Kinematics of the Fingers During Typing

by

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(ABSTRACT)

When typing on a keyboard, the fingers may be in awkward postures, making repetitive motions, and exerting high forces which are risk factors of cumulative trauma disorders. In this experiment, the kinematics of the fingers while typing were investigated for 12 right-handed subjects (6 male and 6 female) to gain a better understanding of factors which influence how a finger strikes a key. The apparatus for this experiment included an exoskeleton to determine angular displacements of the finger joints and a motion analysis system to determine the coordinates of the wrist and the keys on the keyboard.

This experiment examined four dependent variables: the fingertip angle with respect to the horizontal at the point of contact and at the point of maximum depression of the key, and the linear vertical and horizontal components of velocity of fingertip due to the finger joints at the point of contact with the key. The factors investigated included *Gender*, *Finger* (Index, Middle, and Ring), *Row* (Upper, Middle, and Lower), and *Digraph* (typing two letters with the same finger, with two fingers on the same hand, or with two opposite hands).

The results indicated that for all four dependent measures, there was a significant difference between all three levels of *Row*. For the factor *Finger*, there was no significant difference between the middle and ring fingers. Typing with the index finger, typing two letters with the same finger, or typing on the upper row resulted in smaller fingertip

angles than the other conditions. All levels of *Digraph* resulted in significantly different linear vertical velocities of the fingertip while certain combinations of the levels of *Finger*, *Row*, and *Gender* were significantly different for the linear horizontal velocities.

From the results, it appears that the methods employed in this experiment were effective to measure the angle of the fingertip at the point of contact and at the point of maximum depression and to measure the linear vertical and horizontal components of velocity produced by the finger joints. The results for the linear vertical and horizontal components of velocity for the fingertip also indicate that the wrist velocity (which was not measured) may contribute to the overall fingertip velocities at the point of contact with the key and for this reason, should be examined in future research.

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1. INTRODUCTION

1.1 Rationale

The advent of computers into the work environment has increased the efficiency of keyboard operators, but has also increased the repetition of keying tasks. Experienced operators, who typically average 56,000 to 83,000 keystrokes per day (Klemmer, 1971), may have an increased risk of developing cumulative trauma disorders. Repetitive motions and forceful exertions have been identified as risk factors for cumulative trauma disorders and when acting together these two risk factors are multiplicative (Silverstein, Fine, and Armstrong, 1987). This implies that for very repetitive keying tasks, high fingertip forces may contribute to the development of cumulative trauma disorders. A relatively minor reduction in the fingertip forces applied to the keys may significantly reduce the daily cumulative force applied by the fingers (Rempel, Gerson, Armstrong, Foulke, and Martin, 1991).

Only a few studies have attempted to analyze the fingertip forces while keying (Rempel et al., 1991 and Sind, 1989). Rempel and coworkers (1991) investigated the fingertip forces while using three different keyboards which differed only in their key force and displacement characteristics. Only the vertical forces applied to the keyboard by the fingers were measured and this was done by attaching a strain gauge load cell to each side of the keyboard. The results indicated that the average fingertip forces applied by the subjects were 3.1 times greater than the force required for key activation. This study also showed that the effects of keyboard, finger, and the covariate of typing speed were significant while the row of the key was not.

One of Sind's (1989) objectives was to assess the amount of force applied to membrane switches by typical users. The force measurement system was based on the one developed by Young and Barton (1983) and consisted of a rigid platform supported at each of its four corners. Seven miniature strain gauge load cell force transducers (four vertically, two longitudinally, and one laterally) were configured to measure the force of the keypresses. This allowed both horizontal and vertical forces to be measured.

Sind's method for measuring forces at the fingertip did take into account more than just the vertical component of force (unlike Rempel et al., 1991), but both methods measured the force at a location away from the point of contact with the key. For both methods, the force at the fingertip was measured after the force had traveled through the keyboard. The elastic properties of the keyboard may alter the force that is finally recorded by the measuring device. Although the magnitude of this alteration is unknown, even small changes in the force may be significant due to the small size of the force to begin with.

Given the limitations of these measurement techniques and the importance of reducing fingertip forces for epidemologic reasons, there is a need to develop an accurate method for assessing fingertip forces while keying. One alternative is to develop a programmable robotic finger that has a force measurement device in the end of the fingertip. The robotic finger could be used to measure the force exerted by the robotic finger during the actuation of a key. To accurately simulate how the finger strikes a key, the angle of the fingertip with respect to the key and the velocity the fingertip is moving at the point of contact with the key must be known. These two inputs (velocity and angle of the fingertip at the key) would be needed to program the robotic finger to strike a key similar to how a human strikes a key.

This thesis presents a method for determining the angle of the fingertip at the point of contact with the key and the horizontal and vertical components of velocity at the same point. This thesis also investigates the angle of the fingertip at the maximum depression of the key. It is hoped that this position and velocity data will be used in future research to aid in development of an accurate method for determining fingertip forces during typing. Once this method is attained, it could be used to evaluate different keyboards to assess their potential contribution to cumulative trauma disorders.

1.2 Objectives

There were several objectives of this thesis which focused on the kinematics of the fingers during typing:

1. To determine the range of angles of the fingertip at the point of contact with the key and at the point of maximum depression of the key.
2. To determine the range of linear horizontal and vertical components of velocity of the fingertip at the point of contact with the key.
3. To determine whether the angle of the fingertip at the point of contact with the key or at the point of maximum depression of the key is dependent on which finger (index, ring, or middle) is doing the typing; on what row the key is (upper, middle, or low); or on the sequence of typing movements (typing two letters with opposite hands, the same finger, or two fingers on the same hand).
4. To determine whether the linear horizontal or vertical components of velocity of the fingertip at the point of contact with the key is dependent on which finger (index, ring, or middle) is doing the typing; on what row the key is (upper, middle, or low); or on the sequence of typing movements (typing two letters with opposite hands, the same finger, or two fingers on the same hand).

2. LITERATURE REVIEW

2.1 Overview

This literature review is divided into four major sections. First, introductory material related to the anatomy and anthropometry of the hand and fingers will be covered. Second, literature relevant to cumulative trauma disorders and its relation to repetitive motions in keying operations is presented. The third major section of the literature review addresses the kinematics of the hand and fingers during typing. The last section in this literature review covers the techniques for measuring the displacement data of the hand and fingers and for calculating velocity from this displacement data.

2.2 Anatomy and Anthropometry of the Hand

The precise movements of the fingers are attributed to the complex mechanical structure of the hand and wrist. The skeleton of the hand consists of the bones of the carpus (wrist), the metacarpus (palm), and the phalanges (bones of the digits). These bones, as well as their corresponding joints and muscles, are detailed, followed by a description of the carpal tunnel. This section concludes with some anthropometric and link length data of the hand.

2.2.1 Bones of the Wrist, Hand, and Fingers

The bones of the wrist, hand, and fingers are shown in Figure 2.1. The wrist is constructed of eight small, irregular carpal bones which are arranged in two transverse rows (proximal and distal) of four each. The proximal carpal row joins the wrist to the forearm, and the distal row joins the wrist to the fingers. The proximal row, from lateral to medial side, is made up of the scaphoid, lunate, triquetral, and pisiform bones. The distal row, from lateral to medial side, includes the trapezium, trapezoid, capitate, and hamate. As a whole, the carpal bones are bound together so that the anterior (palmar) surface of the carpus is concave forward and the posterior surface is slightly rounded.

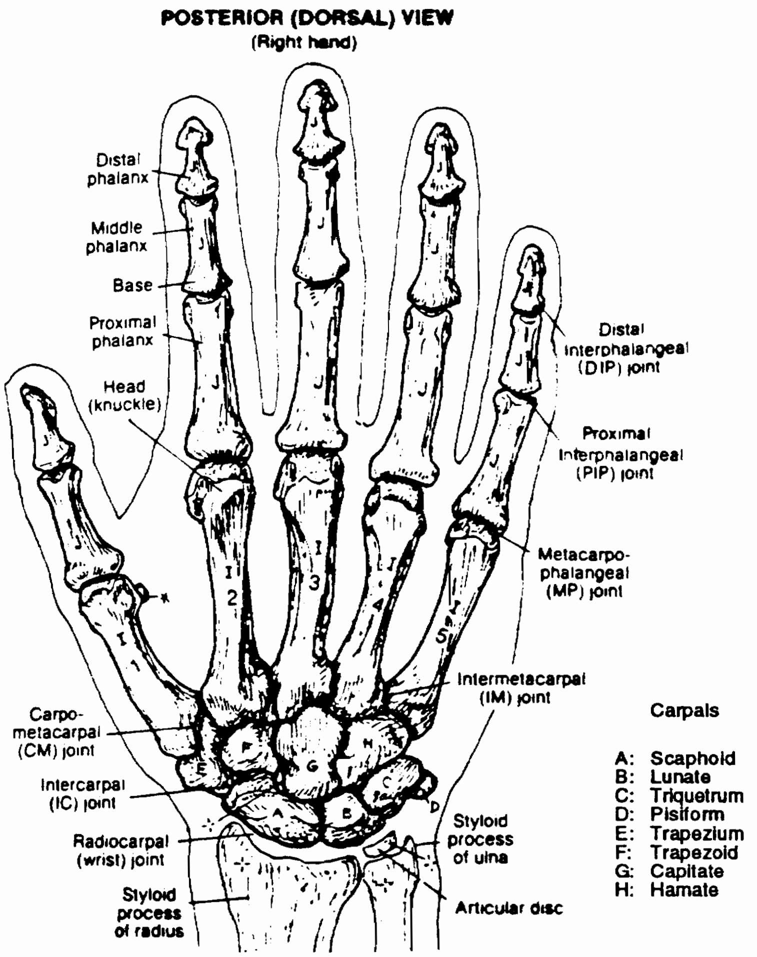

Figure 2.1 Bones and joints of the wrist, hand, and fingers. Taken from Kapit and Elson, 1993.

There are five metacarpal bones in the hand which are numbered from the lateral to the medial side. Each metacarpal bone is comprised of a proximal base, a shaft, and a distal head. The metacarpals for the four fingers are remarkably alike, with length being the main difference between them. The metacarpal for the thumb, which is quite different from the other metacarpals, is much shorter and broader. The metacarpals move with the carpal bones and form a strong framework for the hand and a firm base for movement of the finger bones. The bases of the second to fifth metacarpals are closely bound together by ligaments and articulate to the carpal bones. The heads of the metacarpals articulate with the digits and form the knuckles.

An individual bone in a digit is called a phalanx and collectively they are called phalanges. There are 14 phalanges in each hand, three in each of the digits two to five (fingers) and two in the digit one (thumb). The three bones of each finger are the proximal, middle, and distal phalanges and the two bones of the thumb are the proximal and distal phalanges. A phalanx consists of a shaft and two extremities, the base and the head. The base of the proximal phalanx is oval and concave for articulation with the rounded head of the metacarpal. The base of the proximal phalanx tapers to a slender shaft and ends with a rounded head. The base of the middle phalanx is raised at the center to conform to the rounded head of the proximal phalanx with which it articulates and then also ends with a rounded head. The base of the distal phalanx is shaped to conform with the head of the middle phalanx and then terminates with horseshoe-shaped elevations on the anterior (palmar) side which support the sensitive tissues of the fingertip.

2.2.2 Joints of the Wrist, Hand and Fingers

The different joints in the wrist, hand, and fingers (see Figure 2.1) allow a wide range of movements of the wrist and fingers (see Figure 2.2). There are three types of

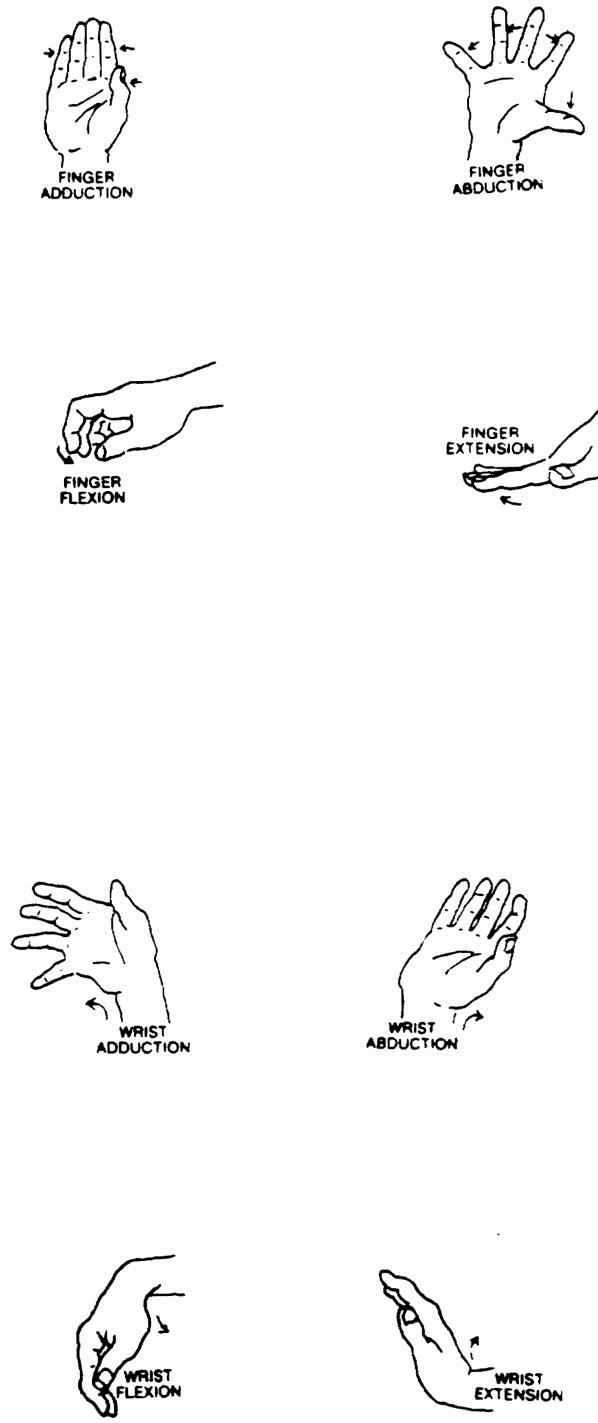

Figure 2.2 Movements of the finger and wrist joints. Taken from Kapit and Elson, 1993.

joints in the carpus including radiocarpal, midcarpal, and intercarpal joints. The major movements of the wrist take place at the radiocarpal and midcarpal joints. The radiocarpal (wrist) joint allows flexion, extension, abduction, adduction, and circumduction of the hand (Crouch, 1985). At the radiocarpal joint, movement takes place between the radius and the scaphoid and lunate bones of the proximal row of carpal bones. The articular cartilage of the ulna extends the radiocarpal joint medially. The articular capsule is lined internally by synovial membrane and completely surrounds the joint. The ulnar and radial collateral ligaments along the sides of the wrist and the palmar and dorsal radiocarpal ligaments strengthen the capsule.

The midcarpal joint (MC) is between the proximal and distal carpals. The articulations between the two rows of carpals are connected by dorsal, palmar, and collateral ligaments. Flexion and extension are the principal movements of the midcarpal joint, although slight rotation is possible. The midcarpal joint working in conjunction with the radiocarpal joint increases the flexibility of the wrist and the range of extension and flexion of the hand. The intercarpal (IC) joints are between adjacent bones of both rows of the carpal bones. These joints permit only a minimal amount of gliding movements between adjacent bones. The bones of each row of carpals are bound together by interosseous, palmar, and dorsal ligaments which maintain the flexible union and alignment of the carpal bones.

For the second to fifth metacarpal bones, there is a common carpometacarpal (CMC) joint which is between the metacarpal bones and distal row of carpal bones. This joint allows a minimal amount of gliding movement and is bounded by dorsal, palmar, and interosseous ligaments. The intermetacarpal joints (IM) extend a short distance distally from the common cavity between the bases of the metacarpal bones. The dorsal, palmar, and interosseous ligaments limit the movement of the metacarpal bones upon each other and ensure that the hand moves the carpal bones as a unit. The articulation of the metacarpal of the thumb with the trapezium of the carpus is saddle-shaped and has a wide range of movements. The joint is covered with a thick, but loose articular capsule and is lined by its own synovial membrane.

The metacarpophalangeal joint (MP) is formed by the articulation of the heads of the metacarpal bones with the bases of the proximal phalanges of the digits. For the fingers, this joint allows both flexion and extension movements and to a limited extent, abduction and adduction. Abduction and adduction are limited by the collateral ligaments, and prevented entirely when the fingers are flexed. Between the thumb and its metacarpal, only flexion and extension are possible. The collateral ligaments which are on the sides of the MP joints tighten during flexion and draw the ends of the bones closely together which precludes adduction and abduction. The palmar ligaments are securely attached to the bases of the phalanges. They blend with the transverse metacarpal ligament which binds the metacarpals together except for the metacarpal of the thumb. Palmar ligaments have grooves anteriorly for the passage of flexor tendons.

The proximal interphalangeal (PIP) and distal interphalangeal (DIP) articulations are hinge joints allowing only flexion and extension movements. Each interphalangeal joint has a palmar and two collateral ligaments (one each side of the joint). These ligaments preclude any lateral movements so that all spreading of the fingers is performed at the metacarpophalangeal joints. Note that the thumb does not have both PIP and DIP joints, but rather has one interphalangeal joint (IP) which is also limited to flexion and extension movements.

2.2.3 Muscles and Tendons of the Wrist and Fingers

The muscles of the wrist and fingers can be divided into those acting primarily on the wrist and hand, and those acting upon the fingers which secondarily produce wrist movements. The muscular system acting at the wrist consists of six muscles. Three of theses muscles are responsible for wrist flexion; namely the flexor carpi radialis, palmaris longus, and flexor carpi ulnaris. The muscles responsible for wrist extension are the extensors carpi radialis longus and brevis and the extensor carpi ulnaris. The flexor carpi radialis and the extensor carpi radialis longus and brevis also contribute to wrist radial deviation while the flexor carpi ulnaris and extensor carpi ulnaris contribute to ulnar deviation. Both the extensor and flexor muscles of the wrist are connected by tendons to the metacarpals.

The finger muscles can be divided into two groups: those muscles in the forearm whose tendons extend across the wrist and hand to attach to the fingers (extrinsic muscles) and those muscles within the hand (intrinsic muscles). The extrinsic muscular system of the forearm consists of five muscles. The flexor digitorum superficialis and flexor digitorum profundus contribute to finger and wrist flexion. The finger tendons of these two muscles pass under the flexor retinaculum. The extensor digitorum, extensor indicis, and extensor digiti minimi contribute to finger and wrist extension. The finger tendons of these two muscles pass under the extensor retinculum. The finger tendons which attach the muscles to the finger bones are surrounded by sheaths of fibrous tissues. Their inner lining, called synovium, produces synovial fluid, which facilitates gliding of the tendons.

The intrinsic muscles are located in the palm of the hand or between the metacarpal bones. There are four lumbricales (one for each finger) which are the only skeletal muscles with no direct bony attachment. There are three palmar interossei and four dorsal interossei. These muscles perform a variety of functions in the fingers including abduction, adduction, flexion, and extension. The hypothenar eminence is formed by the three intrinsic muscles that function at the little finger including the abductor and flexor digiti minimi brevis and the opponens digiti minimi. Table 2.1 summarizes the muscles of the wrist and fingers and their corresponding actions.

Table 2.1 Muscles of the Wrist and Fingers and Their Actions. Adapted from Donnelly, 1990.

	Wrist Flex.	Wrist Ext.	Wrist Radial Dev.	Wrist Ulnar Dev.	Finger Flex.	Finger Ext.	Finger Abd.	Finger Add.
Flexor Carpi Radius	X		X					
Palmaris Longus	X							
Flexor Carpi Ulnaris	X			X				
Extensor Carpi Radialis Longus and Brevis		X	X					
Extensor Carpi Ulnaris		X		X				
Flexor Digitorum Superficialis	X				X			
Flexor Digitorum Profundus	X				X			
Extensor Digitorum		X				X		
Extensor Indicis		X				X		
Extensor Digiti Minimi		X				X		
Abductor Digiti Minimi							X	
Flexor Digiti Minimi Brevis					X			
Opponens Digiti Minimi					X		X	
Dorsal Interossei							X	
Palmar Interossei								X
Lumbricales					X	X		

2.2.4 Carpal Tunnel of the Hand

The carpal tunnel in the wrist is formed by the carpal bones and the transverse carpal ligament. A schematic view of the carpal tunnel is shown in Figure 2.3. On the palmar side of the wrist, the carpal bones form a concave surface which make up the floor and sides of the tunnel. The radial carpal, intercarpal, and carpometacarpal ligaments connect the carpal bones. The transverse carpal ligament, which is attached to the tubercle of the trapezium on the radial side and the hook of the hamate on the ulnar side, covers the carpal bones forming the roof of the tunnel. Passing through the carpal tunnel are the long tendons of the extrinsic finger muscles (flexor digitorum profundus and superficialis) and flexor pollicis longus muscles which connect to the fingers. Also passing through the carpal tunnel are the median nerve and the blood vessels. The median nerve inervates the thumb, the lateral half of the palm up to the thumb, the index and middle fingers, and the radial side of the ring finger.

2.2.5 Hand Anthropometry

There are many different dimensions of the hand that can be easily measured such as hand length, hand breadth, and hand circumference. These dimensions vary over different populations and between males and females. The hand dimensions for adult male and female U.S. civilians in Table 2.2 are from Kroemer, Kroemer, and Kroemer-Elbert (1994). This data is based on a 1988 anthropometric survey of U.S. Army personnel of 2,208 female and 1,774 male soldiers. Kroemer et al.'s decision to use the 1988 Army survey was based on the fact that among the U.S. military services, the Army is the largest and anthropometrically least biased sample of the total U.S. adult population.

Although there are many measurements of the hand that are nonintrusive, accurate measurements of the segment lengths and joint centers-of-rotations of the bones of the

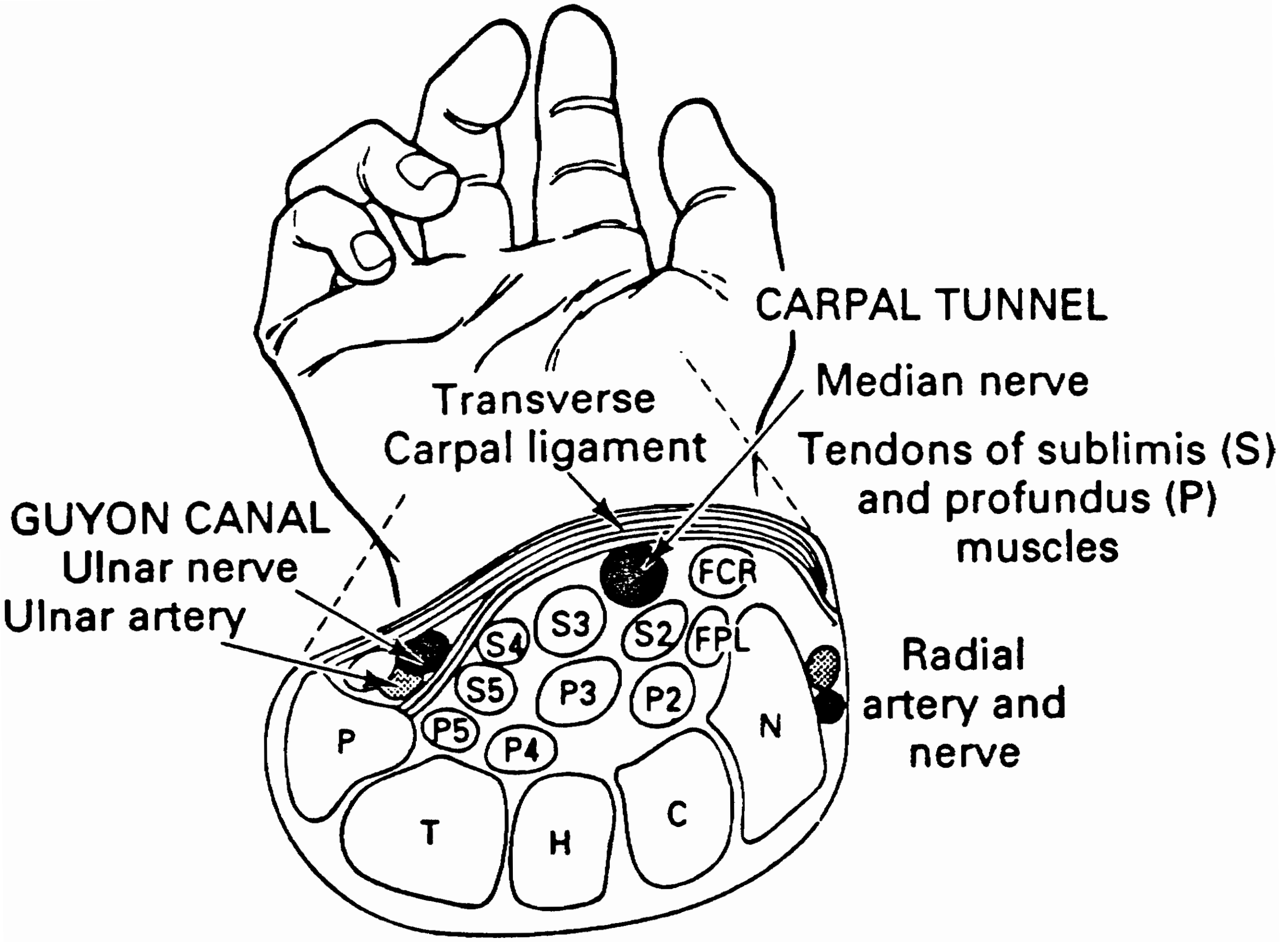

Figure 2.3 Schematic view of carpal tunnel with the tendons of the superficial (S), and profound (P) finger flexor muscles, flexors of the thumb (FCR, FPL), nerves and arteries, carpal bones (P, T, H, C, N) and ligaments. Taken from Kroemer, Kroemer, and Kroemer-Elbert, 1994.

Table 2.2 Hand Dimensions of U.S. Civilian Adults, Female/Male, in mm. Adapted from Kroemer, Kroemer, and Kroemer-Elbert, 1994.

	Percentiles			
	5th	50th	95th	SD
HAND DIMENSIONS				
Circumference, metacarpal	172.5/ 198.5	186.2/ 21.38	200.3/ 230.3	8.5/ 9.7
Hand length	165.0/ 178.7	180.5/ 193.8	196.9/ 210.6	9.7/ 9.8
Hand breadth, metacarpal	73.4/ 83.6	79.4/ 90.4	85.6/ 97.6	3.8/ 4.2
Thumb breadth, interphalangeal	18.6/ 21.9	20.7/ 24.1	22.9/ 26.5	1.3/ 1.4

hand are difficult to attain without invasive measures (e.g., radiographic techniques or use of cadavers). This problem was addressed in a study by Bucholz, Armstrong, and Goldstein (1992). The goal of this study was to model the kinematic anthropometry of the human hand as a function of external hand measurements so that segment link lengths could be predicted noninvasively. The kinematic skeleton of the human hand that was used in this study is shown in Figure 2.4 and the equations in Table 2.3. Six cadaver hands, four from males and two from females, were used to estimate the positions of the centers-of-rotation and the lengths of the kinematic segments of the hand. The model for estimating the lengths of the kinematic segments included four equations for each the five digits of the hand. The only variable needed for these equations is the external hand length. This model accounted for 49 to 99% of the variability of the segment length depending on the particular segment. Table 2.3 gives the equations for estimating the four kinematic segments of digits II, III, and IV (index, middle, and ring fingers) in millimeters. The correlation factor, R^2, for each kinematic segment is shown in parenthesis.

2.3 Cumulative Trauma Disorders

Cumulative trauma disorders, CTDs, are the summary result of repeated microtraumas (Kroemer, 1989). Cumulative trauma disorders have been defined as injuries to the muscles, tendon, blood vessels, and/or nerves of the body that are caused, precipitated, or aggravated by repeated exertions or movements of the body (Kroemer, 1989). These disorders are characterized by discomfort, impairment, disability or persistent pain in the muscles, tendons, joints, and other soft tissues.

Injuries to the muscles from CTDs may include instances where the muscle is stretched resulting in aching and swelling or where the fibers of the muscles or tendons are actually torn. Tendon sheaths may also become inflamed. This is caused by the

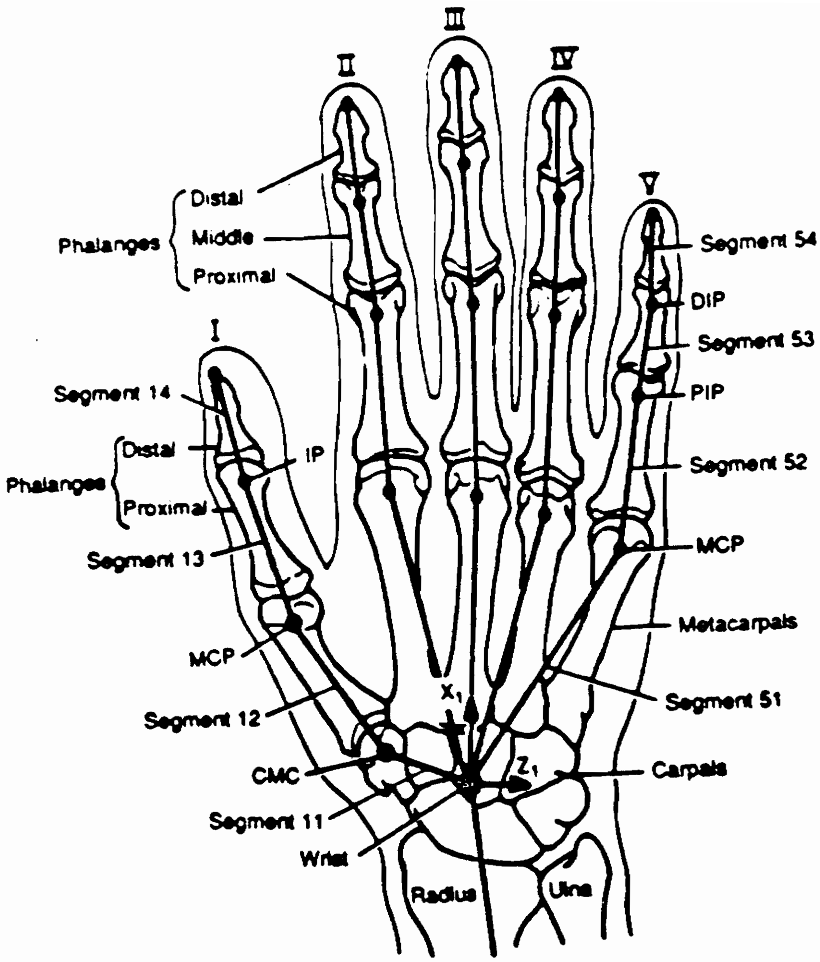

Figure 2.4 Kinematic skeleton of the human hand. Taken from Bucholz, Armstrong, and Goldstein, 1992.

Table 2.3 Estimating Kinematic Segment Lengths of the Hand (mm) from Hand Length(HL). Taken from Bucholz, Armstrong, and Goldstein, 1992.

	Digit		
Segment	II	III	IV
1 - Metacarpal	0.463 * HL	0.446 * HL	0.421 * HL
(R^2)	(0.96)	(0.92)	(0.93)
2 - Proximal Phalanx	0.245 * HL	0.266 * HL	0.244 * HL
(R^2)	(0.99)	(0.85)	(0.77)
3 - Middle Phalanx	0.143 * HL	0.170 * HL	0.165 * HL
(R^2)	(0.83)	(0.69)	(0.99)
4 - Distal Phalanx	0.097 * HL	0.108 * HL	0.107 * HL
(R^2)	(0.73)	(0.56)	(0.63)

HL: Hand Length (mm)

friction between the tendon and its sheath due to the decrease in its synovial fluid. Repeated exertions or sustained pressure may impair the motor, sensory, or autonomic nerve. Damage of the motor nerves reduces the ability to generate force while damage of the sensory nerve causes tingling or numbness. Automatic nerve impairment may cause dryness of the skin areas controlled by that nerve.

