - RestDIP );
XL := ( - 1.0 ) * RRL1 * ( theta1 - RestMCP )
+ rl2 * ( theta2 - RestPIP )
+ rl3 * ( theta3 - RestDIP );

c1 := re3 * ri2 - re2 * ri3 ;
c2 := re1 * ri3 + re3 * ri1 ;
c3 := re1 * ri2 + re2 * ri1 ;
c4 := re2 * rl3 - re3 * rl2 ;
c5 := re1 * rl3 + re3 * RRL1 ;
c6 := re2 * rl1 + re1 * rl2 ;
c7 := ri1 * c4 + ri2 * c5 - ri3 * c6 ;
c8 := RRL1 * c1 - rl2 * c2 + rl3 * c3 ;

FL := ( TQ1 * c1 + TQ2 * ( c1 + c2 ) + TQ3 *
( c1 + c2 - c3 ) ) /
( RRL1 * c1 - rl2 * c2 + rl3 * c3 );
FI := ( TQ1 * c4 + TQ2 * ( c4 - c5 ) + TQ3 *
( c4 - c5 + c6 ) ) /
( ri1 * c4 + ri2 * c5 - ri3 * c6 );
FE := ( - 1.0 ) * ( TQ1 * ( ri3 * c4 * c8 +
rl3 * c1 * c7 ) ) / ( re3 * c7 * c8 ) -
( TQ2 * ( ri3 * ( c4 - c5 ) * c8 + rl3 *
( c1 + c2 ) * c7 ) ) / ( re3 * c7 * c8 ) -
( TQ3 * ( ri3 * ( c4 - c5 + c6 ) * c8 +
rl3 * ( c1 + c2 - c3 ) * c7 + c7 * c8 ) ) /
( re3 * c7 * c8 );

TQL := ( mxlumb * ( RRL1 * c1 - rl2 * c2
+ rl3 * c3 ) )
/ ( M1 * c1 + M2 * ( c1 + c2 ) + M3 *
( c1 + c2 - c3 ) );
TQI := ( mxdi * ( ri1 * c4 + ri2 * c5 - ri3 * c6 ) ) /
( M1 * c4 + M2 * ( c4 - c5 ) + M3 *
( c4 - c5 + c6 ) );
TQE := ( mxed * ( re3 * c7 * c8 ) ) /
( ( - 1.0 ) * M1 * ( ri3 * c4 * c8 +
rl3 * c1 * c7 ) - M2 * ( ri3 * ( c4 - c5 )
* c8 + rl3 * ( c1 + c2 ) * c7 ) - M3 *
( ri3 * ( c4 - c5 + c6 ) * c8 + rl3 *
( c1 + c2 - c3 ) * c7 + c7 * c8 ) );

XE := 16.425 - Abs ( XE );
XI := 4.15 - Abs ( XI );
XL := 4.60 - Abs ( XL );

PercentFE := ( - 9.27 ) * XE * XE + 304.41 * XE

```

```

        - 2400.0 ;
PercentFI := ( -145.16 ) * XI * XI
           + 1204.82 * XI - 2400.0 ;
PercentFL := ( - 99.01 ) * XL * XL
           + 995.02 * XL - 2400.0 ;

ExpMVC := ( TQE * PercentFE + TQI * PercentFI
           + TQL * PercentFL ) / 100.0 ;
FE := FE * PercentFE / 100.0 ;
FI := FI * PercentFI / 100.0 ;
FL := FL * PercentFL / 100.0 ;

NPIPEX := NPIPEX + 1 ;
TotalForce := Abs (FE) + Abs (FI) + Abs (FL) ;

SimResult.MPAngle := MPCount * 15 ;
SimResult.PIPAngle := PIPCount * 15 ;
SimResult.DIPAngle := DIPCount * 15 ;
SimResult.EDForce := FE ;
SimResult.FSForce := 0.0 ;
SimResult.FPForce := 0.0 ;
SimResult.IntForce := FI ;
SimResult.LumbForce := FL ;
SimResult.MVC := ExpMVC ;

Write (OutFile, SimResult) ;

END ;

END ;

END ;
Close (OutFile) ; END ;

