Initial Wrist Posture During Typing as a Function of Keyboard Height and Slope

by

Mary Ann Jedrziewski

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APPROVED:

J. G. Woldstad, Chairman

K. H. E. Kroemer

P. T. Kemmerling

Blacksburg, Virginia

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Committee Chairman: Jeffrey C. Woldstad

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(Abstract)

Carpal tunnel syndrome has been linked to occupations which use a computer workstation. Two factors thought to be responsible for this problem are repetition and awkward wrist postures. This experiment examined wrist flexion-extension, radial-ulnar deviation, and pronation-supination for 24 right-handed subjects at 25 combinations of keyboard height and slope. Keyboard heights tested were: -10, -5, 0, 5, and 10 cm from elbow height, and keyboard slopes tested were: -45, -22, 0, 22, and 45 degrees from horizontal. Keyboard slopes were considered negative if they sloped away from the subject and positive if they sloped towards the subject. Subjects wore a wrist monitor, comprised of metal strips with potentiometers, on each hand and typed a text passage for two minutes in each experimental condition. The number of correct words per minute was also measured in each experimental condition.

Results indicated that flexion was minimum when the keyboard was 45 degrees from horizontal, and that overall the left wrist exhibited extension while the right wrist exhibited flexion. Ulnar deviation was minimized when the keyboard height was -10 cm below elbow height, and both ulnar and radial deviation were minimized at slope conditions 22 and 45 degrees from

horizontal. Higher keyboard heights coupled with positive slopes reduced radial and ulnar deviation as did lower keyboard heights coupled with negative slopes. For low keyboard heights, the right hand exhibited more extreme ulnar deviation than the left hand. Pronation was minimum when the keyboard was 10 cm above elbow height and -45 degrees from horizontal, and was maximum when the keyboard was -5 cm below operator elbow height and 45 degrees from horizontal. Correct words typed per minute was maximum at 0 degrees from horizontal, and decreased quadratically as slope was both increased and decreased.

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1. INTRODUCTION

1.1 Rationale

Carpal tunnel syndrome, a type of cumulative trauma disorder, has recently been linked to occupations which require the use of a computer terminal (VDT workstation). According to Carpi (1989), "about 17 percent of keyboard users can expect to be afflicted with the pain, numbness, and loss of finger control associated with what is known in the medical community as a nerve entrapment disorder." The two main factors thought to be responsible for this problem are increased repetition and awkward wrist postures (Rosch, 1991; Squires, 1991; Pagnanelli, 1989; Segal, 1988; Mallory and Bradford, 1989; Kaplan, 1983; Harvey, 1991; Stack, 1988). Both repetition and awkward wrist posture are among the commonly cited risk factors of cumulative trauma disorders, including carpal tunnel syndrome (Armstrong, 1986; Armstrong et al., 1979; Cannon et al., 1981; Laidlaw, 1987; Lockwood, 1989; Silverstein et al., 1986; Stack, 1988).

With the introduction of electronic keyboards, the typist's job has become increasingly repetitive. Electronic typewriters have eliminated the need to manually correct errors, change the ribbon, and use a carriage return. As a result, the average computer operator repeats the same keystroking motion approximately 72,000 times per day with minimal breaks (Carpi, 1989). According to Putz-Anderson (1991), any motion performed over 720 times during a 6 hour day is considered highly repetitive.

Another problem associated with the advent of electronic keyboards is typing posture. Beginning typists are taught the standard typing posture: the forearms are kept horizontal, the elbows at right angles, and the fingers are resting on the home row of keys (Koskela and Lepisto, 1977). With manual and electro-mechanical keyboards the machine resilience was sufficient to allow typists to rest their fingers on the keys without the introduction of unwanted characters. However, electronic keyboards do not possess sufficient machine resilience to prevent the introduction of unwanted characters, and typists must find alternate resting positions. A study conducted by Stack (1988) found that typists using electronic keyboards have three predominant resting positions. These positions were: holding the forearms and hands in a horizontal cantilever position above the keyboard, removing the arms and hands completely from the keyboard, and collapsing the wrists onto the nearest support available while keeping the fingers on the keys. Of these three positions the third was the most commonly observed. This third position may cause the wrists to be extended if the nearest support available is not approximately level with the keyboard. Therefore, this position may put pressure on the tendons and nerves of the carpal tunnel due to the possible extension of the wrists (Armstrong et al., 1979). Holding the arms above the keyboard for an extended period of time would lead to muscle fatigue, and removing them from the keyboard completely would be inefficient.

Typing posture can also be affected by the adjustment of the computer workstation. If the keyboard is positioned too high or too low, or if the slope of the keyboard has not been properly adjusted, the operator may be using a flexed or extended wrist position. Armstrong et al. (1979) showed that flexion and extension of the wrist lead to increased pressure on the tendons and nerves of the carpal tunnel in the wrist. To help minimize the possibility of computer operators working in potentially hazardous postures, the American

National Standard for Human Factors Engineering of Visual Display Terminal Workstations (ANSI/HFS 100-1988) recommends the use of adjustable computer workstation furniture. ANSI/HFS 100-1988 sets forth the minimum parameters necessary to accommodate the postures of most users (5th percentile female through 95th percentile male) when seated and performing tasks at a visual display terminal.

With the use of electronic keyboards and adjustable workstations comes the need to determine what combinations of keyboard height and slope allow the typist's wrists to remain in a neutral, relaxed position. Beginning typists are taught to keep their forearms horizontal and their elbows at right angles during typing and rest periods. This position may cause operators to extend their wrists onto the nearest support during rest periods or to hold their forearms in a cantilever position above the keyboard. In fact, there is need for a study which determines the optimal combinations of "distance between an operator's elbow height and the height of the working surface" and "slope of the keyboard from horizontal." The optimal combinations(s) would be those which resulted in the least amount of: flexion, extension, ulnar deviation, radial deviation, pronation, and supination. Results from this study would allow operators to adjust their own computer workstations to maintain a neutral, relaxed wrist position while typing. In addition, these results may aid office equipment designers in the development of computer workstations. It is hoped that by using a neutral, relaxed wrist position while typing, the incidence of cumulative trauma disorders among computer operators will decrease significantly.

1.2 Experimental Objectives

The primary objectives of this study were as follows:

Objective 1: To determine which combinations of "distance between operator elbow height and work surface height" and "slope of computer keyboard from horizontal" yield the smallest measurements for: flexion-extension, radial-ulnar deviation, and pronation-supination of the wrist.

Objective 2: To investigate the relationship between correct words typed per minute, keyboard height, and keyboard slope.

2. LITERATURE REVIEW

2.1 Overview

The following sections review relevant literature which provide a background for the purpose and method of this research. First, the anatomy of the wrist and hand are discussed including: carpal bones and joints, metacarpal bones and joints, phalanges, movements of the wrist and hand, innervation of the wrist and hand, blood supply of the wrist and hand, muscles and tendons of the wrist and hand, and the anatomy of the carpal tunnel. Carpal tunnel syndrome is then defined, and predisposing and non-occupational factors are discussed. Next, occupational factors associated with carpal tunnel syndrome are discussed in detail. Last, literature pertaining to the association between the position of computer keyboards and symptoms of carpal tunnel syndrome is reviewed.

2.2 Anatomy of the Hand and Wrist

2.2.1 Carpal Bones and Joints

The wrist (carpus) contains eight carpal bones, which are arranged in two rows of four each. In anatomical position (Figure 2.2), the bones in the proximal row start with the scaphoid on the lateral side. The next two bones, medially, are the lunate and the triquetral. The pisiform, which is a small, pea-shaped bone in the proximal row, is set on the anterior and medial surfaces of the triquetral. The bones in the distal row start with the trapezium on the lateral side and progress medially to the trapezoid and the capitate. The last bone in the distal row is the hamate. Together, the carpal bones have a convex dorsal surface and a concave palmar surface which form the "carpal sulcus" or "carpal groove." A palmar view of the carpal bones can be found in Figure 2.1.

There are joints between adjacent carpal bones as well as the radiocarpal (wrist) joint and midcarpal joints. The radiocarpal (wrist) joint is located between the radius and the scaphoid and lunate bones of the first row of carpal bones. On the ulnar side, the articular cartilage of the ulna is opposed by the triquetral bone and is partially overlapped by the lunate. The midcarpal joints are located between the proximal and distal rows of the carpal bones.

2.2.2 Metacarpal Bones and Joints

There are five metacarpal bones in the hand which are quite similar, with the exception of the metacarpal of the thumb, which is much shorter and broader than the other metacarpals. The metacarpal bones are named, by Roman numerals, from the radial side. All five metacarpals are composed of a proximal base, a body, and a head. Metacarpal bodies are approximately triangular in cross section and are somewhat concave lengthwise on their palmar surfaces. Figure 2.1 shows a palmar view of the metacarpal bones and joints.

2.2.3 Phalanges

Each of the four fingers have three phalanges: a proximal, middle, and distal phalanx, but the thumb has only a proximal and a distal phalanx. The bases of the proximal phalanges are concave which allows for articulation with the rounded heads of the metacarpals. The interphalangeal joints allow for flexion and extension, but do not permit any motion to the sides. The bones and joints of the phalanges can be seen in Figure 2.1.

2.2.4 Movements of the Wrist

There are six basic movements of the wrist: flexion, extension, ulnar deviation, radial deviation, pronation, and supination. Each of the following movements will be described assuming that the hand and wrist are in anatomical position (Figure 2.2). Flexion occurs when the hand is bent toward the anterior surface of the forearm, and extension occurs when the hand is bent toward the posterior surface of the forearm (Putz-Anderson, 1988). Ulnar deviation occurs when the hand is bent at the wrist in the direction of the little finger, and radial deviation occurs when the hand is bent at the wrist in the direction of the thumb. In addition to these four movements, the hand and wrist are capable of supination and pronation. Supination occurs when the forearm and hand are rotated in a manner to turn the hand and palm upward, and pronation occurs when the forearm and hand are rotated in a manner to turn the hand and palm downward (Figure 2.3).

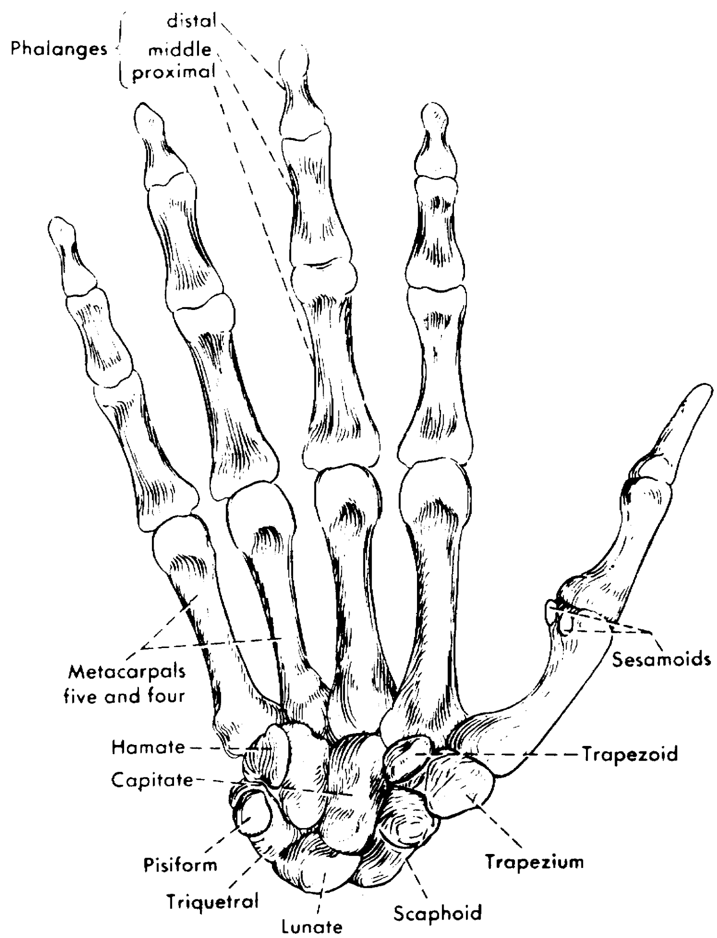


Figure 2.1 Palmar View of the Bones and Joints of the Wrist and Hand. Taken from Hollinshead (1974).

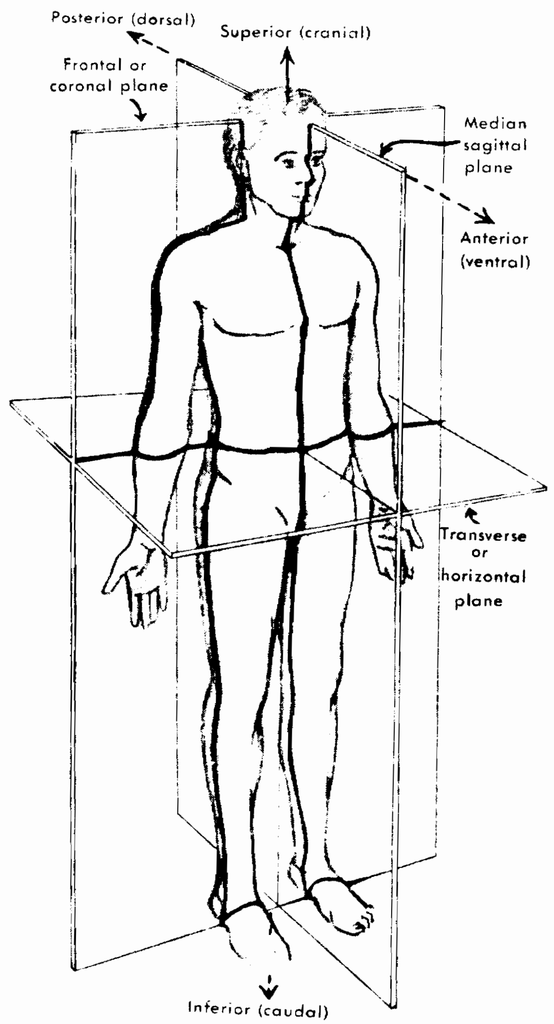


Figure 2.2 Anatomical Position. Taken from Gardner and Osburn (1973).

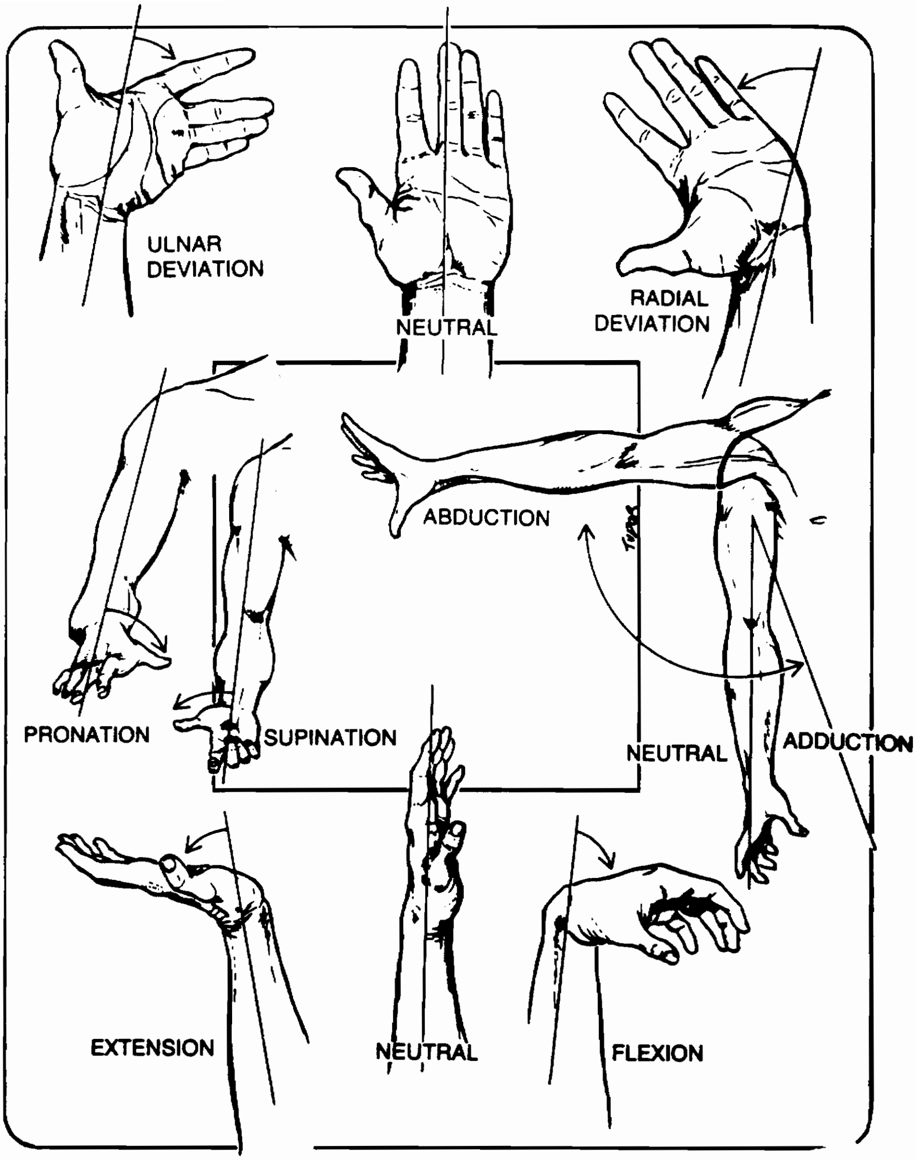


Figure 2.3 Movements of the Wrist and Hand. Taken from Putz-Anderson (1988).

Cave and Roberts (1936) describe a convention for measuring and recording flexion, extension, ulnar deviation, and radial deviation of the wrist. All of these movements, which are measured in degrees, are measured from a designated neutral wrist position which corresponds to zero degrees (Figure 2.4). For radial and ulnar deviation measurements, this neutral position occurs when the third metacarpophalangeal joint, the center of the wrist, and the lateral epicondyle of the elbow are lined up with respect to the palmar-dorsal view. For flexion and extension, this neutral position occurs when the center of the second metacarpal head, the ulnar styloid, and the lateral epicondyle are lined up with respect to the lateral view (Schoenmarklin and Marras, 1991). Radial deviation from the neutral position is measured in positive degrees, and ulnar deviation in negative degrees. Likewise, flexion is measured in negative degrees from the neutral position, and extension in positive degrees. For supination and pronation, the neutral position occurs when the person is standing upright with the arms by the side and the elbows flexed 90 degrees (Chaffin and Andersson, 1984). Supination from this neutral position is considered positive, and pronation is considered negative.