Carpal tunnel syndrome, one of the best known CTDs, is the result of compression of the median nerve as it passes through the carpal tunnel at the base of the palm. The cause of carpal tunnel syndrome is tendosynovitis of the finger flexor tendons. The sheath of the tendon produces excessive synovial fluid which causes the swelling of the sheath reducing the opening of the carpal tunnel and compressing the median nerve and blood vessels. Symptoms of the carpal tunnel syndrome include pain, numbness and tingling in the thumb, index, middle, and radial half of the ring finger, and skin dryness.

2.3.1 Risk Factors of CTDs

There are both occupational and non-occupational factors associated with cumulative trauma disorders. Possible non-occupational factors include diabetes, arthritis, vitamin deficiency, endocrinlogical disorders, pregnancy, use of oral contraceptives, and gynecological surgery. Common occupational risk factors include repetitiveness, force, abnormal postures and motions, mechanical stress, and vibration (Kroemer et al., 1994).

Silverstein, Fine, and Armstrong (1987) examined these occupational risk factors in a study of 652 workers in 39 industrial jobs. They concluded that high repetitiveness appears to be a stronger risk factor of carpal tunnel syndrome than force (odds ratio of 5.5 versus 2.9). Additionally, carpal tunnel syndrome was strongly associated with high force-high repetitive jobs and to a lesser extent with low force-high repetitive jobs and high force-low repetitive jobs (odds ratios of 15.5, 2.7, and 1.8, respectively).

More recently, Stock (1991) performed a review of literature examining the epidemiological evidence of the relationship between the workplace ergonomic factors such as repetition, joint position, force, and static muscle loading and the development of cumulative trauma disorders (CTDs). Based on her statistical analysis of the literature, she concluded that there is "strong evidence of a causal relationship between repetitive, forceful work and the development of musculoskeletal disorders of the tendons and tendon sheaths in the hands and wrists and nerve entrapment of the median nerve at the carpal tunnel." She notes that chronic exposure to biomechanical factors, such as posture and static loads which cause postural discomfort, may eventually lead to musculoskeletal disease and that more studies and better measures for these biomechanical factors are needed to clarify their relationship to musculoskeletal disease.

To the extent that typing tasks are repetitive, forceful, and require awkward postures of the fingers and wrist, Stock's conclusions provide an explanation for the prevalence of cumulative trauma disorders in the office environment. Specifically, the combination of repetitive key entry (keystroke rates can be as high as 50,000 to 150,000 keystrokes a day), awkward wrist and finger postures during typing, and high fingertip forces may contribute to the development of cumulative trauma disorders in video display terminal (VDT) operators.

2.3.2 Incidence of CTDs in VDT Operators

The musculoskeletal problems associated with keying operations existed long before the extensive use of VDTs. Ferguson (1971) and Duncan and Ferguson (1974) reported on pains and muscle cramps in the arms of telegraph operators. Komoike and Horiguchi (1971) reported on the musculoskeletal problems in the neck, shoulders and arms of key punchers, typists, and cashiers.

With the introduction of VDT equipment into the work environment, there have been an increasing number of musculoskeletal problems leading to a renewed interest in the occupational causes of these problems (Arndt, 1983). Ardnt suggests that the increase in problems is due in part to the large number of people working at VDTs and also due in part to the fact that VDTs contribute to simplified, repetitive tasks leading to greater postural constraints.

Hünting, Läubli, and Grandjean (1981) assessed subjective discomfort based on pain, stiffness, fatigue, cramps, numbness, and tremors of 295 workers in office environments. The study was comprised of four groups of workers: 53 did data entry on VDTs, 109 did bank transactions on VDTs, 78 were full-time typists, and 55 were considered the control group which did traditional office work without VDTs. VDT operators reported more incidence of pain in the upper extremities than the full-time typists or control group. It was found that the constrained postures of VDT operators and the full-time typists were associated with physical impairments in the hands, arms, shoulders, and neck. The reported complaints of discomfort were confirmed by medical findings on muscles, tendons, and joints.

Knave, Wiborn, Voss, Hedström, and Bergqvist (1985) compared the subjective symptoms and discomfort of a group of 400 office workers who used VDTs for more than five hours a day and a group of 150 office workers who performed similar tasks without VDTs. VDT operators had more eye discomfort and more musculoskeletal discomfort in the shoulders, neck and back than the referents. Women displayed greater morbidity than men. The results of the study indicated that the number of hours and time spent looking at the VDT screen were related to the degree of discomfort.

Yamamoto (1987) assessed the health complaints of 5,097 VDT workers in 23 enterprises through a questionnaire. The various complaints were classified into two groups, transient (i.e., complaints during and immediately following VDT work) and persistent (i.e., complaints not during VDT work) and then compared. It was found that visual and musculoskeletal complaints were more frequent in the transient group than in the persistent group, whereas the neuropsychological and general body fatigue were found more often in the persistent group than the transient group.

Jeyaratnam, Ong, Ke, Lee, and Koh (1989) examined the musculoskeletal complaints of 672 female VDT operators. The results showed the following prevalence rates: neck discomfort at 60%, low back pain at 54%, shoulder pain at 43%, hand and wrist pain at 18%, and elbow pain at 11%. Significant differences in neck, shoulder, and low back pain were found between operators who worked with VDTs for two to three hours and those who worked for at least four hours. Prevalence was also found to generally decrease with advancing age which the authors noted may be due to selection or survival phenomenon.

Low (1990) assessed the effect of ergonomic factors on the likelihood of developing keyboard-related conditions. A total of 174 females and 63 males, who worked at a keyboard for at least one hour a day, were asked questions including their symptoms, keyboard usage, perceived keystroke rate, and frequency of arm resting. Of those affected, the upper limbs were most commonly cited (74% of cases), then neck (60%), shoulder (36%), upper back (31%), and lower back (29%). More symptoms were found among those who spent more time performing keyboard work and those who rated their own keystroke rate as high. Operators who rested their arms more frequently were less likely to have developed symptoms.

2.4 Keystroke Kinematics During Typing

To examine the keystroke kinematics of the hands and fingers, the process by which a typist types must first be known. The sections below detail this process along with the movements of the hands and individual fingers during typing. The final topic covered in this section concerns the effect of the typing rate on the kinematics of the hand and fingers during typing.

2.4.1 Basic Facts and Definitions Concerning Typing

Typing a word or phrase involves a sequence of standardized keystrokes executed in the correct temporal order. Touch typists are trained to perform the typing task in a standard manner. The "home position" for the fingers, which is above the middle row of keys on a QWERTY keyboard, defines the initial posture of the hands. Typists are trained to type each letter on the keyboard with the use of only one particular finger and to return to the home position after the letter has been typed (Flanders and Soechting, 1992). In this standardized method of touch typing, the coordinates of each key have to be internally specified, relative to some frame of reference, so that the motor system can compute a trajectory for any finger movement, given the current location of the hand (Shaffer, 1986). Experienced typists who use this standardized method of touch typing are able to type 60 to 80 words per minute accurately (Reel, 1975).

In this thesis, a "keystroke" is defined similarly to the definition that Flanders et al. provide (1992). A keystroke is the movement to type a single letter which consists of three components: moving the finger from the home position to a position of contact with the key, depressing the key (keypress), and returning to the home position. The "initial stroke motion" is defined as the finger movement from the home position to a position of contact with the key. It is the initial stoke motion that determines the angle and velocity at which the finger makes contact with the key, which is the focus of this paper. A "keypress interval" refers to the time between two successive keypresses (the time at which each key is depressed).

During the typing of two successive letters, there are three possibilities for finger and hand movements. The following three definitions were used in a typing study of finger movements done by Genter (1981) to define these three possibilities. A "one-finger digraph" occurs when two successive letters are typed by the same finger, such as de. A "two-finger digraph" involves movements by two fingers on the same hand to type two successive letters, such as re. A "two-hand digraph" involves movements by fingers on two different hands to type two successive letters, such as le. The definitions described in this section will be used throughout the rest of this paper.

2.4.2 Keypress Interval Times and Characteristics

The interval between two successive keypresses, the keypress interval, has been investigated in several studies. Fox and Stansfield (1964) examined the keystroke intervals of five experienced typists who averaged 80 words per minute on a typing proficiency test. The typing was done on a standard 'Imperial 66' typewriter which was fitted with photocell, a lamp, and a recording system to obtain a continuous record of successive keystrokes and the time intervals between them. The results showed that the subjects were able to type the pairs of letters faster when alternating hands were used (e.g., le) than when the same hand was used (e.g., re). In the other words, two-hand digraphs were typed faster than two-finger digraphs. For the two-hand digraphs, 75 percent of the keypress intervals were between 80 msec and 110 msec.

Terzuolo and Viviani (1980) examined the characteristics of motor patterns used for typing. This study employed four professional typists who were able to type above 80 words per minute. The experiment was performed using an electric typewriter of an IBM 1800 digital computer which stored the characters and time (in msec) at which the keys were pressed. Three different types of text were used: one text was composed of 25 sentences, the second was a list of unrelated words, and the third was a list of pseudo-words. The keypress intervals for this study ranged from 80 to 250 msec.

Confirming the results of Fox et al. (1964), Terzuolo et al. (1980) found that pairs of letters which were typed with both hands (two-hand digraphs) were typed faster than pairs which were typed with one hand (one and two-finger digraphs). Among the latter, pairs of letters which required the repeated use of the same finger (one-finger digraphs) were the slowest. The authors observed that two-hand digraphs involved bimanual motion and suggested that the movements of the two hands overlapped in time when successive letters were typed by alternate hands. The authors found that pairs of letters which most frequently occur in language were typed faster (on average) than all other pairs of letters. In addition, the average interval between the last letter of any word and the following space and that between a space and the first letter of any word, were both longer than the average interval for all pairs of letters.

In addition to these common characteristics of digraphs, Terzuolo et al. (1980) also reported some within-subject variability when typing the same two successive letters in different words (e.g., for one subject, the keypress interval for typing di varied from word to word by as much as 200%). However, the authors noted that for many of the words studied, there were no significant within-subject differences found between pairs of letters. These comparisons were made independently of the three types of text that were used in this study (i.e., sentences, unrelated words, and pseudo words). From the data analyzed in this study, the authors concluded that the motor sequences (i.e., movements of each of the fingers involved) used by professional typists are characteristic of individual words, not pairs of letters. They also stated that the specific structure of the motor sequences is invariant and independent of the absolute time used for typing the word and that the structure consists of a set of ratios of the time intervals between each successive pairs of keypresses. Furthermore, they concluded that the structure is independent of the text (i.e., whether the word is part of a sentence, a list of unrelated words, or is typed from memory) and may be different from subject to subject.

In one part of Terzuolo and coworkers' study, the fingers of two subjects were loaded up to threefold using rings which carried leaded weight. The subjects' typing pattern was still implemented normally and the average typing rate was unaffected.

Genter (1991) investigated the keypress intervals and finger trajectories during typing. Six professional typists, who had typing rates above 70 words per minute, typed on a high-quality electronic keyboard. Keypresses and corresponding times were recorded by a microcomputer. The typists' hands were also videotaped during the experimental session. The results of this study confirmed the findings of the previous two studies (Fox et al., 1964 and Terzuolo et al., 1980) that two-hand digraphs were typed the faster (average of 118 msec) than two-finger digraphs (average of 145 msec) while one-finger digraphs were typed the slowest (average of 187 msec). Among the typists, the keypress intervals for the two-finger digraphs were the most variable while the two-hand digraphs were the least variable. The standard deviations of the two-finger, one-finger, and two-hand digraphs were 33.5, 24.6, and 18.6 msec, respectively.

Two of the typists in the study had similar overall typing rates, but showed large differences in the keypress intervals for two-finger digraphs. The finger movement trajectories for these two subjects were analyzed using videotapes of their typing. A mirror mounted at the top of the keyboard at a 45 degree angle allowed simultaneous recording of two views of the typists' fingers (i.e., normal and parallel to plane of the keyboard). The video views were recorded every 16.7 msec. The finger coordinates were digitized on a video monitor with the aid of a light pen so that the successive positions of the fingertip in 3-dimensional space could be calculated. The analysis of the videotapes showed that the first typist had longer movement trajectories than the second typist, (e.g., path length of 4.6 cm for the two-hand digraph en for first typist compared to 3.0 cm for second typist). The first typist more than compensated for the longer path by having shorter keypress intervals (i.e., higher finger velocities). When typing two- finger digraphs, the first typist tended to move the fingers of a hand in concert resulting in both longer finger trajectories and longer keypress intervals than the second typist who tended to move the fingers of a hand independently.

The second typist's finger movements were studied further using high speed film to determine the starting and ending times for keystrokes and to determine if the keystrokes overlapped. Overlap occurred when finger movements for a typing a second key were initiated before the previous key was pressed. The analysis was based on 147 keystrokes for letters on the upper or lower rows of the keyboard, where the previous keystroke was not made by the same finger. The results showed that for this one typist, finger movements for successive keystrokes overlapped in 96% of the 147 keystrokes. The starting times of the finger movements were more variable than the timing of the keypresses (the end of the movement). From the findings in this study, Genter concluded that there is more than one way to be a skilled typist. Skilled typists showed patterns of finger movements which were consistent during typing, but there were significant differences among the typists.

2.4.3 Velocity of Finger Movements in Typing

Three studies (Flanders and Soechting, 1992, Soechting and Flanders, 1992, and Angelaki and Soechting, 1993) addressed different aspects of the velocity of the fingers during typing. The technique for measuring the movement of the hand and fingers during typing was the same for all three studies and is described next.

An optoelectronic method was used to record the movements of the hands and the fingers of each hand. Four reflective markers (3 to 4 mm) were placed over the metacarpophalangeal (MP) joint of each finger and four were placed distally on the middle phalanx of each finger for a total of eight reflective markers on the hand. The location of the markers was recorded at a frame rate of 100 Hz by a video camera which had its field of view illuminated by means of infrared emitting diodes. The video image was processed electronically to enhance the contrast of the markers.

The two-dimensional, keyboard fixed coordinate system used to describe the movements of the fingers and wrist was defined with the x-axis parallel and the y-axis perpendicular to the rows of the keyboard. The four proximal markers were used to define the position of the wrist in x and y coordinates and to define the angular orientation of the wrist relative to the y-axis. The four distal markers were used to describe the motion of each finger in the horizontal plane: the length, defined as the distance between the proximal and distal markers on each finger, was used to approximate finger flexion and extension while the angular orientation, defined as the angle between the line connecting each pair of markers and the y-direction, was used to approximate finger abduction and adduction. The time of the keypresses was measured by use of a digital timer. The linear and angular velocities were computed by numerical differentiation after smoothing the data with double-sided exponentials. This technique for measuring linear and angular parameters for the fingers and wrist during typing was used in the three studies discussed below.

2.4.3.1 Movements of the Hands During Typing

Flanders and Soechting (1992) examined the movements of both hands while typing a key with one hand. The three subjects employed in this study were all experienced touch typists with typing rates ranging from 60 to 75 words per minute. The words and phrases were chosen so that all but one letter were typed by the fingers of one hand while the remaining (isolated) letter was typed with the opposite hand (e.g., gat<u>h</u>ered). The isolated letters analyzed were <u>h</u>, <u>u</u>, <u>m</u>, <u>o</u>, and <u>t</u>. One of the words for each of the isolated letters was chosen to be a reference (e.g., gat<u>h</u>ered for <u>h</u>) and was presented at least six times while six other phrases containing that isolated letter were presented at least twice. Words were chosen so that the letters that bracketed the isolated letter were different from word to word (e.g., cas<u>h</u>ews and rec<u>h</u>arged). The rationale was that if the letters that bracketed the <u>h</u> were different, then the movement of the left hand would be different at the time of the typing the <u>h</u>. Therefore, if the two hands were constrained to move in synchrony, the keystroke of <u>h</u> would vary depending on the letters that bracketed the <u>h</u>.

The results showed that the movements of the wrist and fingers began approximately 200 ms before the key was depressed and reached their maximum excursion at the time of the keypress. The authors found that there can be large differences in the kinematics from one subject to the next, but the within-subject variability was small. There was little variability in the trajectories of the fingers and the wrist for an individual letter typed by the experienced typists even though the rate at which the word was typed varied (e.g., for one subject, the interval between <u>t</u> and <u>h</u> for the word ga<u>th</u>ered ranged from 100 to 260 ms).

Examining the words that isolated <u>h</u>, the data showed that both hands were in motion at the same time. While the letter <u>h</u> was being typed with the right hand, the left hand was returning to the home positions from the previous keystroke and/or moving towards the next letter. For each subject, the average velocities of the wrist and fingers for the letter <u>h</u> from the references trials (gat<u>h</u>ered) were compared to the velocities for the twelve test trials where <u>h</u> was bracketed by different letters. At the point the letter <u>h</u> was typed, the averages between the reference and test trials were nearly identical which indicated that the motion of the hand when typing the letter <u>h</u> was the same, no matter what words contained the letter <u>h</u>. From these results, the authors concluded that the hands move simultaneously and independently of each other during typing and that the pattern of motion for typing a single letter shows remarkably little variability from one word to the next. Although the two hands were found to move independently of each other, the fingers within a hand tended to flex and extend together as well as abduct and adduct together, indicating that typing a single letter involves simultaneous motion of all fingers of one hand.

2.4.3.2 Movements of the Fingers During Typing

A second study done by Soechting and Flanders (1992) used a similar technique to examine the organization of sequential typing movements. They examined pairs of letters which were either identical; different, but typed with the same finger; or typed with two different fingers of the same hand. The authors found that when subjects typed the same letter consecutively and also when the second letter was not identical, but was typed with the same finger, the second keystroke began only after the first keypress. When subjects typed a pair of letters in which the second letter in the pair was typed with a different finger (but on the same hand), the second finger could begin to move toward the second key shortly before the keypress by the first finger.

The results of this study indicated that typing movements for one hand are executed primarily in a serial fashion, letter by letter, although there can be some overlap between consecutive keystrokes if they are executed with different fingers (of the same hand). The result from a previous study by Flanders et al. (1992) that the two hands can move independent of each other indicated that the processing of typing with two hands is parallel. Therefore, the results of these two studies suggest that typing represents aspects of both parallel and serial processing. In addition, these two studies showed that the pattern of finger and wrist movements during typing is highly stereotyped by following a repeatable trajectory to strike a key.

From the results of these studies, the Soechting and Flanders also concluded that the velocity with which a letter is typed in a pair appears to be repeatable from one instance to the next, despite the large amount of variability in the keypress intervals for pairs of letters as shown by Terzuolo et al. (1980). Although the velocity for a particular letter may be repeatable when the same letter precedes it, the velocity for a particular letter may be altered when a different letter precedes it.

Soechting et al. (1992) found that the velocity with which a particular letter was typed varied depending on whether the preceding letter was typed by the opposite hand (two-hand digraph), the same finger (one-finger digraph), or by the same hand, but different finger (two-finger digraph). These differences in velocity may be due to the starting position of the second keystroke. For two-hand digraphs, the second keystroke usually begins from the home position. Flanders et al. (1992) showed that for two-hand digraphs, the trajectory and velocity with which the second letter was typed were not dependent on the first letter typed. In this case, the starting position of the second keystroke was not influenced by the keystroke of the first letter. This may not be the case for one and two-finger digraphs.

For one-finger digraphs, the second keystroke begins where the first one finished. Therefore, the starting position for one-finger digraphs may be dependent on the first keystroke. For two-finger digraphs, the first keystroke may simultaneously move the second finger (which is to type the second letter) away from its home position altering the starting position for the second keystroke. For one and two-finger digraphs, the effect of the preceding letter on the velocity of the second letter was not investigated, but it follows from the discussion above that if the starting position for the second keystroke is altered by the keystroke that precedes it, then the trajectory and velocity of the second keystroke may be altered.

2.4.3.3 Effects of Typing Rate on Kinematics of the Fingers and Hand

Angelaki and Soechting (1993) used a technique similar to Flanders et al. (1992) and Soechting et al. (1992) to examine the manner in which the keystroke kinematics of the hand and the fingers varied with the mean rate of typing by experienced typists. Words and phrases were used in which only one letter was typed with the right hand and all remaining letters were typed with the left hand. The results from four experienced typists and three letters (n, u, and o) were analyzed.

The typing rate for this study was varied from 150 msec to 500 msec with the aid of a metronome. These typing rates are slower than of the normal range of keypress intervals of 80 to 250 msec for experienced typists, as previously reported by Terzuolo et al. (1980). Terzuolo et al. (1980) had also found that the ratios of successive keypress intervals did not change when the word was typed faster or slower. Angelaki and Soechting (1993) investigated whether there was a similar scaling of the underlying keystroke kinematics as reported by Terzuolo et al. (1980). The authors did not find a simple scaling that accounted for the variations in the velocity profiles with the typing rate. For some subjects and some letters, the velocities were independent of the typing rate. In other instances, the kinematics did depend on the typing rate, but to a much greater extent prior to the keypress than afterward.

Angelaki and Soechting also noted that there was little variability in finger and wrist kinematics in trials typed at higher typing rates; keypress intervals of 150 and 290 msec which are around the normal range of keypress intervals for experienced typists. The variability increased considerably when the typing rates were very slow; keypress intervals of 390 and 500 msec which are well outside the range of keypress intervals for experienced typists.

2.5 Measuring Complex Motions of the Hand

To determine the angle at which a finger strikes a key, the DIP, PIP, and MP joint angles and the position of the wrist must be known as the finger strikes the key. Furthermore, to determine the velocity of the fingertip at the point of contact with the key, the angular displacement data of the DIP, PIP, and MP joints must be known for the initial stroke motion (i.e., from the typist's home position to contact with the key). To determine both the angle and velocity at which a finger strikes a key, an accurate method for measuring the angular displacement of the finger joints is needed. Once the angular displacement data is collected, a method for calculating the velocity from the displacement data must be used.

The following two sections review techniques for measuring displacement data for hand motions and calculating velocity from displacement data. The actual calculations necessary for determining the angle and velocity at which a finger strikes a key are given in Section 4.0 (Data Analysis).

2.5.1 Techniques for Measuring Displacement Data for the Hand

The positions of the hand and fingers are difficult to monitor due to the small size of the hand, its multiple degrees of freedom, and its rapid, complex motions. There have been many different techniques employed for measuring the motions of the hands. Some of these include hand posture classification systems, photogrammetric and optoelectronic systems, angle transducer gloves, goniometers, and exoskeletons. These techniques along with their advantages and disadvantages are discussed below.

2.5.1.1 Hand Posture Classification Systems

The first attempts to quantify hand postures began with a simple classification of hand grips. Napier (1956) and Landsmeer (1962) divided the activities of the hand into power grasp and precision handling. As workers began experiencing cumulative trauma injuries, researchers began to examine the posture of the hands more closely. Many studies have involved videotaping a task and then classifying the posture of the hand into several posture categories.

Armstrong, Chaffin, and Foulke (1979) investigated hand positions and forces during manual work. Hand position was examined frame-by-frame from film and classified into one of the following postures: pinch, press, and off palm. Armstrong, Foulke, Joseph, and Goldstein (1982) examined cumulative trauma disorders in a poultry processing plant. Part of their investigation involved filming the tasks and then classifying hand position in pulp grasp, medial grasp, pulp pinch, lateral pinch, palm pinch, or finger press, and also indicating the location of hand contact. Punnett and Keyserling (1987) classified hand posture into flat press, pulp inch, and lateral pinch in their investigation of ergonomic stressors in the garment industry.

2.5.1.2 Photogrammetric and Optoelectronic Systems

Although the examination of hand positions provides some information about hand posture, more accurate measurements are needed to analyze complex motions of the fingers such as those that occur in typing. As described previously, Genter (1981) used a photogrammetric technique to analyze the finger trajectories during typing. The finger movements were videotaped and the finger coordinates were digitized with the aid of a light pen. This method of calculating finger coordinates during complex movements is quite time consuming. The data must be analyzed frame-by-frame and the additional calculations (i.e., using a light pen) may produce cumulative error.

Another technique for measuring finger posture during typing, also mentioned previously, was used by Flanders et al. (1992). This technique employed an optoelectronic system to record the movements of the hands and fingers during typing. The particular method employed by Flanders et al. (1992) had several inherent disadvantages. Only changes in finger length as viewed from above were recorded; not the location of the joints of the fingers. Also, only the rotation of the fingers in the horizontal plane was recorded and the location of the distal-most part of the finger was not measured because reflective markers were obscured from the view of the camera.

From these two studies (Genter, 1981 and Flanders et al., 1992), it is evident that photogrammetric and videographic systems have had some success in measuring complex motions of the hand and fingers, but they also have limitations. Both methods are limited in their ability to measure the individual joint angles and in their efficiency as techniques for measuring complex movements of the hand and fingers.

2.5.1.3 Angle Transducer Gloves

Recently, a technique involving the use of a lightweight angle transducer glove has been employed in studies to monitor the joint angles of the fingers in real time during complex movements of the hand. This technique utilizes fiber optic transducers which cover the MP and PIP joints of each finger. The amount of light lost is related in a nonlinear, but predictable manner to joint flexion. The glove is connected to a controller box and a portable computer where the flexion angles are quantified.

Moore, Wells, and Ranney (1991) and Yun (1993) both used angle transducer gloves in their ergonomic studies. Moore et al. (1991) investigated a method for quantifying exposure in manual tasks with cumulative trauma disorder potential. This involved determining the musculoskeletal loads in the hand and wrist which required the joint angles of the fingers as one of the inputs into the model. This was accomplished using an angle transducer glove (Dataglove™, VPL Research). Similarly, Yun (1993) needed the joint angles of the fingers as one input into a measurement system for describing the loads in the hand during manual tool tasks. This study also employed an angle transducer glove (Cyberglove™, Virtual Technologies).

Angle transducer gloves like the Dataglove™ and Cyberglove™ have the advantage of being lightweight, comfortable, and unobtrusive. Note that for both the studies mentioned above (Well, et al., 1991, and Yun, 1993) only the PIP and MP finger joints were investigated. This may have been due to the limitation of the angle transducer gloves which are typically only capable of measuring the MP and PIP joints of the finger; not the DIP joint. Another limitation of angle transducer gloves is the accuracy that is quoted for these types of systems which is usually plus or minus five to ten degrees. These limitations may or may not be significant depending on the nature of the research being conducted.

2.5.1.4 Exoskeletons and Goniometers

The Dexterous Hand Master™ (DHM) by EXOS, Inc. is a device that has been employed in robotics, medical research, and virtual environment applications to measure complex motions of the hand and fingers. DHM is a exoskeleton which measures four joint angular positions on each finger and four on the thumb. The DHM exoskeleton is attached to the user's hand through the use of velcro straps for the digits and a metal backplate attached to the back of the hand. As the hand moves, Hall Effect sensors on the exoskeleton allow the computer to precisely measure the joint motions of the hand. A Hall Effect sensor is a small semi-conductor device which changes its signal output voltage in proportion to the magnetic field it is experiencing. This system has an angular resolution of approximately 0.5 degrees.

One study (Weiss, August, Peters, and Sampalis, 1992) investigated the reliability and validity of using the DHM exoskeleton to measure angular joint rotation of the digits. Historically, goniometers have been used for clinical assessment of joint range of motions for the fingers. Although goniometers may be accurate for static measurements, the authors noted disadvantages of using goniometers for assessing active movements of the hand. They found that goniometers are suited for the measurement of joint range of motion under static conditions (i.e., when the finger joints are not in motion). However, the hands engage primarily in complex, dynamic tasks. Due to complaints about the uncomfortable attachment technique of the DHM, the exoskeleton was modified in Weiss and coworkers' study by replacing the metal backplate with a customized thermoplastic mold and using skin adhesives instead of the velcro straps.

Eight subjects underwent evaluations at six different positions for the MP, DIP, and PIP joints and four positions for MP ulnar-radial deviation. One hundred fifty-nine observations were collected. For every joint and position combination, the measurements were performed twice using the DHM and twice using the goniometer. The two measurements for each method were referred to as the test-retest measures. The individual joint angles were not analyzed separately.

The results of the study showed that the mean difference between the goniometer test-retest measures was significant while the test-retest difference for the DHM was non-significant. To test the validity of the DHM, measurements using the goniometer and the DHM were compared. The results showed that the mean difference between the measurements obtained with the goniometer and the DHM was statistically different for both the test and retest assessment. The measurements obtained with the DHM had a larger mean (by approximately 8 degrees) and a wider range than the measurements made with the goniometer. From these results, the authors suggested that the DHM is a more sensitive instrument than the goniometer.

The DHM exoskeleton has been employed in the experiment presented in this paper. As in the study done by Weiss et al. (1992), the exoskeleton was modified to make it more comfortable and less obtrusive during the experimental task. Details about these modifications and the necessary equipment needed to operate the DHM system are covered in the Section 3.0 (Methods).

2.5.2 Velocity Determination from Displacement Data

Angular displacement-time data do not provide sufficient information about the movement of the finger during keying. The angular velocity of the three individual joints of the finger (i.e., DIP, PIP, and MP) is needed to provide a detailed description of the motions of the finger during keying. Furthermore, the linear velocity at the fingertip must be calculated to fully define the kinematics of the finger when striking a key.

2.5.2.1 Techniques for Determining Velocity

Displacement-time data may contain inherent errors and possible regions of noisy data points. The goal in analyzing the displacement data is to determine the best technique to smooth the raw data with respect to the inherent error and then to provide accurate first and second derivatives of the original data (McLaughlin, Dillman, Lardner, 1977). In biomechanical studies, a variety of mathematical techniques have been employed to smooth raw displacement-time data and to obtain velocity and acceleration patterns including numerical finite differences, polynomial regression, Fourier series, and cubic spline functions.

Different forms of numerical finite differences have been used for differentiation and curve smoothing in several studies (e.g., Widule and Gossard, 1973 and Cavanagh and Gregor, 1975). Widule et al. (1973) provide a description of the numerical finite differences technique. This procedure is based on Taylor series expansions which usually employs a form of the equation $V_n = (X_{n+1} - X_{n-1})/2\Delta t$ where n is the data point and Δt is the time interval. Polynomial regression has been used extensively in biomechanical studies to fit data (Zernicke, Caldwell, and Roberts, 1976).

The use of Fourier transforms for data smoothing has been advocated by Hazte (1976 and 1981) and used in several studies (e.g., Cappozzo, Figura, and Marchetti, 1976). More recently, cubic spline functions have been endorsed for the fitting of empirical data (Wold, 1974, Zernicke et al., 1976, and McLaughlin et al., 1977).

Wold (1974) reiterates the importance that Rice (1969) places on the use of splines in the analysis of empirical two-dimensional data. Functions which express physical relationships are frequently of a disjointed nature meaning their behavior in one region may be unrelated to their behavior in another region. Most mathematical functions, including polynomials, have just the opposite property; meaning their behavior in a small region determines their behavior everywhere. Splines do not have this property since they are defined piecewise (see Section 2.5.2.2) and for $n \geq 3$, they represent smooth curves in the physical world. For this reason, splines have the advantage of being sensitive to quickly varying data of an otherwise uniform curve while not altering the characteristics of the entire curve based on the oscillations at one point. Due to these advantages, cubic splines were used in the experiment presented in this paper to analyze the angular displacement data of the finger joints.

2.5.2.2 Definition of Spline Functions

Spline functions are defined as piecewise polynomials of degree *n* which join at positions called knots. A spline function of degree *n* is a continuous function with *n* - 1 continuous derivatives. Cubic splines, therefore, produce an interpolated function that is continuous through the second derivative. A spline of odd degree (e.g., a cubic spline) is called a natural spline. Wold (1974) defines a natural cubic spline function as:

$$y = F(x) = P(x) = a_j + b_j x + c_j x^2 + d_j x^3$$

$$\xi_{j-1} \leq x < \xi_j; \quad (\xi_0 = -\infty; \xi_{m+1} = \infty) \qquad (1)$$

$$P_j^k(\xi_j) = P_{j+1}{}^k(\xi_j); \quad k = 0,\ 1,\ 2; \quad j = 1,\ 2,\ \ldots m$$

where: P_j^k denotes the kth derivation of the jth polynomial piece; ξ_j denotes the position of the knots; and m denotes the number of knots. Each polynomial piece can have a different set of parameters a, b, c, and d.