PROCEDURE Min_Muscle_Force (KK : integer ; fname : string ; head : string);
BEGIN
MinTOTForce := 9999999999.9 ;
MaxTOTForce := 0.0000000001 ;
Assign (OutFile, fname) ;
Reset (OutFile) ;
For RunCount := 1 to KK Do
begin
Read (OutFile, SimResult) ;
TotalForce := Abs (SimResult.EDForce) + Abs (SimResult.FSForce)
             + Abs (SimResult.FPForce) + Abs (SimResult.IntForce)
             + Abs (SimResult.LumbForce) ;
If TotalForce < MinTOTForce then
begin
MinTOTForce := TotalForce ;
MinMPAngle := SimResult.MPAngle ;
MinPIPAngle := SimResult.PIPAngle ;
MinDIPAngle := SimResult.DIPAngle ;
MinEDForce := SimResult.EDForce ;
MinFSForce := SimResult.FSForce ;
MinFPForce := SimResult.FPForce ;

```

```

    MinFIForce := SimResult.IntForce ;
    MinFLForce := SimResult.LumbForce ;
end
else
begin
    If TotalForce > MaxTOTForce then
        begin
            MaxTOTForce := TotalForce ;
            MaxMPAngle := SimResult.MPAngle ;
            MaxPIPAngle := SimResult.PIPAngle ;
            MaxDIPAngle := SimResult.DIPAngle ;
            MaxEDForce := SimResult.EDForce ;
            MaxFSForce := SimResult.FSForce ;
            MaxFPForce := SimResult.FPForce ;
            MaxFIForce := SimResult.IntForce ;
            MaxFLForce := SimResult.LumbForce ;
        end ;
    end ;
end ;
Close (OutFile) ;

Writeln (lst) ;
Writeln (lst, '***', head, '***') ;
Writeln (lst) ;
Writeln (lst, 'MinTotalForce : ', MinTOTForce) ;
Writeln (lst, 'MCP : ', MinMPAngle, ' ', 'PIP : ', MinPIPAngle, ' ',
    'DIP : ', MinDIPAngle) ;
Writeln (lst, 'ED : ', MinEDForce, ' ', 'FS : ', MinFSForce, ' ',
    'FP : ', MinFPForce) ;
Writeln (lst, 'Int. : ', MinFIForce, ' ', 'Lumb. : ', MinFLForce) ;
Writeln (lst) ;

Writeln (lst) ;
Writeln (lst, 'MaxTotalForce : ', MaxTOTForce) ;
Writeln (lst, 'MCP : ', MaxMPAngle, ' ', 'PIP : ', MaxPIPAngle, ' ',
    'DIP : ', MaxDIPAngle) ;
Writeln (lst, 'ED : ', MaxEDForce, ' ', 'FS : ', MaxFSForce, ' ',
    'FP : ', MaxFPForce) ;
Writeln (lst, 'Int. : ', MaxFIForce, ' ', 'Lumb. : ', MaxFLForce) ;

END ;

PROCEDURE Data_To_TextFile (JJ : integer ; fname : string ; txfname : string) ;

Begin
    Assign (OutFile, fname) ;
    Reset (OutFile) ;
    Assign (TX, txfname) ;
    Rewrite (TX) ;

    For RunCount := 1 to JJ Do
        Begin
            Read (OutFile, SimResult) ;
            TotalForce := Abs (SimResult.EDForce) + Abs (SimResult.FSForce)
                + Abs (SimResult.FPForce) + Abs (SimResult.IntForce)
                + Abs (SimResult.LumbForce) ;

```

```

MaxTOTForce := TotalForce ;
MaxMPAngle := SimResult.MPAngle ;
MaxPIPAngle := SimResult.PIPAngle ;
MaxDIPAngle := SimResult.DIPAngle ;
MaxEDForce := SimResult.EDForce ;
MaxFSForce := SimResult.FSForce ;
MaxFPForce := SimResult.FPForce ;
MaxFIForce := SimResult.IntForce ;
MaxFLForce := SimResult.LumbForce ;

Writeln (TX, 'TotalForce : ', MaxTOTForce, ' ',
          'MCP : ', MaxMPAngle, ' ', 'PIP : ', MaxPIPAngle, ' ',
          'DIP : ', MaxDIPAngle ) ;
Writeln (TX, 'ED : ', MaxEDForce, ' ', 'FS : ', MaxFSForce, ' ',
          'FP : ', MaxFPForce, ' ',
          'Int. : ', MaxFIForce, ' ', 'Lumb. : ', MaxFLForce ) ;
end ;
Close (OutFile) ;
Close (TX) ; END ;

```

BEGIN

```

CompuForceMCPFlex (NMCPFX) ;
CompuForcePIPFlex (NPIPFX) ;
CompuForceMCPEExt (NMCPEX) ;
CompuForcePIPEExt (NPIPEX) ;

```