2.2.5 Innervation of the Wrist and Hand

There are three main nerves which innervate all the structures of the upper limb, including the hand. These nerves are the radial nerve, the median nerve, and the ulnar nerve. The median nerve supplies the flexor and pronator muscles of the forearm and hand with the exception of the flexor carpi ulnaris and the medial half of the flexor digitorum profundus. In addition, the median nerve supplies: the majority of the thenar muscles of the thumb, the abductor pollis brevis, the opponens pollicis, the superficial head of the flexor pollicis brevis, and the lateral two lumbrical muscles. Sensory fibers from the median nerve supply: the palmar aspect of the thumb, second, third, and the lateral half of the fourth finger; the dorsal tips of the second, third, and fourth fingers, and the lateral half of the palm up to the wrist crease.

The ulnar nerve supplies the following muscles: the flexor carpi ulnaris, the medial half of the flexor digitorum profundus, the interosseous muscles, the medial two lumbrical muscles, the hypothenar muscles, the palmaris brevis, the deep head of the flexor pollicis brevis, and the adductor pollicis muscle. Many of the muscles that the ulnar nerve supplies are intrinsic muscles of the hand, therefore the ulnar nerve is quite important for delicate movements of the hand. Sensory fibers from the ulnar nerve cover: the ulnar side of the palm, both surfaces of the fifth finger, and the adjacent side of the fourth finger.

The radial nerve primarily supplies the extensor and supinator muscles of the upper limb. In particular it innervates: the triceps, the anconeus muscles, a part of the brachialis, the extensor muscles of the wrist, the supinator, the extensor muscles of the fingers and thumb, and the long abductor muscle of the thumb. Sensory fibers from the radial nerve cover: half of the dorsum of the hand, the dorsal portion of the thumb and second finger, and the lateral half of the fourth finger with the exception of the skin over the distal phalanges, which is innervated by the median nerve. Figure 2.5 shows the various branches of the ulnar, radial, and median nerves.

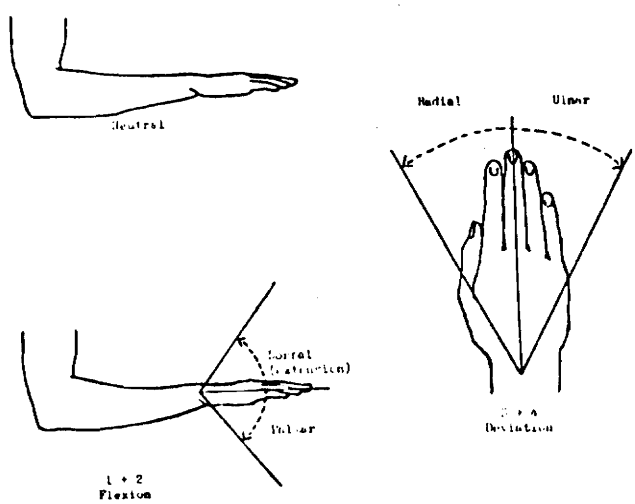


Figure 2.4 Convention for Recording Movements of the Wrist and Hand. Taken from Cave and Roberts (1936).

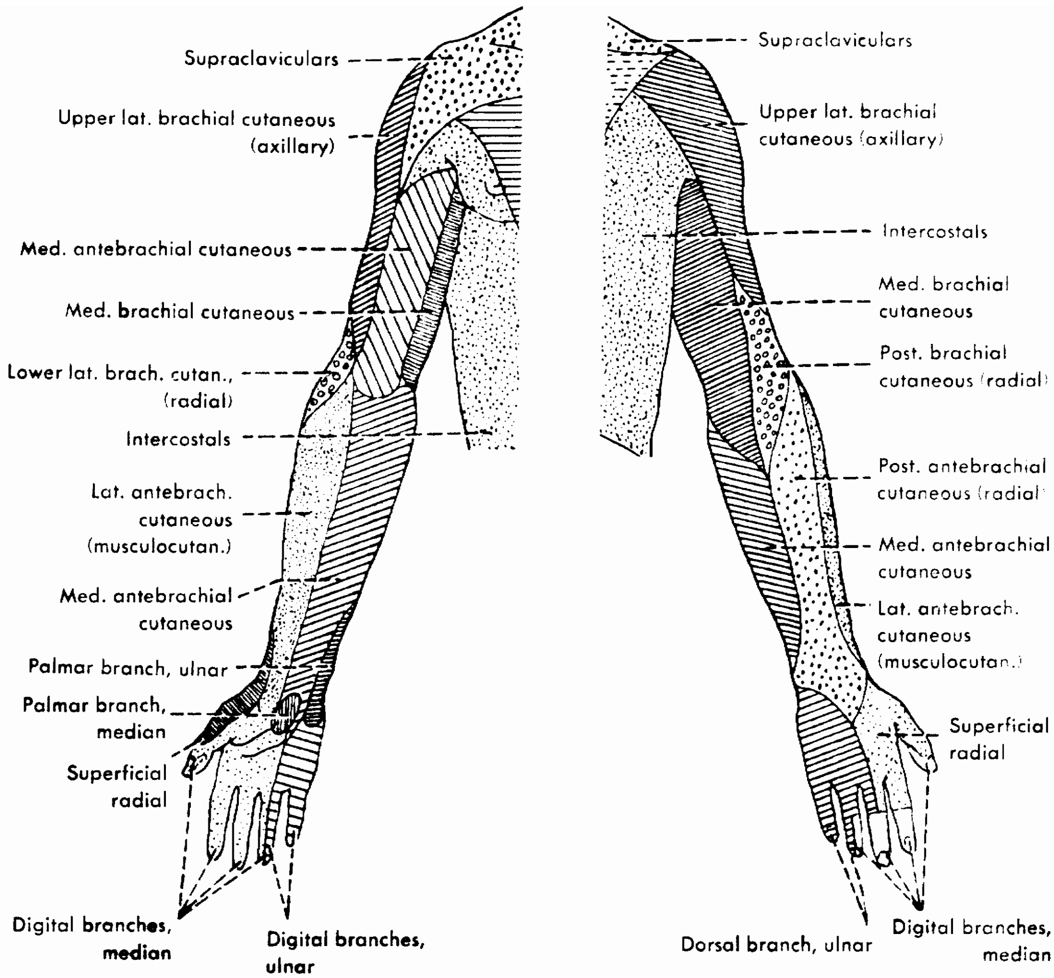


Figure 2.5 Branches of the Ulnar, Median, and Radial Nerves. Taken from Hollinshead (1974).

2.2.6 Blood Supply of the Wrist and Hand

The ulnar and radial arteries, which supply the wrist and hand with blood, are united by four arterial arches. These arches are: the deep palmar arch, the superficial palmar arch, the anterior carpal arch, and the posterior carpal arch. The arteries of the wrist and palm can be seen in Figure 2.6.

2.2.7 Muscles and Tendons of the Wrist and Hand

The flexor and extensor muscles of the wrist pass over the wrist joint and are connected by tendons to the metacarpals. The flexors and extensors of the digits cross over the wrist joint and connect to the middle and distal phalanges. The flexors of the wrist and fingers include: the flexor carpi ulnaris, the palmaris longus, the flexor carpi radialis, the flexor digitorum superficialis, and the flexor digitorum profundus. The extensors of the wrists and fingers include: the extensor carpi ulnaris, the extensor digiti minimi, the extensor digitorum, the extensor indicis, the extensor carpi radialis longus, and the extensor carpi radialis brevis.

There are four primary forearm muscles which operate the thumb: the flexor pollicis longus, the extensor pollicis longus, the extensor pollicis brevis, and the abductor pollicis longus. These four muscles connect at the base of the metacarpal and two phalanges of the thumb. In addition to these four muscles, there are four intrinsic thumb muscles of the hand: the abductor pollicis brevis, the flexor pollicis brevis, the opponens pollicis, and the adductor pollicis. These muscles are connected to the proximal phalanx of the thumb. The muscles and tendons of the wrist and hand are shown in Figure 2.7.

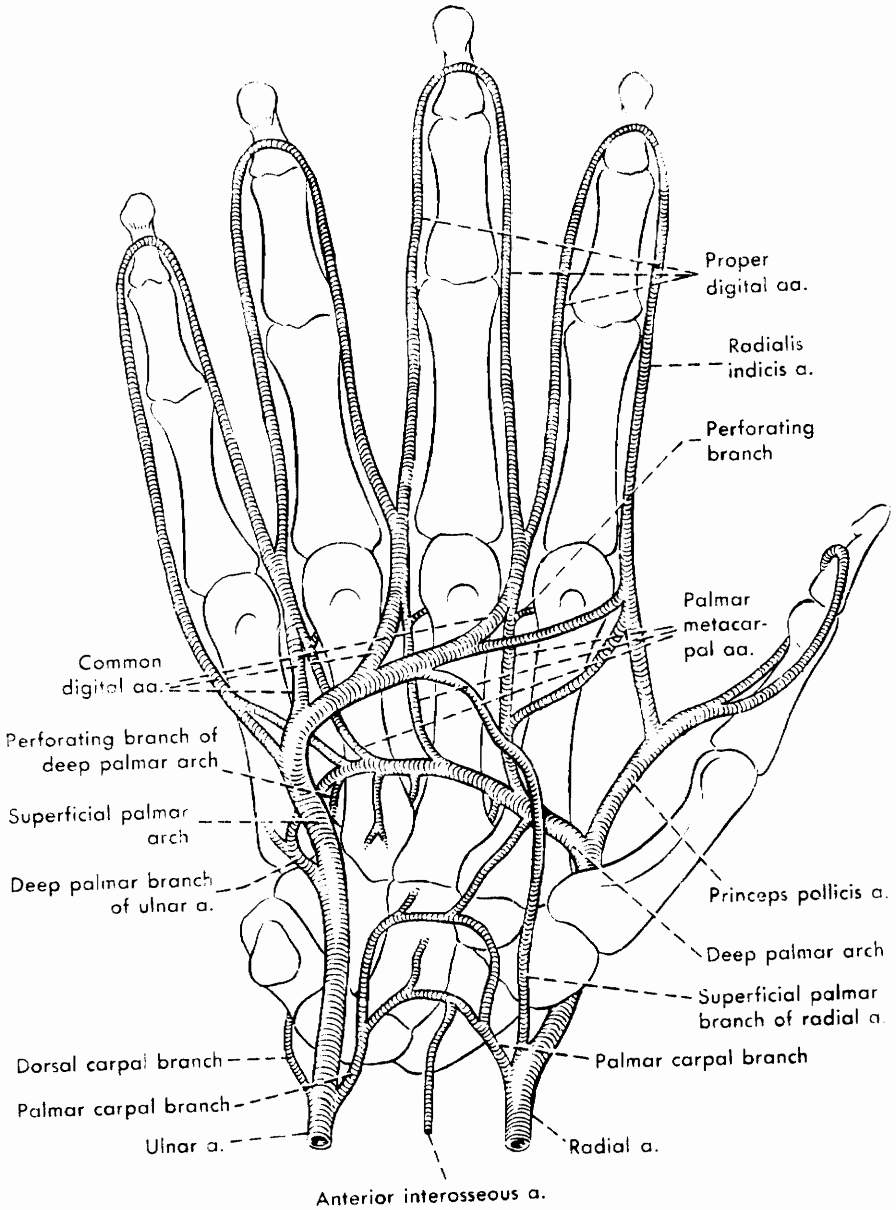


Figure 2.6 Blood Supply of the Wrist and Hand. Taken from Hollinshead (1974).

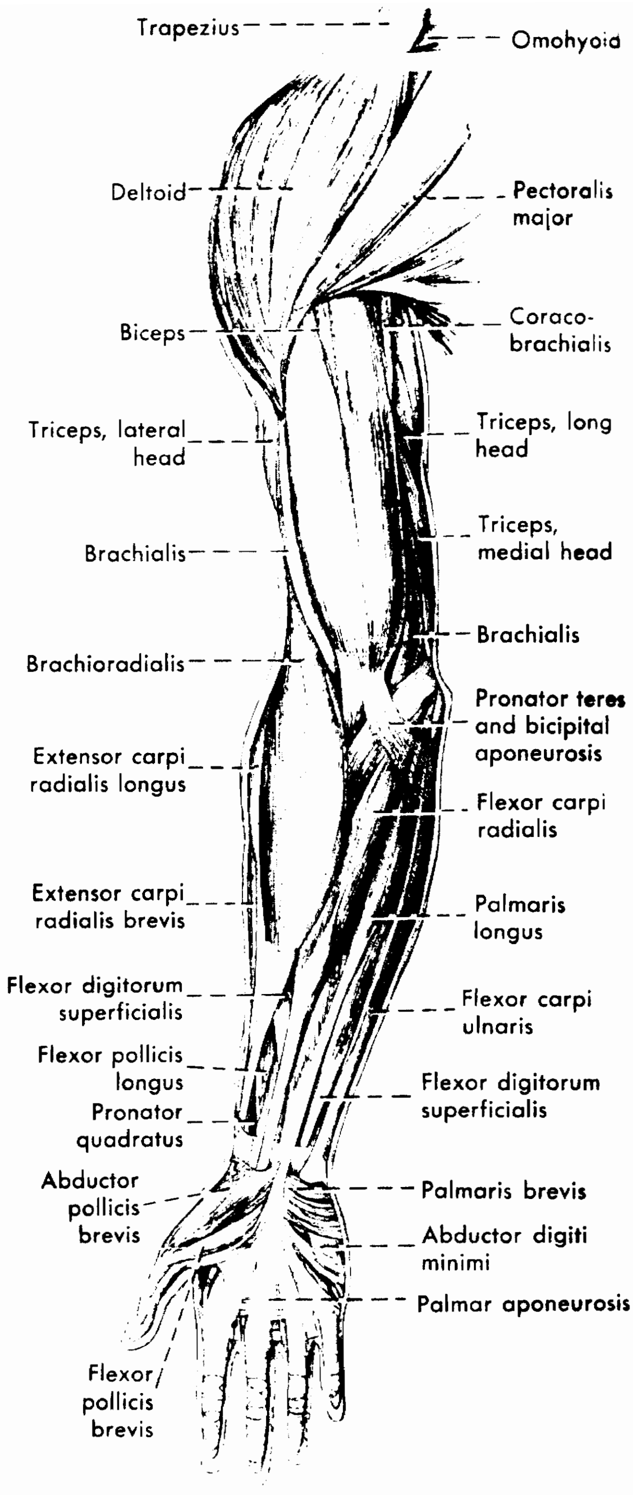


Figure 2.7 Ventral View of the Muscles and Tendons of the Wrist and Hand. Taken from Gardner and Osburn (1973).

2.2.8 The Carpal Tunnel

The carpal tunnel is a rigid, 2-3 cm long tunnel in the wrist formed by the carpal bones and the flexor retinaculum. The carpal bones, which form a concave surface, comprise the floor and sides of the tunnel. They are connected by the radial carpal ligament, the intercarpal ligament, and the carpometacarpal ligament. The flexor retinaculum (transverse carpal ligament), which forms the roof of the tunnel, is attached to the pisiform bone and the hook of the hamate on the ulnar side. On the radial side, it is attached to the tubercle of the scaphoid and to both lips of the groove of the trapezium. The long, digital flexor tendons pass through this tunnel as well as the median nerve and the blood vessels of the wrist and hand. A cross-sectional view of the carpal tunnel is shown in Figure 2.8.

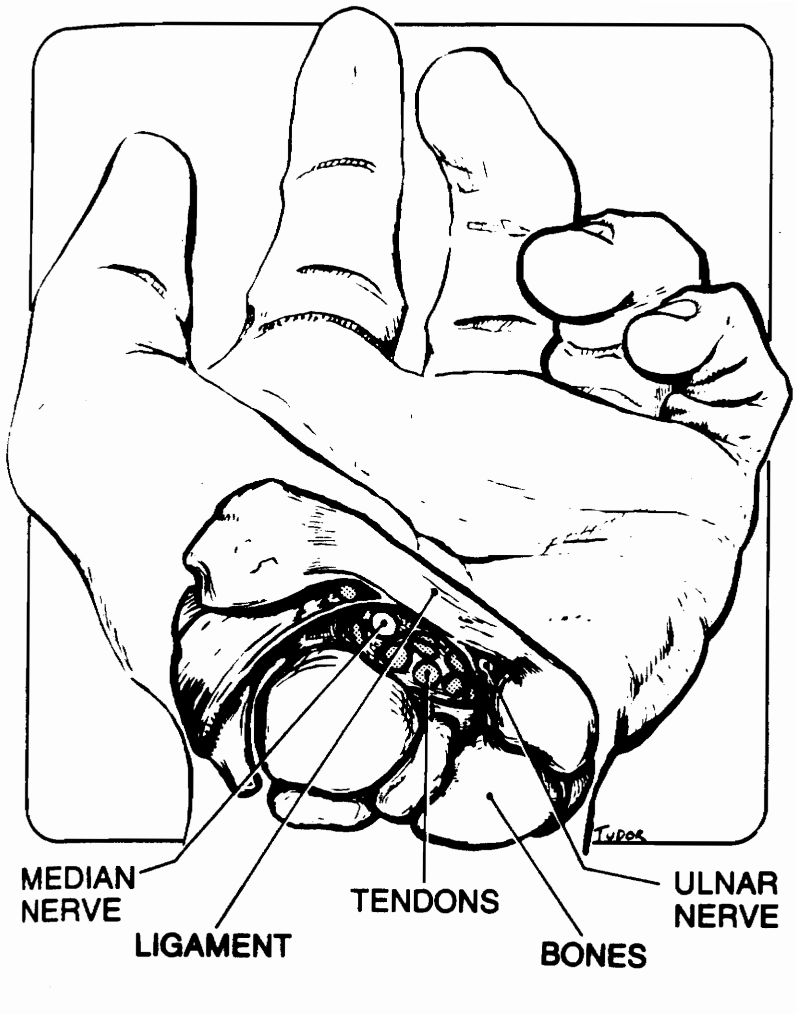


Figure 2.8 Cross-sectional View of the Carpal Tunnel. Taken from Putz-Anderson (1988).

2.3 Definition of Carpal Tunnel Syndrome

Carpal tunnel syndrome is a type of cumulative trauma disorder which occurs when the median nerve, which runs through the carpal tunnel of the wrist, is compressed. Cumulative trauma disorders are the result of a series of "microtraumas," which collectively cause injury to the affected body part (Kroemer, 1989). Other terms for carpal tunnel syndrome include: writer's cramp, neuritis, median neuritis, and partial thenar atrophy (Putz-Anderson, 1988).