2.5.2.3 Calculations of Spline Functions

The most common method for evaluating cubic splines is based on an algorithm by Reinsch (1967). This algorithm was used to evaluate cubic splines in several studies mentioned previously (Zernicke et al., 1976 and McLaughlin, 1977). The result of this algorithm is a smoothing spline. This is a cubic spline with knots at all the data abscissas. The data are represented as (x_i, y_i) where x_i are the time steps and y_i the corresponding data points. F(x) is the cubic spline and Q is the smoothing function which minimizes the following:

$$Q = \int_{x_0}^{x_N} F''(x)^2 \, dx \tag{2}$$

subject to the constraint:

$$\sum_{i=0}^{N} \left[\frac{F(x_i) - y_i}{\delta y_i} \right]^2 \leq S \tag{3}$$

where N is the total number of data points, S is the smoothing parameter, and δy_i is the relative weight of the data points. The weight of each data point, δy_i , can be described as the mean error band associated with each point. This number is typically a constant because the amount of error associated with each data point is usually dependent on the error inherent in the measurement technique. Varying the smoothing parameter, S, varies the extent of smoothing for the cubic spline. When the smoothing parameter is equal to the number of data points, N, the degree of smoothing is affected only by the values for the weight of each data point, δy_i .

2.6 Summary of Literature Review

- Precise movements of the fingers are attributed to the complex mechanical structure of the hand and wrist. The bones of the index, middle, and ring finger are remarkably alike and mainly differ in length. The muscular control of these three fingers is also similar with the main difference in their mobility being attributed to their anatomical position on the hand (Langman et al., 1978).
- Repetitive motions and forceful exertions are risk factors for cumulative trauma disorders. When acting together, these two risk factors are multiplicative which implies that for very repetitive keying, high fingertip forces may contribute to cumulative trauma disorders (Silverstein et al., 1987).
- Pairs of letters which are typed with both hands (two-hand digraphs) are typed faster than pairs which are typed with one hand (one and two-finger digraphs). Among the latter, pairs of letters which require the repeated use of the same finger (one-finger digraphs) are the slowest (Fox et al., 1964, Terzuolo et al., 1980, and Genter, 1981).
- The keypress intervals between the same pair of letters vary from word to word for the some subjects, indicating within-subject variability for certain pairs of letters. Keypress intervals for the two-finger digraphs are the most variable while the two-hand digraphs are the least variable (Terzuolo et al., 1980, and Genter, 1981).
- Typing represents aspects of both parallel and serial processing. When typing with two hands, the hands are able to move independently of each other. When typing with one hand, the keystrokes are executed primarily in a serial fashion, letter by letter, although there can be some overlap between consecutive keystrokes if they are executed with different fingers (Flanders et al., 1992 and Soechting et al., 1992).
- The pattern of finger and wrist movements during typing is highly stereotyped with movements beginning from a standard starting position and following a highly repeatable trajectory to strike the key. When typing an individual letter, there may be

large differences in the kinematics of the fingers among subjects, but the within-subject variability is very small. This is true even when the typing rate of the word containing the letter varies (Flanders et al., 1992 and Soechting et al., 1992).

- The typing velocity of a particular letter may depend on whether the preceding letter is typed by the opposite hand (two-hand digraph), the same finger (one-finger digraph), or by the same hand, but different finger (two-finger digraph) (Soechting et al., 1992).
- The full effect of the typing rate on the kinematics of the hand and fingers is not known. In some instances the typing rate may influence the kinematics and in others it may not. For higher typing rates (keypress intervals of 150 and 290 msec), there is less variability in finger and wrist kinematics than at lower typing rates (keypress intervals of 390 and 500 msec) (Angelaki et al., 1993).
- Dexterous Hand Master™ is an exoskeleton that has been shown to be reliable and accurate for measuring the range of motions for the individual joints of the fingers (Weiss, 1992).
- Cubic splines are piecewise polynomials that are continuous through the second derivative. They offer the advantage of being sensitive to quickly varying data, but not allowing oscillations in one part of the curve to affect the rest of the curve (Rice, 1969).

3. METHODS

3.1 Subjects

Twelve right-handed subjects (six males and six females) were employed in this experiment. All participants were screened through a health questionnaire for possible health problems including hand or wrist abnormalities, arthritis, nerve disorders, or any other medical impairment that could be aggravated by the experiment or affect typing performance during the experiment. All subjects passed a typing test which required the subjects to use a touch-typing technique and to type a minimum of 50 words per minute. The typing rate of the subjects ranged from 51 to 90 words per minute with the average being 67 words per minute. Only subjects that passed both the medical screening and the typing test participated in the experiment. The total amount of time required for each subject was approximately two hours. Subjects were compensated by $5.00 per hour.

3.2 Apparatus

The apparatus for this experiment included a standard IBM AT computer and keyboard, an exoskeleton for measuring the DIP, PIP, and MP joint angles of the fingers, and a posture recording system for measuring the three dimensional wrist and key positions. Figure 3.1 shows a schematic of the experimental system.

3.2.1 Computer and Keyboard System

An IBM AT computer used in this experiment had a model M keyboard with the following characteristics: slope of 12 degrees; horizontal and vertical centerline distances between keys of 19 and 20 mm, respectively; and a key travel of 4.0 mm.

3.2.2 Joint Measurement System

The EXOS Dexterous Hand Master exoskeleton (DHM) exoskeleton was used to record the angular joint motions of the fingers during the experimental trials. The DHM

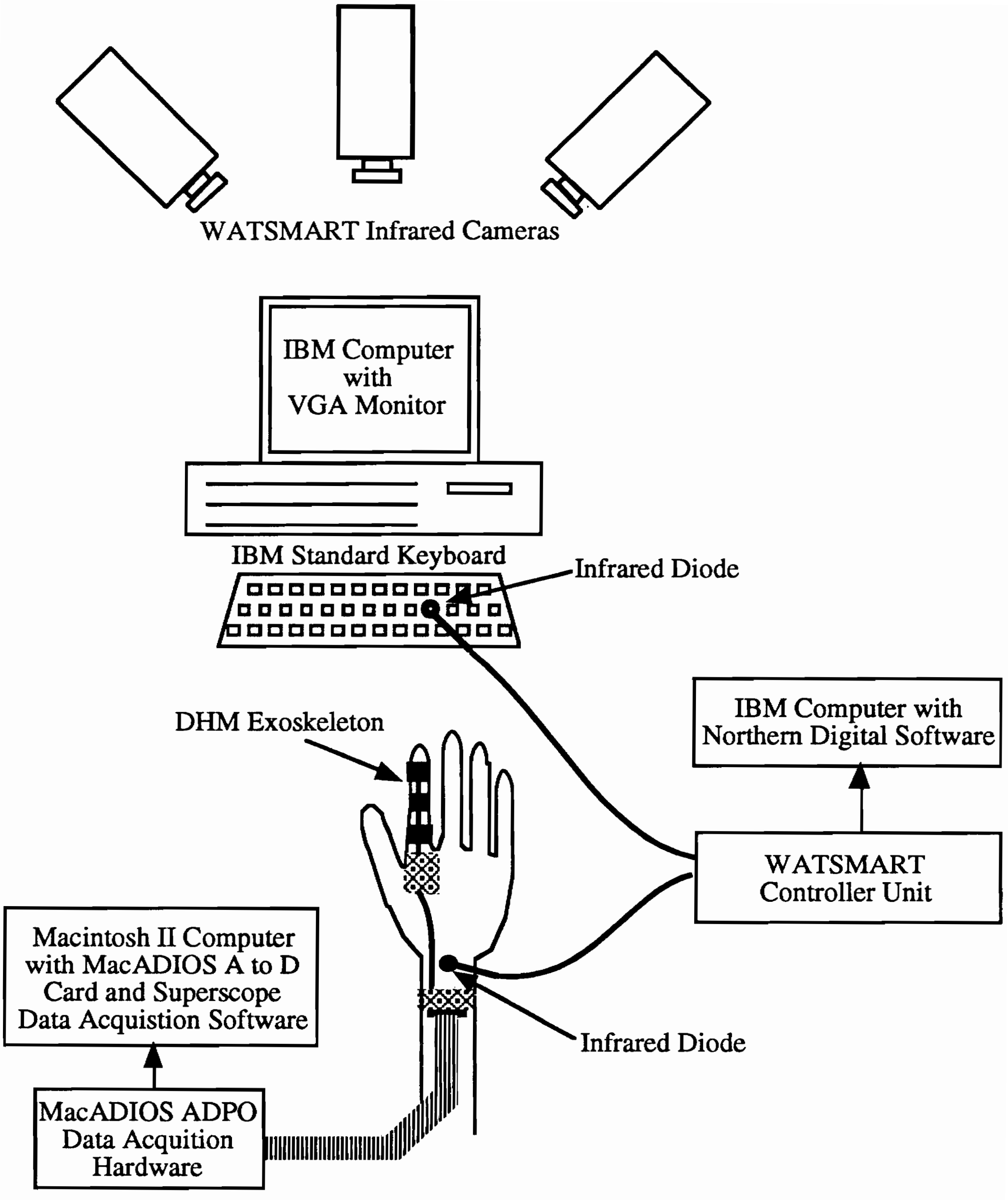

Figure 3.1 Experimental setup.

utilizes Hall Effect sensors which are small semi-conductor devices that change the signal output voltage in proportion to the magnetic field they are experiencing. The DHM exoskeleton was connected to a microcomputer system to collect the angular displacement of the DIP, PIP, and MP joints of the finger during typing. The angular resolution for each joint is 0.5 degrees.

To minimize the exoskeleton's interference with the experimental task of typing and to allow a more comfortable fit for different hand sizes, the DHM was modified for this experiment. The original DHM exoskeleton had the attachments for the all four fingers and the thumb connected to a metal backplate which fits around the palm of the hand. The exoskeleton was attached to the fingers by velcro straps which were wrapped around the finger and tightened by a spring loaded mechanism. A wrist connection assembly was used to connect the exoskeleton to the computer. The weight of the exoskeleton was 343 grams and the wrist connection assembly was 86 grams.

For this experiment, the DHM exoskeleton was modified so that only one finger was attached to it (Figure 3.2). The plastic casing to attach the wrist connection assembly to the wrist was removed and replaced with an adjustable elastic band to allow a closer fit for the wrist. To allow a more comfortable fit for different hand sizes, the metal backplate of the exoskeleton was replaced with an adjustable elastic band which was attached to the top of the hand through the use of skin adhesives. The velcro straps for the fingers were replaced with skin adhesives and the spring loaded mechanisms for the three finger joints were removed to avoid accidental activation of keys during the typing task and to reduce the load on the fingers. The weight of the exoskeleton was reduced to 57 grams and the weight of the wrist connection assembly to 50 grams. The exoskeleton finger was attached to a MacADIOS ADPO interface which converted analog to digital signals. The digital signals were converted to voltages and processed by SuperScope software which is capable of collecting and editing the data. The microcomputer system

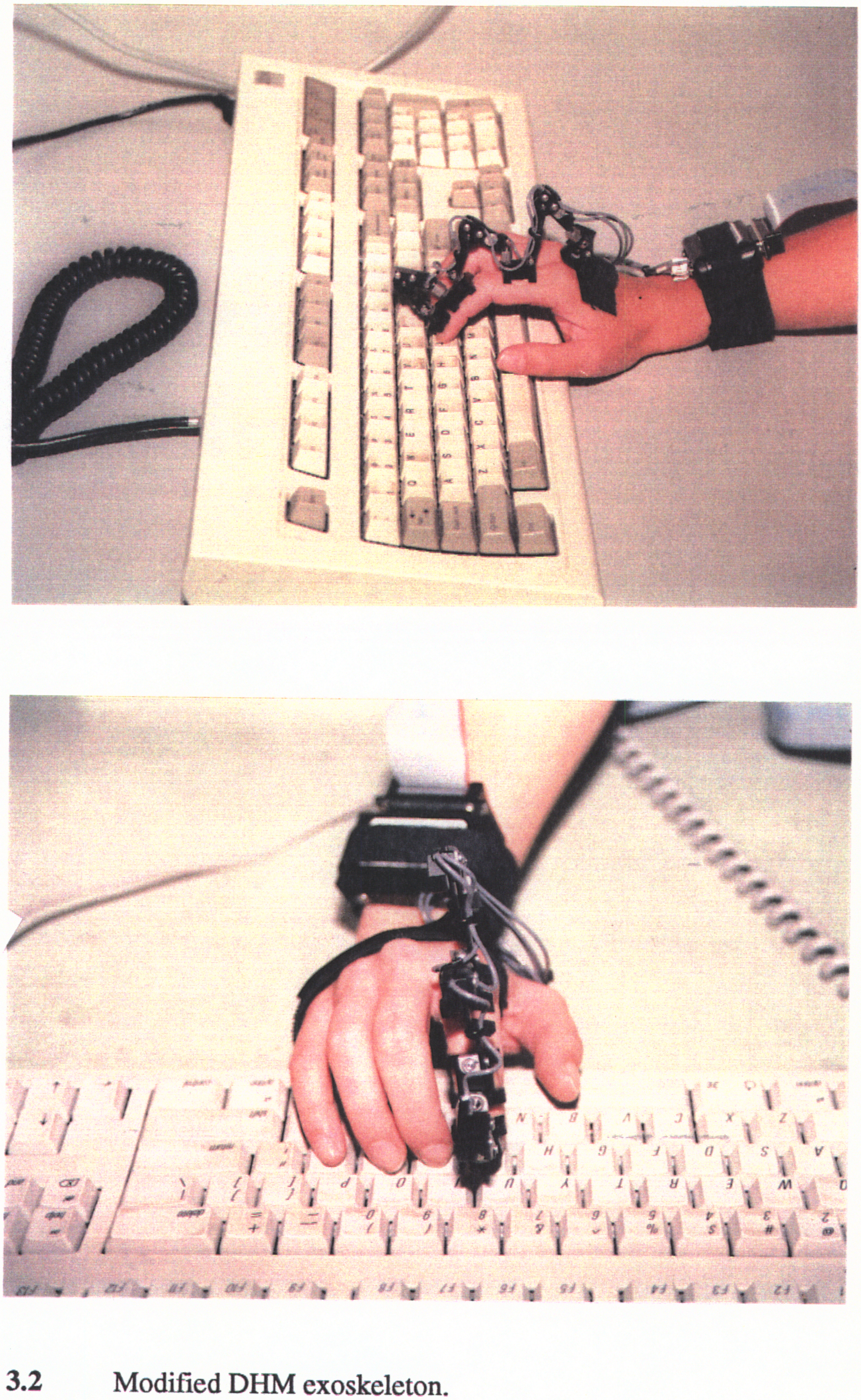

Figure 3.2 Modified DHM exoskeleton.

consisted of a Macintosh II computer with a 13 inch color monitor, a Mac ADIOS II Analog-to-Digital board, and SuperScope data acquisition software. The sampling frequency for the experiment was 200 Hz.

3.2.3 Posture Measurement System

The Northern Digital WATSMART motion analysis system was used to record the three-dimensional wrist posture of the subject and the three-dimensional position of the keys of interest on the keyboard. The system includes infrared emitting diodes, a calibration frame, three infrared cameras, and the system unit which is connected to an IBM personal computer. The cameras of WATSMART system track the infrared diodes when attached to the targets. The system was configured to track the diodes at a sampling rate of 200 Hz. Prior to the experimental trials, diodes were attached to the **u**, **j**, and **m** keys and the WATSMART system was used to calculate the three-dimensional position of these keys. During an experimental trial, a diode was attached to the subject's wrist to calculate the wrist position when each key of interest was typed.

3.3 Procedures

3.3.1 Experimental Design

The experimental design was a mixed factors design with one between-subjects factor (*Gender)* and three within-subjects factors (*Finger*, *Row*, and *Digraph*). The levels for each of these factors are shown in Table 3.1. There were 27 treatment conditions which each subject completed.

Gender (G), a between-subjects factor, had 2 levels. *Finger* (F), a within-subjects factor, had 3 levels: index, ring, and middle fingers. Only the right hand fingers were examined in this experiment. *Row* (R), a within-subjects factor, had 3 levels: upper, middle, and lower rows of the keyboard. Each finger of interest (i.e., the right index, middle, and ring fingers) typed one key on the upper, middle, and lower rows of the

Table 3.1 Experimental Variables.

Independent Variables (between-subjects)

Gender (G) - 2 levels (male, female)

Independent Variables (within-subjects)

Finger (F) - 3 levels (index, middle, ring)

Row (R) - 3 levels (upper, middle, lower)

Digraph (D) - 3 levels (one-finger, two-finger, two-hand)

Measured Dependent Variables

DIP angular displacement (degrees)

PIP angular displacement (degrees)

MP angular displacement (degrees)

Wrist position x, y, and z coordinates (mm)

Key position x, y, and z coordinates (mm)

Calculated Dependent Variables

Vk_x - x component of linear velocity of fingertip at key (cm/s)

Vk_y - y component of linear velocity of fingertip at key (cm/s)

$Ø_k$ at contact - angle of fingertip at point of contact with key (degrees)

$Ø_k$ at depression - angle of fingertip at point of maximum depression of key (degrees)

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keyboard. Figure 3.3 and Table 3.2 illustrate the nine keys of interest for this experiment. These nine keys were chosen due to their location on keyboard. The keys of interest on the middle row (j, k, and l) are the home positions for the index, middle, and ring fingers, respectively. The upper and lower keys of interest are located at the same angle in the horizontal plane with respect to the middle key of interest for all three fingers.

Digraph (D), a within-subjects factor, had 3 levels: one-finger, two-finger, and two-hand. Each of the nine keys of interest was investigated as part of the three digraphs, totaling 27 different pairs of characters analyzed in this experiment. A one-finger digraph occurs when the key of interest and the key preceding the key of interest are typed with the same finger on the right hand, (e.g., ju). A two-finger digraph occurs when the key of interest and the key preceding it are typed with two different fingers on the right hand, (e.g., lu). A two-hand digraph occurs when the key of interest is typed with the right hand and the key preceding it is typed with the left hand, (e.g., tu). The basis for the selection of the 27 digraphs is explained in detail in Section 3.3.2 (Experimental Task).

The dependent measures for this experiment included the angular displacement of the DIP, PIP, and MP joints and the position of the keys of interest and the wrist (see Table 3.1). The angular displacement of the DIP, PIP, and MP joints was measured using the DHM exoskeleton and was in volts. The voltages were converted into degrees (see Section 3.3.3 Exoskeleton Application and Calibration). The coordinates of the keys and the wrist were recorded by the WATSMART system in millimeters.

These dependent variables served as inputs for the data analysis to calculate the four measures which were subjected to a statistical analysis. These four calculated dependent measures (shown in Table 3.1) included the vertical and horizontal linear velocity components of the fingertip and the angle of the fingertip at the point of contact with the key and the angle of the fingertip at the point of maximum depression of the key (i.e., the maximum displacement of the key).

Table 3.2 Keys of Interest.

Finger	Index	Middle	Ring
Upper Row	**u**	**i**	**o**
Middle Row	**j**	**k**	**l**
Lower Row	**m**	**,**	**.**

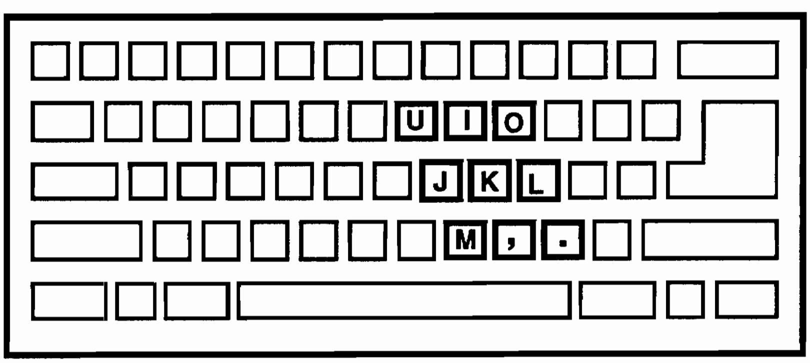

Figure 3.3 Keyboard showing keys of interest.

3.3.2 Experimental Task

The 27 digraphs examined in this experiment were incorporated into 6 sentences. The experimental task for this study involved typing these 6 sentences. The 27 digraphs are shown in Table 3.3 and the 6 sentences in Table 3.4. Each sentence was considered a trial. The six sentences were divided into three groups of two sentences. Each group of sentences contained the nine digraphs for one of the fingers (i.e., index, middle, or ring fingers). All the sentences had between 8 and 12 words and each sentence contained 4 to 5 digraphs of interest.

The three groups of sentences and the order of the two sentences in each group were randomly assigned within each subject. Subjects were asked to type each sentence as fast as possible without making mistakes. The subjects were directed not to correct their typing errors. If a typing error occurred in word which contained a digraph of interest, the trial was repeated. The sentence to be typed was clipped to a document holder attached to the left side of the computer monitor.

The selection of the 27 digraphs and 6 sentences was based on several factors. First, the second character of the digraph was one of the keys of interest while the first character of the digraph was chosen to fulfill one of the three digraph conditions (i.e., one-finger, two-finger, or two-hand). Furthermore, for one-finger digraphs, the digraph contained two different characters. Also for one-finger digraphs, the keystroke movement was between two rows, not three (e.g., ju not mu). This was done to reduce the amount of variability that may occur when the finger has to travel different lengths to type a character. For two-finger digraphs, the characters of the digraph were on two different rows (e.g., lu not iu) ensuring that the second keystroke was distinct from the first. For two-hand digraphs, the first character of the digraph (which was typed with the left hand) was typed by the index, middle, or ring finger.

Table 3.3 Digraphs for the Keys of Interest.

Finger	Index			Middle			Ring		
Digraph	1F	2F	2H	1F	2F	2H	1F	2F	2H
Upper Row	**ju**	**lu**	**tu**	**ki**	**li**	**ri**	**lo**	**mo**	**to**
Middle Row	**mj**	**oj**	**rj**	**ik**	**ok**	**rk**	**ol**	**ul**	**bl**
Lower Row	**jm**	**im**	**em**	**k,**	**l,**	**t,**	**l.**	**k.**	**d.**

(1F: one-finger, 2F: two-finger, 2H: two-hand)

Table 3.4 Sentences for Experimental Task.

INDEX FINGER

m2f m1f l1f l2h

Two Trojad creamjars are beside a Sejma coffeemaker. (8)

u1f m2h u2h l2f u2f

A perjured carjacker stuttered after five crimes were alluded to. (10)

MIDDLE FINGER

m1f l1f l2f l2h u1f

The rescuers like to travel by truck, vessel, boat, and skis. (10)

m2h m2f u2h u2f

Remarkably the lady who broke her vertebrae strived to stay alive. (11)

RING FINGER

l2h u1f m2f l1f

The Med. student's slow intern schedule was quite unusual. (9)

m1f u2h u2f m2h l2f

The cold mean storekeeper was smothered by the table near the deck. (12)

(u: upper row, m: middle row, l: lower row)

(1f: one-finger, 2f: two-finger, 2h: two-hand)

(Numbers in parenthesis indicate number of words in sentence.)

Once the 27 digraphs were chosen, they were incorporated into words and then into six sentences. This was done to create a realistic typing task for the experiment. Certain factors were taken into consideration when choosing the words for the digraphs. Except for the digraphs which ended with a punctuation mark, the digraphs were embedded in the words (i.e., there was at least one letter before and after the digraph of interest). This was done to allow the key of interest to be typed with a continuous motion. Furthermore, the letter immediately preceding and succeeding the digraph was typed with the left hand. This was done to isolate the keystroke for the key of interest and to help ensure that this keystroke was only influenced by digraph, not the entire word. Isolation of the keystroke was also done to assist in analyzing the raw data for the keystroke of interest.

3.3.3 Exoskeleton Calibration and Application

There were two parts to the calibration procedure for the exoskeleton finger. The first part involved taking angle measurements of the subject's finger joints in three different positions without the exoskeleton on while the second part involved taking voltage measurements of the subject's finger joints in the same three positions with the exoskeleton on.

For the first part of the calibration, a goniometer was used to measure the DIP, PIP, and MP joints to the nearest 0.5 degree for each of the three positions. Figure 3.4 illustrates the three positions and the apparatus used to maintain the posture of the three joints during the measurements. The apparatus included a flat surface to hold the wrist and forearm stationary. For two of the three positions, the apparatus also included a dowel that was covered with Air Putty™, a non-sticky substance. When the finger pressed on this substance, a mold of the finger was created. One of these positions had a large dowel (6 cm diameter) while the other had a smaller dowel (3 cm diameter).

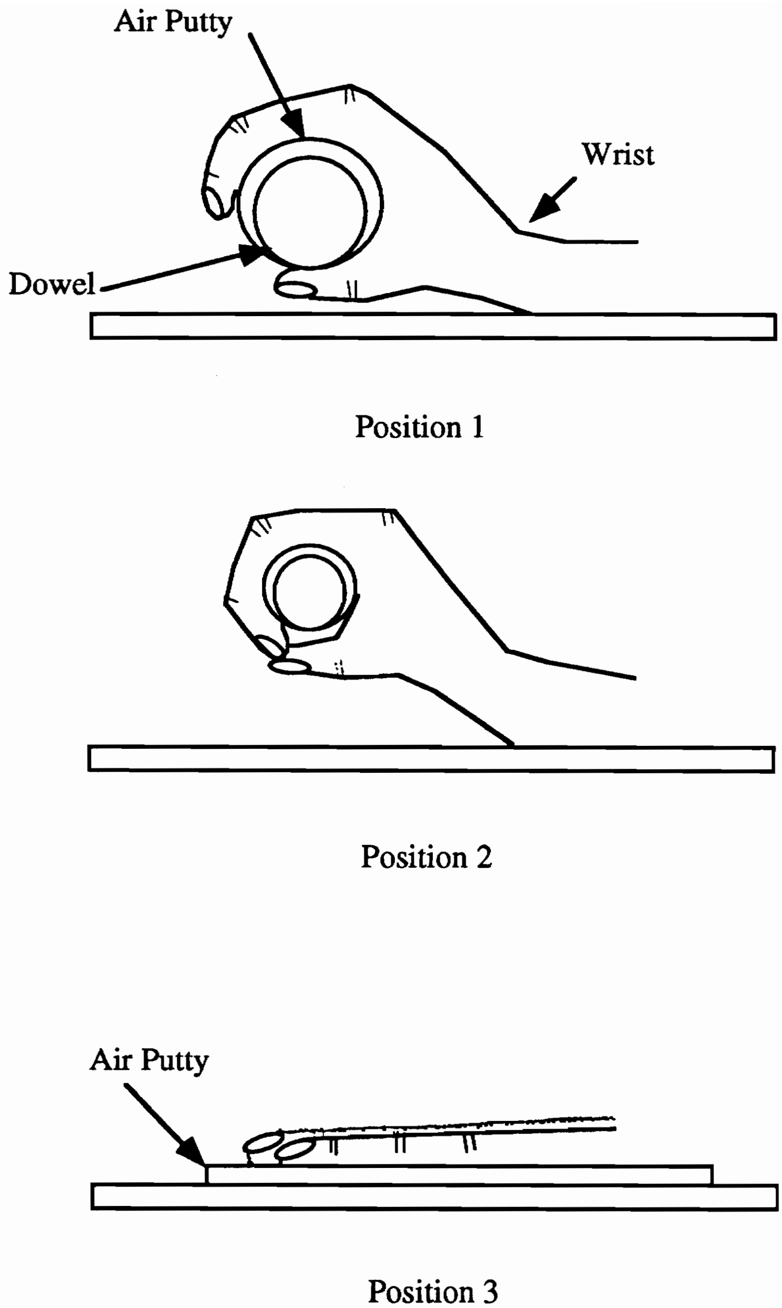

Figure 3.4 Three positions for collection of calibration parameters.

For the two positions that utilized the dowel, the subject's forearm was on a flat surface and the subject wrapped his or her entire hand around the dowel, pressing lightly on the Air Putty™ to make an impression of the fingers of the hand. Wrapping the entire hand around the dowel immobilized the three joints of the fingers. The subject then removed his or her hand. Next, the subject's hand and fingers were realigned with the mold just taken and a goniometer was used to measure the angles of the three joints for the three fingers of interest. The realignment was done to ensure that the subject was not pressing into the Air Putty™ when the measurements were taken. For the position that did not require the use of the dowel, the subject's forearm was also on a flat surface and the subject placed his or her hand flat on the Air Putty™ to make impression of the fingers. As with the two other positions, the subject's hand was removed, realigned, and then three joint angles for the three fingers were measured.

After the goniometer measurements were taken for all three fingers at all three positions, the second part of the calibration began with the exoskeleton finger being attached to the subject's finger. The second part of the calibration, as detailed below, was completed for all three fingers of interest.

First, the elastic band for wrist was fit to the subject's wrist. Skin adhesives were placed on the top of the subject's hand and the elastic band for the top of the hand was attached. Skin adhesives were then placed on the subject's distal, middle, and proximal phalanges. The sensor for the MP joint was aligned directly over the knuckle and the plastic linkages for each phalanx were placed on their corresponding phalanges. The subject practiced typing with the exoskeleton finger. Any adjustments to the exoskeleton were made after the practice session.

Next, the hand was realigned to one of the three calibration positions and the SuperScope data acquisition software was used to collect the voltage data at 200 Hz for two seconds for the DIP, PIP, and MP joints of the finger with the attached exoskeleton.

For each joint, the last 20 data points of the 400 collected were averaged together to give the voltage measurement for the corresponding angle measurement taken during the first part of the calibration procedure. The last 20 data points were chosen to eliminate any finger joint movement that might occur immediately following the realignment of the hand to the calibration position and to eliminate any noise in the voltage data that might be associated with the start up of the system. The same procedure was done for the other two calibration positions. This second part of the calibration process (i.e., attaching the exoskeleton and collecting the voltage data) was then completed for the other two fingers.

For each of the three finger joints (i.e., DIP, PIP, and MP) of the each of the three fingers, there were three angle measurements made in degrees with the goniometer and the corresponding voltage measurements taken with the DHM exoskeleton finger and SuperScope software. The Hall Effect sensors of the DHM have approximately a linear relationship with degrees (EXOS, 1990). For this reason, the method used to convert the voltage data to degrees data assumed a linear relationship. The three data points per joint were used to calculate a linear regression on the voltage/degree data to determine the conversion equation. This was done for each of the three joints totaling three conversion equations for each finger. Since there were three fingers of interest, there were a total of nine conversion equations for each subject (3 per finger for each of the 3 fingers).

3.4 Experimental Protocol

Before the subject arrived, the WATSMART frame was used to calibrate the experimental area including an IBM standard keyboard and the area surrounding the keyboard. The keyboard was securely fastened to the keyboard support surface during the entire experiment. Infrared diodes were placed on the **u**, **j**, and **m** keys and the WATSMART system was used to collect the coordinates of this key.

The experimental session took approximately two hours for each subject. When the subject arrived, he or she completed an informed consent form (Appendix A) and a health questionnaire (Appendix B). The health questionnaire was reviewed. No subjects had any health problems which could have been aggravated by typing or could have influenced their typing performance. Subjects were then asked to adjust the computer chair so that both of their feet were firmly on the ground and their wrists and hands were in a comfortable position for typing. Subjects was asked to maintain the same typing position throughout the experimental session.

Next, the subjects were asked to type two short passages. The passages were triple-controlled at the average difficulty level with syllable intensity of 1.5 syllables per word, and average word length of 5.6 strokes per word (Fries and Clayton, 1975). The first typed passage was used to warm-up the fingers and wrists of the subjects and to ensure the subjects possessed a touch-typing technique. The second passage was timed for one minute to ensure that the subjects could type a minimum of 50 words per minute with less than three errors per sentence. For this second passage, the subjects were asked to type as quickly as possible while avoiding mistakes, and not to correct any mistakes they made. Five male subjects were rejected from the study because they did not use the standard touch-typing technique and one female subject was rejected for being unable to type 50 words per minute.