```

Min_Muscle_Force (NMCPFX, 'CSTMCPFX.DAT', 'Non-Constant M-A MCP Flexion');
Min_Muscle_Force (NPIPFX, 'CSTPIPFX.DAT', 'Non-Constant M-A PIP Flexion');
Min_Muscle_Force (NMCPEX, 'CSTMCPFX.DAT', 'Non-Constant M-A MCP Extension');
Min_Muscle_Force (NPIPEX, 'CSTPIPEX.DAT', 'Non-Constant M-A PIP Extension');

```

```

RawData_Print (NMCPFX, 'CSTMCPFX.DAT');
RawData_Print (NPIPFX, 'CSTPIPFX.DAT');
RawData_Print (NMCPEX, 'CSTMCPFX.DAT');
RawData_Print (NPIPEX, 'CSTPIPEX.DAT');

```

```

Data_To_TextFile (NMCPFX, 'CSTMCPFX.DAT', 'CTMFXTX.TXT');
Data_To_TextFile (NPIPFX, 'CSTPIPFX.DAT', 'CTPFXTX.TXT');
Data_To_TextFile (NDIPFX, 'CSTDIPFX.DAT', 'CTDFXTX.TXT');
Data_To_TextFile (NMCPEX, 'CSTMCPFX.DAT', 'CTMEXTX.TXT');
Data_To_TextFile (NPIPEX, 'CSTPIPEX.DAT', 'CTPEXTX.TXT');
Data_To_TextFile (NDIPEX, 'CSTDIPEX.DAT', 'CTDEXTX.TXT');

```

END.

## BASIC Source List for Sampling EMG Signals and A/D Conversions

```

10 '*****
20 ' PROGRAM NAME : MVCTEST.BAS (EMG at MVC)
30 '*****
40 ' PROGRAMMED BY : KOO-HYOUNG LEE
50 ' : JANUARY 26, 1991
60 '*****
70 '
80 ' PURPOSE : TO COLLECT DIGITIZED DATA OF SURFACE
          ELECTROMYOMGAPHY USING
90 ' DASH-8 A/D BOARD AND IBM PC/AT COMPUTER.
100 '
110 ' SYMBOLS : DASH8 ..... A SETUP PARAMETER
120 ' MD% ..... DASH8 MODE SETTING
130 ' LT% ..... CHANNEL SCAN LIMITS
140 ' DIO% .....
150 ' FLAG% ..... ERROR CODE
160 ' FORCE ..... FINGER FORCE
170 ' EMG% ..... ELECTROMYOGRAPHY
180 ' SBJ$ ..... SUBJECT NUMBER
190 ' TEST$ ..... TEST CODE NUMBER
200 '
210 '*****
220 CLS
230 DEFINT I,J,K,L,M,N
240 X = 0
250 ' INITIALIZING DASH8
260 OPEN "DASH8.ADR" FOR INPUT AS #1
270 INPUT #1, BASADR%
280 CLOSE #1
290 MD% = 0
300 DASH8 = 0
310 FLAG% = 0
320 CALL DASH8 (MD%, BASADR%, FLAG%)
330 IF FLAG% < > 0 THEN LOCATE 12, 20 : PRINT "Initialization error !" : GOTO 1080
340 IF FLAG% = 0 THEN LOCATE 15, 20 : PRINT "Initialization is O.K. !"
350 ' SET SCAN LIMITS
360 DIM LT%(2), DIO%(2)
370 CLS
380 MD% = 1
390 LT%(0) = 1
400 LT%(1) = 1
410 FLAG% = X
420 CALL DASH8 (MD%, LT%(0), FLAG%)
430 IF FLAG% < > 0 THEN LOCATE 12, 20 : PRINT "Error in setting scan limits !" :
      GOTO 1080

```