There are many factors which can cause carpal tunnel syndrome, the most common of which is tenosynovitis of the flexor tendons of the fingers (Phalen, 1966). When tenosynovitis occurs, increased synovial fluid fills the tendon sheaths to help lubricate the tendons as they move. This fluid increase causes the tendons to swell, which in turn, reduces the opening of the carpal tunnel and can compress the median nerve. Symptoms of carpal tunnel syndrome include: numbness in the thumb, index, middle, and radial half of the ring finger (especially at night); pain; loss of dexterity; and tingling sensations. Symptoms of advanced cases of carpal tunnel syndrome can include the atrophy of the thenar muscles at the base of the thumb and a notable weakness or clumsiness of the affected hand(s). Also, the affected area(s) may appear to be dry due to the autonomic nerve impairment (Armstrong, 1983). The symptoms of carpal tunnel syndrome are often most severe during sleep. Carpal tunnel syndrome may affect one or both hands, however studies have shown that carpal tunnel syndrome occurs significantly more frequently in the dominant hand of both right- and left-handed persons (Reinstein, 1981; Phalen, 1966).

Several personal factors can place an individual at a higher risk of developing carpal tunnel syndrome. These include: pregnancy, diabetes mellitus, hypothyroidism, acromegaly, rheumatoid arthritis, gout, Paget's disease (Feldman, Goldman, and Keyserling, 1983), hand or wrist abnormalities or malaligned fractures, oral contraceptive use, neoplasms, neuromas of the median nerve, myxedema, amyloidosis, multiple myeloma, Raynaud's disease, menopause (Cannon, Bernacki, and Walter, 1981), gender (Phalen, 1966; Lockwood, 1989), age (Silverstein, Fine, and Armstrong, 1986), and retention of fluid (Phalen, 1966; Dionne, 1984; Laidlaw, 1987).

2.4 Incidence of Carpal Tunnel Syndrome

Carpal tunnel syndrome has been estimated (Squires, 1991) to account for approximately 50% to 75% of all cumulative trauma disorders. Several studies on the incidence rates of carpal tunnel syndrome have been conducted, but the results varied greatly and the overall incidence rate of carpal tunnel syndrome is still unknown. The following paragraphs review the studies conducted on incidence rates of carpal tunnel syndrome with particular emphasis on the data collection method and possible error sources. Not all of the studies reviewed were directly related to the incidence rate of carpal tunnel syndrome in keyboarding, however these studies were included to show the high incidence rate of carpal tunnel syndrome in industry.

A study performed by Cannon, Bernacki, and Walter (1981) found 30 cases of carpal tunnel syndrome in a population of 20,000 hourly workers located in four plants of the Pratt and Whitney Aircraft Company in East Hartford, Connecticut over a 1 year time period. Cases of carpal tunnel syndrome were identified through two methods. The first method selected all people who received workers' compensation benefits for injuries to the wrist, arm or hand during the period from June 30, 1977 to July 1, 1979. The plant medical records for these people were then reviewed to determine whether they were receiving benefits for the treatment of carpal tunnel syndrome; 16 people were identified by this method as having carpal tunnel syndrome. The second method was to have medical department personnel identify all other individuals who had been diagnosed as having carpal tunnel syndrome between June 30, 1977 and July 1, 1979, but who were not receiving workers' compensation; 14 people were identified as having carpal tunnel syndrome by this method. This incidence rate could be an underestimate due to people not reporting their symptoms or people visiting their private physician rather than the plant medical department.

Armstrong et al. (1981) noted 8 cases of carpal tunnel syndrome or other nervous disorders per 200,000 hours in an investigation of cumulative trauma disorders in a poultry processing plant. There were only 12.8 total cases of cumulative trauma disorders identified, with nervous disorders accounting for approximately 62.5% of the total. The method used to determine the incidence rates of cumulative trauma disorders was to review the injury logs of the plant for the 8 months preceding the study. Cumulative trauma disorders of the hand, wrist, forearm, and elbows were classified as either nervous, tendinous, or nonspecific. A nervous disorder was defined as "a diagnosed injury or illness of a nerve such as carpal tunnel syndrome or numbness in the upper extremity that could not be attributed to an acute episode." A tendinous disorder was defined as "an inflammation, tearing, or any other injury or illness of a tendon or tendon sheath that could not be attributed to an acute episode." Finally, a nonspecific disorder was defined as "any complaint of soreness, aching swelling, or knots, that could not be attributed to an acute episode." Incidence rates for particular departments were computed from the number of disorders per department and the number of work hours to adjust for exposure. Possible error sources include workers who did not report their symptoms and workers who visited a private physician rather than the plant medical department.

A study conducted by Silverstein et al. (1986) found 51 of 574 hourly workers from six different industrial sites to be afflicted with some form of cumulative trauma disorder. The six industries included in the study were: electronics assembly, major appliance manufacturing, investment casting of turbine engine blades, apparel sewing, ductile iron foundry, and bearing manufacturing. The breakdown of specific disorders is as follows: 29 cases of tendinitis, tenosynovitis, or deQuervain's disease; 7 cases of carpal tunnel syndrome; 5 cases of tendon related disorders; 3 cases of guyon tunnel syndrome; 4 cases of digital neuritis; 1 case of Raynaud's phenomenon; and 2 cases of non-specific pain. Cumulative trauma disorders were diagnosed through the use of structured interviews and standardized non-invasive physical examinations. The interviews compiled data on: demographics, prior health and work history information (years on the job, prior hand or wrist injuries, chronic diseases, reproductive status of women, and recreational activities), and hand or wrist pain or discomfort experienced in previous years. If the interview revealed that a worker had experienced recent difficulty in one or more parts of the hand or wrist, more detailed information was gathered concerning: location of pain, duration, onset, aggravating factors, and treatment. After the interview, workers received a standardized physical examination from a research team, who had no information about medical history or exposure to ergonomic risk factors. The examination included: inspection and palpation; active, passive, and resisted range of motion testing; palpation of pulses; deep tendon reflexes; and dermatome evaluation. The types of cumulative trauma disorders diagnosed were tendon related disorders (tendinitis, tenosynovitis, deQuervain's disease, trigger finger) and nerve entrapments (carpal tunnel syndrome, Guyon tunnel syndrome, digital neuritis, Raynaud's phenomenon). If none of these disorders was diagnosed, a non-specific designation was given. The criteria used to diagnose a cumulative trauma disorder were: (interview) symptoms of pain, numbness, or tingling; symptoms lasting more than 1 week or more than 20 times in the previous year, or both; no evidence of acute traumatic onset, no related systemic diseases, onset since working on current job; (physical examination) characteristic signs of muscle, tendon, or peripheral nerve lesion, and having ruled out other conditions with referred symptoms.

Jensen, Klein, and Sanderson (1983) studied the Supplementary Data System (SDS) for 1979 developed by the Bureau of Labor Statistics. The SDS for 1979 summarized workers' compensation records from 26 states who had reported wrist compensation cases relating to inflammation or irritation of joints, tendons, or muscles; or diseases of the nerves and peripheral ganglia. In addition, the wrist compensation claim had to be attributable to one of the following types of accident or exposure: repetitive pressure; voluntary motions; overexertions; lifting objects; pulling objects; throwing objects; or nonspecific overexertion. Any wrist compensation claim which met these criteria was labeled a "non impact wrist disorder." Data were collected on the number of workers in 7 industries (agriculture, construction, manufacturing, transportation, trade, finance, services) for all 50 states, and it was determined that the 26 states in the study represented 43 percent of the total workforce employed in the 7 industries. The SDS showed that for the 26 states reviewed, non impact wrist disorders accounted for more than 6 percent of the total number of compensable cases involving the wrist, and more than 10 percent of the compensable cases involving the wrist in the manufacturing industry. The manufacturing industry also accounted for 69.6% of the total number of non impact wrist disorders identified in this study. In addition, non impact wrist disorders average $618 in medical payments and $1,026 in indemnity compensation per case. The percentage of claims for non impact wrist disorders submitted by men (50.6 percent) and women (49.4 percent) were similar, with the mean age of woman claimants (33.7 years) being 3.8 years older than men claimants (29.9 years) at the 0.0001 level of significance. Possible error sources for this study include: differences among State workers' compensation coverage and reporting requirements, the fact that compensation claim data only reflects the likelihood of a worker filing a claim and does not indicate the true incidence of the injury, the fact that many workers are not covered by State compensation programs (farm owners, railroad employees, maritime workers, Federal employees), and the fact that many workers with symptoms of non impact wrist disorders have been transferred to alternate jobs where their symptoms have reduced sufficiently to not report a compensation claim.

Recent surveys and studies have investigated the incidence of carpal tunnel syndrome in people who work with visual display terminals. Bammer (1988) conducted a study in 1986 to determine the incidence of cumulative trauma disorders among office workers in 7 countries. Women office workers in the Departments of History and Physics from Universities in Australia, Japan, Sweden, England, Germany, the USA, and Canada were interviewed for one hour during working hours. The interview consisted of a standard set of questions pertaining to health problems, work organization and job satisfaction. The interview questions relating to health problems concentrated on neck and upper limb disorders. Workers were provided with drawings of front, side and back views of the body as well as a list of symptoms. They were instructed to mark the appropriate portion(s) of the body where they had experienced or were experiencing symptoms. The subjects were then asked a further series of questions which separated them into three categories: no symptoms, mild symptoms and severe symptoms. Subjects in the severe symptoms category had to meet the following criteria: an ache or pain which occurred for more than 30 days in 1 year or which occurred between 8 and 30 days and prompted the person to take some action (going to a doctor, modifying the work environment, modifying the home). Table 2.1 shows the sample sizes, percentage of sample using VDTs and average age of subject.

Table 2.1

Sample sizes; percentages using VDTs; average age; and percentage of sample with no, mild or severe upper limb disorders. Taken from Bammer (1988).

	Aus.	Jap.	Swe.	Eng.	Ger.	USA	Can.
Total number office staff	35	42	9	19	27	41	20
# interviewed	27	7	4	8	9	18	12
% using VDTs	93	86	25	75	56	89	83
average age	38	35	52	44	43	39	35
% sample with no problems	6	40	30	35	20	25	70
% sample with mild problems	25	40	70	35	20	45	70
% sample with severe problems	69	20	0	30	60	30	10

Results indicated that neck and upper limb disorders were a common complaint among office workers in all countries surveyed, with the highest number of cases reported in Australia. The incidence of neck and upper limb disorders were obtained by determining if a person had suffered from this type of disorder at any time during their life. Varying methods of diagnosing these disorders from country to country could account for inconsistent incidence rates. Also, the sample sizes used in this study were very small, therefore the results may not be an accurate indication of the similarities and differences between the incidence rates for neck and upper limb disorders in the seven countries.

According to Carpi (1989), 17% of keyboard operators are expected to develop carpal tunnel syndrome in their lifetime. This figure is based on the results of several small surveys Carpi conducted. Also, a survey conducted by LeGrande, the health and safety director of the Communications Workers of America, reported 125 of the 500 keyboard operators interviewed had carpal tunnel syndrome or preliminary symptoms. LeGrande states that 20 of every 40 people with carpal tunnel syndrome are medically disabled and cannot perform even simple tasks with the affected hand(s). In 1984 a study was performed by the South Australian Health Commission which determined that 56% of keyboard operators had recurring symptoms of carpal tunnel syndrome, and 8% of these injuries were medically disabling (Rosch, 1991).

Armstrong (1986) believes that the incidence of cumulative trauma disorders are even higher than studies indicate. Employees may not recognize the early symptoms of these disorders as serious problems. Also, employees may prefer to visit their own physician, therefore these symptoms would remain unreported to their employer. Even in the cases which are reported to the medical department, many people are not identified in studies as having a cumulative trauma disorder unless they are receiving workers' compensation benefits. Lastly, people may not report health problems to avoid being labeled as troublemakers or hypochondriacs.

2.5 Occupational Factors and Carpal Tunnel Syndrome

Kroemer (1989) summarized information from Armstrong (1983), Chatterjee (1987), Ferguson (1981), Peres (1961), Silverstein (1985), and himself (Kroemer, 1989) about the types of activities which are generally associated with carpal tunnel syndrome. Bodily activities which may lead to carpal tunnel syndrome include: repeated wrist flexion or extension, rapid wrist rotation, radial or ulnar deviation, forceful wrist motions and deviation, pressure with the palm, and pinching. These bodily activities have been associated with, but are not limited to, the following occupational and non-occupational activities: buffing, grinding, polishing, sanding, assembly work, typing, keying, cashiering, playing musical instruments, surgery, packing, housekeeping, cooking, carpentering, brick laying, butchering, hand washing or scrubbing, knitting, sewing, racket sports, and hammering.

The following occupational factors will be discussed in detail: repetitive motions, forceful motions, awkward postures of the wrist (flexion, extension, ulnar deviation, and radial deviation), mechanical stresses, vibration, and cold temperatures.

2.5.1 Repetitive Motions

According to Armstrong (1986), repetitive motions are one of the most frequently stated risk factors of carpal tunnel syndrome. He warns, however, that repetitive motions should be defined as those motions which are extremely similar or involve the same muscle groups. Suggestions to reduce repetitive motions include: increasing rest time, restructuring the job to include a wider variety of motions, using mechanical aids, and rotating workers. Repetition has also been determined to be the most critical factor involved in musicians who develop carpal tunnel syndrome (Lockwood, 1989). In addition, a study conducted by Cannon, Bernacki, and Walter (1981) found repetitive motions to be significantly related (p=0.05) with the onset of carpal tunnel syndrome.

Silverstein, Fine, and Armstrong (1986, 1987) conducted two similar studies, which examined the association between forceful and/or repetitive job attributes and the development of cumulative trauma disorders of the hand and wrist. The only main difference between the two studies was the number of subjects used. In the study conducted in 1986, 574 workers from 6 different industrial sites were examined; in 1987, 652 workers from 7 industrial sites were tested. All other aspects of the studies (purpose, methods, etc.) were the same. All jobs at the sites which contained at least 20 workers each performing that job per day were classified in terms of force and repetition by observers, who were blinded to worker health problems. Only workers who had performed the job for at least a year were studied. Jobs were classified into four exposure groups: low force-low repetitive (LOF.LOR), high force-low repetitive (HIF.LOR), low force-high repetitive (LOF.HIR), and high force-high repetitive (HIF.HIR). In each job analyzed, any sequence which was repeated was called a "fundamental cycle." High repetitive jobs were selected on the basis that they contain a fundamental cycle of less than or equal to 30 seconds or used 50% of the total time performing a fundamental cycle. Low repetitive jobs, accordingly, had fundamental cycle times of more than 30 seconds or less than 50% of the time spent performing a fundamental cycle. Jobs were considered "high force" if the estimated hand force was greater than 4 newtons and "low force" if the estimated hand force was less than 1 newton. Workers in the low force-low repetition group were used as a comparison group for the other three groups.

Next, jobs were analyzed in terms of wrist posture, hand posture, and required hand force. Wrist and hand posture were determined from videotapes of the jobs, and forces were recorded from bilateral surface electromyographic (EMG) readings. Hand positions were classified into the following six categories: pulp pinch, palm pinch, pulp grasp, lateral pinch, finger press, and medial grasp. Wrist positions were grouped into extension (<-15 degrees), neutral (>-15 degrees and <+15 degrees), and flexion (>+15 degrees).

After jobs were analyzed, the employees performing these jobs were given structured interviews and screening physical examinations to determine whether they should be diagnosed as having carpal tunnel syndrome. Workers were diagnosed as having carpal tunnel syndrome if they met the following criteria: (in the interview) symptoms of pain; numbness; or tingling in the median nerve distribution of the hand; nocturnal exacerbation; symptoms occurring more than 20 times or lasting more than 1 week in the previous year; no history of acute traumatic onset of symptoms; no history of rheumatoid arthritis; onset of symptoms since on current job; (in the physical examination) positive modified Phalen's test or Tinel's sign; and no cervical root, thoracic outlet, or pronator teres syndromes.

The results of the 1986 study found that employees in the HIF.HIR group were 5 times more likely to develop carpal tunnel syndrome than employees in the LOF.LOR group. This study also found that repetition, irrespective of force, was associated with the development of carpal tunnel syndrome ($p<0.005$). Force, irrespective of repetition, was also found to be significant ($p<0.0001$).

Results of the 1987 study indicated that employees in the HIF.HIR group were 15 times more likely to be at risk of developing carpal tunnel syndrome than employees in the LOF.LOR group. Repetitiveness was determined to be the most important risk factor of those risk factors examined ($p<0.05$), but force, irrespective of repetitiveness, was not statistically significant.

An examination of any significant changes in the tissue densities of the tendons, tendon sheaths, and nerves of the wrists of six cadavers was conducted by Armstrong et al. (1984). These changes, which were analyzed by their location and character, were thought to have been caused by repeated exertions with a flexed or extended wrist beyond 15 degrees from neutral. These findings suggest that anyone performing an activity with a flexed or extended wrist beyond 15 degrees from neutral has an increased risk of developing a cumulative trauma disorder, such as carpal tunnel syndrome. The results of this study support the theory that computer operators should not type with their wrists bent or extended beyond 15 degrees from neutral.

With the advent of computers and electronic keyboards, the job of the typist has become much more repetitive (Stack, 1988). When manual or electro-mechanical typewriters were used, the typist still performed tasks such as changing the paper, correcting errors, and pressing the return carriage. Electronic keyboards make it possible for typists to key up to 14,000 keystrokes per hour without changing tasks (Laidlaw, 1987). Laidlaw reports Stone's (1984) warning that keying rates of 12,000 to 14,000 put an operator at risk of developing a cumulative trauma disorder such as carpal tunnel syndrome.

2.5.2 Forceful Motions

Silverstein, Fine, and Armstrong (1986) conducted a study which found that force, irrespective of repetitiveness, was highly associated with the development of carpal tunnel syndrome ($p<0.0001$). When force and repetition were both high, people were five times as likely to develop carpal tunnel syndrome than if these factors were both low.

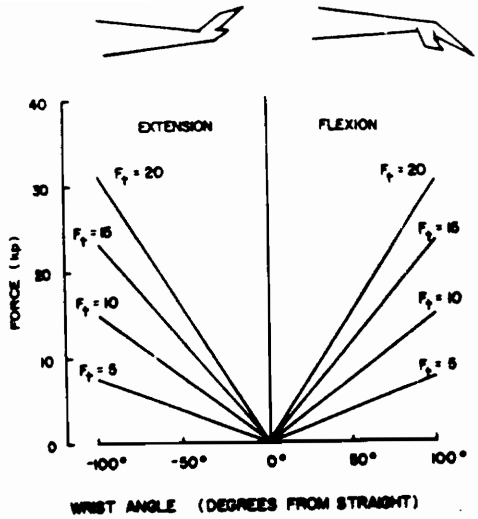
One study (Armstrong and Chaffin, 1979) examined the possible effect(s) of hand size and work methods on the likelihood of developing carpal tunnel syndrome. Two groups of female subjects were analyzed; one of the groups had a history of carpal tunnel syndrome (the diseased group) and the other did not (the control group). Both groups were employed in the production sewing of seat covers. The job, which required the workers to sew heavy fabrics with commercial sewing machines, involved considerable force and repetition (30 to 250 pieces per hour). The anthropometric hand data that was collected included the following dimensions: hand length, palm width, wrist width, wrist thickness, third metacarpal length, carpal height, carpal-ulnar distance, carpal tunnel width, carpal width, radius-ulna width, carpal angle, carpal height ratio, and carpal-ulna distance ratio. When t-tests were performed on these factors, no significant differences were noted (p <= 0.05) between the groups. Three elements of subjects' work methods were examined: hand position, wrist position, and hand force. Hand positions were classified into the following three categories: pinch, fingers opposing the palm, and pressing. Wrist positions were grouped into extension (<-15 degrees), neutral (>-15 degrees and <+15 degrees), and flexion (>+15 degrees). Hand forces, which were obtained from an electromyography (EMG) reading, were measured in kiloponds.