Subjects that passed both the medical and typing screening had their hand dimensions measured. The order of the fingers was randomly assigned. The calibration measurements without the exoskeleton finger (as described in Section 3.3.3) were then taken for the first finger. After the first part of the calibration, the subject was fitted with the exoskeleton finger. The donning procedure for the exoskeleton consisted of fitting the elastic wrist band to the subject and using skin adhesives to secure the elastic band to the top of the hand and exoskeleton finger to the three finger joints. The WATSMART infrared diode was then attached to the subject's wrist through the use of skin adhesives. The position of the diode for the wrist joint was placed at approximately the point where the metacarpal bone for the finger of interest articulates with the carpal bones. After the exoskeleton finger and the diode were securely attached to the subject's hand, the subject typed a one-page passage to become accustom to the devices. This passage included the pairs of letters and words to be typed during the experimental trials for the finger with the attached exoskeleton. After this practice session, any needed adjustments to the exoskeleton finger were made. Next, the exoskeleton device was calibrated for three channels, one for each of the finger joints.

Following the calibration, the subjects were shown and asked to read one of the two sentences to be typed for the finger with the attached exoskeleton. The order of the two sentences was random. The subjects practiced typing the sentence ten times to improve their accuracy. The subject was then asked to type the sentence as quickly as possible without making mistakes. They were instructed not to correct their mistakes. At the same time the subjects began typing the sentence, the WATSMART program to collect the wrist position data and the SuperScope program to collect the finger displacement data were started and then ended after 15 seconds. The experimenter immediately checked the typed sentence for errors. If any errors were found in words containing one of the 27 digraphs of interest, the sentence was typed over. After successfully completing the first sentence, the second sentence was typed using the same procedures. When both sentences were completed, the exoskeleton finger was then removed. The same procedures were used to don and calibrate the second and third exoskeleton fingers and to type their corresponding two sentences.

When the six experimental trials were completed, the diode and exoskeleton finger were removed. The subject was debriefed, paid, and thanked for participating.

4. DATA ANALYSIS

For each of the 27 keystrokes of interest in the experiment, the data collected included the displacement trajectories of the DIP, PIP, and MP joints in volts and the three-dimensional coordinate positions of the wrist and the key of interest in mm. As described in Section 3.3.3, the voltage data for the DIP, PIP, and MP joints was converted to degrees (β_1, β_2, and β_3, respectively). The three-dimensional coordinates of the wrist and key collected by the WATSMART system were converted into the two-dimensional coordinates for the wrist (W_x, W_y) and key (K_x, K_y) used in this thesis. Appendix C details these calculations. The two-dimensional coordinate system in this thesis was defined with the x-axis parallel to the support surface for the keyboard and in line with the metacarpal for the finger of interest and the y-axis perpendicular to the top of the keys. Values of x increase to the right of K_x (towards the lower row of keys) and values of y increase above K_y (vertically upwards), Figure 4.1

Before performing a statistical analysis on the collected data, they were transformed to the x and y components of linear velocity for the fingertip at the key, the angle with which the fingertip contacts the key, and the angle of the fingertip at the maximum depression of the key. Figure 4.2 outlines the flow of these calculations and the sections below describe the transformation of the data.

4.1 Position Data and Angular Velocity

Before the experimental trials, the WATSMART system was used to measure the three-dimensional coordinate positions of the **u**, **j**, and **m** keys. Appendix C details the how this data were converted into the x and y coordinates of the nine keys of interest (i.e., K_x, K_y). The x and y coordinates of the keys were used when calculating the x and y components of linear velocity for the fingertip at the key and the angle with which the fingertip contacts the key. When calculating the angle of the fingertip at the maximum

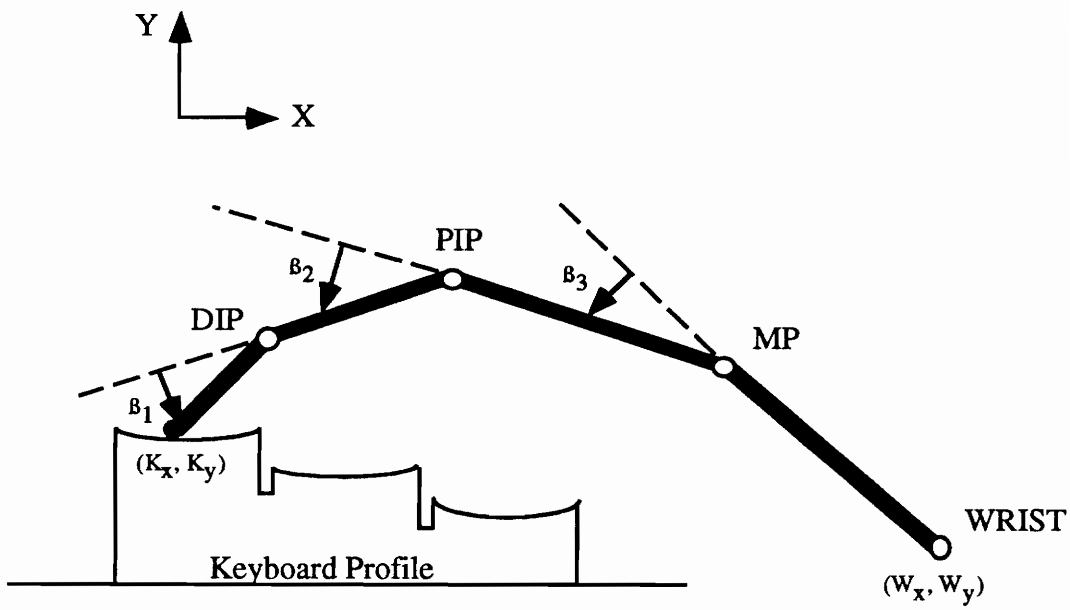

Figure 4.1 Data collected during each keystroke of interest.

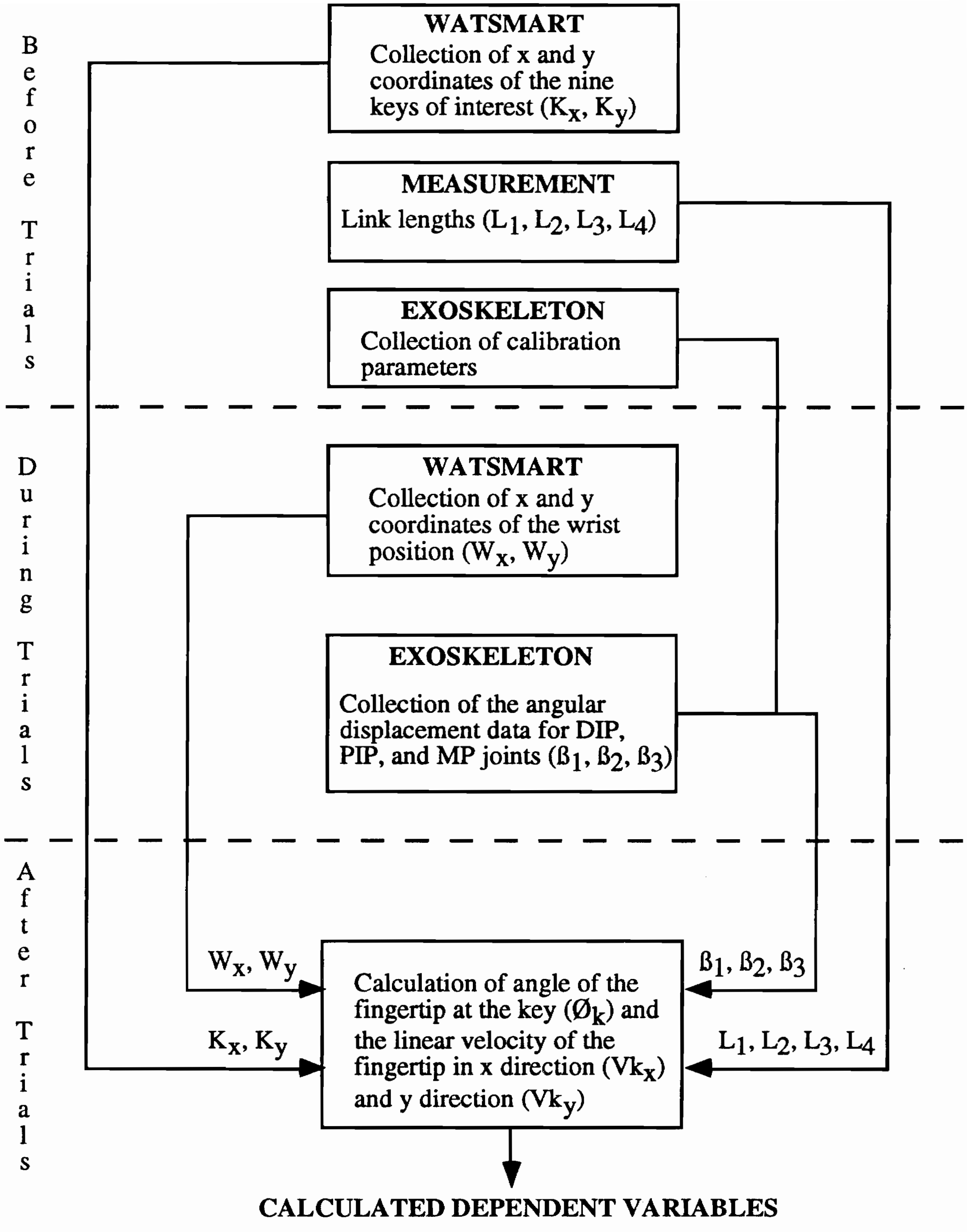

Figure 4.2 Flow of Calculations.

depression of the key, the K_y coordinate was decreased by 4 mm, the maximum travel distance of the key.

During each experimental trial (i.e., each typed sentence), the WATSMART system was run at 200 Hz for 15 seconds to collect the posture data for the wrist position. Appendix C details the calculations that were necessary to convert this collected data into the x and y coordinates of the wrist position (i.e., W_x, W_y). As the WATSMART system was collecting data, the SuperScope program for the exoskeleton was also collecting the voltage displacement data of the DIP, PIP, and MP at 200 Hz for 15 seconds.

After converting these voltage data points to degrees, the angular displacement trajectories for the DIP, PIP, and MP joints were used to calculate the velocity trajectories of the joints for each sentence. This was done through the use of cubic splines which were described in Section 2.5. A program was written in FORTRAN to access a cubic spline routine from the International Mathematical Statistical Library (IMSL). The program was used to calculate the 1st derivative for the DIP, PIP, and MP joints which gave the velocity trajectory for each of the joints during the keystrokes of interest. The IMSL routine is based on Reinsch's algorithm (1967) for evaluating the cubic splines. As suggested by McLaughlin et al. (1977), the smoothing parameter was set equal to the number of data points (i.e., 3000 for each sentence), so that the degree of smoothing was affected only by the weight of each data point. The weight of each data point was set at 0.25 degrees (see Equation 3 in Calculations of Spline Functions, Section 2.5.2.3).

For each keystroke of interest, the voltage displacement trajectories for the three joints were graphically analyzed with the SuperScope software to determine the fingertip's point of contact with the key (i.e., key contact point) and the fingertip's point of maximum depression of the key (i.e., key depressed point).

Figure 4.3 shows the voltage displacement trajectories for the three joints during the keystroke for the letter u. Prior to point A, the finger is traveling to the key. Point A is the point of contact with the key indicated by a change in the displacement trajectories of the three joints. From Point A to Point B, the key is being depressed. Point B is the point of maximum depression of the key indicated by the sharp change in the trajectories. After Point B, the finger finishes depressing the key and returns to its starting position.

For each keystroke of interest, the key contact point (Point A described above) was used to locate the corresponding angular velocity data points for the DIP, PIP, and MP joints (μ_1, μ_2, and μ_3, respectively), and the angular position data points for the DIP, PIP, and MP joints ($Ø_1$, $Ø_2$, and $Ø_3$, respectively). Similarly, the key depressed point (Point B described above) was used to locate the corresponding data set for the point of maximum depression of the key. Appendix D details how the x and y data points for the wrist (i.e., W_x, W_y) were located for each keystroke of interest.

4.2 Calculation of the Angle at the Key

Figure 4.4 shows the coordinate system for the angles to be calculated in this section with respect to the horizontal axis. Clockwise angular rotation is negative and counterclockwise is positive.

Given the link length data (L_1, L_2, L_3, and L_4), the angular position of the DIP, PIP, and MP joints ($Ø_1$, $Ø_2$, and $Ø_3$, respectively), and the x and y coordinates of the key of interest (K_x, K_y) and the wrist (W_x, W_y) at the point of contact with the key, the angle of the fingertip ($Ø_k$) at the point of contact with the key was determined through the use of inverse kinematics (Figure 4.5). The same set of data for the key depressed point was needed to determine the angle of the fingertip ($Ø_k$) at the point of maximum depression of the key. The calculations shown in this section were done for both sets of data (i.e., to determine $Ø_k$ at the point of contact and the point of maximum depression).

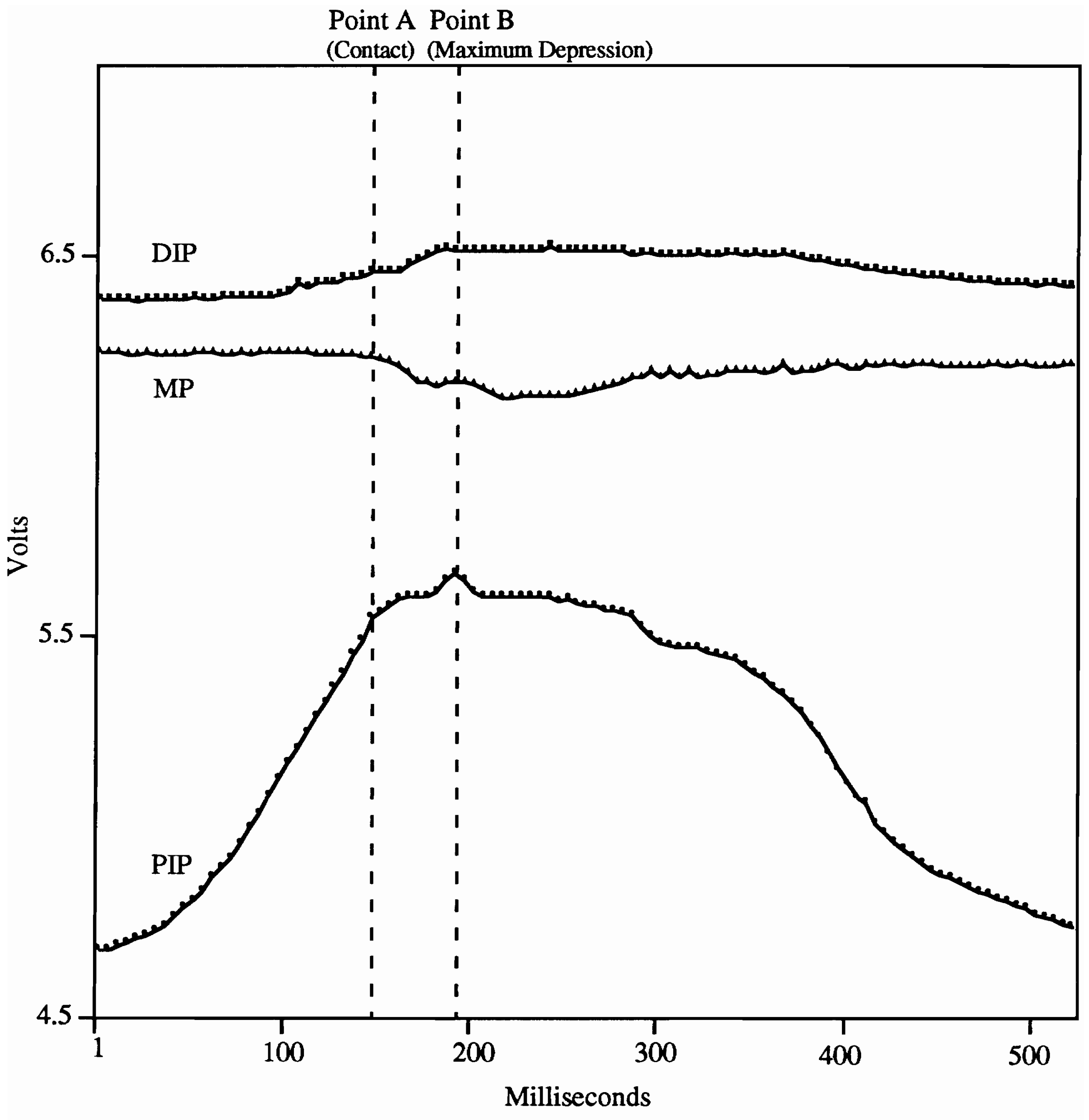

Figure 4.3 Voltage displacement trajectories of DIP, PIP, and MP joints during the keystroke for the letter u.

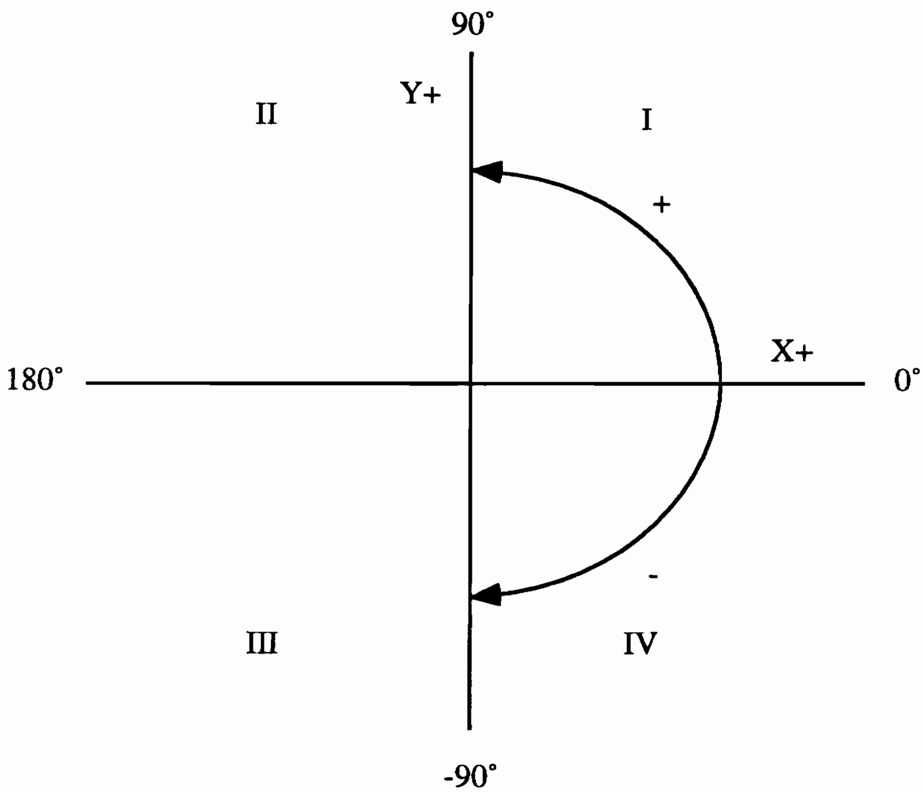

Figure 4.4 Coordinate system for angles with respect to the horizontal, quadrants are shown with roman numerals.

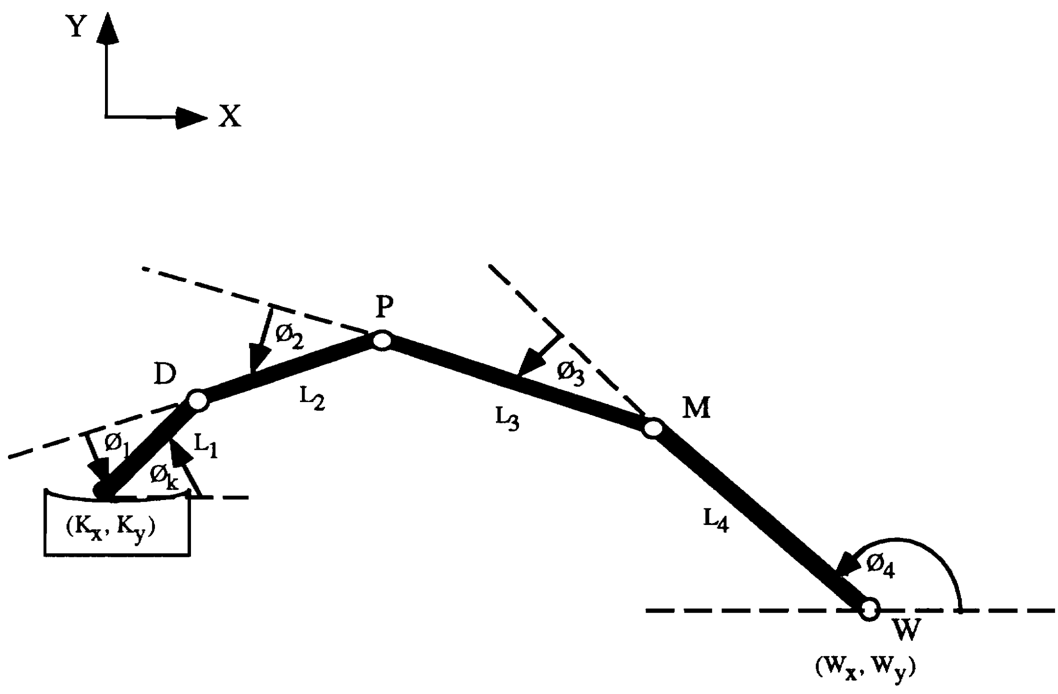

Figure 4.5 Inputs needed to determine the angle of the fingertip at the key, $\emptyset_k$.

The first step in the process was to use the key and wrist x and y coordinates to calculate the distance from the wrist to the key (L_5, Figure 4.6a and 4.6b).

$$L_5 = [(W_y - K_y)^2 + (W_x - K_x)^2]^{1/2} \qquad (4.1)$$

Next, the angle of the wrist with respect to the horizontal axis was calculated ($Ø_4$) which involved calculating L_6, $Ø_5$ and $Ø_6$ (see Figures 4.6a, 4.6b). Figures 4.6a shows the case where the vertical wrist position is lower than the vertical key position ($W_y < K_y$) while Figure 4.5b shows the opposite case ($W_y > K_y$). To calculate L_6, the orthogonal x and y distances (O_x and O_y, see Figure 4.6c) from the MP joint to the key had to be determined through inverse kinematics. In the following equations, "C" and "S" stand for cosine and sine, respectively, and the numbers following the C and S refer to the sum of the angles (e.g., C_{12} stands for cosine($Ø_1 + Ø_2$)).

$$O_x = L_3C_3 + L_2C_{23} + L_1C_{123} \qquad (4.2)$$

$$O_y = L_3S_3 + L_2S_{23} + L_1S_{123}$$

After O_x and O_y were determined, the following equation calculated the distance L_6.

$$L_6 = [O_x^2 + O_y^2]^{1/2} \qquad (4.3)$$

The law of cosines was used to calculate $Ø_5$ and then the tangent equation for $Ø_6$.

$$Ø_5 = \cos^{-1}[(L_6^2 - L_4^2 - L_5^2)/(-2L_4L_5)] \qquad (4.4)$$

$$Ø_6 = \tan^{-1}[(W_y - K_y)/(W_x - K_x)] \qquad (4.5)$$

For $Ø_6$, the positive value of the angle was taken and following the conditions below (Equation 4.6) which are based on the two cases in Figures 4.6a and 4.6b, $Ø_4$ was determined.

$$\begin{aligned} &\text{If } W_y < K_y \text{ then} \quad Ø_4 = \pi - Ø_5 - Ø_6 \\ &\text{If } W_y > K_y \text{ then} \quad Ø_4 = \pi - Ø_5 + Ø_6 \qquad (4.6) \\ &\text{If } W_y = K_y \text{ then} \quad Ø_4 = \pi - Ø_5 \end{aligned}$$

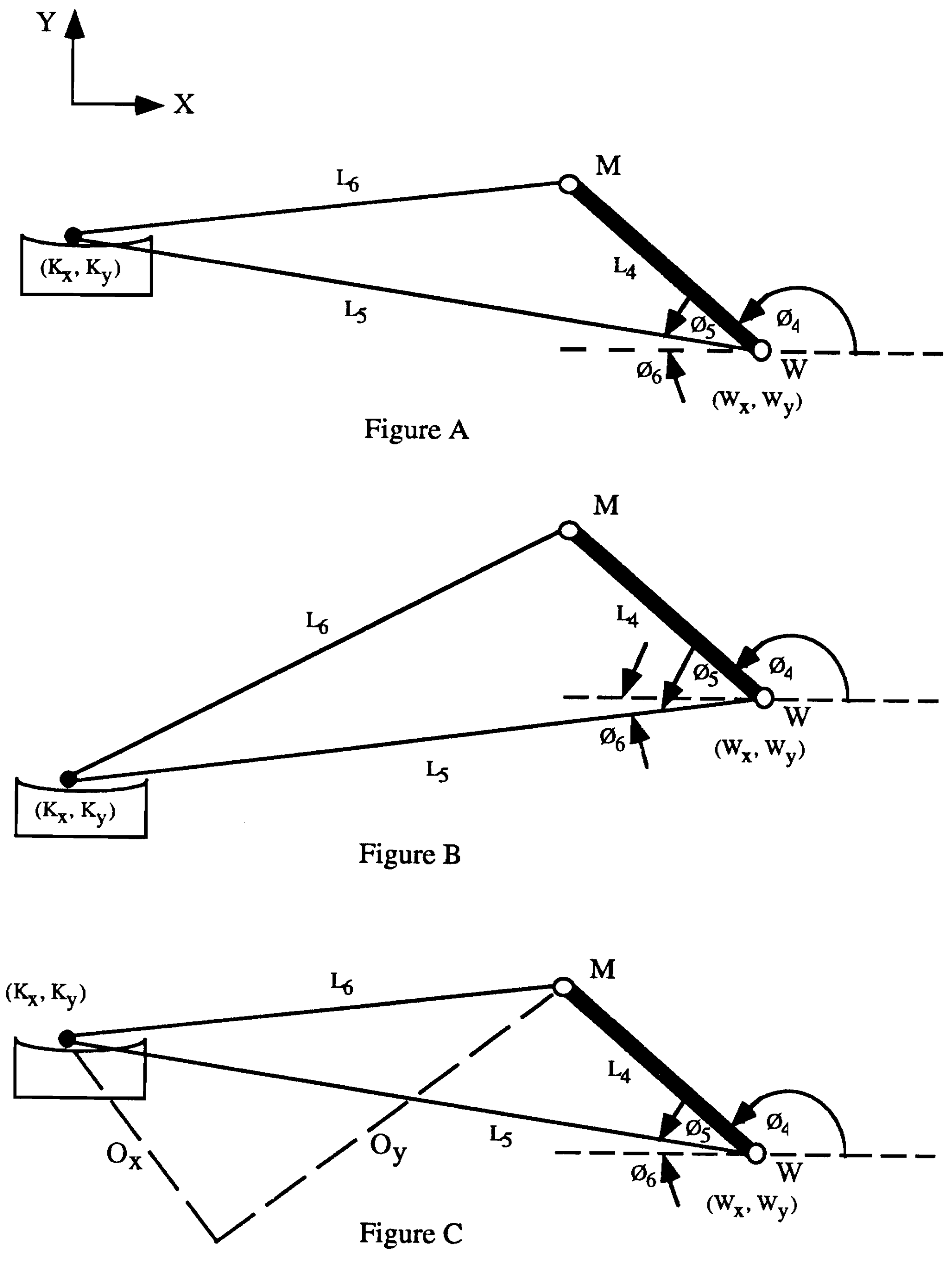

Figure 4.6 Calculations and inputs needed for determining angle at wrist, Ø4.

Given $Ø_4$, the x and y coordinates for the DIP joint (D_x, D_y) were calculated from which the angle at the key, $Ø_k$, was determined.

$$D_x = W_x + L_4C_4 + L_3C_{34} + L_2C_{234}$$

$$D_y = W_y + L_4S_4 + L_3S_{34} + L_2S_{234} \quad (4.7)$$

$$Ø_k = \tan^{-1}[(K_y - D_y)/(K_x - D_x)] \quad (4.8)$$

For $Ø_k$, the positive value of the angle was taken and following the conditions below (Equation 4.9) which are based on the possible range of motion for the fingertip, the final value of $Ø_k$ was determined. Figure 4.7a shows an example of the range of motion that is feasible for the fingertip, L_1, during typing, which is the first and second quadrants of the coordinate system (0° to approximately 160°).

$$\begin{aligned} &\text{If } D_x < K_x \text{ then} && Ø_k = \pi - Ø_k \\ &\text{If } D_x > K_x \text{ then} && Ø_k = Ø_k \\ &\text{If } D_x = K_x \text{ then} && Ø_k = \pi/2 \end{aligned} \quad (4.9)$$

For each subject, the angular displacement data, the position data for the wrist, and the position data for the key of interest were transformed using the above calculations to determine the angle of the fingertip with respect to the horizontal axis when striking the key of interest. The final results, $Ø_k$ at the point of contact and $Ø_k$ at the point of maximum depression, were statistically analyzed using a repeated measures design as explained in Results (Section 5).

4.3 Calculation of the Linear Velocity at the Key

Since the linear velocity at the point of maximum depression will nearly be zero, the linear velocity components for the fingertip were only calculated for the point of contact with the key. Calculating this linear velocity required the link length data, the angle of the fingertip at the key ($Ø_k$, calculated in Section 4.2), and the angular velocities

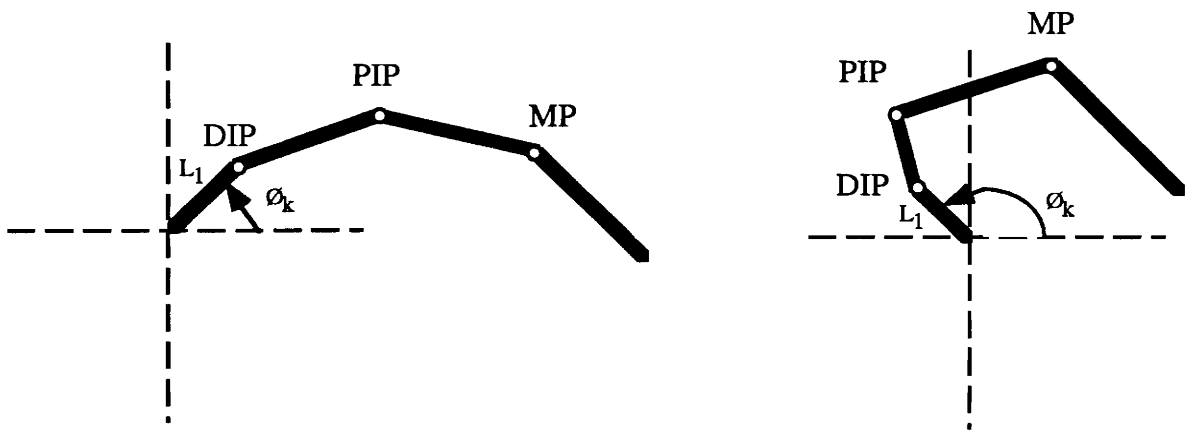

Figure A - Range of Motion for L_1 (Fingertip)

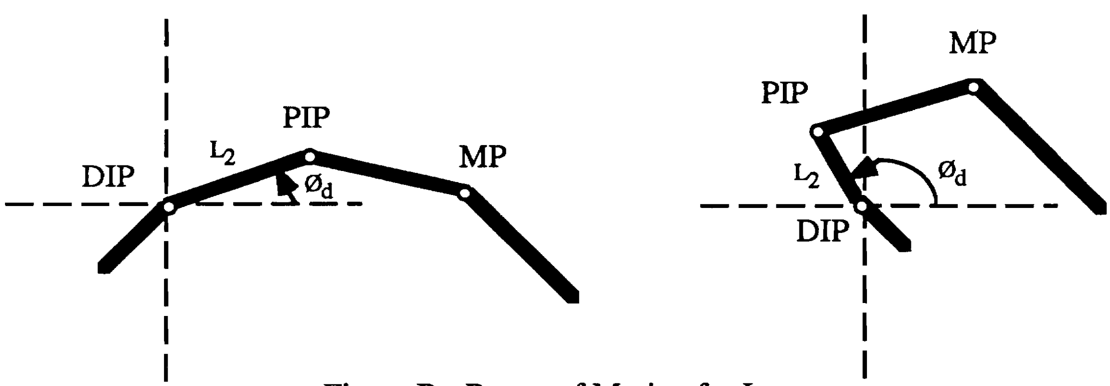

Figure B - Range of Motion for L_2

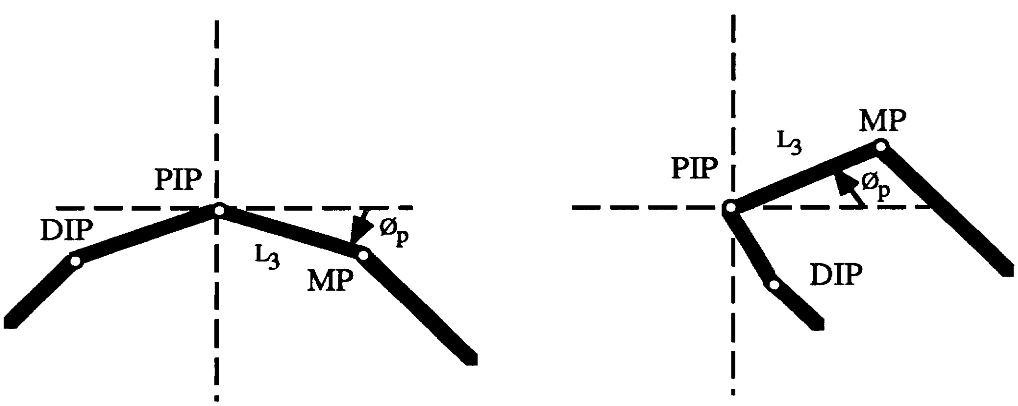

Figure C - Range of Motion for L_3

Figure 4.7 Range of motion for L_1, L_2, and L_3 during typing.

of the DIP, PIP, and MP joints (μ_1, μ_2, and μ_3, calculated in Section 4.1). Furthermore, the angles at the DIP ($\O_d$) and PIP ($\O_p$) joints with respect to the horizontal needed to be calculated. Figure 4.8 gives the inputs needed to determine the angular velocity at the fingertip (Vk_x, Vk_y).