```

440 IF FLAG% = 0 THEN LOCATE 12, 20 : PRINT "Setting scan limit is O.K. !"
450 ' SET SAMPLING RATE
460 CLS
470 MD% = 10
480 DIO%(0) = 2
490 DIO%(1) = 3
500 FLAG% = X
510 CALL DASH8 (MD%, DIO%(0), FLAG%)
520 IF FLAG% < > 0 THEN LOCATE 12, 20 : PRINT "Error in setting counter 2 !" :
    GOTO 1080
530 MD% = 11
540 DIO%(0) = 2
550 DIO%(1) = 4056 'Sampling rate is 1000 Hz
560 CALL DASH8 (MD%, DIO%(0), FLAG%)
570 IF FLAG% < > 0 THEN LOCATE 12, 20 : PRINT "Error in setting sampling rate !" :
    GOTO 1080
580 IF FLAG% = 0 THEN LOCATE 12, 20 : PRINT "Everything is O.K. for the test"
590 PRINT
600 PRINT "Press any key to start test !"
610 IF INKEY$ = "" GOTO 610
620 CLS
630 LOCATE 8, 12
640 INPUT "Enter subject number :", SB$
650 PRINT
660 INPUT "Enter test direction (U, D, F, B) :", TST$
670 PRINT
680 INPUT "Enter the desired output file name (without extension) :", FLN$
690 PRINT
700 'Collect data
710 DIM EMG%(5000)
720 XC = - 11
730 CLS : LOCATE 12, 20
740 PRINT "Press <SPACE> key to start A/D conversions !"
750 IF INKEY$ = "" THEN GOTO 750
760 FOR M=1 TO 300
770 M = M + 1
780 NEXT M
790 BEEP : CLS
800 LOCATE 12, 20 : PRINT "Now, performing A/D conversions ! Please wait."
803 LOCATE 14, 20 : PRINT "Test number : " XC
805 CX$ = STR$(XC)
810 MD% = 5
820 DIO%(0) = VARPTR(EMG%(1))
830 DIO%(1) = 5000
840 CALL DASH8 (MD%, DIO%(0), FLAG%)
850 IF FLAG% < > 0 THEN LOCATE 12, 20 : PRINT "Error in A/D conversions !" :
    GOTO 1080
860 ' Store the data on hard disk
870 BEEP : BEEP
880 CLS : LOCATE 12, 15
890 PRINT "Press any key to start store data on hard disk !"
900 IF INKEY$ = "" THEN GOTO 900
910 BEEP
920 CLS : LOCATE 12, 20 : PRINT "Storing data on hard disk. Please wait !"
930 FL$ = FLN$ + "."
940 FL$ = FL$ + CX$

```

```
950 OPEN FL$ FOR OUTPUT AS #1
970 FOR I=1 TO 5000
980 PRINT #1, I; EMG%(I)
990 NEXT I
1000 CLOSE #1
1010 XC = XC - 1
1020 BEEP : PRINT "Press <SPACE> key to perform another MVC test !"
1030 PRINT
1040 PRINT "Press <Q> key to finish the MVC test !"
1050 A$ = INKEY$ : IF A$ = "" THEN 1050 ELSE 1060
1060 IF A$ = "Q" THEN 1090
1070 IF A$ = "q" THEN 1090 ELSE 730
1080 CLS : LOCATE 12, 20 : PRINT "Check the system and re-run the program !" : GOTO 1120
1090 CLS
1100 LOCATE 12, 15
1110 PRINT "Well done ! MVC test at this position is O.K."
1120 END
```

## Vita

Koo-Hyoung Lee was born on April 20, 1953, in Korea, and received B.S. and M.S. degrees in Industrial Engineering from Seoul National University, Seoul, Korea. After receiving the M.S. degree with major in Human Factors Engineering, he taught Human Factors Engineering and Industrial Engineering courses in several universities for seven years as an instructor. He worked at the Korea Sports Science Institute of the Korean Olympic Committee, in which he was a head researcher and director of Sports Physiology. He was a member of the Biomechanics Committee in the Seoul Olympic Scientific Congress Organizing Committee and of the Biomechanics and Exercise Physiology Subcommittee of the International Olympic Committee in Seoul Olympic Organizing Committee. He was a visiting scholar in Sports Science and Medicine of the United States Olympic Committee. He was also a invited researcher in the Public Health and Physical Fitness Research Institute in the Medical School of Seoul National University.

He conducted numerous experiments and research on assessment of human capabilities and performance, and is a author of many seminars and publications which include biomechanical, physiological, and psychophysical aspects of Human Factors Engineering. His research interests include ergonomic design and evaluation of industrial products, assessment of human capabilities and performance, biomechanics, work physiology, mental workload assessment, human factors in aviation (cockpit), human-computer interface, industrial safety, rehabilitation engineering, application of microcomputers in the laboratory, and application of human factors engineering to sports science.

He is a member of Alpha Pi Mu, Human Factors Society, Society for Information Display, Korean Institute of Industrial Engineers, and Korean Society of Operations Research and Management Science.

A handwritten signature in black ink, reading "Koo-Hyoung Lee", is written over a horizontal line.