Results indicated that the diseased group exerted significantly (p<=0.05) more force in these pinch positions than did the control group. The average hand force used by the diseased group was significantly greater (p<=0.05) than that used by the control group. The results obtained from this study help support the idea that force is an occupational factor associated with carpal tunnel syndrome.

2.5.3 Awkward Postures of the Wrist and Hand

According to Armstrong (1986) awkward postures of the wrist are the most frequently cited occupational risk factor of carpal tunnel syndrome. When the wrist is varied from the neutral or straight position, the tendons of the finger become displaced past and against the adjacent walls of the carpal tunnel (Armstrong and Chaffin, 1979). For example, if the wrist is flexed, the finger tendons are displaced against the flexor retinaculum, and when the wrist is extended, these tendons are displaced against the carpal bones (Figure 2.9). The force which is exerted by tendons on the sides of the carpal tunnel is a function of the wrist angle and the tendon load (Figure 2.9). If these movements which cause the finger tendons to be compressed are repeated frequently, inflammation of the tendon sheaths can occur and lead to compression of the median nerve within the carpal tunnel. This reasoning is the basis for the statement "repeated exertions with a flexed wrist contributes to occupational carpal tunnel syndrome" (Armstrong, 1983). Accordingly, wrist flexion can be used to precipitate acute symptoms of carpal tunnel syndrome in diagnostic tests (Phalen, 1966).

Nerves are also compressed against adjacent structures of the carpal tunnel during wrist flexion and extension (Phalen, 1966). In wrist flexion, the median nerve is compressed between the finger flexor tendons and the flexor retinaculum. When the wrist is extended, the median nerve is compressed between the finger flexor tendons. In a study conducted by Armstrong and Chaffin (1979), symptoms of carpal tunnel syndrome were associated with awkward postures of the wrist and hand. A significant difference in hand



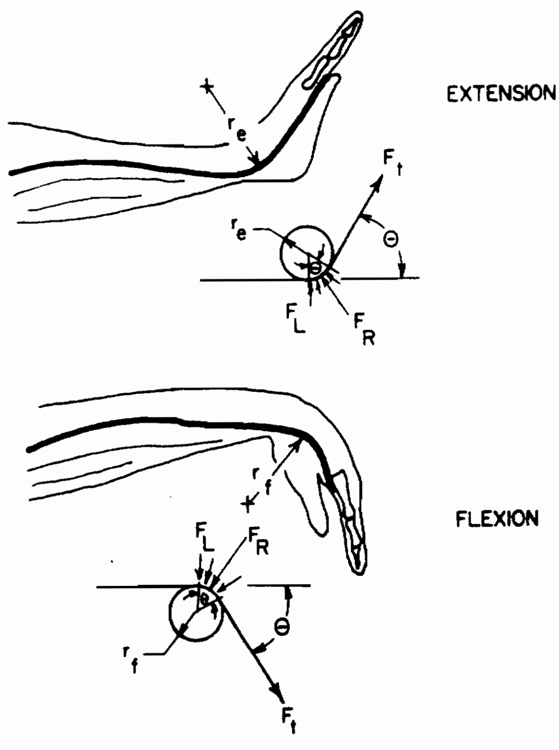


Figure 2.9.a Positions of the Finger Flexor Tendons During Flexion and Extension.

Figure 2.9.b Force Exerted by Tendons on Adjacent Wrist Structures as a Function of Wrist Angle and Tendon Load. Taken from Armstrong et al. (1979).

position between the two groups was found ($p<0.05$). This was thought to be primarily from the difference in pinch usage of the two groups; the diseased group used the pinch position 51.9% of the time, whereas the control group used the pinch position only 43.9% of the time. Also, a significant difference was noted ($p<0.05$) for wrist position between the two groups. The primary reason for this difference was found to be the use of an extended wrist position. The diseased group used the extended wrist position 32.3% of the time, whereas the control group used the extended wrist position only 26.3% of the time.

Another study conducted by Armstrong et al. (1984) found significant changes in the tissue densities of the tendons, tendon sheaths, and nerves of the wrists of six cadavers. These changes, which were analyzed by their location and character, were thought to have been caused by repeated exertions with a flexed or extended wrist. Armstrong and his associates concluded that movements with a flexed or extended wrist should be avoided in order to help prevent symptoms of carpal tunnel syndrome.

Ulnar and radial deviation have been associated with disorders such as de Quervain's disease (Armstrong, 1986; Tichauer, 1976). Radial and ulnar deviation cause the tendons of the fingers to be placed under mechanical stress. This stress can cause the tendons and their sheaths to become irritated and inflamed, which can cause compression of the nerves in the wrist. In a study conducted by Armstrong et al. (1982), a process which required ulnar wrist deviation and flexion was redesigned to keep the wrist in a neutral position. According to laboratory and field testing, the redesign reduced the symptoms of carpal tunnel syndrome.

2.5.4 Mechanical Stresses

Armstrong (1986) states that when the tendons of the wrist and hand are mechanically stressed by hard or sharp objects held in the base of the palm, carpal tunnel syndrome may result. He describes how the forces an average man can exert with his hand (540 to 640 newtons of hand force) or a woman (290 to 340 newtons of hand force) are transmitted via the skin of the hand to the tendons of the fingers. In addition, he warns against using the base of the palm as a tool to pound objects.

According to Armstrong (1983), the median nerve can be compressed due to repeated or sustained stresses over the base of the palm. In fact, some tests to diagnose carpal tunnel syndrome press the base of the palm to try to bring on the symptoms of the disease. Tools should not be designed to concentrate the stress in the middle of the palm (screwdrivers, buffers, and paint brushes), but rather they should try to distribute the stresses over the entire hand, especially on the muscles at the base of the thumb and little finger.

Another problem which can arise from mechanical stresses at the base of the palm is obstructed blood flow to the hand (Tichauer, 1976). Of particular concern is the superficial artery of the hand, which supplies the ring and little fingers with blood. According to Tichauer, when the superficial artery is compressed, these fingers will start to tingle and then become numb.

2.5.5 Vibration

Vibration is a major source of cumulative trauma disorders such as occupational vibration syndrome (Raynaud's Phenomenon, White Finger) and tendonitis (Armstrong, 1983; Armstrong, 1986; Armstrong et al., 1986; Kroemer, 1989; Putz-Anderson, 1988; Silverstein et al., 1987; Radwin et al., 1985; Feldman et al., 1983) and is sometimes cited as an occupational factor of carpal tunnel syndrome (Armstrong, 1986, 1983; Cannon et al., 1981). Occupational vibrations could occur from powered tools (i.e. drills, saws, grinders, sanders, and buffers) or simply grasping the wheel of a motor vehicle.

A study by Cannon, Bernacki, and Walter (1981) performed a case study of 30 people (3 males and 27 females) with carpal tunnel syndrome to examine several personal and occupational factors associated with carpal tunnel syndrome. A control group of 90 people (9 males and 81 females) without a history of carpal tunnel syndrome was selected to allow three controls per subject, matched on sex. The following factors were compared for the patient group and the control group: age, race, sex, history of diabetes, presence of hypertension, type of gynecological surgery performed, body weight, and occupational status. Results showed three factors for which the diseased group was significantly different than the controls. These factors were: use of vibrating hand tools (<0.01), history of gynecological surgery (<0.01), and duration of employment (<0.01). Subjects had a higher incidence of using vibrating hand tools and history of gynecological surgery than controls, but had been on the job significantly less time than the controls. According to Cannon and his associates, low-frequency vibrations in particular should be avoided.

Armstrong et al. (1985) examined epidemiological studies, clinical case analyses, and studies of short term effects to determine the contribution of vibration in carpal tunnel syndrome. Based on the fact that vibration stimulates muscle contraction (the tonic vibration reflex), a case study of workers using powered hand tools was performed to determine any effect(s) vibration had on the force required to use the hand tools. The dominant frequencies of the tools tested ranged from 20 Hz to 160 Hz, and the tools weighed anywhere between 15 N to 30 N. The grip force of subjects was then analyzed for 2 cylindrical handles, weighing 15 N and 30 N. Each handle was vibrated at 0 Hz, 40 Hz, and 160 Hz; had amplitudes of 9.8 m/s^2 and 49 m/s^2; and direction included three orthogonal axes. No significant effect was found for the direction of the vibration. There was a significant weight effect, with grip force increasing 55% when the 30 N handle was substituted for the 15 N handle. There was only a significant vibration effect at the 40 Hz frequency. When the amplitude was 9.8 m/s^2 and the frequency was 40 Hz, grip force increased 21 % from no vibration; when the amplitude was 49 m/s^2 and the frequency was 40 Hz, grip force increased 52% from no vibration. These results can be interpreted to show that exposure to 40 Hz vibration at 49 m/s^2 has virtually the same effect as doubling the weight of the tool from 15 N to 30 N.

Vibration also causes a decrease in tactility, which affects how much force is required to hold an object. In fact, studies have shown that a loss in tactility of the thumb and index finger requires twice as much force to be exerted to grip an object than with complete sensitivity (Armstrong et al., 1985).

Another study conducted by Silverstein et al. (1987), which examined whether forceful and/or repetitive motions were associated with carpal tunnel syndrome, found vibration to have a significant association. This study found that workers in high force-high repetitive jobs were 6 times more likely to develop carpal tunnel syndrome than workers in low force-low repetitive jobs, and this ratio was approximately doubled when continuos exposure to vibration was taken into account.

Issues to consider in vibration control include: frequency and magnitude of the vibration source; duration of exposure; temporal exposure patterns; forces applied by the tool operator; direction of vibration; skill of the operator; and posture of the hand, arm, and body during exposure (Armstrong et al., 1986). Two methods of avoiding exposure to vibration are to use engineering controls, such as the use of vibration absorbing tool handles, and to avoid critical frequencies (Tichauer, 1976).

2.5.6 Cold Temperatures

Although no direct association has been determined between low temperatures and cumulative trauma disorders, low temperatures may aggravate the symptoms of cumulative trauma disorders (Armstrong, 1986). Low temperatures impair hand-sensory and motor functions, which reduces manual dexterity and accentuates symptoms of nerve disorders (such as carpal tunnel syndrome). Despite the lack of a standard for finger temperature, Armstrong recommends keeping the fingers above 25 degrees Celsius to prevent loss of dexterity. Recommended methods for regulating finger temperature include: using gloves, constructing handles from materials with low thermal conductivity, directing exhaust air away from the worker, and having employees wear additional garments on the torso.

2.6 Computer Keyboard Position as a Factor

Conventionally, typists have been taught to keep their forearms horizontally positioned at keyboard height and parallel with the top of the desk while typing (Koskela and Lepisto, 1977). However, a study conducted by Stack (1988) found that this position may cause electronic keyboard operators to either extend their wrists, hold their forearms above the typewriter, or remove their fingers from the keys during rest breaks. Armstrong et al. (1979) found that extending the wrist puts pressure on the tendons and nerves of the carpal tunnel, and holding the forearms above the keyboard may cause muscle fatigue. With manual and electro-mechanical typewriters, the machine resilience or tactile feedback was adequate to allow typists to rest their fingers on the keys without producing unwanted characters. Because electronic keyboards do not possess the machine resilience to make this possible, typists must find other positions for rest. Stack found that operators either: hold their fingers above the keyboard while keeping their forearms straight, remove their hands entirely from the keyboard, or collapse their wrists in an extended position on the nearest support available. Of these three positions, the last position was most frequently observed. Stack reasoned that perhaps by either increasing or decreasing the slope of the keyboard from the horizontal plane, less force would be exerted on the keyboard, therefore allowing operators to rest their fingers on the keys (Figure 2.10). Stack also suggested wrist rests, which are positioned at the same height as the home row of keys, may prevent operators from extending their wrists during rest periods.

Duncan and Ferguson (1974) examined the relationship between keyboard operating posture and symptoms of carpal tunnel syndrome. The study observed the posture of 90 male telegraphists with symptoms of carpal tunnel syndrome to determine the frequency of the following positions: shoulder depression, shoulder flexion, shoulder abduction, ulnar deviation, and wrist extension. A control group of 45 unaffected telegraphists was observed in the same fashion. Both ulnar deviation and wrist extension were significantly greater ($p<0.001$) in the dominant hand of the diseased group. These findings reinforce that theory that awkward postures of the wrist and hand are an occupational factor of carpal tunnel syndrome.

Laidlaw (1987) conducted a study of wrist strains in 56 telephone operators using VDTs to determine any associations between keying force, keying posture, and symptoms of carpal tunnel syndrome. Operators were observed, photographed, and interviewed. Laidlaw found that operators with wrist strains appeared to use significantly higher keying force than other operators without any wrist strains ($p<0.05$). While it was noted that very few operators kept their wrists straight while typing, no significant relationship was determined between wrist angle(s) and symptoms of carpal tunnel syndrome. This finding was quite surprising, and may have occurred due to the fact that wrist angles were observed rather than accurately measured. Observations may not have recorded small changes in wrist posture, which may have led to significant results.

Hedge and Powers (1991) compared hand and wrist posture at a Protex computer keyboard to a traditional desktop keyboard. A Protex keyboard is an adjustable keyboard, which can be adjusted at negative slopes. The study compared hand and wrist deviations, both flexion/extension and ulnar/radial deviation, for 12 office workers using a traditional keyboard and a Protex keyboard. Using both keyboards, subjects were asked to transcribe four text documents into a word processing program. Subjects were allowed to adjust the tilt of both keyboards for their comfort. Hand and wrist deviations were

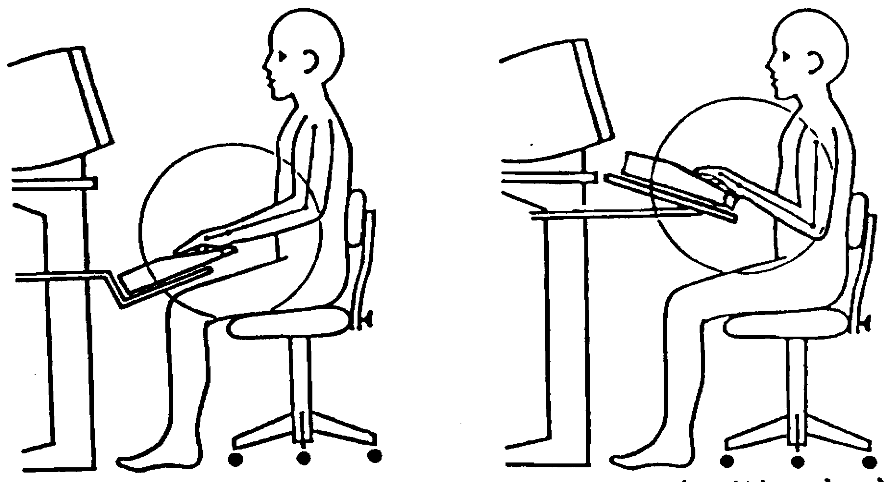


Figure 2.10 Positive and Negative Slope of Keyboard. Taken from Stack (1988).

detected from a Peak-Performance 2-D video-motion analysis system. Two cameras were used; one camera recorded postures from above and one from the side. Results indicated that wrist extension was significantly less (p=0.0) when subjects used the Protex system. Subjects consistently chose lower keyboard slopes with the Protex system (-11 degrees) than with traditional keyboards (15 degrees). Results did not show any significant differences in ulnar or radial deviation between the two keyboards.

Miller and Suther (1981) conducted an investigation to determine the preferred visual display terminal (VDT) adjustments for American and Oriental operators ranging from the 5th to 95th percentile. The American sample consisted of 29 operators, and the Oriental sample consisted of 8 operators; there were a total of 22 male and 15 female operators selected. The operators were asked to adjust a specially designed N.K.R. display station for their comfort, taking into consideration: seat height, backrest height, backrest tension, distance from the computer, keyboard support surface height, keyboard slope, computer support surface height, and computer slope. Subjects were then asked to transcribe a page of text, from a document holder, while they were videotaped and photographed.

Preferences for keyboard slope ranged from 14 degrees to 25 degrees with a mean slope of 18 degrees; negative keyboard slopes were not investigated. Operators preferred a keyboard support surface height from 560 mm to 725 mm (22.0 inches to 28.5 inches) with a mean of 630 mm (24.8 inches). Considering that the keyboard tested had a home row height of 77 mm, the preferred home row height above the floor ranged from 637 mm to 802 mm (25.1 inches to 31.6 inches) with a mean of 707 mm (27.8 inches). Miller and Suther encourage the use of keyboard support surfaces with minimal thickness to allow a broader range of keyboard support surface height adjustment without interference.

Emmons and Hirsch (1982) examined the relationship between keyboard height and keying performance and investigated operator preference for keyboard height. The objectives of the study were: to determine the relative productivity of IBM keyboard with home row heights measured from the floor of 30, 38, and 45 millimeters (5 degree, 12 degree, and 18 degree slopes) and a non-IBM keyboard with 30 millimeter (5 degree slope) home row height; to compare the SPACE-bar row error rates among the four keyboards; and to collect operator performance data and comments regarding fatigue for the four keyboard configurations. As the slope of the keyboard was increased, the height of the keyboard from the floor also increased due to the interrelationship of these two variables. Twelve skilled typists from a temporary-help agency were asked use the four typewriters to perform 20 experimental conditions, each 10 minutes long. The sessions consisted of keying meaningful textual material that was presented on a CRT. The following seven performance measures were computed for each experimental condition: throughput (effective keystrokes/total time), free-keying rate (effective keystrokes/(total time-wasted time)), percent operator corrected errors (single or sequence of multiple cursor positioning keystrokes leading to the replacement of previously keyed characters/(effective keystrokes*100)), percent erased keystrokes (erased keystrokes/effective keystrokes*100), percent wasted time (wasted time/total time*100), percent operator uncorrected errors (uncorrected errors/effective keystrokes*100), and percent SPACE-bar row errors.