The same steps used to calculate $\O_k$ were used to calculate $\O_d$ and $\O_p$. Given $\O_4$ and $\O_3$ and the x and y coordinates of the DIP joint (D_y, D_x) from the calculations in the sections above, $\O_d$ was be determined.

$$P_x = W_x + L_4C_4 + L_3C_{34}$$

$$P_y = W_y + L_4S_4 + L_3S_{34} \qquad (4.10)$$

$$\O_d = \tan^{-1}[(D_y - P_y)/(D_x - P_x)] \qquad (4.11)$$

For $\O_d$, the positive value of the angle was taken and following the conditions below (Equation 4.12), which are based on the possible range of motion for the fingertip, the final value of $\O_d$ was determined. Figure 4.7b shows an example of the range of motion that is feasible for the L_2 during typing, which is in the first and second quadrants of the coordinate system (approximately 0° to 160°).

$$\begin{aligned} &\text{If } P_x < D_x \text{ then} && \O_d = \pi - \O_d \\ &\text{If } P_x > D_x \text{ then} && \O_d = \O_d \qquad (4.12) \\ &\text{If } P_x = D_x \text{ then} && \O_d = \pi/2 \end{aligned}$$

Similarly for $\O_p$, given $\O_4$ the x and y coordinates of the PIP joint (P_y, P_x) from above, $\O_p$ was determined.

$$M_x = W_x + L_4C_4$$

$$M_y = W_y + L_4S_4 \qquad (4.13)$$

$$\O_p = \tan^{-1}[(P_y - M_y)/(P_x - M_x)] \qquad (4.14)$$

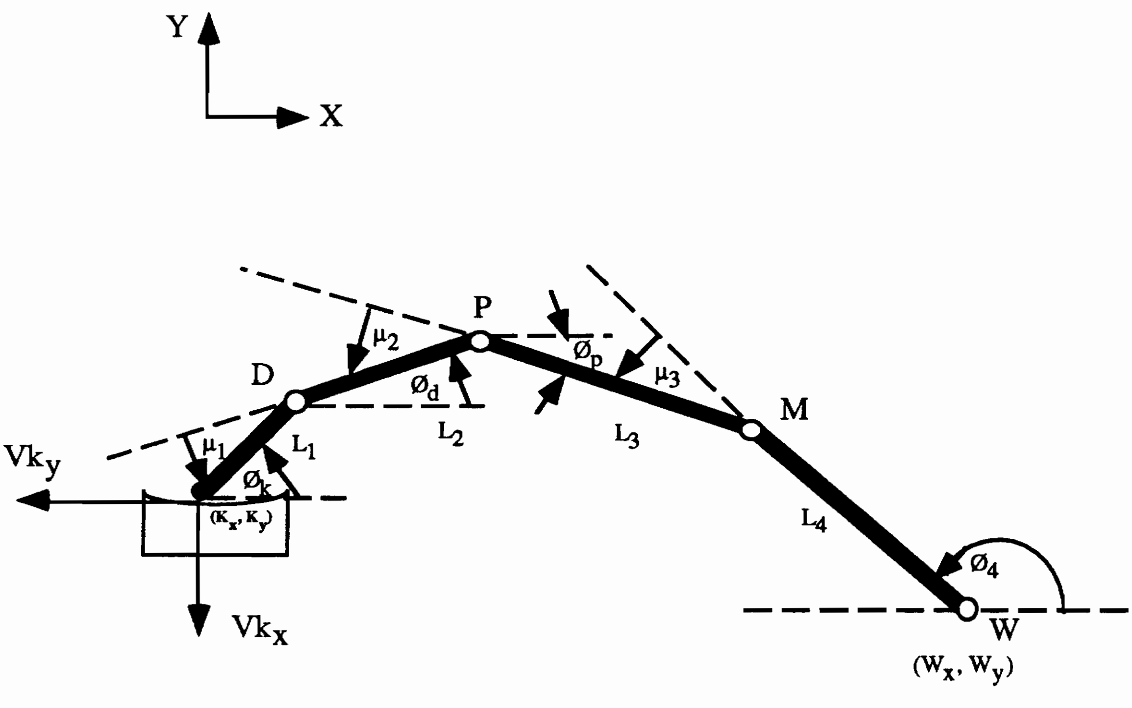

Figure 4.8 Inputs needed to determine the linear velocity of the fingertip (Vk_x, Vk_y).

For $\O_p$, the positive value of the angle was taken and following the conditions below (Equation 4.15), which are based on the possible range of motion for the fingertip, the final value of $\O_p$ was determined. Figure 4.7c shows an example of the range of motion that is feasible for the L_3 during typing, which is in the first and fourth quadrants of the coordinate system (approximately -80° to 90°).

$$\begin{array}{ll} \text{If } M_y < P_y \text{ then} & \O_p = -1 * \O_p \\ \text{If } M_y > P_y \text{ then} & \O_p = \O_p \\ \text{If } M_y = P_y \text{ then} & \O_p = 0 \end{array} \tag{4.15}$$

After all the needed angles were calculated (i.e., $\O_k$, $\O_d$, and $\O_p$), the linear velocity for the fingertip at the point of contact with the key was determined. This involved transforming the angular velocities for each joint into the linear velocities for their corresponding segments by multiplying angular velocity by segment length. The equations below illustrate this, (angular velocities must be in radians).

$$\begin{array}{l} V_1 = \mu_1 * L_1 \\ V_2 = \mu_2 * L_2 \\ V_3 = \mu_3 * L_3 \end{array} \tag{4.16}$$

After the linear velocities of each segment were determined, the x and y components of the velocity for each segment were calculated and the appropriate direction was determined. The equations below calculate the x and y components of velocity.

$$\begin{array}{ll} V_{1x} = V_1 * \sin \O_k & V_{1y} = V_1 * \cos \O_k \\ V_{2x} = V_2 * \sin \O_d & V_{2y} = V_2 * \cos \O_d \\ V_{3x} = V_3 * \sin \O_p & V_{3y} = V_3 * \cos \O_p \end{array} \tag{4.17}$$

Table 4.1 gives the appropriate direction of the x and y components of velocity depending on the direction of the angular velocity and the angle of the segment with respect to the horizontal. Note that angular velocity in the clockwise direction is negative and in the counter-clockwise direction is positive. Figure 4.9 shows two examples of how the linear velocity is determined for a segment. After the directions of the components were determined, the final step for determining the x and y components of linear velocity for the fingertip involved the simple addition of the components for each link segment.

$$Vk_x = V_{1x} + V_{2x} + V_{3x}$$
$$Vk_y = V_{1y} + V_{2y} + V_{3y} \qquad (4.18)$$

Since the link length data was measured in mm and the time period between two data points was 0.005 seconds, the x and y velocity components above were multiplied by 20 to convert them to cm/sec. The final results, Vk_x and Vk_y, were both statistically analyzed through a repeated measures design as explained in Results (Section 5).

Table 4.1 Direction for x and y Linear Components of Velocity.

Angle	Angular Velocity Direction	V_x	V_y
-90° < Ø < 0°	+	-	-
-90° < Ø < 0°	-	+	+
Ø = 0°	+	0	-
Ø = 0°	-	0	+
0° < Ø < 90°	+	+	-
0° < Ø < 90°	-	-	+
Ø = 90°	+	+	0
Ø = 90°	-	-	0
90° < Ø < 180°	+	+	+
90° < Ø < 180°	-	-	-

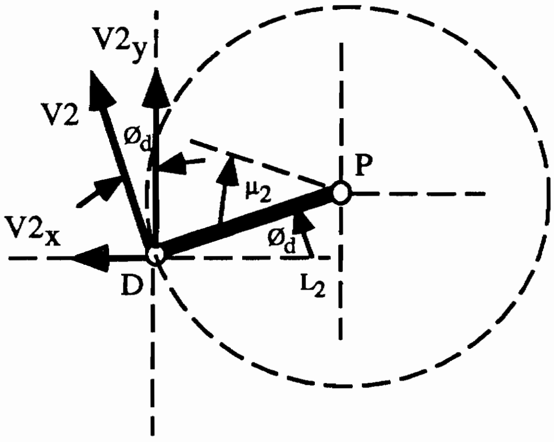

Figure A - Negative angular velocity, 0° < $Ø_d$ < 90°

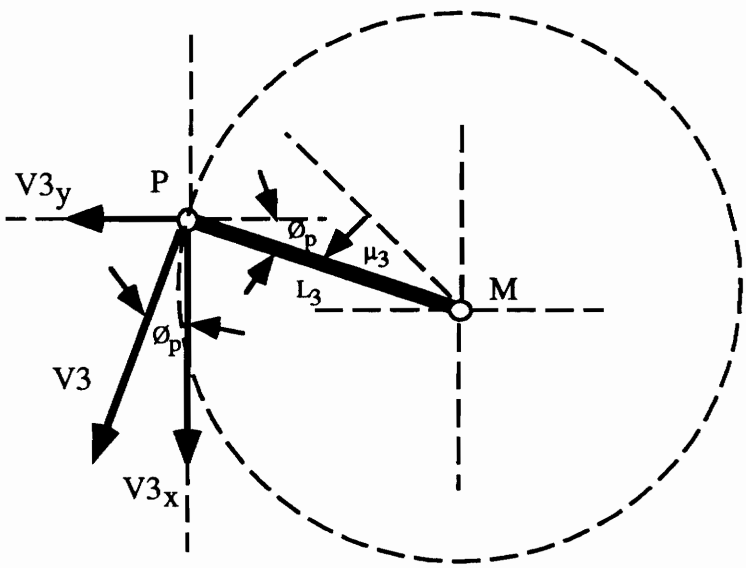

Figure B - Positive angular velocity, -90° < $Ø_p$ < 0°

Figure 4.9 Example calculations for x and y components of linear velocity.

5.0 RESULTS

5.1 Data Reduction

The four calculated dependent variables for this experiment included: the fingertip angle at the point of contact with the key, the fingertip angle at the point of maximum depression of the key, the linear y component of velocity (Vk_y), and the linear x component of velocity (Vk_x). Before a statistical analysis was performed on these dependent variables, the key and wrist data collected from the WATSMART system and the finger joint displacement data collected with the SuperScope program had to be reduced. This included the following steps: (1) the x and y coordinates of the nine keys were determined, (2) the units of raw data from the SuperScope program were converted from voltage to degrees, (3) the points of contact and points of maximum depression for each keystroke of interest were determined from a graphical analysis of the finger joint displacement data, (4) the wrist data and the finger joint displacement data for each trial were then synchronized, (5) the x and y coordinates of the wrist were determined for the points of contact and points of maximum depression, (6) the velocity of the finger joint displacement data was determined through a cubic spline program, and (7) the angles of the fingertip at the key ($\emptyset_k$) for the point of contact and point of maximum depression, the linear y component of velocity (Vk_y), and the linear x component of velocity (Vk_x) were the calculated using the steps described in Sections 4.2 and 4.3.

5.2 Statistical Analysis

A multivariate analysis of variance (MANOVA) was performed for the four dependent variables followed by a separate univariate analysis of variance (ANOVA) on each dependent variable. The MANOVA analysis was done to determine the overall significance of the factors of interest and to minimize the alpha error that may become excessive when multiple ANOVAs are used on the same set of data (Finkleman, Wolf, and Friend, 1977). When separate ANOVAs are done for each dependent measure, the per experiment alpha (α,Type I Error) may become excessive, actual alpha may be as high as $1 - (1 - \alpha)^k$, where k equals the number of ANOVAs. In this thesis there are four dependent measures and the alpha tested is 0.05, therefore the actual alpha being tested may be as high as 0.19. Also, using multiple ANOVAs on the same data may reduce the power to reject a false null hypothesis. This may occur when there is an underlying mechanism that is spread across more than one measure which is not detected by the separate ANOVAs. The MANOVA detects the overall significance for an effect while the ANOVA calculates the impact of significant independent variables and interactions on each of the dependent measures. Since these ANOVAs are used as a post-comparison technique after significant effects are found using the MANOVA, the results of the ANOVAs are limited to only the effects found significant in the MANOVA.

The MANOVA was calculated for the four dependent measures using the Statistical Analysis System (SAS). The *p*-values for the Wilks' Lambda statistic were used. Table 5.1 shows the results of the MANOVA. The main effects of *Finger*, *Row*, and *Digraph*, the two-way interaction of *Row by Gender* and the three-way interactions of *Finger by Row by Digraph* and *Finger by Row by Gender* were significant at $p<0.05$. Each of the four calculated dependent variables were analyzed by means of a standard analysis of variance (ANOVA) using the SuperAnova Data Analysis Package for the Macintosh. Greenhouse-Geisser corrected values for p were used to help correct for the inherent correlation of repeated measurements. Note that because of the skewdness of the F-distribution, the Greenhouse-Geisser correction may actually decrease the *p*-values when they are at or below the maximum probability of the F-distribution. This will only occur when the F-values are clearly not significantly (i.e., F-values that are less than one).

All effects that were found significant in the MANOVA were also found significant for at least one ANOVA. Also, there was only one interaction (*Finger by*

Digraph) for one dependent measure, linear x velocity, which was found significant by the ANOVA, but not significant by the MANOVA ($p<0.05$). Newman-Keuls post-hoc tests with $\alpha=0.05$ were done on the means of the effects found significant in the ANOVAs. The Greenhouse-Geisser correction was not carried through for these post-hoc comparisons. While there is some debate, Vasey and Thayer (1987) indicate that the Greenhouse-Geiseer correction is adequate when applied to the overall tests for main effects of or interactions with the repeated measures, but the corrections do not protect the post-hoc tests. Newman-Keuel post-hoc comparisons may therefore be biased under conditions of high to moderate nonsphericity. The results of the four separate ANOVAs and their corresponding post-hoc tests are detailed next.

Table 5.1 MANOVA Summary Table for All Four Dependent Variables

Factor	Wilks' Lamda	F-Value	Num DF	Den DF	p-Value	
Gen	0.593	1.203	4	7	0.3887	
Fin	0.177	5.848	8	34	0.0001	**
Row	0.0687	11.962	8	34	0.0001	**
Dig	0.262	4.059	8	34	0.0018	**
Fin * Gen	0.788	0.536	8	34	0.8213	
Row * Gen	0.408	2.407	8	34	0.0355	**
Dig * Gen	0.687	0.876	8	34	0.5461	
Fin * Row	0.524	1.674	16	114	0.0616	
Fin * Dig	0.602	1.283	16	114	0.2201	
Row * Dig	0.699	0.885	16	114	0.5879	
Fin * Row * Gen	0.500	1.811	16	114	0.0376	**
Fin * Dig * Gen	0.643	1.104	16	114	0.3598	
Row * Dig * Gen	0.774	0.621	16	114	0.8614	
Fin * Row * Dig	0.338	2.608	32	286	0.0001	**
Fin * Row * Dig * Gen	0.721	0.826	32	286	0.7379	

** Significant at $p<0.05$

Dependents:
- Fingertip Angle at Point of Contact (Degrees)
- Fingertip Angle at Point of Depression (Degrees)
- Linear Y Velocity (cm/sec)
- Linear X Velocity (cm/sec)

Legend:
- Gen: Gender (2 levels)
- Fin: Finger (3 levels; index, middle, ring)
- Row: Row (3 levels; upper, middle, lower)
- Dig: Digraph (3 levels; one-finger, two-finger, two-hand)

5.3 Fingertip Angle at Point of Contact

For fingertip angle at point of contact, the ANOVA revealed that the main effects of *Finger*, *Row*, and *Digraph* , the two-way interaction of *Row by Gender*, and the three-way interaction of *Finger by Row by Digraph* were significant at $p<0.05$ using the Greenhouse-Geisser corrected p values. Table 5.2 shows the ANOVA summary table for this dependent variable, fingertip angle at the point of contact.

The mean values for the main effect of *Finger* are graphed in Figure 5.1, which also presents the results of Newman-Keuls post-hoc test of the means with $\alpha=0.05$. The mean fingertip angle for the index finger (31.4 degrees) was significantly different from both the middle and the ring fingers (72.8 and 73.8 degrees, respectively), which were not significantly different from each other.

Figure 5.2 shows the mean values for the main effect of *Row*. The results of the Newman-Keuls post-hoc test of the means revealed that all three levels of *Row* (i.e., upper, middle, and lower) were significantly different. The mean fingertip angle for the upper, middle, and lower rows were 45.3, 59.5, and 73.1 degrees, respectively.

The mean values for the main effect of *Digraph* are graphed in Figure 5.3, which also presents the results of Newman-Keuls post-hoc test of the means. The mean fingertip angle for the one-finger digraphs (55.5 degrees) was significantly different from both two-finger and two-hand digraphs (61.6 and 60.7 degrees, respectively), which were not significantly different from each other.

The two-way interaction of *Row by Gender* is graphed in Figure 5.4. The Newman-Keuls post-hoc test of the means revealed that the mean fingertip angles for the males and females were significantly different only for the upper row. At the upper row, the mean fingertip angle for the males was 20 degrees more than that of the females.

The three-way interaction of *Finger by Row by Digraph* is graphed in Figure 5.5. The Newman-Keuls post-hoc test revealed that for the two-finger digraphs, the largest angle for the index finger occurred at the lower row and for the middle and ring fingers at the middle row. For the other row and finger levels, the largest angle tended to occur for two-hand digraphs and the smallest angle for one-finger digraphs.

Figure 5.6 illustrates the ranges of fingertip angles at the point of contact with the key. The figure is divided by finger and then by row. Overall, the fingertip angles at the point of contact ranged from 1 to 126 degrees. For the index finger, the range was from 1 to 108 degrees with an average of 31.4 degrees. For the middle finger, the range was from 2 to 122 degrees with an average of 72.8 degrees. Not significantly different from the middle finger, the fingertip angle at the point of contact for the ring finger had an average of 73.8 degrees and a range from 3 to 126 degrees. For the upper row, the fingertip angles at the point of contact ranged from 2 to 93 degrees with an average of 45.3 degrees. For the middle row, the range was from 1 to 125 degrees with an average of 59.5 degrees. The average fingertip angle at the point of contact for the lower row was higher at 73.1 degrees and had a range from 1 to 126 degrees.

Table 5.2 ANOVA Summary Table for Fingertip Angle at Point of Contact

Factor	df	Sum of Squares	Mean Square	F-Value	p-Value	G-G
Between-Subjects						
Gen	1	5845.96	5845.96	1.19	0.3010	
Sub/Gen	10	49145.73	4914.57			
Within-Subjects						
Fin	2	126300.55	63150.28	27.92	0.0001	0.0001**
Fin * Gen	2	1826.08	913.04	0.40	0.6732	0.5728
Fin * Sub/Gen	20	45230.92	2261.55			
Row	2	41840.58	20920.29	48.36	0.0001	0.0001**
Row * Gen	2	5906.46	2953.23	6.83	0.0055	0.0092**
Row * Sub/Gen	20	8652.31	432.62			
Dig	2	2355.50	1177.75	8.63	0.0020	0.0084**
Dig * Gen	2	545.42	272.71	2.00	0.1618	0.1816
Dig * Sub/Gen	20	2730.21	136.51			
Fin * Row	4	5326.99	1331.75	3.25	0.0213	0.0643
Fin * Row * Gen	4	3290.79	822.70	2.01	0.1122	0.1643
Fin * Row * Sub/Gen	40	16407.48	410.19			
Fin * Dig	4	315.43	78.86	0.48	0.7515	0.6995
Fin * Dig * Gen	4	597.04	149.26	0.91	0.4702	0.4501
Fin * Dig * Sub/Gen	40	6596.33	164.91			
Row * Dig	4	387.03	96.76	0.58	0.6805	0.5973
Row * Dig * Gen	4	508.82	127.21	0.76	0.5578	0.4999
Row * Dig * Sub/Gen	40	6699.64	167.49			
Fin * Row * Dig	8	4267.00	533.38	3.15	0.0038	0.0380**
Fin * Row * Dig * Gen	8	797.65	99.71	0.59	0.7842	0.6307
Fin * Row * Dig * Sub/Gen	80	13543.02	169.29			
Totals	323	349116.94				

** Significant at p<0.05 for both MANOVA and ANOVA

Dependent: Fingertip Angle at Point of Contact (Degrees)

Legend:

Gen: Gender (2 levels)

Fin: Finger (3 levels; index, middle, ring)

Row: Row (3 levels; upper, middle, lower)

Dig: Digraph (3 levels; one-finger, two-finger, two-hand)

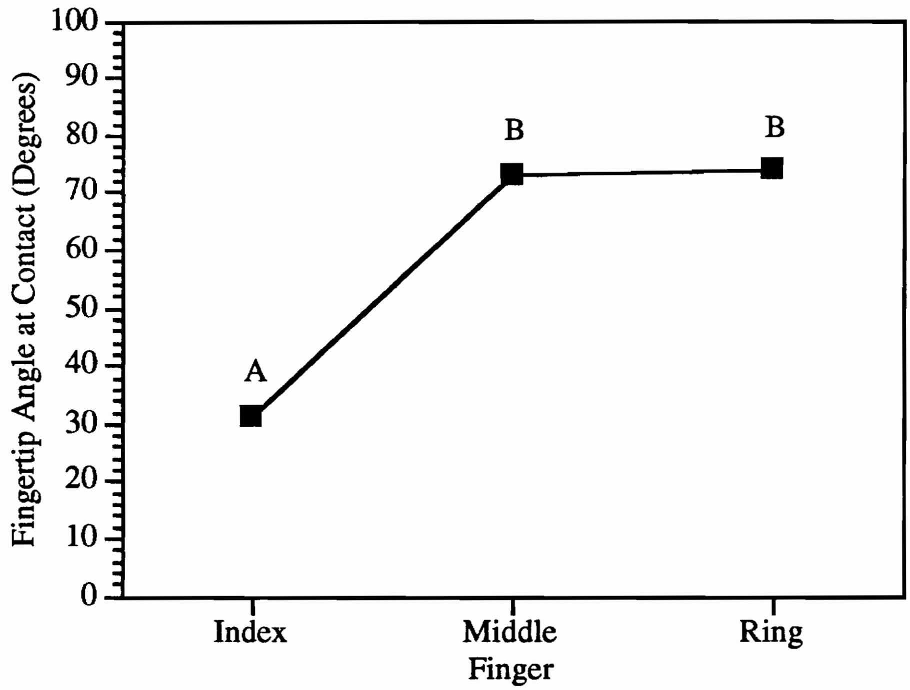

Figure 5.1 *Finger* main effect for fingertip angle at point of contact. Points with the same letters are not significantly different at $p<0.05$ using a Newman-Keuls post-hoc test.

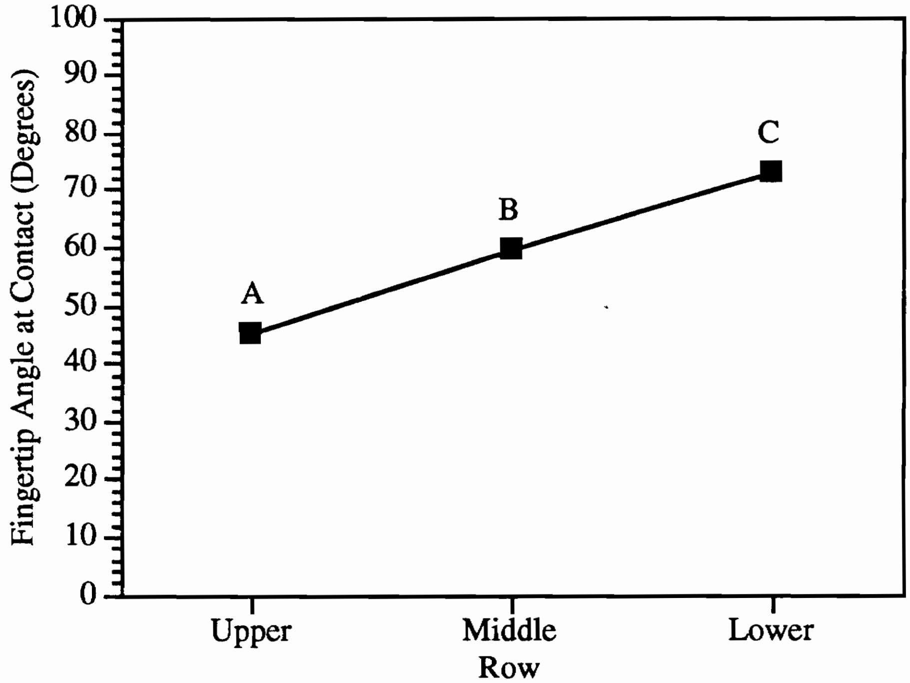

Figure 5.2 *Row* main effect for fingertip angle at point of contact. Points with the same letters are not significantly different at $p<0.05$ using a Newman-Keuls post-hoc test.

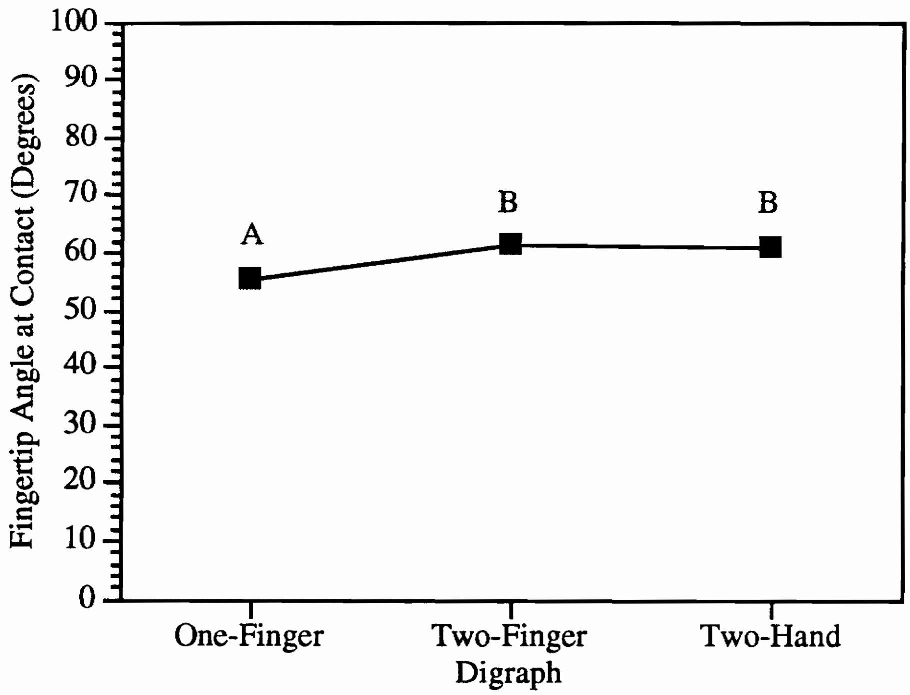

Figure 5.3 *Digraph* main effect for fingertip angle at point of contact. Points with the same letters are not significantly different at $p<0.05$ using a Newman-Keuls post-hoc test.

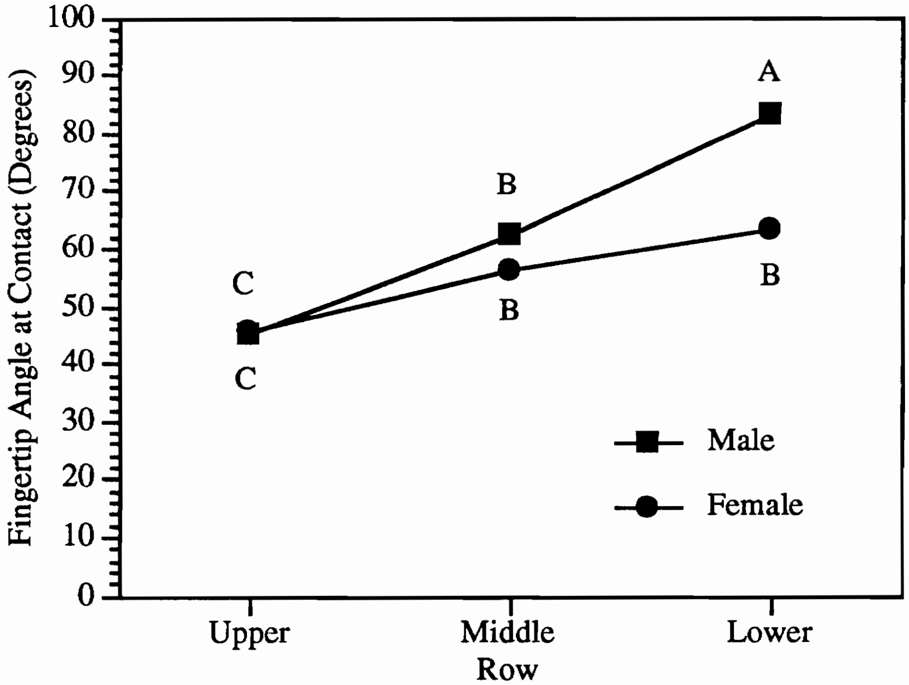

Figure 5.4 *Row by Gender* interaction for fingertip angle at point of contact. Points with the same letters are not significantly different at $p<0.05$ using a Newman-Keuls post-hoc test.

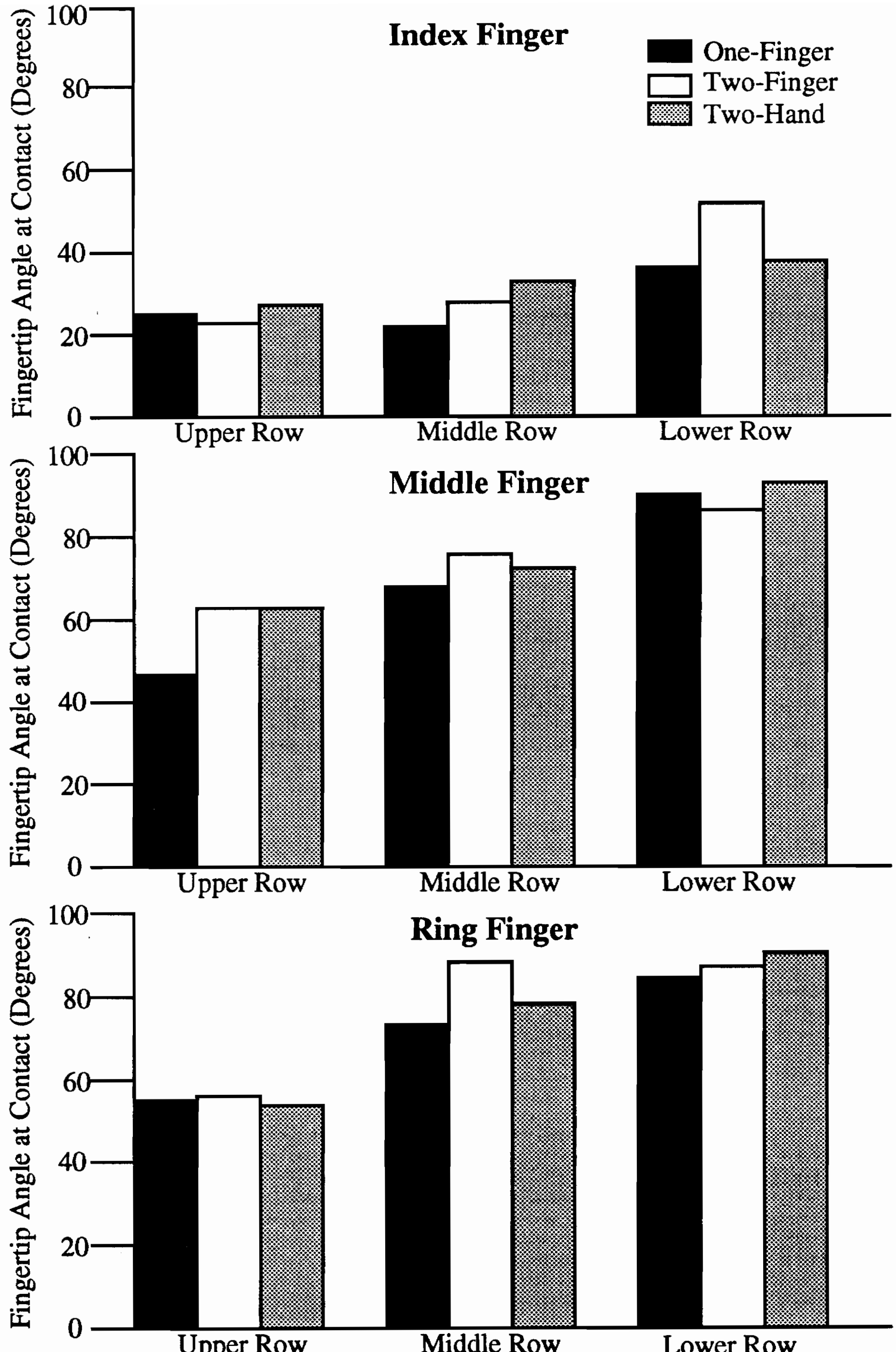

Figure 5.5 *Finger by Row by Digraph* interaction for fingertip angle at point of contact.

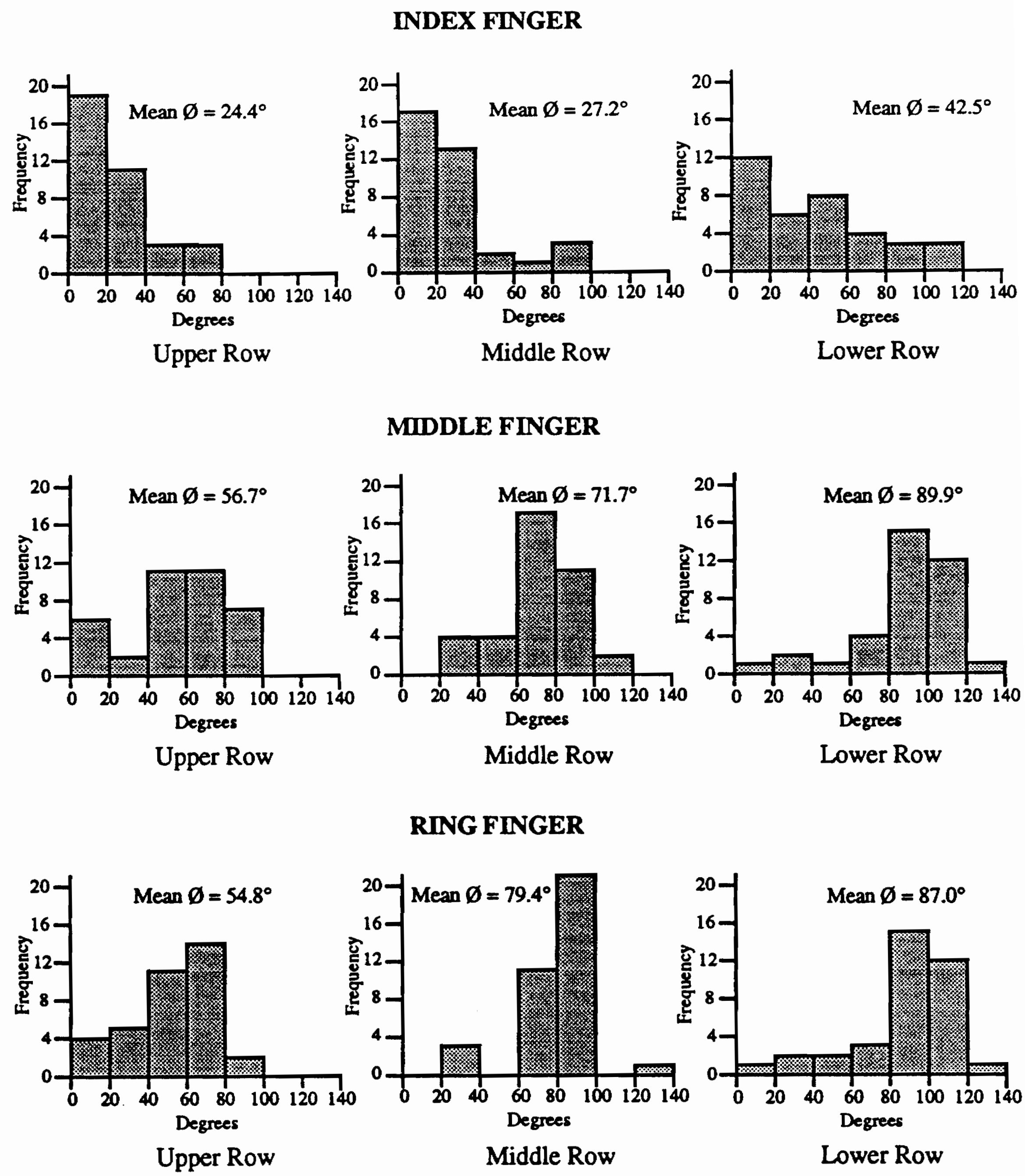

Figure 5.6 Range of fingertip angles at point of contact.

5.4 Fingertip Angle at Point of Maximum Depression

For the dependent variable, fingertip angle at point of maximum depression, the ANOVA revealed that the main effects of *Finger*, *Row*, and *Digraph* were significant at $p<0.05$ using the Greenhouse-Geisser corrected p values. The two-way interaction of *Row by Gender* was also significant at $p<0.05$. Table 5.3 shows the ANOVA summary table for this analysis.

The mean values for the main effect of *Finger* are graphed in Figure 5.7 which also presents the results of Newman-Keuls post-hoc test of the means with $\alpha=0.05$. The mean fingertip angle for the index finger (29.7 degrees) was significantly different from both the middle and the ring fingers (73.0 and 73.8 degrees, respectively), which were not significantly different from each other.

Figure 5.8 shows the mean values for the main effect of *Row*. The results of the Newman-Keuls post-hoc test of the means revealed that all three levels of *Row* (i.e., upper, middle, and lower) were significantly different. The mean fingertip angle for the upper, middle, and lower rows were 45.6, 58.6, and 72.3 degrees, respectively.

The mean values for the main effect of *Digraph* are graphed in Figure 5.9, which also presents the results of Newman-Keuls post-hoc test of the means. The mean fingertip angle for the one-finger digraphs (55.9 degrees) was significantly different from both two-finger and two-hand digraphs (60.2 and 60.4 degrees, respectively), which were not significantly different from each other.

The two-way interaction of *Row by Gender* is graphed in Figure 5.10. The Newman-Keuls post-hoc test of the means revealed that the mean fingertip angles for the males and females were significantly different only for the upper row. At the upper row, the mean fingertip angle for the males was 22 degrees more than that of the females.

Figure 5.11 illustrates the ranges of fingertip angles at the point of maximum depression of the key. The figure is broken down by finger and then by row. Overall, the fingertip angles at the point of maximum depression ranged from 1 to 164 degrees. Only one fingertip angle was greater than 140 degrees. This angle of 164 degrees, which is not shown in Figure 5.11, occurred when typing with the middle finger on the lower row. For the index finger, the range of fingertip angles at the point of maximum depression was from 1 to 108 degrees with an average of 29.7 degrees. For the middle finger, the range was from 2 to 164 degrees with an average of 73.0 degrees. Not significantly different from the middle finger, the fingertip angle at the point of maximum depression for the ring finger had an average of 73.8 degrees and a range from 3 to 133 degrees. For the upper row, the fingertip angles at the point of maximum depression ranged from 1 to 93 degrees with an average of 45.6 degrees. For the middle row, the range was from 1 to 103 degrees with an average of 58.6 degrees. The average fingertip angle at the point of maximum depression for the lower row was higher at 72.3 degrees and had a range from 1 to 164 degrees.

Table 5.3 ANOVA Summary Table for Fingertip Angle at Point of Depression

Factor	df	Sum of Squares	Mean Square	F-Value	p-Value	G-G
Between-Subjects						
Gen	1	8009.65	8009.65	1.66	0.2260	
Sub/Gen	10	48119.55	4811.96			
Within-Subjects						
Fin	2	137703.24	68851.62	30.10	0.0001	0.0001**
Fin * Gen	2	1833.52	916.76	0.40	0.6751	0.5710
Fin * Sub/Gen	20	45755.15	2287.76			
Row	2	38455.56	19227.78	34.95	0.0001	0.0001**
Row* Gen	2	6241.05	3120.53	5.67	0.0112	0.0232**
Row * Sub/Gen	20	11004.19	550.21			
Dig	2	1393.05	696.52	8.53	0.0021	0.0040**
Dig * Gen	2	361.10	180.55	2.21	0.1356	0.1464
Dig * Sub/Gen	20	1632.41	81.62			
Fin * Row	4	5239.49	1309.87	2.71	0.0433	0.0989
Fin * Row * Gen	4	3650.50	912.63	1.89	0.1309	0.1828
Fin * Row * Sub/Gen	40	19308.24	482.71			
Fin * Dig	4	361.43	90.36	0.46	0.7668	0.6637
Fin * Dig * Gen	4	462.17	115.54	0.58	0.6759	0.5869
Fin * Dig * Sub/Gen	40	7910.91	197.77			
Row * Dig	4	789.64	197.41	1.14	0.3530	0.3455
Row * Dig * Gen	4	324.29	81.07	0.47	0.7596	0.6662
Row * Dig * Sub/Gen	40	6945.61	173.64			
Fin * Row * Dig	8	2998.14	374.77	2.16	0.0393	0.0939
Fin * Row * Dig * Gen	8	302.10	37.76	0.22	0.9869	0.9221
Fin * Row * Dig * Sub/Gen	80	13875.24	173.44			
Totals	323	362676.23				

** Significant at $p<0.05$ for both MANOVA and ANOVA

Dependent: Fingertip Angle at Point of Maximum Depression (Degrees)

Legend:

Gen: Gender (2 levels)

Fin: Finger (3 levels; index, middle, ring)

Row: Row (3 levels; upper, middle, lower)

Dig: Digraph (3 levels; one-finger, two-finger, two-hand)

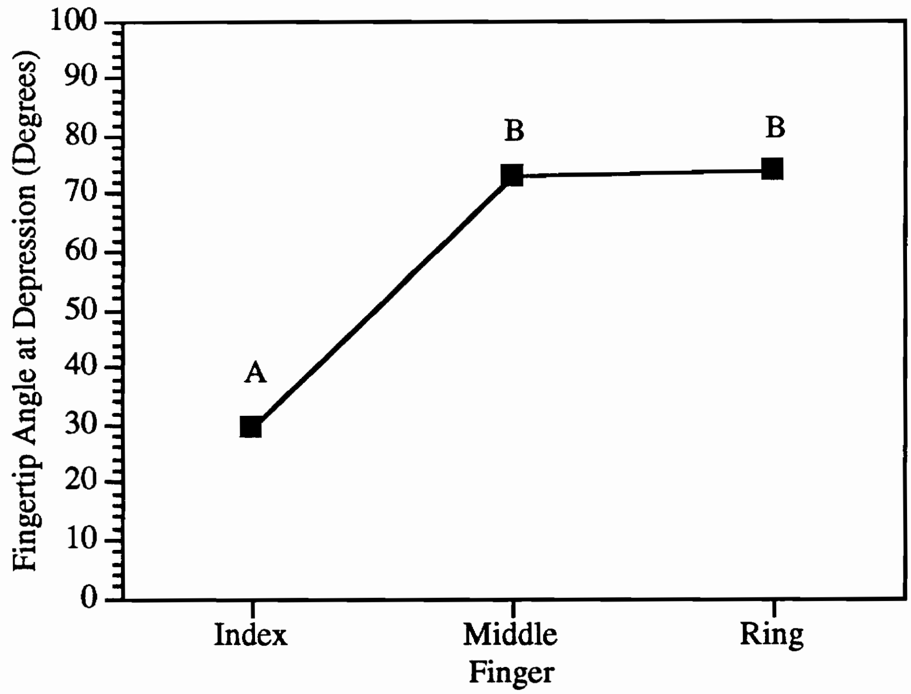

Figure 5.7 *Finger* main effect for fingertip angle at point of maximum depression. Points with the same letters are not significantly different at $p<0.05$ using a Newman-Keuls post-hoc test.

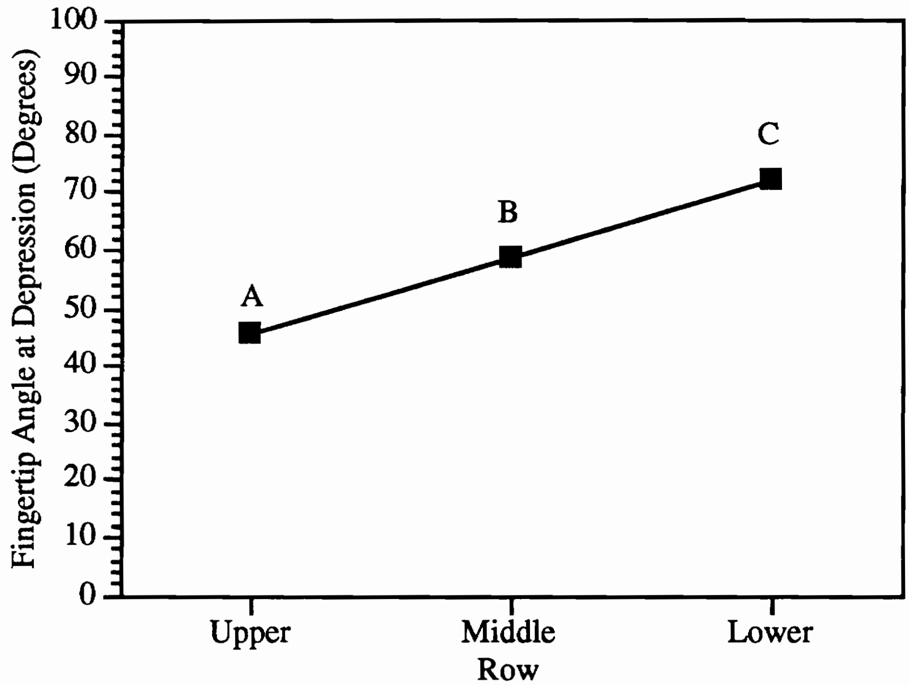

Figure 5.8 *Row* main effect for fingertip angle at point of maximum depression. Points with the same letters are not significantly different at $p<0.05$ using a Newman-Keuls post-hoc test.

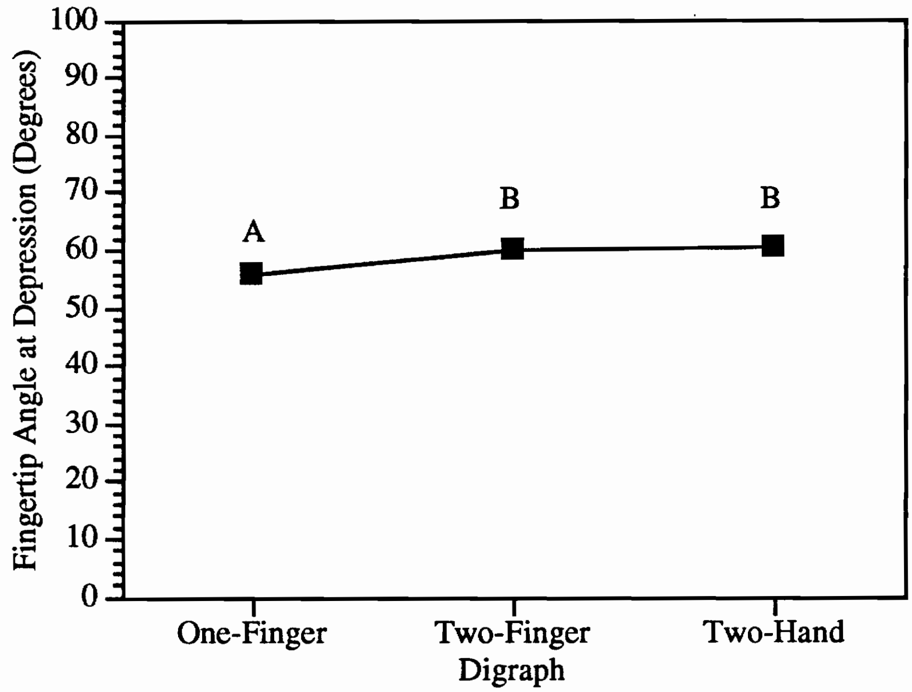

Figure 5.9 *Digraph* main effect for fingertip angle at point of maximum depression. Points with the same letters are not significantly different at $p<0.05$ using a Newman-Keuls post-hoc test.

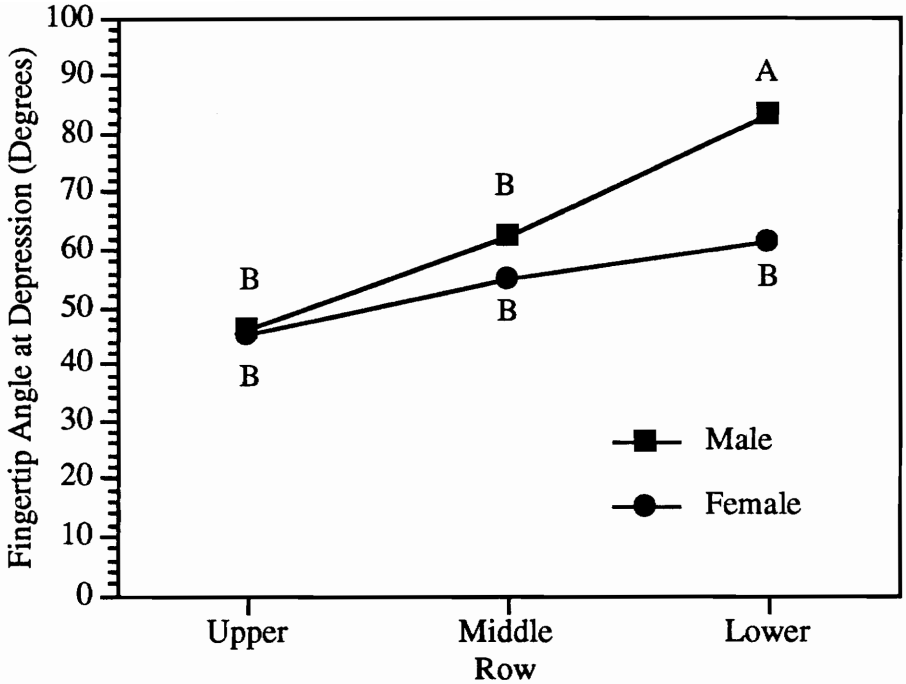

Figure 5.10 *Row by Gender* interaction for fingertip angle at point of maximum depression. Points with the same letters are not significantly different at $p<0.05$ using a Newman-Keuls post-hoc test.

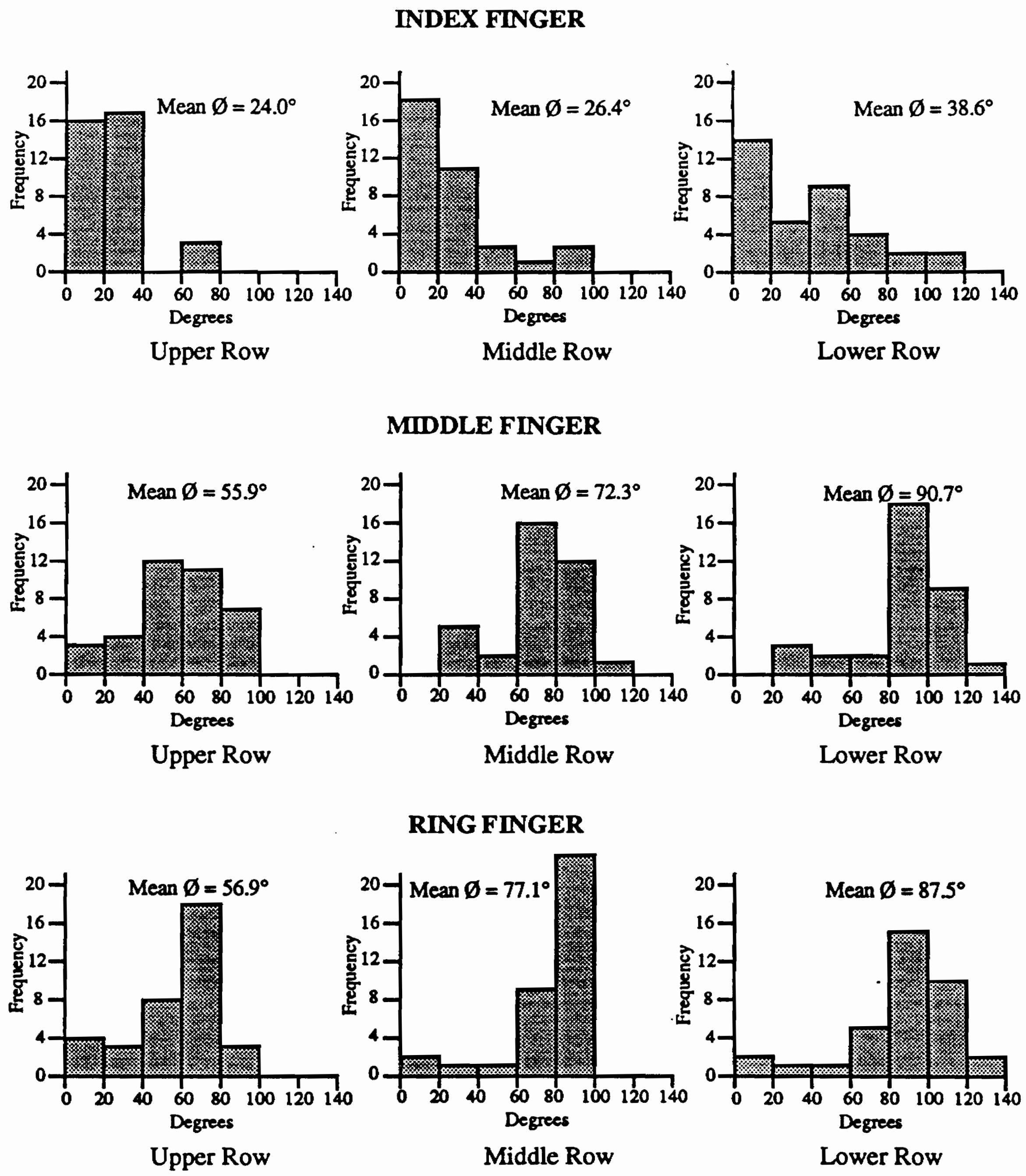

Figure 5.11 Range of fingertip angles at point of depression.

5.5 Linear Y Velocity of Fingertip at the Key

For the dependent variable, linear y velocity of the fingertip (Vk_y), the ANOVA revealed that the main effects of *Finger*, *Row*, and *Digraph* and the three-way interaction, *Finger by Row by Digraph*, were significant at $p<0.05$ using the Greenhouse-Geisser corrected p values. The ANOVA summary table is shown in Table 5.4.

Note that for the coordinate system defined in this thesis, positive linear y velocity of the fingertip indicates the fingertip is moving upwards at the point of contact with the key and negative linear y velocity of the fingertip indicates the fingertip is moving downwards at the point of contact with the key. The linear y velocities of the fingertip that are reported here were due only to the velocity of DIP, PIP, and MP joints, not the wrist. This is discussed in detail in Section 6.2 (Fingertip Velocity at the Key).

The mean values for the main effect of *Finger* are graphed in Figure 5.12, which also presents the results of Newman-Keuls post-hoc test of the means with $\alpha=0.05$. The mean linear y velocity of the fingertip for the index finger (0.3 cm/sec) was significantly different from both the middle and the ring fingers (-3.0 and -2.3 cm/sec, respectively), which were not significantly different from each other.

Figure 5.13 shows the mean values for the main effect of *Row*. The results of the Newman-Keuls post-hoc test revealed that all three levels of *Row* (i.e., upper, middle, and lower) were significantly different. The mean linear y velocity of the fingertip for the upper, middle, and lower rows were 1.5, -1.9, and -4.5 cm/sec, respectively.

The mean values for the main effect of *Digraph* are graphed in Figure 5.14, which also presents the results of Newman-Keuls post-hoc test of the means. The mean linear y velocity of the fingertip for all three levels of *Digraph* (i.e., one-finger, two-finger, and two-hand) were significantly different. The mean linear y velocity of the fingertip for one-finger, two-finger, and two-hand digraphs were -0.6, -2.7, and -1.7 cm/sec, respectively. The three-way interaction of *Finger by Row by Digraph* is graphed in

Figure 5.15. The Newman-Keuls post-hoc test revealed that positive linear y values tended to occur for the index finger, for the upper row, and for one-finger digraphs.

Figure 5.16 illustrates the ranges of linear y velocities of the fingertip at the point of contact with the key. The figure is broken down by finger and then by row. Overall, the range of values for the linear y velocity was from -17.7 to 15.6 cm/sec with an overall average of -1.7 cm/sec. The overall average is small since both the positive and negative values that occurred for the linear y velocity were averaged together. When considering only the positive linear y velocities, the average was 3.3 cm/sec and when considering only the negative linear y velocities, the average was -4.1 cm/sec.

For the index finger, the range of linear y velocities was from -12.7 to 15.6 cm/sec. The range of linear y velocities was from -14.1 to 8.9 cm/sec for the middle finger and from -17.7 to 12.3 cm/sec for the ring finger. The linear y velocities for the upper row ranged from -12.8 to 12.3 cm/sec. For the middle row, the range was from -13.4 to 15.6 cm/sec and for the lower row, the range was from -17.6 to 4.7 cm/sec.

Table 5.4 ANOVA Summary Table for Linear Y Velocity of the Fingertip

Factor	df	Sum of Squares	Mean Square	F-Value	p-Value	G-G
Between-Subjects						
Gen	1	50.46	50.46	0.63	0.4471	
Sub/Gen	10		805.76	80.58		
Within-Subjects						
Fin	2	642.73	321.37	12.52	0.0003	0.0013**
Fin * Gen	2	43.71	21.85	0.85	0.4416	0.4153
Fin * Sub/Gen	20		513.24	25.66		
Row	2	1951.74	975.87	46.38	0.0001	0.0001**
Row * Gen	2	84.89	42.44	2.02	0.1592	0.1593
Row * Sub/Gen	20		420.85	21.04		
Dig	2	248.09	124.05	12.86	0.0003	0.0003**
Dig * Gen	2	4.41	2.20	0.23	0.7979	0.7931
Dig * Sub/Gen	20		192.99	9.65		
Fin * Row	4	86.97	21.74	1.53	0.2127	0.2265
Fin * Row * Gen	4	104.79	26.20	1.84	0.1402	0.1594
Fin * Row * Sub/Gen	40	569.50	14.24			
Fin * Dig	4	49.97	12.49	1.80	0.1485	0.1889
Fin * Dig * Gen	4	49.63	12.41	1.78	0.1510	0.1909
Fin * Dig * Sub/Gen	40	278.12	6.95			
Row * Dig	4	66.91	16.73	1.98	0.1164	0.1416
Row * Dig * Gen	4	19.68	4.92	0.58	0.6775	0.6246
Row * Dig * Sub/Gen	4	338.20	8.45			
Fin * Row * Dig	8	280.93	35.12	3.75	0.0009	0.0139**
Fin * Row * Dig * Gen	8	109.89	13.74	1.47	0.1829	0.2352
Fin * Row * Dig * Sub/Gen	80	749.64	9.37			
Totals	323	7663.1				

** Significant at p<0.05 for both MANOVA and ANOVA

Dependent: Linear Y Velocity of Fingertip (cm/s)

Legend:

Gen: Gender (2 levels)

Fin: Finger (3 levels; index, middle, ring)

Row: Row (3 levels; upper, middle, lower)

Dig: Digraph (3 levels; one-finger, two-finger, two-hand)

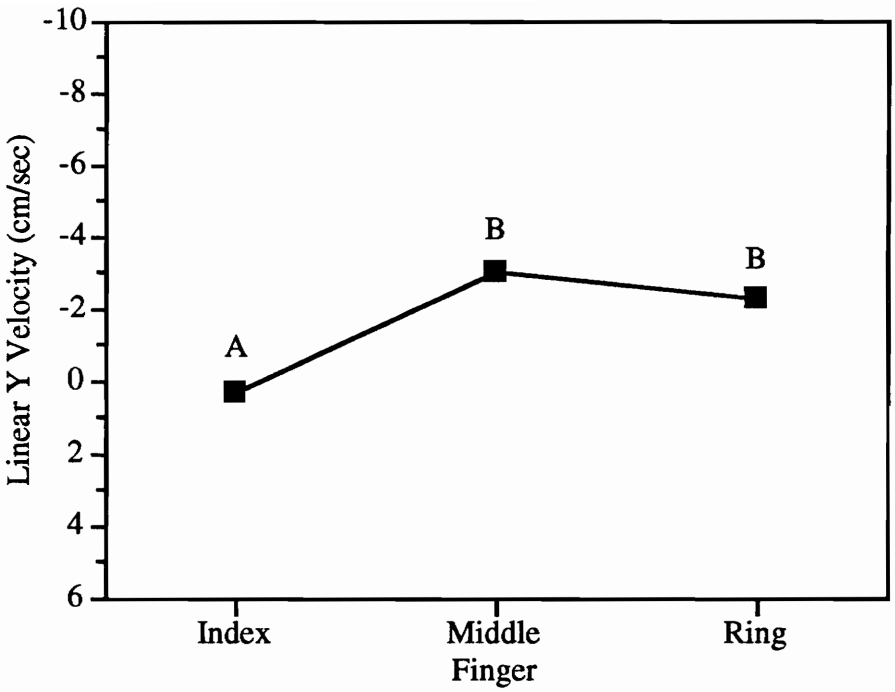

Figure 5.12 *Finger* main effect for linear y velocity. Points with the same letters are not significantly different at $p<0.05$ using a Newman-Keuls post-hoc test.