The study found that keyboards with home row heights greater than 30 mm (slopes greater than 5 degrees) were significantly better in throughput and free-keying rate at the 0.05 level of confidence. The four keyboards did not significantly differ in any of the other performance measures, however. Operators significantly preferred ($p<0.05$) keyboards with home row heights greater than 30 mm (slopes greater than 5 degrees). Evidence suggested that keyboards with a home row height greater than 30 mm produced less fatigue and discomfort than keyboards with a 30 mm home row height. This study did not consider the possibility of keyboards with negative slopes.

Another study which examined operator preference for visual display terminal adjustments was conducted by Grandjean, Hunting, and Pidermann (1983). The variables examined included: keyboard height above the floor, screen height above the floor, screen distance from the table edge, screen inclination, and source document holder inclination. Keyboard slope was not specifically addressed in this study. The adjustment preferences for the five variables previously mentioned were recorded for sixty-eight subjects (48 females and 20 males) from four companies over a period of five days. For the first two days subjects were required to use a forearm-wrist support, which was placed between the table edge and the keyboard. On the third and fourth days, subjects were not allowed to use the forearm-wrist support, and use of the forearm-wrist support on the fifth day was optional.

The preferred range of keyboard height above the floor was 73 to 85 cm for 95% of the sample population. It was also noted than when the forearm-wrist rest was used, 80% of the subjects rested their forearms or wrists, whereas 50% of the subjects rested their forearms or wrists when no support was provided. The forearm-wrist supports were judged comfortable by 80% of the subjects, and only 3% found the support uncomfortable. When no support was provided, 52% of the subjects found it comfortable to rest their forearms or wrists on the table, and 21% of the subjects found it uncomfortable.

Cushman (1984) investigated the relationships between keyboard height and: keying rate, error rate, and operator preference. Twenty experienced female VDT operators were asked to enter text for 10 minutes for the following five keyboard heights: 70 cm, 74 cm, 78 cm, 82 cm, and 86 cm. Data were collected on keying rate, error rate, and operator preference for each of the five keyboard heights.

No significant differences ($p<0.05$) were found for keying rate or error rate between the five conditions, although errors were the smallest when the keyboard was at a home row height of 74 cm. Subjects preferred a keyboard height of 75.7 cm, which was 5-10 cm higher than the mean elbow height.

Weber, Sancin, and Grandjean (1984) conducted a study of twenty trained typists performing a 10 minute typing task in various conditions to examine: body postures, EMG of the trapezius muscle, pressure load exerted on the support, and subjective feelings of pain and tension. The six experimental conditions included: preferred keyboard height, 5 cm above preferred keyboard height, 5 cm below preferred keyboard height each with and without a forearm-wrist rest. The following dimensions were recorded for each subject: keyboard height (with and without support), screen inclination, screen distance from table edge, height of screen, height of source document holder, inclination of source document holder, height of seat surface, and seat backrest inclination. EMG was recorded by surface electrodes placed on the right trapezius pars descendens, as well as the pressure loads of the forearms, wrists, and hands on the support and on the keyboard. Subjects were asked to rate their feelings of pain and tension in their neck, shoulder, back, and arms at the end of each session. In addition, the following body postures were recorded: elbow angle, arm abduction, arm anteversion, and epicondylus lateral height.

EMG activity was significantly ($p<0.001$) less for each keyboard height when subjects were required to use a forearm-wrist rest. When no wrist rest was used, EMG activity increased significantly as keyboard height increased ($p<0.001$), therefore EMG activity was not at its lowest when the keyboard was at the preferred setting. The mean pressure exerted on the keyboard when no support was used was approximately 0 for all keyboard heights, however the mean pressure was between 15 and 35 N when the support was used and increased significantly ($p<0.001$) as keyboard height increased. A negative correlation ($p<0.001$) was noted between pressure exerted and EMG activity. In short, the more the hands and wrists rested on the support, the less electrical activity that occurred in the trapezius. The mean preferred keyboard height was 78 cm with the forearm-wrist support and 77 cm without the support. When the wrist support was used elbow angle, arm abduction and anteversion were significantly ($p<0.001$) greater than without the support, and arm abduction and anteversion increased significantly ($p<0.001$) with increased keyboard height. When the support was not used, elbow angle decreased with increasing keyboard height ($p<0.001$). These results suggest that VDT operators use arm abduction and anteversion to adapt to different keyboard heights when a support is available and use elbow angle to adapt to different keyboard heights when no support is available. Subjective ratings of tension in the neck, shoulder, and back were significantly ($p<0.01$) lower for all heights when a support was used. Although the results were not significant ($p<0.05$) the mean tension in the neck, shoulders, arms, and back was lowest at the preferred setting.

2.7 American National Standard for Human Factors Engineering of Visual Display Terminal Workstations (ANSI/HFS 100-1988)

According to ANSI/HFS 100-1988, "keyboards, in combination with their supporting surface, chair, and other furniture elements, *shall* permit users to adopt and maintain arm positions in section 8.4.1 and meet the leg clearance requirements in section 8.2." Each of these sections will be described in detail in the following paragraphs.

Section 8.4.1 of ANSI/HFS 100-1988, "Independent Keyboard and Display Supports," delineates suggested arm postures while working at a visual display terminal workstation. The keyboard support surface should enable the seated operator to adopt a posture with the forearm between 70+Y/2 degrees and 90+Y/2 degrees from the superior frontal plane, where Y is the seat back angle from the vertical in degrees. In addition, the angle between the upper arm and forearm should be greater than 70 degrees and less than 135 degrees. These dimensions can be seen in Figure 2.11. Anthropometric data (McConville, Kennedy, and Kroemer, 1985; McConville and Laubach, 1978) specify that an independent adjustable keyboard support surface shall range in height from at least 23.0 to 28.0 inches (58.5 to 71.0 cm) to accommodate the 5th percentile female and the 95th percentile male. Figure 2.12 shows the recommended range of adjustment for a visual display terminal workstation taking into consideration: seat height, keyboard thickness, forearm inclination, and resting elbow height.

Section 8.2 of ANSI/HFS 100-1988, "Clearances Under Workstations," sets forth guidelines on the minimum leg clearance of a seated operator in

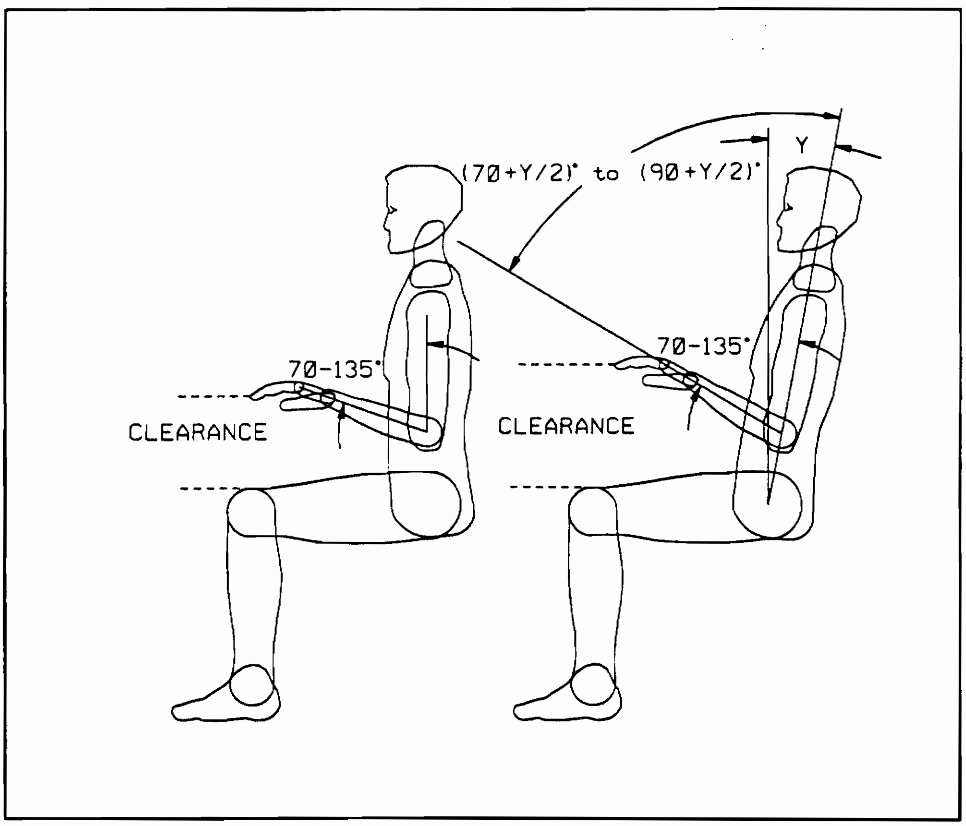


Figure 2.11 Height of the Keyboard Support Surface. Taken from ANSI/HFS 100-1988.

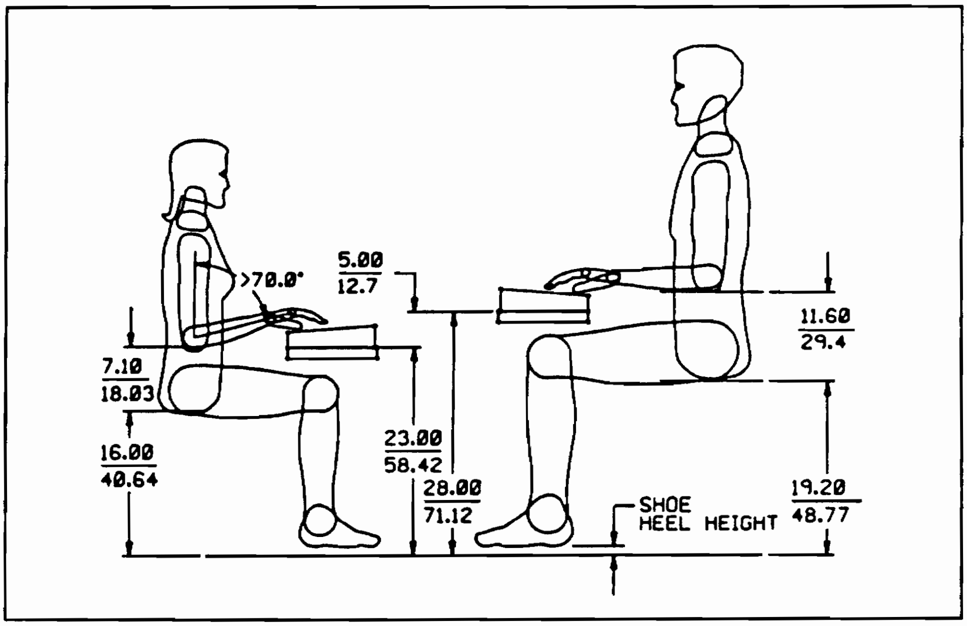


Figure 2.12 Range of Height of the Keyboard Support Surface. Taken from ANSI/HFS 100-1988.

terms of depth, width, and height. The minimum leg clearance depth of a seated operator at knee level should be approximately 60 percent of the buttock-to-knee length, and the minimum leg clearance depth at foot level should be 75 percent of the sum of buttock-to-popliteal length plus the foot length (with the lower leg perpendicular to the floor). If, however, a workstation supports the lower leg forward of perpendicular, the minimum leg clearance depth at foot level should be 75 percent of the sum of buttock-to-popliteal length and the foot length, plus the popliteal height times the sine of the angle between the vertical and the lower leg (Figure 2.13).

The minimum leg clearance width for a seated operator should be approximately 1 inch (2.54 cm) larger than the thigh breadth of the 95th percentile female, which is 17.2 inches (43.7 cm). Taking into consideration clothing and freedom of movement, the minimum leg clearance width should be at least 20 inches (50.8 cm), however the preferred leg clearance is 24 inches (61 cm).

The minimum leg clearance height should be at least equal to the highest point on the thigh or knee, when the operator is wearing shoes and has his/her lower leg in a normal, relaxed position (Figure 2.14). Specific dimensions for the minimum leg clearances described are outlined in Table 2.2.

ANSI/HFS 100-1988 also discusses the relationship between keyboard height and keyboard slope. Keyboard height is defined as the perpendicular vertical distance from a horizontal support surface to the geometric center of the key top strike area in the home row when the key is in the non-depressed position; keyboard slope is defined as the angle between the plane of the support surface and the plane passing through the centers of keys, or other

Table 2.2

Minimum Knee Space Dimensions (cm/inches)

Minimum Knee Space	5th Percentile Female	95th Percentile Male
Minimum Depth		
Depth at knee level	31.0/12.2	38.0/15.0
Depth at toe level	47.5/18.7	59.0/23.5
Minimum Width	50.8/20.0	50.8/20.0
Minimum Height		
Adjustable surface	51.3/20.2	66.5/26.2
Non adjustable surface		66.5/26.2

equivalent and corresponding points of keys, in the rows containing q and z in the qwerty layout. As the slope of the keyboard is increased, the height of the home row of keys increases, and as the slope of the keyboard is decreased, the height of the home row of keys decreases. In summary, increasing/decreasing the slope of the keyboard increases/decreases the height of the keyboard, however the opposite is not true. Changing the height of the keyboard does not affect the slope of the keyboard.

According to ANSI/HFS 100-1988, research has indicated a preference for keyboard slopes of 10-20 degrees (Emmons and Hirsch, 1982; Miller and Suther, 1981). In addition, a range of forearm angles was found which resulted in equal preference and equal performance in terms of keying speed and errors (Cushman, 1984; Grandjean, Hunting and Pidermann, 1983; Miller and Suther, 1981; Weber, Sancin and Grandjean, 1984). Therefore, ANSI/HFS 100-1988

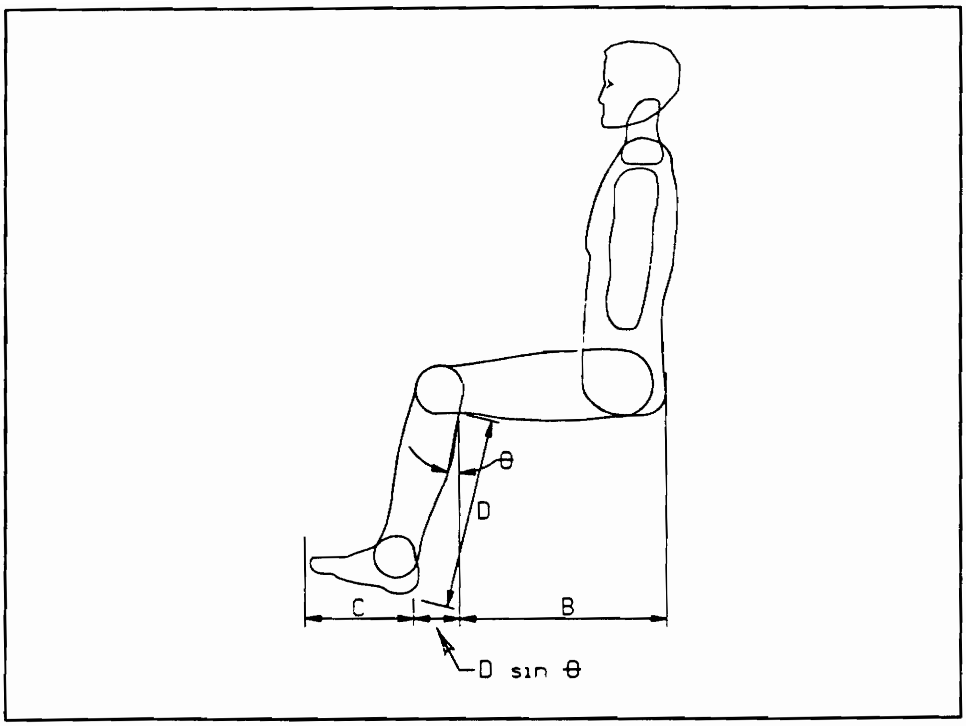


Figure 2.13 Clearance Under the Worksurface, Depth. Taken from ANSI/HFS 100-1988.

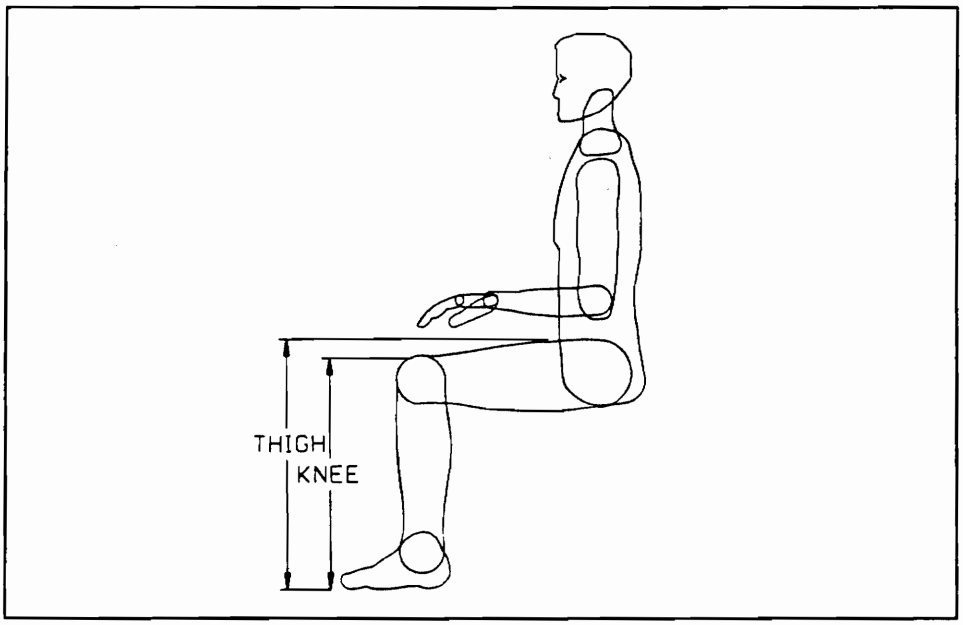


Figure 2.14 Clearance Under the Worksurface, Height. Taken from ANSI/HFS 100-1988.

recommends that keyboard slope be between 0 and 25 degrees.

Recommendations on display support surfaces and seating are also proposed by ANSI/HFS 100-1988. It is recommended that the height of the display support surface should allow the primary viewing area of the display to be located between 0 and 60 degrees below the horizontal plane passing through the eyes. When following this recommendation, care should be taken not to violate the minimum leg clearances proposed in Table 2.2.

The seat height for an operator at a visual display terminal workstation should allow the operator to place his/her feet firmly on a support surface while maintaining a 90 degree angle between the upper and lower leg. The minimum range of adjustment for seat height in shown in Figure 2.15.