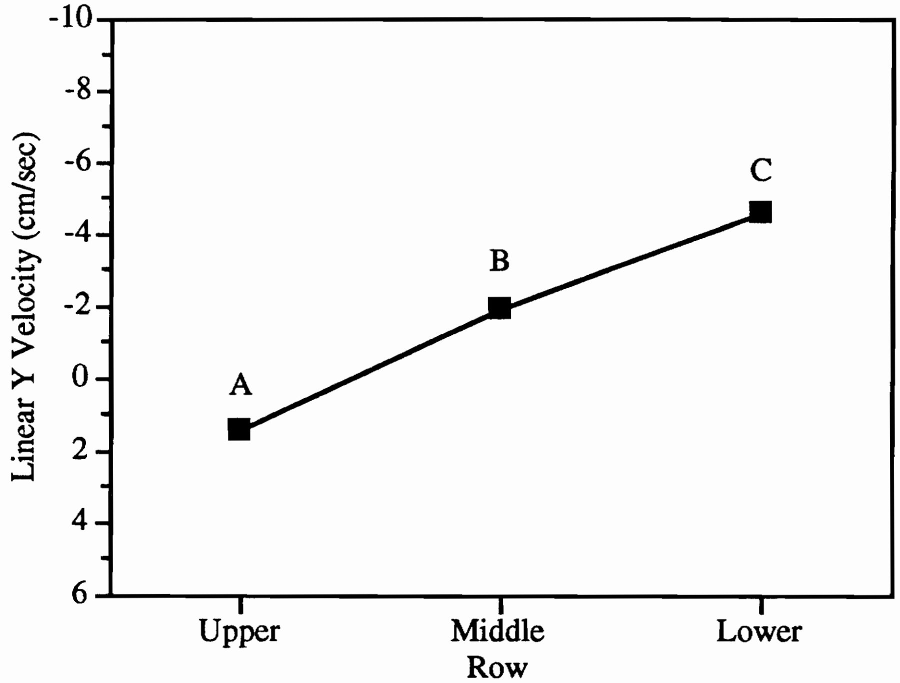

Figure 5.13 *Row* main effect for linear y velocity. Points with the same letters are not significantly different at $p<0.05$ using a Newman-Keuls post-hoc test.

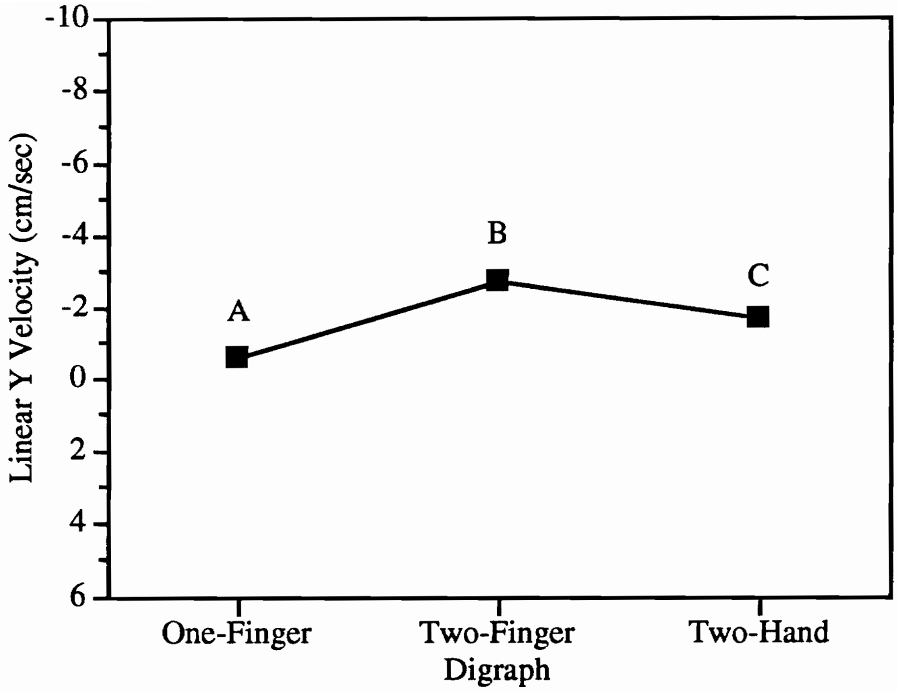

Figure 5.14 *Digraph* main effect for linear y velocity. Points with the same letters are not significantly different at $p<0.05$ using a Newman-Keuls post-hoc test.

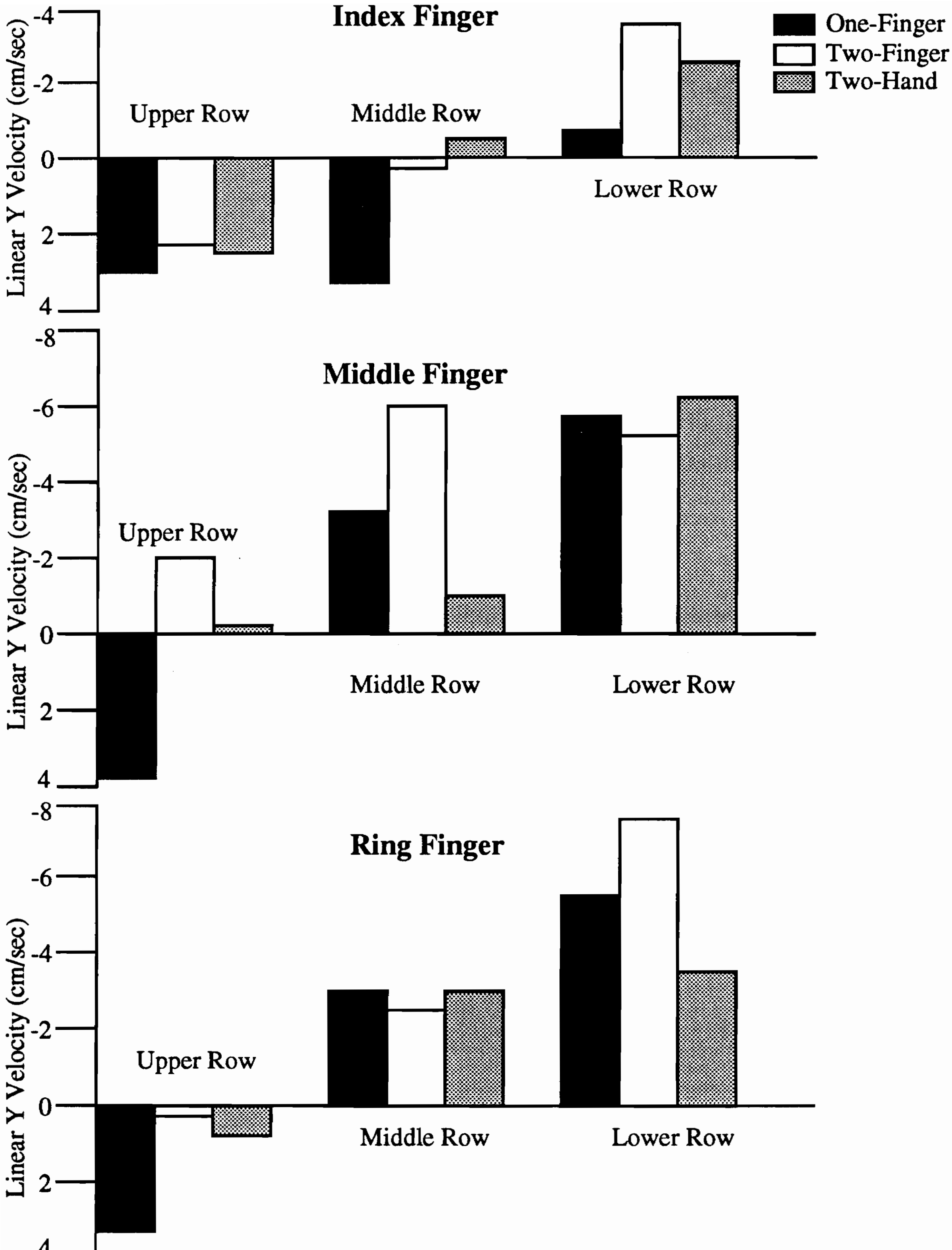

Figure 5.15 *Finger by Row by Digraph* effect for linear y velocity.

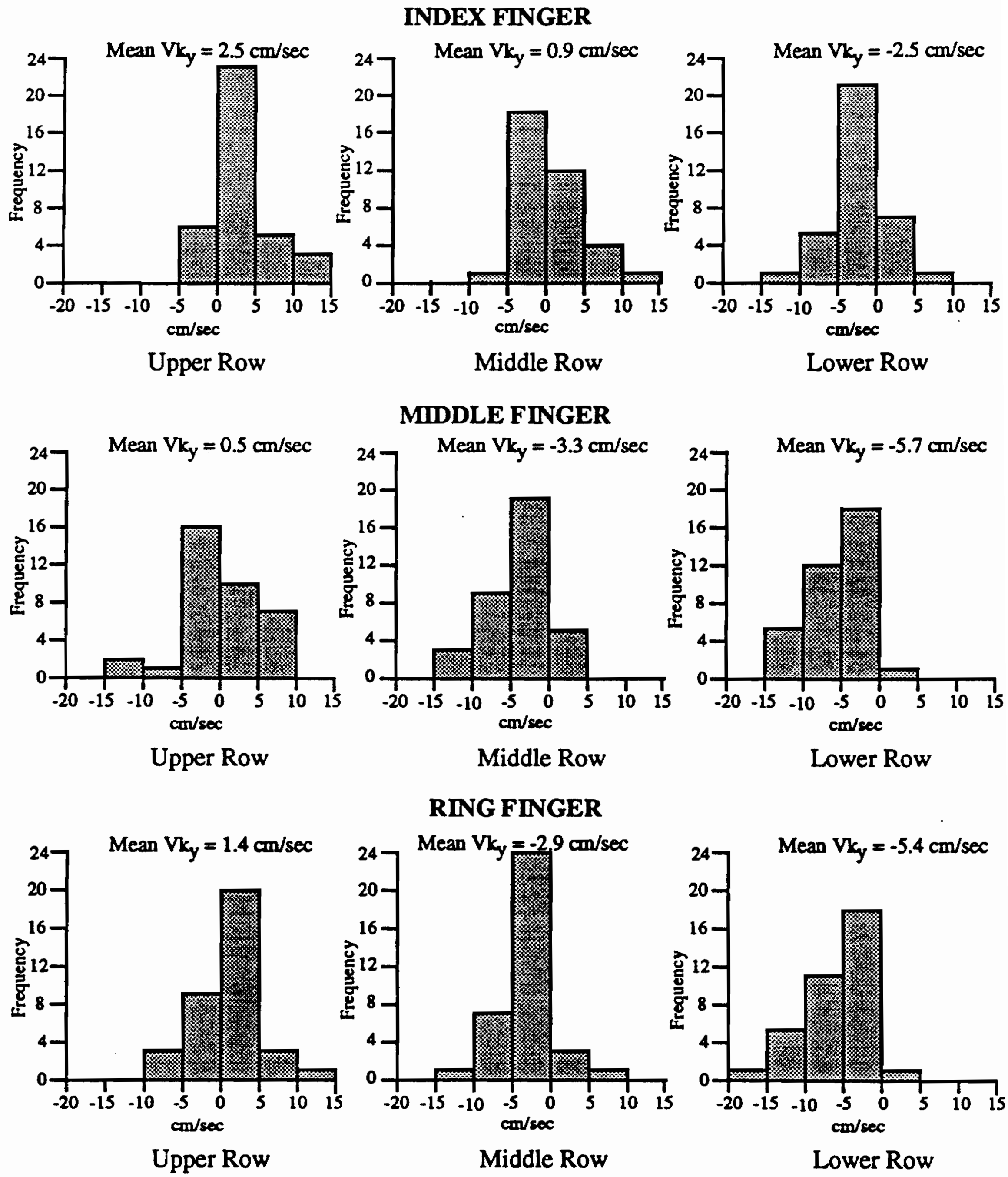

Figure 5.16 Range of linear y velocities of fingertip at point of contact.

5.6 Linear X Velocity of Fingertip at the Key

For the dependent variable, linear x velocity of the fingertip (Vk_X), the ANOVA revealed that the main effect of *Row* and the three-way interaction of *Finger by Row by Gender* were significant at $p<0.05$ using the Greenhouse-Geisser corrected p values. The ANOVA summary table for linear x velocity of the fingertip is shown in Table 5.5.

Note that the coordinate system was previously defined with the x-axis parallel to the support surface for the keyboard and in line with the metacarpal for the finger of interest with values of x increasing towards the lower row of keys. Therefore, positive linear x velocity of the fingertip indicates the fingertip is moving towards the lower row of keys at the point of contact with the key while negative linear x velocity of the fingertip indicates the fingertip is moving towards the upper row of keys. The linear x velocities of the fingertip that are reported here were due only to the velocity of DIP, PIP, and MP joints, not the wrist. This is discussed in detail in Section 6.2 (Fingertip Velocity at the Key).

The mean values for the main effect of *Row* are graphed in Figure 5.17, which also presents the results of Newman-Keuls post-hoc test of the means with $\alpha=0.05$. The mean linear x velocity of the fingertip for the lower row (-1.2 cm/sec) was significantly different from both the upper and the middle rows (-4.7 and -3.8 cm/sec, respectively), which were not significantly different from each other.

The three-way interaction of *Finger by Row by Gender* is graphed in Figure 5.18. The Newman-Keuls post-hoc test revealed that when typing on the middle or lower rows with any of the three fingers, the females' linear x velocity of the fingertip tended to be larger than the males'. It also revealed that when typing of the upper row with the middle or ring fingers, the males' linear x velocity of the fingertip tended to be larger than the females'.

Figure 5.19 illustrates the ranges of linear x velocities of the fingertip at the point of contact with the key. The figure is broken down by finger and then by row. The range of values for the linear x velocity was from -37.6 to 5.1 cm/sec with an overall average of -3.2 cm/sec. When considering only the positive linear x velocities, the average was 2.4 cm/sec and when considering only the negative linear x velocities, the average was -5.1 cm/sec. Ninety-eight percent of the linear x velocities fell in the range of -20.0 to 5.1 cm/sec. One female subject accounted for the other three percent (i.e., 7 data points) which ranged from -20.4 to -37.6 cm/sec. Of these seven data points, which are not shown in Figure 5.19, six of them were typed with the ring finger.

For the index finger, the range of linear x velocities was from -17.3 to 10.2 cm/sec. The range of linear x velocities was from -24.0 to 7.3 cm/sec for the middle finger and from -37.6 to 12.3 cm/sec for the ring finger. The linear x velocities for the upper row ranged from -31.3 to 12.3 cm/sec. For the middle row, the range was from -37.6 to 7.3 cm/sec and for the lower row, the range was from -23.2 to 12.3 cm/sec.

Table 5.5 ANOVA Summary Table for Linear X Velocity of the Fingertip

Factor	df	Sum of Squares	Mean Square	F-Value	p-Value	G-G
Between-Subjects						
Gen	1	124.27	124.27	0.57	0.4694	
Sub/Gen	10	2197.47	219.75			
Within-Subjects						
Fin	2	783.69	391.84	3.63	0.0452	0.0670
Fin * Gen	2	78.02	39.01	0.36	0.7011	0.6271
Fin * Sub/Gen	20	2158.56	107.93			
Row	2	711.53	355.77	6.38	0.0072	0.0175**
Row * Gen	2	349.00	174.50	3.13	0.0658	0.0896
Row * Sub/Gen	20	1115.84	55.79			
Dig	2	83.53	41.76	3.08	0.0680	0.0772
Dig * Gen	2	15.48	7.74	0.57	0.5735	0.5514
Dig * Sub/Gen	20	270.81	13.54			
Fin * Row	4	154.90	38.73	1.54	0.2078	0.2298
Fin * Row * Gen	4	362.65	90.66	3.62	0.0131	0.0317**
Fin * Row * Sub/Gen	40	1002.73	25.07			
Fin * Dig	4	149.11	37.28	3.13	0.0247	0.0409
Fin * Dig * Gen	4	87.39	21.85	1.84	0.1407	0.1628
Fin * Dig * Sub/Gen	40	475.70	11.89			
Row * Dig	4	25.02	6.25	0.34	0.8486	0.7815
Row * Dig * Gen	4	52.81	13.20	0.72	0.5834	0.5389
Row * Dig * Sub/Gen	40	733.48	18.34			
Fin * Row * Dig	8	150.38	18.80	1.58	0.1449	0.2106
Fin * Row * Dig * Gen	8	105.94	13.24	1.11	0.3649	0.3619
Fin * Row * Dig * Sub/Gen	80	953.61	11.92			
Totals	323	12141.92				

** Significant at p<0.05 for both MANOVA and ANOVA

Dependent: Linear X Velocity of Fingertip (cm/s)

Legend:

Gen: Gender (2 levels)

Fin: Finger (3 levels; index, middle, ring)

Row: Row (3 levels; upper, middle, lower)

Dig: Digraph (3 levels; one-finger, two-finger, two-hand)

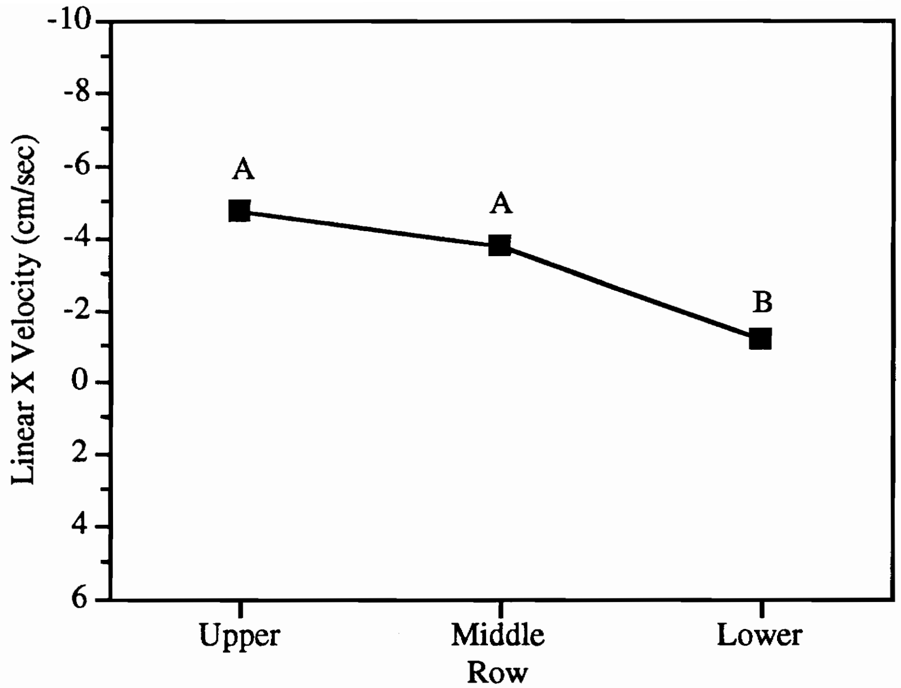

Figure 5.17 *Row* main effect for linear x velocity. Points with the same letters are not significantly different at $p<0.05$ using a Newman-Keuls post-hoc test.

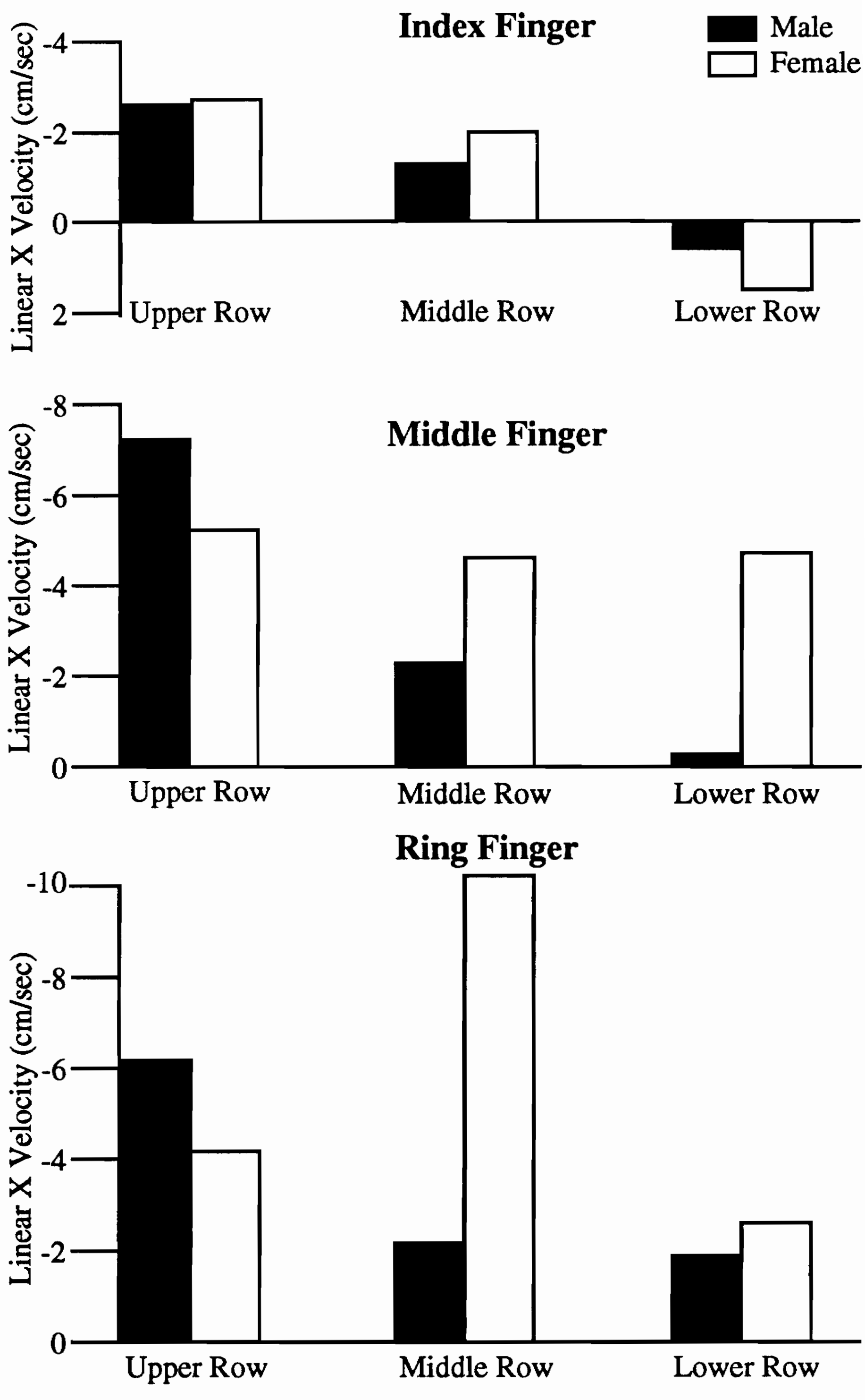

Figure 5.18 *Finger by Row by Digraph* interaction for linear x velocity.

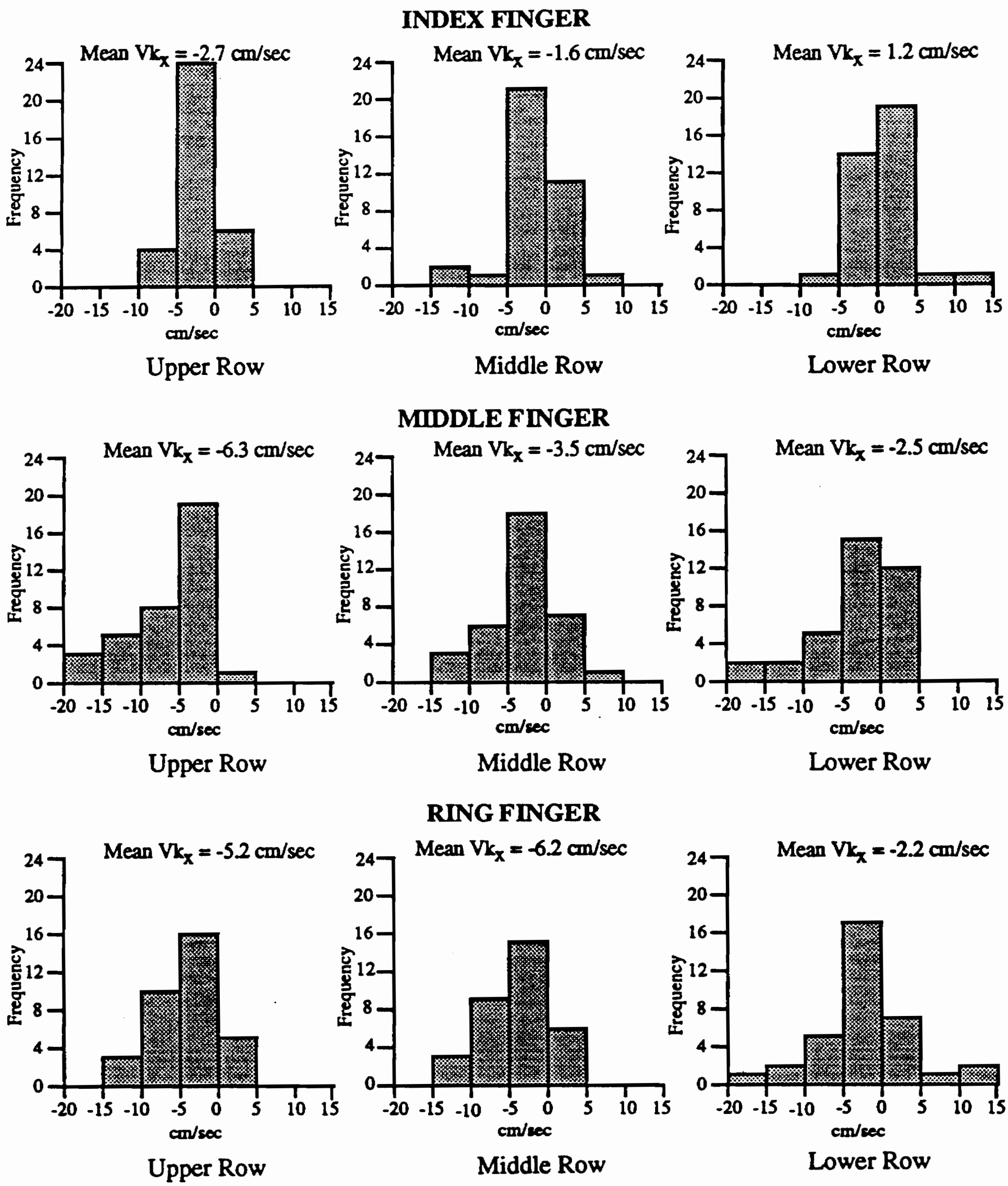

Figure 5.19 Range of linear x velocities of fingertip at point of contact.

6. DISCUSSION

This section is divided into four sub-sections. The first section discusses the results for the fingertip angle at the point of contact and at the point of maximum depression, while the second section covers the linear y and x velocity components of the fingertip at the key. The third section details the limitations and assumptions that were made in this experiment which is followed by suggestions for improvement and future research.

6.1 Fingertip Angles at the Key

The results of this study indicate that the angle of the fingertip at the point of contact with the key was significantly affected by *Finger*, *Row*, and *Digraph* ($p<0.05$).

For the factor of *Finger*, the mean fingertip angle at the point of contact for the index finger was significantly smaller than the mean fingertip angles for both the middle and ring fingers, which were not significantly different from each other. The mean fingertip angle for the index finger was, on average, 42 degrees smaller than the mean fingertip angle for the middle and ring fingers. This is most likely due to the anthropometric characteristics and anatomical location of these three fingers. The middle and ring fingers are both longer in length compared to the index finger. Also, the index finger is not bound by fingers on both sides as the middle and ring fingers are, which allows the index finger a larger range of abduction movement . These characteristics of the index finger may decrease the index fingertip angle at the point of contact.

All three levels of *Row* (i.e., upper, middle, and lower) significantly affected the mean fingertip angle at the point of contact ($p<0.05$). The mean fingertip angles for the upper, middle, and lower rows were 45.3, 59.5, and 73.1 degrees, respectively. This result was expected due to the location of the rows of the keyboard. For the upper row, the fingers must extend to reach the keys, decreasing the fingertip angle at the point of contact. For the lower row, the fingers must flex to strike the keys on the lower row, increasing the fingertip angle at the point of contact. For the middle row, the fingertip angle at the point of contact falls between the fingertip angle for the upper and lower rows.

The interaction of *Row by Gender* was also significant for the fingertip angle at the point of contact of the key ($p<0.05$). There was no significant difference between the mean fingertip angles for the males and females at the upper and middle rows, only at the lower row. At the lower row, the males' mean fingertip angle at the point of contact was 20 degrees more than the females'. This may be due to the fact that the male subjects had longer fingers than the female subjects. Considering the distal, middle, and proximal phalanges, the average length of the index, middle, and ring fingers for the male subjects was 99.8, 111.3, and 105.0 mm, respectively. For the female subjects, the lengths of the index, middle, and ring fingers were 86.2, 97.0, and 90.5 mm, respectively. Due to the longer length of their fingers, the male subjects may have flexed their fingers more when typing a key on the lower row than the female subjects, resulting in a larger fingertip angle at the point of contact for the males.

One interesting result from the analysis of the fingertip angle at the point of contact was that the factor of *Digraph* was significant ($p<0.05$). The mean fingertip angle at the point of contact for the one-finger digraphs was on average six degrees smaller than the angles for two-finger and two-hand digraphs. This may be due to the fact that when typing one-finger digraphs, the finger is moving from one key directly to the second key while when typing two-finger and two-hand digraphs, the finger may be positioned over the second key. For this reason, when typing one-finger digraphs the finger may reach for the second key resulting in a smaller fingertip angle at the point of contact than that of the two-finger and two-hand digraphs where the finger is already positioned over the second key.

The second dependent variable, fingertip angle at the point of maximum depression, had very similar ANOVA results to the first dependent variable, fingertip angle at the point of contact. Like the fingertip angle at the point of contact, the ANOVA for fingertip angle at the point of maximum depression revealed that the main effects of *Row*, *Finger*, and *Digraph* and the two-way interaction of *Row by Gender* were significant ($p<0.05$). The reasoning behind the significance of these effects are most likely the same as those explained above for the fingertip angle at the point of contact.

The ranges and averages of the fingertip angles at the point of maximum depression were very similar to those for the fingertip angles at the point of contact. For the fingertip angle at the point of maximum depression, the averages for the index, middle, and ring fingers were less than one degree different than those for the fingertip angle at the point of contact. Likewise, for the upper, middle, and lower rows, there was less than one degree difference between the averages for the fingertip angle at the point of maximum depression and the fingertip angle at the point of contact.

A closer analysis did reveal differences between the fingertip angles at the point of contact and point of maximum depression. When comparing the angle of the fingertip at the point of contact and at the point of maximum depression, the results showed that 49.7% of the time, the fingertip angle at the point of maximum depression was larger than the fingertip angle at the point of contact. This suggests that half of the time the fingertip angle was decreasing as the key was pressed and half the time the fingertip angle was increasing as the key was pressed. Since the fingertip angle at the point of maximum depression was almost equally divided between increasing and decreasing, as compared to the fingertip angle at the point of contact, the mean fingertip angles at the point of contact and at the point of maximum depression are almost identical.

A closer analysis of the data also revealed that the fingertip angle for the index finger tended to decrease (65% of the time) from the point of contact to the point of maximum depression while the fingertip angle for the ring finger tended to increase (63% of the time) from the point of contact to the point of maximum depression. Half of the time the fingertip angle for the middle finger increased from the point of contact to the point of maximum depression and half of the time it decreased. For both increasing and decreasing fingertip angles at the point of maximum depression, the largest mean difference between the fingertip angles at the point of contact and the point of maximum depression occurred for the upper row and the one-finger digraphs (average of six degrees). These differences between the fingertip angles at the point of contact and the point of maximum depression indicate that there is a change in the fingertip angle as the key is depressed and that the direction and magnitude of the change may be influenced by the finger, row, and digraph.