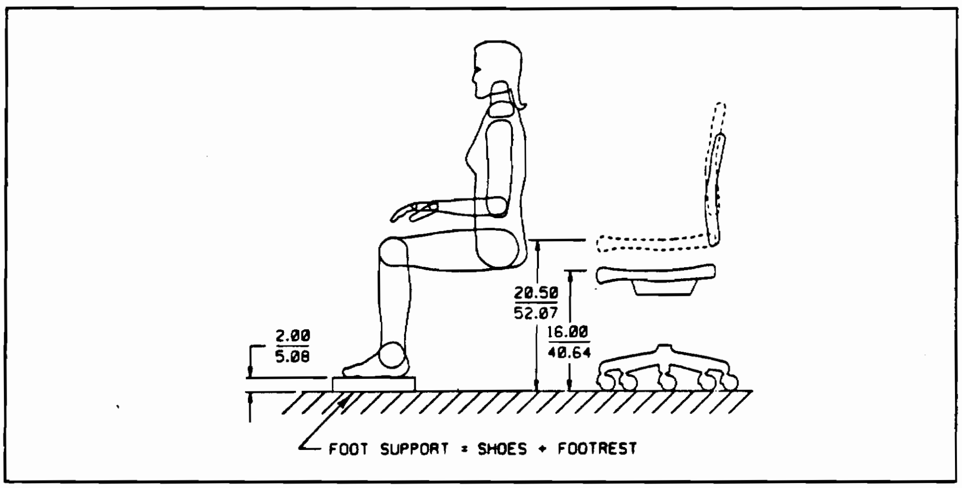


Figure 2.15 Seat Height Adjustment Range. Taken from ANSI/HFS 100-1988.

2.8 Summary

The preceding literature review describes several main points which can be summarized as follows:

- A study performed by the South Australian Health Commission determined that 56% of keyboard operators had recurring symptoms of carpal tunnel syndrome, and 8% of these injuries were medically disabling (Rosch, 1991). In addition, carpal tunnel syndrome accounts for 50% to 75% of all cumulative trauma disorders (Squires, 1991).
- Bodily activities which may lead to carpal tunnel syndrome include: repeated wrist flexion or extension, rapid wrist rotation, radial or ulnar deviation, forceful wrist motions and deviation, pressure with the palm, and pinching (Kroemer, 1989; Armstrong, 1983; Chatterjee, 1987; Ferguson, 1981; Peres, 1961; and Silverstein, 1985).
- Stack (1988) found that the conventional typing posture (forearms horizontally positioned at keyboard height and parallel with the top of the desk) caused operators to either: extend their wrists, hold their forearms above the typewriter, or remove their fingers from the keys while typing. This finding is due to the fact that electronic keyboards do not possess sufficient machine resilience to support the fingers without producing unwanted characters. Stack suggested that by either increasing or decreasing the keyboard slope from the horizontal plane, less force would be exerted on the keys allowing the fingers to rest on the keys.
- Hedge and Powers (1991) found that wrist extension was significantly

less ($p=0.0$) when subjects typed with a Protex adjustable keyboard rather than a traditional keyboard. Subjects consistently preferred negative keyboard slopes when given the choice.

- Miller and Suther (1981) found that operators prefer a keyboard slope of 18 degrees from horizontal. They did not investigate negative keyboard slopes.
- Emmons and Hirsch (1982) found that keyboard slopes greater than 5 degrees were significantly better in throughput and free-keying rate at the 0.05 level of significance. In addition, operators significantly preferred ($p<0.05$) keyboard slopes greater than 5 degrees. Negative keyboard slopes were not investigated.
- Cushman (1984) found that operators preferred a mean keyboard height of 75.7 cm, which was 5-10 cm higher than mean elbow height.

3. METHOD

3.1 Subjects

For this experiment, 24 right-handed subjects (12 male, 12 female) were employed. Originally 25 subjects were used, but one subject's data had to be eliminated due to equipment problems. Only subjects who had completed a touch-typing course and could type a minimum of 30 words per minute were utilized. Subjects were screened, and only subjects who met the following criteria and were therefore not predisposed to developing cumulative trauma disorders were selected: no history of hand or wrist abnormalities, malaligned fractures, diabetes mellitus, hypothyroidism, acromegaly, rheumatoid arthritis, gout, Paget's disease, neoplasms, neuromas of the median nerve, myxedema, amyloidosis, multiple myeloma, Raynaud's disease; not pregnant; and not experiencing menopause (Feldman, Goldman, and Keyserling, 1983; Cannon, Bernacki, and Walter, 1981; Phalen, 1966; Lockwood, 1989; Silverstein, Fine, and Armstrong, 1986; Dionne, 1984; Laidlaw, 1987). The total amount of each subject's time commitment was three hours, which was completed during one session. Subjects were compensated at a rate of $5.00 per hour, for a total of $15.00 per subject.

3.2 Apparatus

An experimental system was designed and constructed specifically for this study. The system was composed of: 1) two wrist monitor apparatuses; 2) a microcomputer with accompanying data acquisition hardware and software; and 3) an adjustable computer workstation where subjects performed the experimental tasks. Each of these subsystems will be discussed below. Figure

3.1 shows a schematic diagram of the experimental system.

3.2.1 Wrist Monitor Apparatus

A specialized wrist monitor was constructed by the Biodynamics Laboratory at The Ohio State University (Schoenmarklin and Marras, 1991). The wrist monitor is comprised of three measurement devices, which collect data on: ulnar/radial deviation, flexion/extension, and pronation/supination. The measurement devices for both ulnar/radial deviation and flexion/extension consist of a rotary potentiometer which is attached to two thin strips of metal by a pin. The pin allows each metal strip the freedom to rotate 360 degrees in the horizontal plane, and the potentiometer measures the angle between the metal strips. One metal strip is 16 cm long and 1.25 cm wide; the other metal strip is 9 cm long and 1.25 cm wide. The longer metal strips are positioned on the forearm with adhesive tape, while the shorter metal strips move through sliders (2.25 cm long by 2.75 cm wide) which are positioned with adhesive tape on the hand. The measurement device for pronation/supination consists of a rod (diameter = .1588 cm) attached to brackets on the proximal and distal ends of the forearm. The bracket on the distal end of the forearm attaches to a potentiometer which rotates with respect to the fixed rod, and the bracket on the proximal end of the forearm attaches to a cuff which is placed around the forearm. The wrist monitor apparatus is small and weighs approximately 0.05 kg. Two wrist monitors were used for this experiment, one for each hand.

3.2.2 Microcomputer System and Data Acquisition Hardware and Software

The wrist monitors were attached to a MacADIOS ADPO interface which

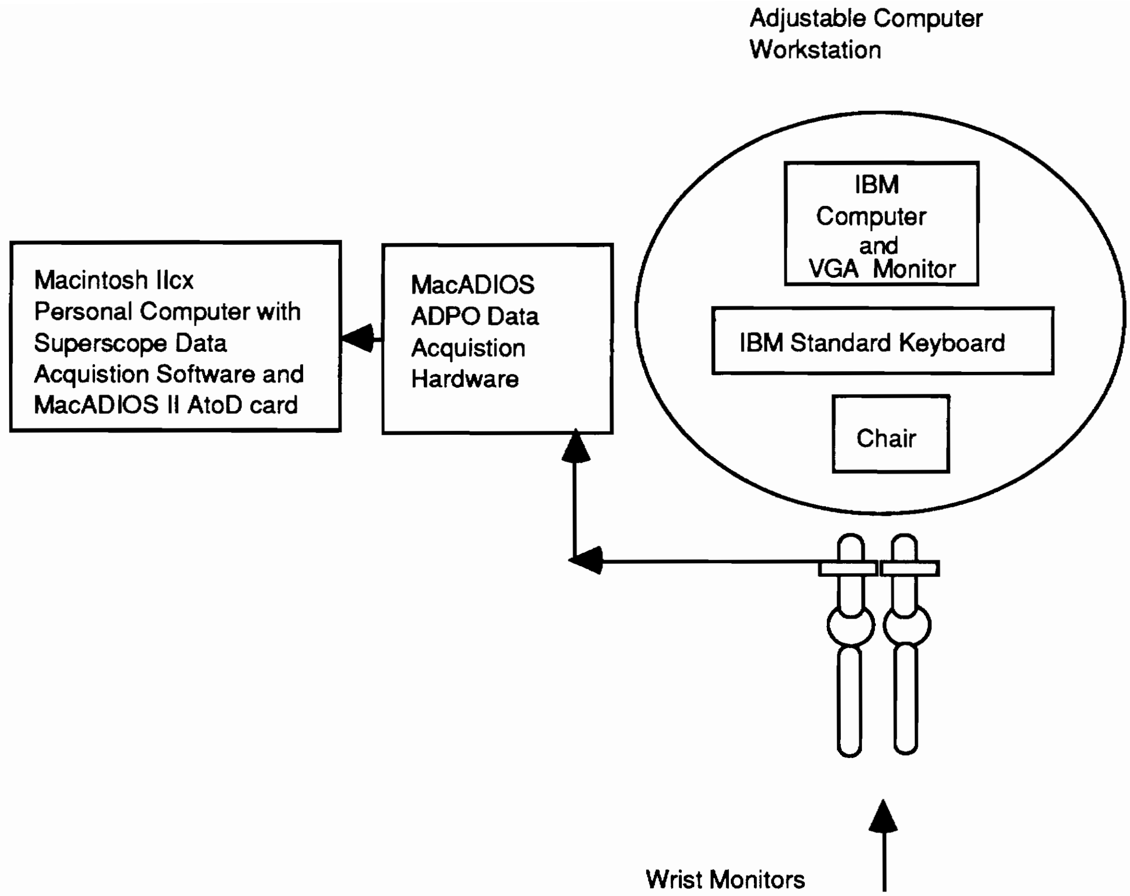


Figure 3.1 Schematic Diagram of Experimental System.

converted the analog signals to digital signals. These digital signals were then converted to voltage signals and processed by the experiment specific software, "Superscope." The microcomputer system consisted of a Macintosh IIcx computer with a MacADIOS II Analog-to-Digital (AtoD) board, Superscope data acquisition software, and a VGA color monitor connected to the Macintosh IIcx computer. The MacADIOS II board contains eight 12-bit analog-to-digital converters which are capable of receiving analog input voltages within the range of 0 to +10V (unipolar) or -10 to +10V (bipolar). The analog-to-digital conversion resolution for this board is twelve bits (4096 counts). Superscope data acquisition software is capable of collecting data from eight channels simultaneously and can emulate oscilloscope, chart recorder, spectrum analyzer, and XY recorder modes. In addition, data can be created, synthesized, digitized, analyzed, transferred, archived, edited, viewed, and deleted using Superscope.

3.2.3 Adjustable Computer Workstation

A specialized, adjustable computer workstation was built in the Virginia Tech Manufacturing Laboratory for this experiment. The workstation was designed to accommodate the 5th percentile female up to the 95th percentile male and allows keyboard height, keyboard slope, monitor height, and seat height to be adjusted. The ranges of adjustability for the variables of this workstation are listed in Table 3.1.

Table 3.1

Range of Adjustability for Experimental Apparatus

Variable	Range of Adjustability
Keyboard Height	30-82 cm
Keyboard Slope	360 degrees
Monitor Height	79-105 cm
Seat Height	45-60 cm

Keyboard height was measured as the perpendicular vertical distance from the floor to the geometric center of the key top strike area in the home row when the key is in the up (non-depressed) position. Keyboard slope was measured as the angle between the horizontal plane and the plane passing through the centers of keys, or other equivalent and corresponding points of keys, in the rows containing q and z in the qwerty layout. Keyboard slope was considered positive if the keyboard was sloped towards the subject and negative if it was sloped away from the subject. Monitor height was measured as the vertical distance from the floor to the top of the monitor. Sitting elbow rest height was measured as the vertical distance from the floor to the bottom of the elbow. This measurement was taken when the subject was sitting erect with his upper arms hanging relaxed and forearms and hands extended forward horizontally. The computer which was used by subjects to perform the experimental tasks was an IBM AT personal computer with a standard IBM keyboard and a color display monitor.

3.3 Procedures

3.3.1 Experimental Design

The experimental design used for the wrist movement direction data of this study was a repeated measurements design with one between-subjects factor, Gender, and three within-subjects factors: distance of keyboard from operator elbow height, slope of keyboard, and hand. The order of presentation for all experimental conditions was partially counterbalanced using a latin square design (See Appendix C). Males and females were randomly assigned to a presentation order. The order of presentation for the text passages the subjects typed was randomly assigned for each subject. The experimental design used for the input performance data of this study was a repeated measurements design with one between-subjects factor, Gender, and two within-subjects factors: "distance of keyboard from operator elbow height" and "slope of keyboard."

Wrist posture data and input performance data were the two categories of dependent variables measured. The following three wrist movement directions were measured in degrees from a neutral position (see section 2.2.4): flexion-extension, radial-ulnar deviation, and pronation-supination. Correct words typed per minute was the input performance dependent variable. Correct words typed per minute was measured as (total number of words typed - number of errors) / number of minutes typed. Table 3.2 lists the experimental variables and their levels.

Table 3.2

Experimental Variables

Independent Variables (between subjects)
Gender
Independent Variables (within subjects)
Distance between sitting elbow height and work surface height
5 levels (-10, -5, 0, 5, 10 cm)
Slope of keyboard (degrees from horizontal)
5 levels (-45, -22, 0, 22, 45)
Hand
2 levels (right, left)
Dependent Variables
Wrist Postures (degrees from a neutral position):
Wrist Flexion-Extension
Radial-Ulnar deviation
Pronation-Supination
Input Performance Measure:
Correct words typed per minute

3.3.2 Experimental Tasks

Subjects were asked to type a passage of text for two minutes in each of the 25 experimental conditions. The passage of text which was typed in each condition was randomly assigned without replacement from 25 possible passages for each subject. All possible passages were triple-controlled at the average difficulty level with syllable intensity of 1.5 syllables per word, average word length of 5.6 strokes per word, and high-frequency words of 80 percent (Fries and Clayton, 1975). The source for the high-frequency-word selections was taken from "The 1260 Most-Used Words in Business Communication" by James E. Silverthorn and Devern J. Perry (Fries and Clayton, 1975). The passage of text which was typed was clipped to a document holder which was attached to the left side of the computer monitor. Subjects were directed not to correct typing errors and to inform the investigator when they finished typing a page of text. The investigator turned the pages of the text for the subjects to allow the subjects to keep their hands at the keyboard.

3.3.3 Wrist Monitor Application

The components of each wrist monitor were applied in the following order: radial/ulnar deviation device, flexion/extension device, and pronation/supination device. The subject was in the following position for the wrist monitor to be applied: seated upright with the shoulder abducted 90 degrees from the chest and the elbow flexed 90 degrees. The lateral epicondyle, the center of wrist rotation, and the third phalange were in line when viewed in the radial/ulnar plane. The wrist, forearm, and third metacarpophalangeal joint were in line when viewed in the flexion/extension plane. The radial/ulnar deviation device was positioned on top of the forearm with the potentiometer placed directly on top of the center of wrist rotation. This point was palpated and is located halfway between the hamate and the capitate bones. The proximal and distal metal strips of the device were in line with the lateral epicondyle and third phalanx, respectively. The subject flexed and extended his or her wrist to help the investigator ensure that the potentiometer was placed directly over the center of wrist rotation. Two pieces of tape were positioned around the forearm on the proximal metal strip of the device: one as close to the potentiometer as possible, the other near the proximal end of the strip. A slider was then positioned on the distal strip of the device, and the subject was asked to flex and extend his or her wrist to ensure the slider would not slip off the distal end or interfere with the proximal end of the device. When the correct position of this slider was determined, a piece of tape was placed over the slider taking care not to tape the metal strip on the distal end of the device.

In order to apply the flexion/extension and pronation/supination devices, the subject was in the same position as previously described with the exception that the forearm was positioned vertically upwards. The subject was asked to keep his or her fingers upright and together. In the flexion/extension plane, the potentiometer was placed proximal to the ulnar styloid process. The distal strip of the device was in line with the fingers at all times, and the subject flexed and extended his wrist to help the investigator ensure that the distal strip was positioned properly. The proximal strip of the device was in line with the subject's olecranon. A slider was then positioned on the distal strip of the device so that when the subject deviated his wrist radially or ulnarly, the slider would not slide off or interfere with the device. Next, a piece of tape was positioned over this slider making sure not to tape the distal metal strips of either the flexion/extension or the radial/ulnar deviation device. The subject then flexed, extended, radially deviated, and ulnarly deviated to ensure that no sliders slid off or had inhibited movement.

To apply the pronation/supination device, the gauge which contains the metal rod was placed directly over the proximal strip of the flexion/extension device. The subject ulnarly deviated as much as possible to make sure there was no interference with the flexion/extension potentiometer. This gauge was in line with the flexion/extension device and the olecranon of the subject. Two pieces of tape were placed around this gauge, on the proximal and distal sides of the gauge and as close to the gauge as possible. The cuff was then placed around the proximal end of the forearm, and the rod from the gauge slid through the screw on the cuff. The rod was then turned from one extreme to the other and tightened at the approximate center of its rotation. The subject then moved his arm and wrist around in all directions to ensure all equipment was properly positioned and stable. The wires were then connected to the three potentiometers (radial/ulnar deviation, flexion/extension, and pronation/supination) and kept out of the subject's way by a piece of velcro around his upper arm.

3.3.4 Calibration Procedure

To calibrate the radial/ulnar deviation device, the subject was seated upright with the shoulder abducted 90 degrees from the chest and the elbow flexed 90 degrees. The subject's lateral epicondyle, center of wrist rotation, and third phalange were in line when viewed in the radial/ulnar plane. This position was considered the neutral position (0 degrees) for the radial/ulnar deviation device, and a voltage measurement was taken in this position. While keeping the wrist and forearm straight, the subject then ulnarly deviated his hand as much as possible. A voltage measurement was taken in this position, which was recorded in negative degrees. The subject then returned his hand to the neutral position, and while keeping the wrist and forearm straight, radially deviated the hand as much as possible. A voltage measurement was taken in this position, which was recorded in positive degrees.

For the flexion/extension device the neutral position was when the subject's wrist, forearm, and third metacarpophalangeal joint were in line when viewed in the flexion/extension plane. A voltage measurement was taken in this position, which was slightly below horizontal. From this position, the subject flexed his wrist as much as possible while keeping his fingers together. A voltage measurement was taken in this position and was recorded in negative degrees. From the neutral position, the subject then extended his wrist as much as possible. A voltage measurement was taken in this position and was recorded in positive degrees.

For the pronation-supination calibration data, the subject was standing with his arms next to his body and his elbows flexed 90 degrees. The subject grasped the handle of the calibration device so that center of the handle was in line with the radial/ulnar deviation device. The position where the subject was gripping the handle in its approximately vertical position was considered the neutral position, and a voltage measurement was taken. While keeping the elbow and forearm still, the subject pronated his wrist as much as possible. A voltage measurement was taken in this position and was recorded in negative degrees. From the neutral position, and while keeping the elbow and forearm still, the subject supinated his wrist as much as possible. A voltage measurement was taken in this position and was recorded in positive degrees.

The method used to convert the wrist posture data assumed a linear relationship between voltage and degrees. For the first three subjects, five data points per channel were used to calculate linear regressions on the voltage/degree data to determine the conversion equations and to determine the significance of the fits. The regression data for the first subject, as well as graphs of the conversion relationships for the channels of one hand, are shown in Appendix E. For the remainder of the subjects, voltage measurements were taken for three wrist movement directions (flexion-extension, radial-ulnar deviation, and pronation-supination) for both hands at the neutral wrist position, the maximum wrist position, and the minimum wrist position. A linear conversion was then computed for each channel of the wrist monitor for each individual subject.

3.4 Experimental Protocol

The experiment was conducted in one three-hour session. When subjects arrived, they were given written instructions to read (Appendix A), and the experimenter reviewed the experimental procedures verbally and answered any questions. Subjects were then given an Informed Consent Form to read and sign (Appendix B). Subjects were asked to warm up their wrists by flexing, extending, radially deviating, ulnarly deviating, supinating, and pronating for several minutes. Subjects then adjusted their chair so they were sitting with their knees and ankles at right angles. Sitting elbow rest height was then measured as the vertical distance from the floor to the bottom of the elbow. For this measurement, the subject was sitting erect with his upper arms hanging relaxed and forearms and hands extended forward horizontally. After this, subjects were asked to type a passage of text for two minutes to ensure that they possessed touch-typing technique and could type a minimum of 30 words per minute. If it was determined that subjects did not meet these criteria, they were dismissed from the study at this point.

After subjects had been screened and had filled out all necessary forms, they were fitted with the experimental apparatus. This consisted of a wrist monitor being attached to each hand with adhesive tape. The device was then calibrated for all channels. Subjects then typed a passage of text from a document holder attached to the left side of the computer monitor for two minutes in all experimental conditions. For each experimental condition, three data samples were collected; each sample collected data for 5 seconds at 10 Hz. Data samples were collected at 0 seconds, 60 seconds, and 115 seconds. Subjects were given a new passage of text to type in every condition, whether or not they finished the previous text. After the experiment was finished, subjects were thanked for their participation and given a copy of their informed consent form to keep.

4. DATA ANALYSIS

4.1 Data Reduction

Before any analyses on the wrist posture data could be performed, the data from the wrist monitor was reduced by employing the following steps: (1) the units of raw data were converted from voltage to degrees, (2) the first data sample was eliminated for all wrist movement data sets, and (3) the last two data samples for all wrist movement data sets were averaged together. When *Time* was considered as a main effect, it was significant ($p<.0295$) only for the wrist movement direction flexion-extension. The ANOVA summary table for this analysis is shown in Appendix D, and the trend for this effect is seen in Figure 4.1. Means comparisons performed on *Time* revealed that the first data point was significantly ($p<.05$) different than the other two points, which were not significantly different from one another. It was observed that during the time period when the first sample was recorded, subjects were still adjusting their hands on the keyboard. The assumption was then made that the first data sample in each data set represented an adjustment period rather than the average typing position for that condition. Under this assumption, the first data sample was eliminated and the other two data samples in the data set were averaged together and used for a particular wrist movement measurement.

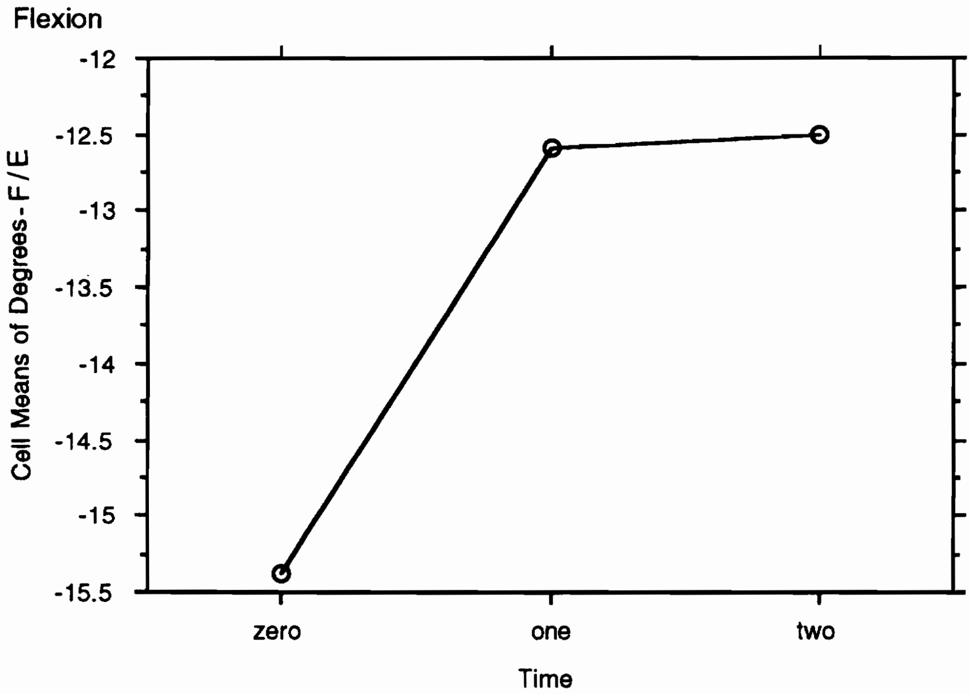


Figure 4.1 Main effect *Time* plotted against Degrees of Flexion from a neutral position.

4.2 Flexion-Extension

4.2.1 Analysis of Variance

Three repeated measures analysis of variance (ANOVA's) were conducted on the wrist movement data using the SuperAnova Data Analysis Package for the Macintosh. Each ANOVA examined the means associated with one of the three wrist movement directions measured: flexion-extension, radial-ulnar deviation, and pronation-supination. Greenhouse-Geisser corrected values for *p* were used to help correct for the inherent correlation of repeated measurements.

For the wrist movement direction flexion-extension, the ANOVA revealed that the main effects of *Slope* and *Hand* were significant at $p<.0001$. Table 4.1 shows the ANOVA summary table for this analysis. The significant main effect *Slope* indicated that when the keyboard was -45 degrees from horizontal, the greatest amount of wrist flexion occurred, and when the keyboard was +45 degrees from horizontal the least amount of wrist flexion occurred. This trend is shown in Figure 4.2. Means contrasts indicated that the*Slope* mean for -45 degrees was significantly different from all other *Slope* means. *Slope* means for -22, 0, and 22 degrees were not significantly different from one another, but were significantly different from *Slope* mean 45 degrees. *Slope* means for 22 and 45 degrees were not significantly different from one another. Orthogonal polynomial contrasts were performed on the main effect *Slope* to test for any linear, quadratic , or cubic trends. The analysis revealed that *Slope* had a significant ($p<.0001$) linear effect. Table 4.2 shows the results from the Orthogonal Polynomial Contrast analysis.

The significant main effect of *Hand* ($p<.0001$) for the wrist movement direction flexion-extension revealed that on the average the left hand exhibited wrist extension ($\bar{x}$ = 29.325 degrees) while the right hand exhibited wrist flexion ($\bar{x}$ = -41.718 degrees).

Table 4.1

ANOVA Summary Table for degrees from neutral for flexion-extension.

Source	df	SS	MS	F	P	Greenhouse-Geisser P
Between-Subjects						
Gender (G)	1	23412.2113	23412.2113	.8256	.3734	
Subjects/G	22	623879.1647	28358.1439			
Within-Subjects						
Height (H)	4	1507.8324	376.9581	1.3912	.2436	.2569
HxG	4	2980.4491	745.1123	2.75	.0331	.0603
HxSubjects/G	88	23843.9865	270.9544			
	Greenhouse-Geisser Epsilon = .6317					
Slope (S)	4	28493.1749	7123.2937	13.753	.0001	.0001
SxG	4	5760.1773	1440.0443	2.7803	.0316	.0682
SxSubjects/G	88	45579.1035	517.9444			
	Greenhouse-Geisser Epsilon = .5396					
Hand (HA)	1	1514128.8736	1514128.8736	62.8339	.0001	.0001
HAxG	1	24348.8495	24348.8495	1.0104	.3257	.3257
HAxSubjects/G	22	530141.0973	24097.3226			
	Greenhouse-Geisser Epsilon = 1.0000					
HxS	16	4674.683	292.1677	1.0816	.371	.3691
HxSxG	16	6525.9617	407.8726	1.51	.0933	.2097
HxSxSubjectsG	352	95080.2489	270.1143			
	Greenhouse-Geisser Epsilon = .2341					
HxHA	4	412.8685	103.2171	.3311	.8564	.7419
HxHAxG	4	1776.4927	444.1232	1.4248	.2324	.2502
HxHAxSubjects/G	88	27431.1608	311.7177			
	Greenhouse-Geisser Epsilon = .5552					
SxHA	4	1935.8414	483.9604	1.2075	.3134	.3136
SxHAxG	4	1689.9042	422.4761	1.0541	.3842	.3724
SxHAxSubjects/G	88	35270.4217	400.8002			
	Greenhouse-Geisser Epsilon = .7063					
HxSxHA	16	4500.1709	281.2607	1.1405	.3157	.3417
HxSxHAxG	16	9035.8882	564.743	2.29	.0034	.0744
HxSxHAxSubjects/G	352	86808.6215	246.6154			
	Greenhouse-Geisser Epsilon = .2220					

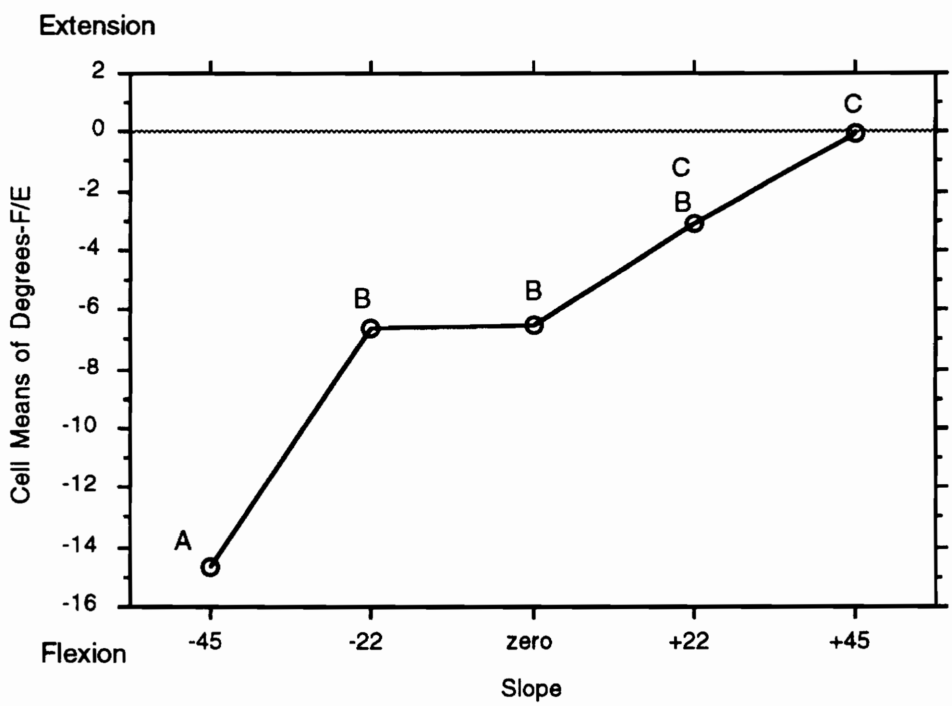


Figure 4.2 Significant main effect of *Slope* plotted against Degrees of Flexion or Extension from a neutral position. (Conditions with same letters are not significantly different using post hoc means contrasts.)

Table 4.2

Orthogonal Polynomial Contrast analysis on main effect *Slope*.

Fit	df	SS	MS	F	p
Linear	1	25583.985	25583.985	49.3952	.0001
Quadratic	1	776.3276	776.3276	1.4989	.2241
Cubic	1	1379.272	1379.272	2.663	.1063

Two interaction effects, *Height x Gender* and *Slope x Gender*, were significant without the Greenhouse-Geisser correction, but were not significant when the correction was employed. These effects were still included in the results due to the negative bias imposed by the Greenhouse-Geisser correction. The *Height x Gender* interaction is shown in Figure 4.3. This interaction implies that for *Height* conditions -10 and -5 cm below operator elbow height, females exhibit wrist extension ($\bar{x}$ = 1.5 degrees) while males exhibit wrist flexion ($\bar{x}$ = -10.5 degrees). For *Height* conditions 0 and 5 cm above operator elbow height, females flexed their wrist approximately -2 degrees. When the keyboard was at operator elbow height, males flexed their wrists approximately -10 degrees, and when the keyboard was 5 cm above operator elbow height, males flexed their wrists approximately -12 degrees. For *Height* condition 10 cm above operator elbow height, both males and females exhibited approximately the same amount of wrist flexion ($\bar{x}$ = -8 degrees).

The *Slope x Gender* interaction is graphed in Figure 4.4. This interaction shows that for *Slope* conditions 45 and 22 degrees from horizontal, females exhibit extension, whereas males exhibit flexion. At *Slope* condition 45 degrees, the amount of extension is greater than at *Slope* condition 22 degrees. In addition, the amount of flexion is greater at *Slope* condition 22 degrees than at 45 degrees. For *Slope* conditions 0 and -22 degrees from horizontal, females exhibit approximately the same amount of extension ($\bar{x}$ = -2.5 degrees), while males exhibit approximately the same amount of flexion ($\bar{x}$ = -11 degrees). Both males and females demonstrated approximately the same amount of flexion ($\bar{x}$ = -15 degrees) at *Slope* condition -45 degrees.

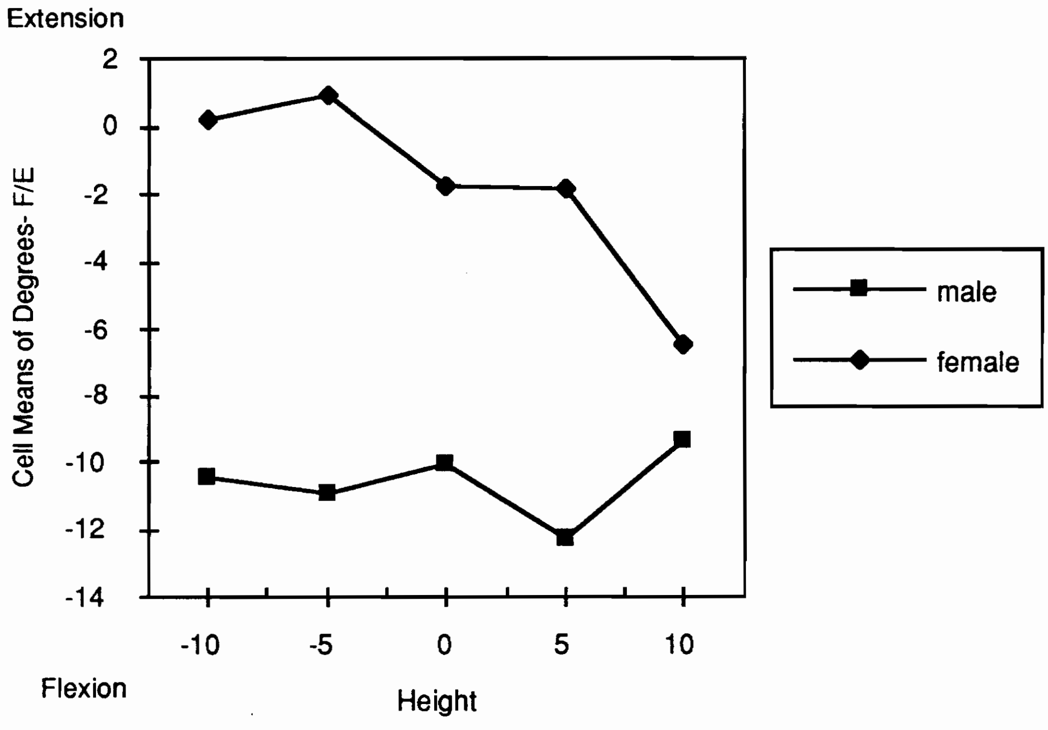


Figure 4.3 *Height x Gender* interaction effect plotted against Degrees of Flexion or Extension from a neutral position.

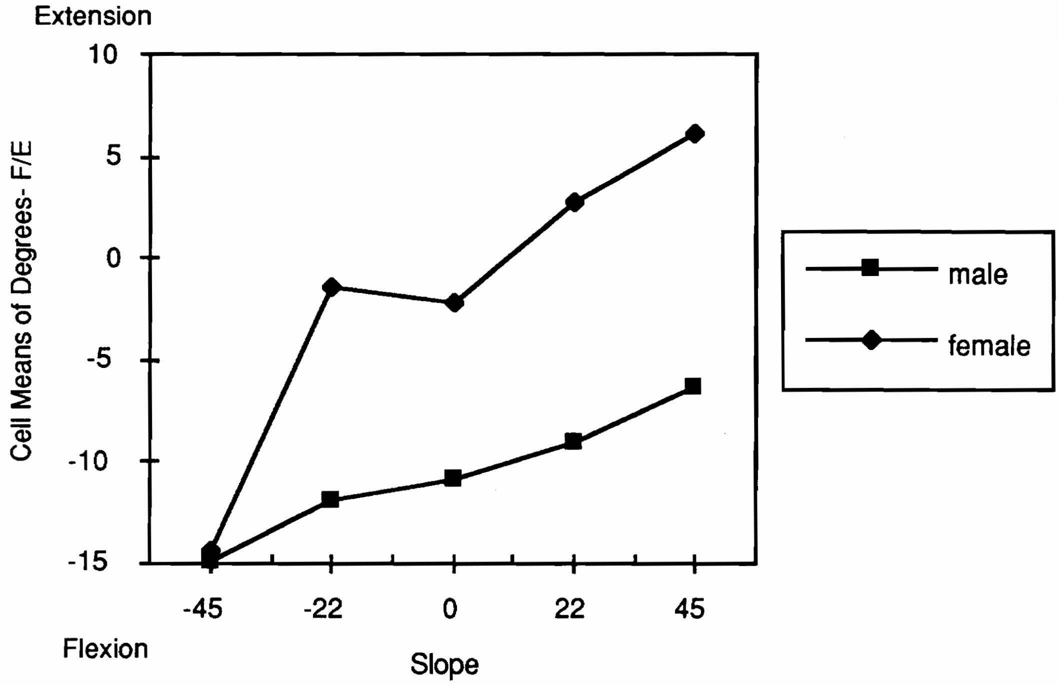


Figure 4.4 *Slope x Gender* interaction effect plotted against Degrees of Flexion or Extension from a neutral position.