6.2 Fingertip Velocity at the Key

The results of this study indicate that the linear y velocity (Vk_y) at the point of contact with the key was significantly affected by *Finger*, *Row*, and *Digraph* ($p<0.05$). For this dependent variable, the three-way interaction of *Finger by Row by Digraph* was also highly significantly ($p<0.05$) and will be used to help interpret the results for the linear y velocity.

Recall that negative linear y velocities indicate the fingertip is moving vertically down at the point of contact with the key while positive linear y velocities indicate the fingertip is moving vertically upwards to strike the key. Negative linear y velocities occurred 67% of time and positive linear y velocities the other 33% of the time.

The effect of *Finger* revealed the largest magnitude of linear y velocity for the middle and ring fingers, which were not significantly different. This was true even when positive and negative linear y velocities were considered separately. This may be due to the fact that the index finger is shorter and is generally reaching for the keys instead of being positioned over them as the middle and ring fingers may be. For the effect of *Row*, the largest negative linear y velocities occurred when typing on the lower row followed by the middle and upper rows while the largest positive velocities occurred when typing on the upper rows followed by the middle and lower rows. These results were expected since the fingers are generally located near the home position and must move downward to strike a key on the lower row and upward to strike a key on the upper row.

For the effect of *Digraph*, two-hand and one-finger digraphs had the smaller linear y velocities than two-finger digraphs . For two-hand digraphs, the finger that strikes the second key may be positioned over it while the first key is struck which reduces the travel distance for the second keystroke so that the finger does not need to move as fast to maintain the keystroke rate. For one-finger digraphs, the finger must move from one key directly to the next which increases the travel distance of the finger. Since the finger may be limited in its ability to cover these distances quickly, the velocities with which it can reach the second key may be reduced. For two-finger digraphs, the finger does not have the large travel distances that occur in one-finger digraphs, but may also not positioned over the key as in two-hand digraphs, which may be the reason for its larger velocity.

As stated previously, negative y velocities occurred 67% of time and positive linear y velocities the other 33% of the time. This result is best explained through the three-way interaction of the *Finger by Row by Digraph*, graphed in Figure 5.13, which revealed that the largest positive linear y velocities occurred for the index finger, the upper row, and for one-finger digraphs. Sixty-six percent of the positive linear y velocities occurred when typing a key on the upper row which suggests that the fingertip was moving upward to reach the key on the upper row and at the point of contact with the key, the fingertip had not begun to move downwards. This was especially true when the finger was typing a one-finger digraph on the upper row which accounted for 29% of all instances of positive linear y velocity. In this case, the finger was always moving from the middle row to the upper row.

Over half of all instances of positive linear y velocity (52%) occurred when the typing was done with the index finger. This may be due in part to the fact that the index finger is the shorter than the middle and ring fingers and may have to reach for the keys instead of being positioned over them. A closer examination of the three-way interaction reveals another explanation for the large number of instances of positive linear velocity for the index finger. For the index, middle, and ring fingers, the mean linear y velocities when typing the one-finger digraph on the middle row were 3.1, -3.1, and -3.0 cm/sec, respectively. This reveals that when typing a one-finger digraph on the middle row, the results of the mean linear y velocity for index finger were almost exactly opposite of those for the middle and ring fingers. This is most likely due to the fact that for the middle and ring fingers, the one-finger digraph consisted of typing a key on the upper row then the key on the middle row while for the index finger, the one-finger digraph consisted of typing a key on the lower row then the key on the middle row. These results suggest that for one-finger digraphs, the linear y velocity may also be influenced by the row of the key typed prior to the key of interest.

For the second velocity dependent variable, the linear x velocity at the point of contact with the key (Vk_x), the main effect of *Row* and the three-way interaction of *Finger by Row by Gender* were significant ($p<0.05$). Positive and negative values occurred for the linear x velocity. Recall for this dependent variable, positive linear x velocity of the fingertip indicates the fingertip is moving backwards (towards the lower row of keys) at the point of contact with the key while negative linear x velocity of the fingertip indicates the fingertip is moving forwards (towards the upper row of keys).

As stated in the previous chapter, the mean linear x velocity of the fingertip for the lower row (-1.2 cm/sec) was significantly different from both the upper and the middle rows (-4.7 and -3.8 cm/sec, respectively), which were not significantly different from each other. Positive linear x velocity occurred 25% of the time. Of this 25% of the time, 53% occurred when typing a key on the lower row while only 15% and 32% occurred when typing a key on the upper and middle rows, respectively. These positive linear x velocities for the lower row were expected since the fingers are usually positioned near the home row and must move backwards (towards the lower row) to strike a key on the lower row.

The three-way interaction of *Finger by Row by Gender* revealed that when typing on the middle or lower rows with any of the three fingers, the females' linear x velocity of the fingertip tended to be larger than the males'. While when typing on the upper row with the middle or ring fingers, the males' linear x velocity of the fingertip tended to be larger than the females'. This may be due to the fact that the females had shorter fingers than the males. For this reason, the females may have been reaching to type the keys on the top row, which may have resulted in smaller the linear x velocities in comparison to the males whose longer fingers may have been positioned over the keys. The females' linear x velocities were generally higher than the males which is most likely due to the high linear x velocities of one female subject.

The three-way interaction of *Finger by Row by Gender* also revealed that for the lower row, the mean linear x velocity was only positive for index finger on the lower row. This indicates that the index finger was moving backwards (towards the lower row) and the middle and ring fingers were moving forwards (towards the upper row) when striking a key on the lower row. This may be due to the fact that the middle and ring fingers are longer than the index finger. For the longer fingers, when typing a key on the lower row, the finger may move vertically upwards to be positioned above and slightly behind the key, and then move forward and downward to strike the key. This may be in contrast to the index finger which is shorter and may move directly backwards to strike a key on lower row, thus yielding the positive x velocities.

For both the linear x and y velocities of the fingertip at the point of contact, the velocity due to the DIP, PIP, and MP joints was calculated. The velocity of the fingertip due to wrist movement was not calculated because it was initially assumed that at the point of contact, the wrist velocity was negligible. Although this may hold true some of the time, it may not hold true for individuals who tend to move their wrists more than their fingers when striking a key and also for the finger and row combinations which require the largest travel distance to strike a key. For these reasons, the interpretation of the results for the linear x and y components of velocities of the fingertip may not be accurate in cases where the wrist velocity was significantly contributing to the overall fingertip velocity at the point of contact with the key. Therefore, the contribution of the wrist velocity to the overall fingertip velocity should be investigated further.

Wrist velocity may be broken down into the velocity due to the rotation (flexion/extension) of the wrist and the velocity due to the movement of the forearm. Although the three-dimensional wrist position was measured in this thesis, it can not be used to interpret the wrist's effect on fingertip velocity because the rotation of the wrist with respect to the forearm was not measured. For example, the y coordinate of the wrist may be moving vertically upwards due to forearm movement (contributing to positive linear y velocity of the fingertip), but it is not known whether the wrist was also flexed during this time (contributing to negative linear y velocity of the fingertip). For the linear x velocity of the fingertip, there may be no change in the x coordinate of the wrist during flexion of the wrist, although flexion of the wrist may be contributing to negative linear x velocity of the fingertip.

For these reasons, both the wrist rotation and movement of the forearm must be considered when trying to determine the extent of the wrist velocity on the linear x and y velocities of the fingertip. Using the WATSMART system, infrared diodes could be placed on the wrist joint, the metacarpal bone, and the forearm to determine the angle of the wrist with respect to the forearm and movement of the forearm. This is discussed further is Section 6.5 (Future Research).

6.4 Limitations of Experiment

This experiment was the first attempt to use the EXOS DHM exoskeleton and the WATSMART system to investigate the kinematics of the fingers while typing. From the results, it appears that this method was effective to measure the angle of the fingertip at the point of contact and at the point of maximum depression and to measure the linear x and y components of velocity produced by the DIP, PIP, and MP joints. This method of measurement has several equipment limitations and methodology assumptions which are detailed below.

6.4.1 Limitation of Equipment

- The DHM exoskeleton has a reported accuracy of 0.5 degrees. The exoskeleton was attached to the subject's finger through the use of skin adhesives. The subject's skin may have moved while performing the typing tasks. Thus, the Hall Effect sensors may have moved from their calibrated position.
- The exoskeleton was not calibrated in the same position as the position where subjects performed the experimental tasks. Thus, the posture data from the exoskeleton may not have accurately represented the subjects' true finger posture.
- The exoskeleton may have interfered with the task of typing. Subjects may have altered their typing posture or speed due to the exoskeleton on their finger.
- The WATSMART system had an average RMS error of 1.56 mm. The infrared diode was attached to the subject's hand through the use of skin adhesives. The subject's

skin may have moved while performing the typing tasks which may have moved the infrared diode from its original placement on the hand.

- The measurement of the link lengths may not have been from the true joint centers of rotation which means the link lengths may have slightly changed depending on the angle of finger joints.

6.4.2 Assumptions

The following methodological decisions were made which may have affected the validity of this experiment.

- It was assumed that the exoskeleton device was attached properly and calibrated accurately.
- The assumption was made that the WATSMART diode was positioned properly and accurately on the wrist and on the keys.
- It was assumed that the link lengths were measured properly and accurately.
- Since the x and y coordinates of the keys were calculated for the middle of the keys, the assumption was made that the fingertip strikes the middle of the keys.
- The assumption was made that the points of contact and the points of maximum depression were accurately located from the finger joint displacement data.
- The synchronization of the WATSMART and exoskeleton systems was assumed to be accurate.
- Since there are many different possibilities for pairs of characters for the one-finger, two-finger, and two-hand digraphs, it was assumed that the pairs of characters examined in this experiment were representative of the other possibilities.

6.4.3 Additional Important Limitations

There are several important additional limitations to consider when interpreting the results of this study. First, as discussed in Section 6.2 (Fingertip Velocity at the Key) the linear x and y components of velocity for the fingertip were due only to the velocity produced by the DIP, PIP, and MP joints, not the wrist. It is believed that in some cases the wrist velocity may contribute significantly to the overall fingertip velocity at the point of contact with the key. For this reason, the values reported for the linear x and y components of velocity may not be representative of the overall fingertip velocities at the point of contact with key and therefore should not be used in applications which require the overall fingertip velocity at the point of contact with the key (e.g., in the programming of a robotic finger for typing tasks).

Another limitation of this study was that only the index, middle, and ring fingers of the right hand were examined. For this reason, it can not be assumed that the results hold for the same fingers of the left hand. In addition, only certain keys were typed with these fingers which limits the results from being interpreted for other keys. Also, only one keyboard was used in this study so it can not be assumed that the results hold for different keyboards. These considerations are discussed further in Section 6.5 (Future Research).

6.5 Future Research

The findings and results of this study indicate several areas for future investigation which are listed below:

- Since this was the first attempt to use the EXOS DHM exoskeleton and the WATSMART system to investigate the kinematics of the finger while typing, the experimental method may be improved upon by finding a more accurate and easier method for calibrating the exoskeleton; locating the points of contact and points of maximum depression; and synchronizing the WATSMART and exoskeleton systems.
- One assumption of this study was that the wrist velocity at the point of contact was negligible. Further research should examine the wrist velocity while typing with

different fingers and different rows to determine the wrist's affect on the overall fingertip velocity at the point of contact with the key.

- An investigation of the same factors used in this study, but done for the left hand to determine the difference between the two hands while typing.
- Further extension of this study using different keyboards which have different keyboard characteristics such as maximum key travel distance, keyboard slope, key actuation force, and key spacing.
- A three-dimensional analysis of the fingertip velocity at the point of contact.
- Further extension of this study to examined different pairs of letters for the one-finger, two-finger and two-hand digraphs.

7. REFERENCES

Angelaki, D. E., and Soechting, J. F. (1993). Non-uniform temporal scaling of hand and finger kinematics during typing. *Experimental Brain Research*, *95*, 319-329.

Armstrong, T. J., Chaffin, D. B., and Foulke, J. A. (1979). A methodology for documenting hand positions and forces during manual work. *Journal of Biomechanics*, *12*, 131-133.

Armstrong, T. J., Foulke, J. A., Joseph, B. S., and Goldstein, S. A. (1982). Investigation of cumulative trauma disorders in a poultry processing plant. *American Industrial Hygiene Association Journal*, *43*, 103-116.

Arndt, R. (1983). Working posture and musculoskeletal problems of video display terminal operators - Review and reappraisal. *American Industrial Hygiene Association Journal*, *44*, 437-446.

Bucholz, B., Armstrong, T. J., and Goldstein, S. A. (1992). Anthropometric data for describing the kinematics of the human hand. *Ergonomics*, *35*, 261-273.

Cappozzo, A., Marchetti, M., and Pedotti, A. (1976). The interplay of muscular and external forces in human ambulation. *Journal of Biomechanics*, *9*, 35-43.

Cavanagh, P. R., and Gregor, R. J. (1975). Knee joint torque during the swing phase of normal treadmill walking. *Journal of Biomechanics*, *8*, 337-344.

Crouch, J. E. (1985). *Functional living anatomy*. Philadelphia, PA: Lea and Febiger.

Donnelly, J. E. (1990). *Living anatomy*. Champaign, IL: Human Kinetics Books.

EXOS, Inc. (1990). *Dexterous Hand Master Manual*. Burlington, MA: EXOS, Inc.

Ferguson, D. (1971). An Australian study of telegraphists' cramp. *British Journal of Industrial Medicine*, *28*, 280-285.

Ferguson, D., and Duncan, J. (1974). Keyboard design and operating posture. *Ergonomics*, *17*, 731-744.

Finkleman, J. M., Wolf, E. H., and Friend, M. A. (1977). Modified discriminant analysis as a multivariate post-comparison extension of MANOVA for interpretation of simultaneous multimodality measures. *Human Factors*, *19*, 253-261.

Flanders, M., and Soechting, J. F. (1992). Kinematics of typing: Parallel control of two hands. *Journal of Neurophysiology*, *67*, 1264-1274.

Fox, J. G., and Stansfield, R. G. (1964). Digram keying times for typists. *Ergonomics*, *7*, 317-320.

Fries, A. C., and Clayton, D. (1975). *Timed writings about careers*. OH: South-Western.

Genter, D. R. (1981). *Skilled finger movements in typing*. San Diego, CA: Center for Human Information Processing, University of California, San Diego, CHIP 104.

Hatze, H. (1976). A method for describing the motion of biological systems. *Journal of Biomechanics*, *9*, 101-104.

Hatze, H. (1981). The use of optimally regularized Fourier series for estimating higher-order derivatives of noisy biomechanical data. *Journal of Biomechanics*, *14*, 13-18.

Hünting, W., Läubli, T., and Grandjean, E. (1981). Postural and visual loads at VDT workplaces, I. Constrained postures. *Ergonomics*, *24*, 917-931.

Jeyaratnam, J., Ong, C. N., Kee, W. C., Lee, J., and Koh, D. (1989). Musculoskeletal symptoms among VDU operators. In M. J. Smith and G. Salvendy (Eds.), *Work with computers: Organizational, management, stress and health aspects* (pp. 330-337). Amsterdam: Elsevier Science.

Kapit, W., and Elson, L. M. (1993). *Anatomy Coloring Book*. N.Y.: HarperCollins.

Klemmer, E. T. (1971). Keyboard entry. *Applied Ergonomics*, *2*, 2-6.

Knave, B. G., Wibom, R., Voss, M., Hedström, L. D., and Bergqvist, U. (1985). Work with video display terminals among office employees. *Scandinavian Journal of Work Environment Health*, *11*, 457-466.

Komoike, Y., and Horiguchi, S. (1971). Fatigue assessment on key punch operators, typists and others. *Ergonomics, 14*, 101-109.

Kroemer, K. H. E. (1989). Cumulative trauma disorders: Their recognition and ergonomics measures to avoid them. *Applied Ergonomics, 20*, 274-280.

Kroemer, K. H. E., Kroemer, H. B., and Kroemer-Elbert, K. E. (1994). *Ergonomics: How to Design for Ease and Efficiency*. Englewood Cliffs, N.J.: Prentice Hall.

Landsmeer, J. M. F. (1962). Power grip and precision handling. *Annals of the Rheumatic Disease, 21*, 164-169.

Langman, J., and Woerdeman, M. W. (1978). *Atlas of medical anatomy*. Philadelphia, PA: Saunders.

Low, I. (1990). Musculoskeletal complaints in keyboard operators. *Journal of Occupational Health and Safety, 6* (3), 205-211.

McLaughlin, T. M., Dillman, C. J., and Lardner, T. J. (1977). Biomechanical analysis with cubic spline functions. *Research Quarterly, 48*, 569-582.

Moore, A., Wells, R., and Ranney, D. (1991). Quantifying exposure in occupational manual tasks with cumulative trauma disorder potential. *Ergonomics, 34*, 1433-1453.

Napier, J. R. (1956). The prehensile movements of the human hand. *The Journal of Bone and Joint Surgery, 38B(4)*, 902-913.

Punnett, L., and Keyserling, W. M., (1987). Exposure to ergonomic stressors in the garment industry: application and critique of job-site work analysis methods. *Ergonomics, 30*, 1099-1116.

Reel, R. M. (1975). *Exploring Secretarial Careers*. Cincinnati, OH: South-Western.

Reinsch, C. H. (1967). Smoothing by spline functions. *Numerische Mathematik, 10*, 177-183.

Rempel, D., and Gerson, J., Armstrong, T., Foulke, J., and Martin, B. (1991). Fingertip forces while using three different keyboards. In *Proceedings of the Human Factors Society 35h Annual Meeting* (pp. 253-255). Santa Monica, CA: Human Factors Society.

Rice, J. R. (1969). *The approximation of functions*, Vol. II. Reading, MA: Addison-Wesley.

Shaffer, L. H. (1986). Skilled typing performance and keyboard design. *Current Psychological Research and Review, Summer Issue,* 119-129.

Silverstein, B. A., Fine, L. J., and Armstrong, T. J. (1987). Occupational factors and carpal tunnel syndrome. *American Journal of Industrial Medicine*, *11*, 343-358.

Sind, P. M. (1989). *The effects of structural and overlay design parameters of membrane switches on the force exerted by users.* Unpublished doctoral dissertation. Virginia Polytechnic Institute and State University.

Soechting, J. F., and Flanders, M. (1992). Organization of sequential typing movements. *Journal of Neurophysiology*, *67*, 1275-1290.

Stock, S. R. (1991). Workplace ergonomic factors and the development of musculoskeletal disorders of the neck and upper limbs: A meta-analysis. *American Journal of Industrial Medicine*, *19*, 87-107.

Terzuolo, C. A., and Viviani, P. (1980). Determinants and characteristics of motor patterns used for typing. *Neuroscience*, *5*, 1085-1103.

Vasey, M. V., and Thayer, J. F. (1987). The continuing problem of false positives in repeated measures ANOVA in psychophysiology: A multivariate solution. *Psychophysiology*, *24 (4)*, 479-486.

Weiss, P. L., August, S., Peters, G., and Sampalis, J. (1992). Using the Exos Handmaster to measure digital range of motion. In *Proceedings of the RESNA International 1992 Conference,* (pp. 4-6). Toronto, Ontario, Canada: RESNA.

Wold, S. (1974). Spline functions in data analysis. *Technometrics*, *16*, 1-11.

Yamamoto, S. (1987). Visual, musculoskeletal and neuropsychological health complaints of workers using videodisplay terminal and an occupational health guideline. *Japanese Journal of Ophthalmology, 31*, 171-183.

Young, R. M. and Barton, J. S. (1983). Force-sensitive platform for measuring keypresses. *Ergonomics, 26*, 243-249.

Yun, M. H. (1993). A hand posture measurement system for evaluating manual tool tasks. In *Proceedings of the Human Factors Society 37th Annual Meeting* (pp. 754-758). Santa Monica, CA: Human Factors Society.

Zernike, R. F., Caldwell, G., and Roberts, E. M. (1976). Fitting biomechanical data with cubic spline functions. *Research Quarterly, 47*, 9-19.

APPENDIX A: Informed Consent Form for Experiment

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants of Investigative Projects

I. THE PURPOSE OF THIS RESEARCH/PROJECT

You are invited to participate in a study investigating typing techniques. Further details about the project will be explained at the end of the experiment.

II. PROCEDURES

You will be asked to type several passages and six experimental sentences. The time and conditions required for you to participate in this project is approximately 2 hours consisting of the typing several passages and six experimental trials. Through the use of skin adhesives, an exoskeleton finger will be attached to your finger and an infrared emitting diode (IRED) to your wrist.

The possible risks or discomfort to you as a participant may be pulling of some finger or wrist hair during the removal of the exoskeleton finger or IRED. There is no risk of electric shock due to the IRED or any other part of the testing apparatus.

The safeguard that will be used to minimize your risk or discomfort is the use of adhesives specially designed for the skin.

III. BENEFITS OF THIS PROJECT

Your participation in the project will provide the following information that may be helpful. This experiment will address the techniques used for typing. This type of information may help improve the design of keyboards to reduce cumulative trauma disorders.

No guarantee of benefits has been made to encourage you to participate.

You may receive a synopsis of this research when it is completed. Please leave (or bring back) a self-addresses envelope.

IV EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. At no time will the researchers release the labeled individual results of the study to anyone other than individuals working on the project without your written consent. The information you provide will have your name removed and only a subject number will identify you during analysis and any written reports of the research.

V. COMPENSATION

Monetary

For participation in the project you will receive $5.00 for each hour completed.

VI. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time without penalty. If you chose to withdraw, you will be compensated for the portion of the time of the study in which you participated.

VII. APPROVAL OF RESEARCH

This research project has been approved, as required, by the Institutional Review Board for projects involving human subjects at Virginia Polytechnic Institute and State University, by the Department of Industrial and Systems Engineering.

VIII. SUBJECT'S RESPONSIBILITIES

I know of no reason I cannot participate in the study. I have the responsibility to complete the health questionnaire.

____

Signature and Date

IX. SUBJECT'S PERMISSION (Tear off at dashed line and give to subject)

I have read and understand the informed consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

Should I have any questions about this research or its conduct, I will contact:

Manda M. Long, Investigator	231-6053
Dr. J. C. Woldstad, Faculty Advisor	231-4927
Chair, Institutional Review Board, Research Division	231-9359

APPENDIX B: Subject Health Questionnaire

SUBJECT HEALTH QUESTIONNAIRE

Subject's Name:______________________________ SSN: _______________

Address: ____

Telephone Number: (____) ______________________

Sex: _________ Date of Birth: __________

Number of years typing experience: ________________

Have you had any joint dislocations, broken bones, or other physical injuries to your hand or wrist in the last year (Yes or No)? ______________________________________

Have you ever had any other serious musculoskeletal injury (Yes or No)? ___________

Have you ever had surgery on your hand, fingers, or wrist (Yes or No)? ___________

Have you ever had any swelling or discomfort in your fingers or hand (Yes or No)? ____

Are you presently taking any medication or drugs (Yes or No)? __________________

Do you presently have any physical impairment or injury worth noting (Yes or No)? ___

Can you think of any injury, or illness you might have which could by aggravated by participation in this experiment (Yes or No)?_________________________________

If you answered yes to any of the above or have any other remarks you feel are pertinent to your participation, please elaborate in the space below or on the back of this page:

____

Signature and Date

APPENDIX C: Calculations from WATSMART Data

Several additional calculations were necessary to transform the wrist posture data collected by WATSMART into the proper coordinate system. Figure C1.A shows the axis system as defined by the WATSMART calibration frame. In this axis system, the z-axis is perpendicular to the top of the keyboard; the x-axis is parallel to the horizontal row of keys on the keyboard; and the y-axis is horizontal to the keyboard display surface. Figure C1.B shows the axis system adopted for all calculations shown in this thesis, including this Appendix. In this axis system, the y-axis is perpendicular to the top of the keyboard; the z-axis is parallel to the horizontal row of keys on the keyboard; and the x'-axis is horizontal to the keyboard display surface. The x-axis, as defined previously in this thesis, is in line with the finger of interest. The calculations to determine the x and y coordinates of the wrist required the calculation of the z coordinate of the keys which is explained next.

As described in Section 3.2.3, a diode was placed on the **j**, **u**, and **m** keys. The WATSMART system was used to collect the x', y, and z coordinates (axis system of Figure C1.B) of these three keys for two seconds at 200 Hz, (i.e., $K_{X'}$, K_Y, K_Z). The last 20 points were averaged to give the x', y, and z coordinates of each of these keys. These coordinates and the horizontal distance between two adjacent keys on the same row (19 mm from center to center) were used to determine the x', y, and z coordinates for the remaining keys (i.e., **i o k l , .**). For **i** and **o** keys, the x' and y coordinates are the same as the **u** key. To determine the z coordinates for the **i** and **o**, the z coordinate for the **u** key was decreased by 19 mm and 38 mm, respectively. Similarly for **k** and **l** keys, the x' and y coordinates are the same as the **j** key. To determine the z coordinate for the **i** and **o**, the z coordinate for the **j** key was decreased by 19 mm and 38 mm, respectively. For **,** and **.** keys, the x' and y coordinates are the same as the **m** key. To determine the z coordinate for the **,** and **.**, the z coordinate for the **m** key was decreased by 19 mm and 38 mm, respectively. These z coordinates were only used to determine the x and y coordinates of the wrist.

As described in Section 3.2.3, a diode was placed on the subject's wrist near the base of the metacarpal of the finger of interest. The WATSMART system was used to collect the x', y, and z coordinates (axis system of Figure C1.B) of the wrist at 200 Hz for each of the six experimental trials. For both the point of contact point and the point of maximum depression, the x' coordinate for the wrist posture had to be transformed to the x coordinate of the wrist posture which was in line with the finger of interest. As shown in the calculations below, the x' and z coordinates for the key of interest ($K_{X'}$, K_Z) and the x' and z coordinates of the wrist ($W_{X'}$, W_Z) were needed. Figure C2 shows the coordinates and axis used for the calculations.

$$\varnothing = \tan^{-1}[(W_Z - K_Z)/(W_{X'} - K_{X'})$$

$$W_X = K_{X'} + [(W_{X'} - K_{X'})*\cos\varnothing]$$

Since the $K_{X'}$ and W_X coordinates in the line on the same axis, the $K_{X'}$ is referred to as K_X for the remainder of this thesis. Note that no calculations were needed to transform the y coordinate of the wrist. For the remainder of the calculations in this thesis involving the coordinates of the keys and wrist, only the x and y coordinates of the keys (K_X, K_y) and wrist (W_X, W_y) are utilized.

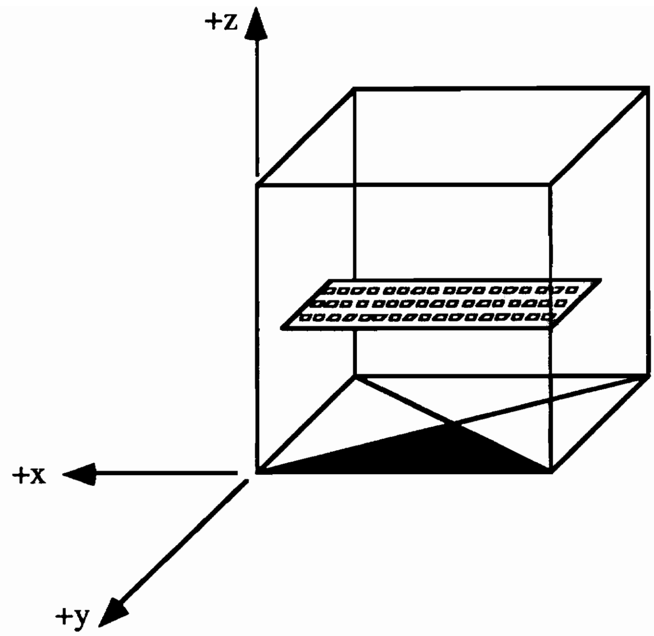

Figure A. Axis system in the WATSMART system as determined by the calibration frame

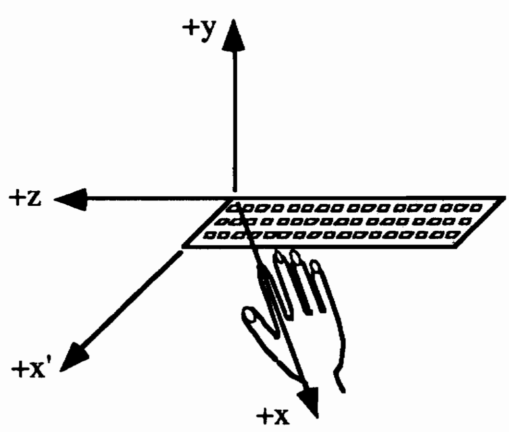

Figure B. Axis system for thesis calculations, x axis shown for index finger

Figure C1. Axis systems for WATSMART system and keyboard.

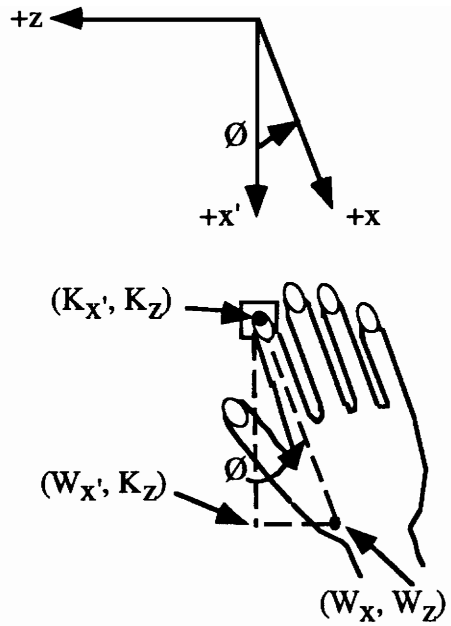

Figure C2. Coordinates and axis system for wrist data, top view of keyboard.

APPENDIX D: Calculations for Locating Wrist Posture Data

When collecting data during the experimental trials, the WATSMART program for collecting the wrist data and SuperScope program for collecting the finger joint displacement data were started at approximately the same time. Since the systems have slightly different start times after being activated, a method for synchronizing the two systems was developed. As explained in Section 4.1, the finger joint displacement data was analyzed to determine the finger's point of contact with the key for each keystroke of interest. After this was completed, the wrist posture data for each keystroke of interest was analyzed to determine an adjustment factor to synchronize the two systems. This was done by analyzing the x, y, and z coordinates of the wrist posture during at least two keystrokes of interest for each sentence. Below are shown the words and keystrokes in bold that were analyzed for each sentence. These keystrokes were chosen because they occur on the upper or lower row of the keyboard.

Sentence 1	Sej**m**a	coffee**m**aker	
Sentence 2	perj**u**red	st**u**ttered	cri**m**es
Sentence 3	ski**,**	truck**,**	vessel**,**
Sentence 4	str**i**ved	al**i**ve	
Sentence 5	Med**.**	sl**o**w	usual**.**
Sentence 6	st**o**rekeeper	sm**o**thered	deck**.**

During the keystrokes on the lower row (i.e., **m , .**), the wrist posture coordinates change in the following manner: z and y coordinates slightly decrease while the x coordinate slightly increases. After the keystroke is completed, the three coordinates change in the opposite direction. During the keystrokes on the upper row (i.e., **u i o**), the wrist posture coordinates change in the following manner: z and y coordinates slightly increase while the x coordinate slightly decreases. Again, after the keystroke is completed, these three coordinates change in the opposite direction.

By analyzing the wrist posture coordinates for the keystrokes of interest on the lower and upper rows, the point of contact for each of these keystrokes was determined and then compared to the point of contact previously determined from the finger joint displacement data for the same keystroke. For each sentence, the difference between the points of contact determined by the two methods was used as the adjustment factor to locate the proper wrist coordinates for each keystroke of interest in the sentence. The average adjustment factor for the wrist posture data was 0.36 seconds (72 data points) with a standard deviation of 0.05 seconds (10 data points).

VITA

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