4.2.2 Student's t-tests

In addition to the ANOVAs conducted on the wrist movement data, two-tailed t-tests were performed independently on the means of the main effects *Height* and *Slope* and the interaction effect *Height* x *Slope*. Because these tests were performed independently, no adjustment for joint confidence was considered. These tests were performed to detect any significant differences between the wrist posture values for the treatment means and the neutral wrist positions. These t-tests were more powerful than the ANOVAs because they were comparing only 2 means rather than 10. The null and alternate hypotheses are as follows:

$$H_O: \bar{x} = 0$$

$$H_A: \bar{x} \neq 0$$

alpha = .05

Decision to Reject: Reject H_O if t-observed > t-tabled

where t-observed = $\bar{x} - \mu$ / X(standard error)

The results of the t-tests performed on flexion-extension are shown in Table 4.3. This analysis revealed that the *Height* means for 5 cm and 10 cm and the Slope means for -22 degrees and -45 degrees from horizontal were significantly different from the neutral position for flexion-extension. The *Height* x *Slope* interaction means of (0 cm, -45 degrees), (5 cm, -45 degrees), (10 cm, -45 degrees)were also significantly different from the neutral position for flexion-extension.

Table 4.3

Results for t-tests performed that the means of effects = 0. * indicates the mean for that effect was significantly different from neutral at a level of significance of p<0.05. F/E represents flexion-extension.

Effect	Mean	t-obs	Significance
Height (-10)	-5.1135	1.4823	
Height (-5)	-5.0171	1.5743	
Height (0)	-5.9122	1.8214	
Height (5)	-7.0267	2.1156	*
Height (10)	-7.9137	2.456	*
Slope (-45)	-14.6578	4.6617	*
Slope (-22)	-6.6176	2.1686	*
Slope (0)	-6.5060	1.9295	
Slope (22)	-3.12	0.9388	
Slope (45)	-.0818	0.02369	
H/S (-10,-45)	-10.7568	1.5947	
H/S (-10,-22)	-5.7571	0.84855	
H/S (-10,0)	-8.7011	0.993	
H/S (-10,22)	-3.6072	0.4588	
H/S (-10,45)	3.2547	0.3891	
H/S (-5,-45)	-12.9975	1.9761	
H/S (-5,-22)	-4.0605	0.5965	
H/S (-5,0)	-1.8973	0.2754	
H/S (-5,22)	-5.826	0.7624	
H/S (-5,45)	-.3043	0.0391	
H/S (0,-45)	-16.9158	2.3	*
H/S (0,-22)	-6.8963	0.9539	
H/S (0,0)	-5.0849	0.719	
H/S (0,22)	-.4955	0.0703	
H/S (0,45)	-.1683	0.022	
H/S (5,-45)	-16.1994	2.0426	*
H/S (5,-22)	-6.1595	0.9528	
H/S (5,0)	-9.8968	1.2465	
H/S (5,22)	-.7193	0.0983	
H/S (5,45)	-2.1585	0.288	
H/S (10,-45)	-16.4195	2.446	*
H/S (10,-22)	-10.2145	1.445	
H/S (10,0)	-6.95	0.9737	
H/S (10,22)	-4.952	0.6557	
H/S (10,45)	-1.0324	0.1353	

4.3 Radial-Ulnar Deviation

4.3.1 Analysis of Variance

For the wrist movement direction radial-ulnar deviation, the ANOVA revealed that *Height* ($p<.0001$), *Slope* ($p<.0001$), *Height* x *Slope* ($p<.0001$), and *Height* x *Hand* ($p<.005$) were significant. Table 4.4 is the ANOVA summary table for the analysis. The significant main effect of *Height* ($p<.0001$) demonstrated that the least amount of ulnar deviation occurred when the keyboard was positioned -10 cm below subject elbow height. Means contrasts revealed that as the keyboard height was increased, the amount of ulnar deviation became significantly ($p<.0001$) greater and was greatest at +10 cm above subject elbow height. This trend is illustrated in Figure 4.3. Orthogonal polynomial contrasts were performed on the main effect *Height* to test for any linear, quadratic, or cubic trends. The analysis revealed that *Height* had a significant ($p<.0001$) linear effect. Table 4.5 shows the results from the Orthogonal Polynomial Contrast analysis.

The significant main effect *Slope* ($p<.0001$) for the wrist movement direction radial-ulnar deviation found that ulnar deviation was the greatest when the keyboard was -45 degrees from horizontal. As the keyboard slope was increased, means contrasts showed that ulnar deviation became significantly ($p<.0001$) less and was at a minimum when the keyboard was +22 degrees from horizontal. When the keyboard was +45 degrees from horizontal, radial deviation was observed. This trend is illustrated in Figure 4.4. Orthogonal polynomial contrasts were performed on the main effect *Slope* to test for any linear, quadratic, or cubic trends. The analysis revealed that *Slope* had a significant ($p<.0001$) linear effect. Table 4.6 shows the results from the

Table 4.4

ANOVA Summary Table for degrees from neutral for radial/ulnar deviation.

Source	df	SS	MS	F	P	Greenhouse-Geisser P
Between-Subjects						
Gender (G)	1	1615.4462	1615.4462	.6668	.4229	
Subjects/G	22	53295.1289	2422.5059			
Within-Subjects						
Height (H)	4	34815.5883	8703.8971	206.4399	.0001	.0001
HxG	4	524.0423	131.0106	3.1073	.0193	.056
HxSubjects/G	88	3710.2464	42.1619			
		Greenhouse-Geisser Epsilon = .4887				
Slope (S)	4	228766.3344	57191.5836	291.2329	.0001	.0001
SxG	4	1689.586	422.3965	2.1509	.0812	.1348
SxSubjects/G	88	17281.2176	196.3775			
		Greenhouse-Geisser Epsilon = .4452				
Hand (HA)	1	596.657	596.657	.4419	.5131	.5131
HAxG	1	576.2309	576.2309	.4268	.5203	.5203
HAxSubjects/G	22	29701.5671	1350.0712			
		Greenhouse-Geisser Epsilon = 1.000				
HxS	16	2152.6822	134.5426	4.5642	.0001	.0001
HxSxG	16	724.1491	45.2593	1.5354	.0849	.1495
HxSxSubjectsG	352	10376.1065	29.4776			
		Greenhouse-Geisser Epsilon = .4908				
HxHA	4	449.6	112.4	5.7557	.0004	.0036
HxHAxG	4	84.4904	21.1226	1.0816	.3706	.3547
HxHAxSubjects/G	88	1718.5138	19.5286			
		Greenhouse-Geisser Epsilon = .5894				
SxHA	4	330.8456	82.7114	.8615	.4904	.4061
SxHAxG	4	497.402	124.3505	1.2952	.2781	.2805
SxHAxSubjects/G	88	8448.6139	96.007			
		Greenhouse-Geisser Epsilon = .3884				
HxSxHA	16	138.3153	8.6447	.6668	.8266	.7216
HxSxHAxG	16	155.4042	9.7128	.7492	.7426	.6492
HxSxHAxSubjects/G	352	4563.5257	12.9646			
		Greenhouse-Geisser Epsilon = .5046				

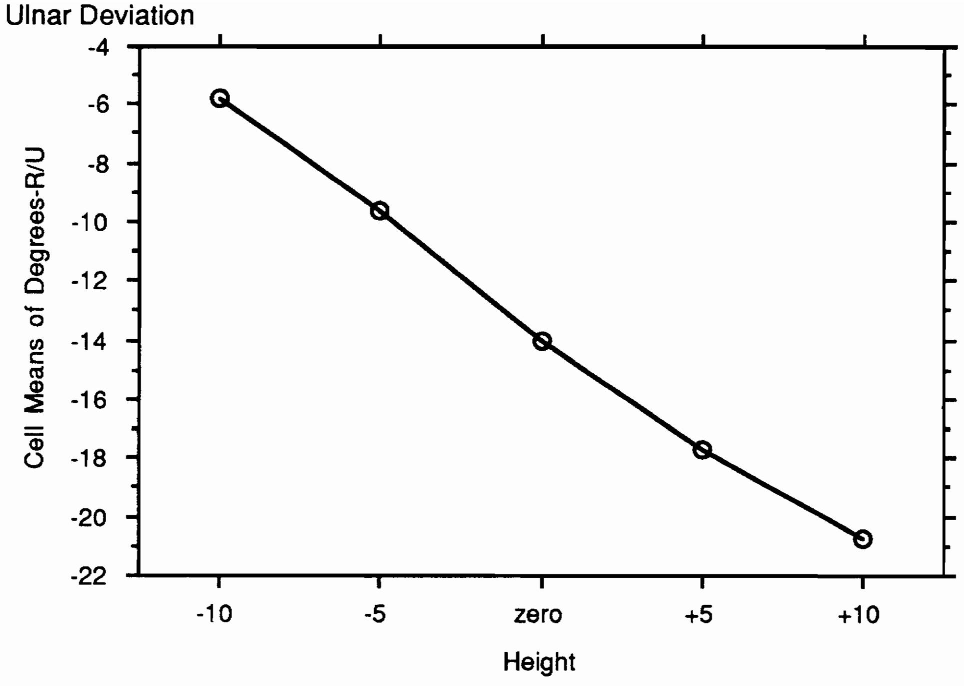


Figure 4.5 Significant main effect of *Height* plotted against Degrees of Ulnar Deviation from a neutral position.

Table 4.5

Orthogonal Polynomial Contrast analysis on main effect *Height.*

Fit	df	SS	MS	F	p
Linear	1	34680.0278	34680.0278	822.5444	.0001
Quadratic	1	87.9742	87.9742	2.0866	.1521
Cubic	1	41.6704	41.6704	.9883	.3229

Table 4.6

Orthogonal Polynomial Contrast analysis on main effect *Slope.*

Fit	df	SS	MS	F	p
Linear	1	228405.6191	228405.6191	1163.0948	.0001
Quadratic	1	180.0973	180.0973	.9171	.3409
Cubic	1	180.5223	180.5223	.9193	.3403

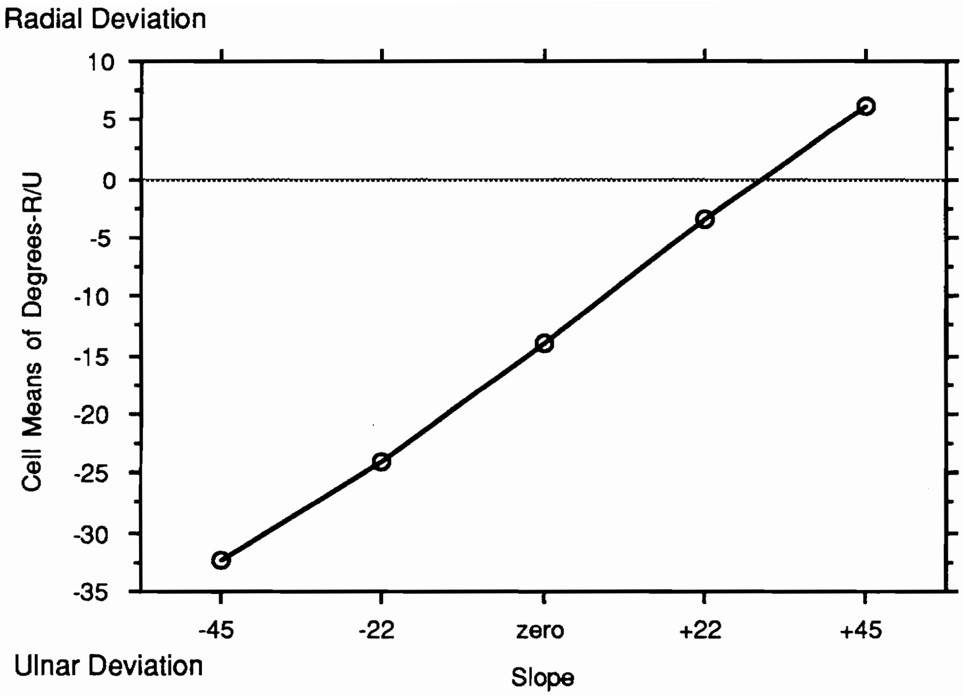


Figure 4.6 Significant main effect of *Slope* plotted against Degrees of Radial or Ulnar Deviation from a neutral position.

Orthogonal Polynomial Contrast analysis.

The *Height* x *Slope* significant interaction (p<.0001) indicated that for slope conditions -45, -22, and 0, the amount of ulnar deviation decreased as height was decreased from +10 cm above subject elbow height to -10 cm above subject elbow height. When the Slope condition was +22 degrees, ulnar deviation decreased as height was decreased from +10 cm to -5 cm. When the slope was + 22 degrees and the height was -10 cm, radial deviation was observed. The difference in the amount of radial-ulnar deviation as a function of slope height, was less at positive slopes (45 degrees) than at negative slopes (-45 degrees). Figure 4.5 illustrates this trend.

For the significant (p<.005) *Height* x *Hand* interaction, means contrasts revealed that for height conditions -10 cm and -5 cm, the right hand had significantly (p<.0001) more ulnar deviation than the left hand. The amounts of ulnar deviation at height conditions 0 cm, 5 cm, and 10 cm were not statistically different from one another. Figure 4.6 exemplifies the *Height* x *Hand* interaction effect.

4.3.2 Student's t-tests

For the wrist movement direction radial-ulnar deviation, all *Height* and *Slope* treatment means were significantly different from the neutral radial-ulnar deviation position. For the *Height* x *Slope* interaction, the following three treatment means were not significantly different from the neutral radial-ulnar deviation position: (-5 cm, +22 degrees), (+5 cm, +45 degrees), and (+10 cm, +45 degrees).

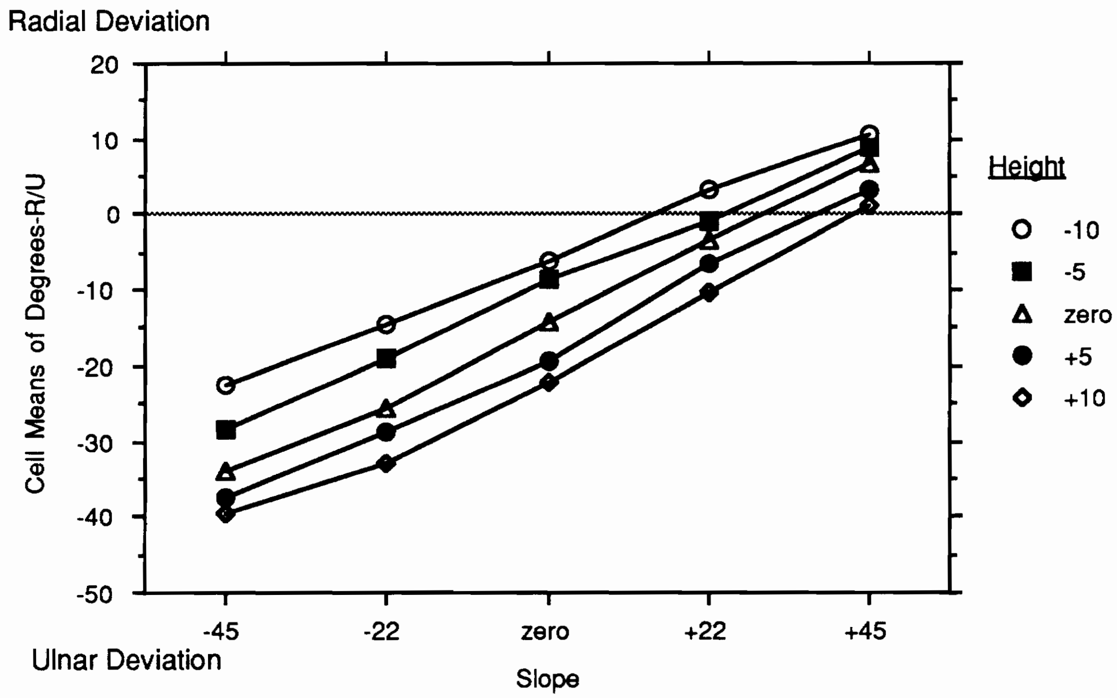


Figure 4.7 *Height* x *Slope* interaction effect plotted against Degrees of Radial or Ulnar Deviation from a neutral position.

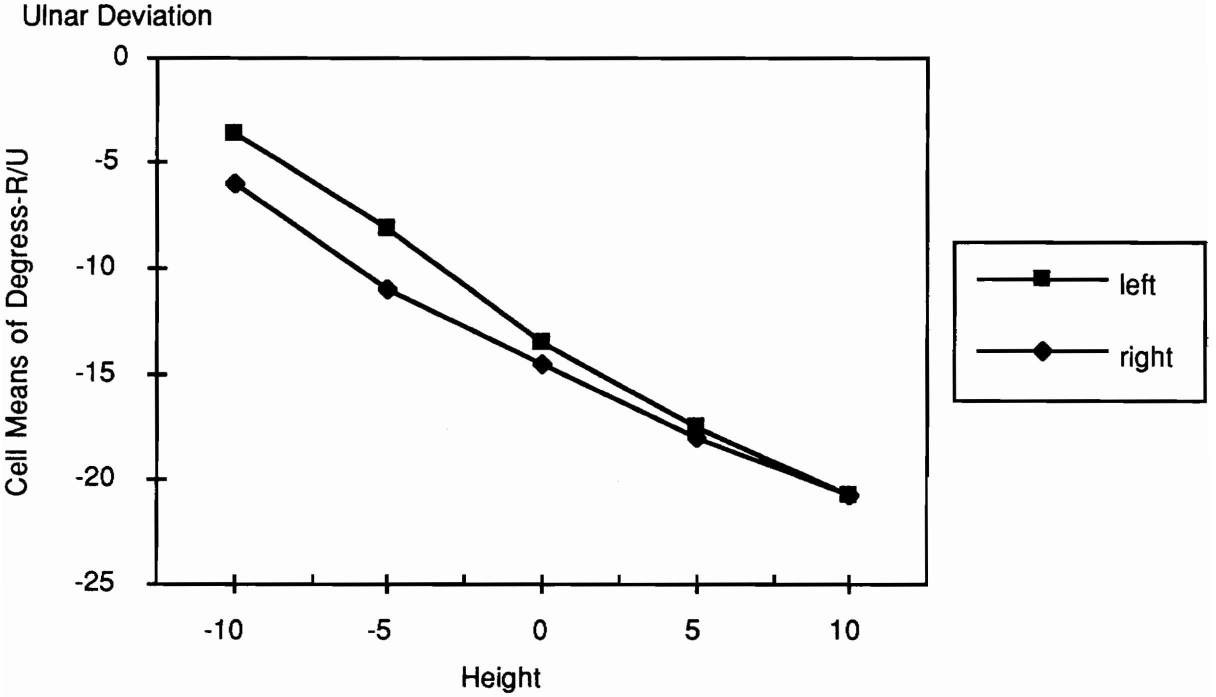


Figure 4.8 *Height* x *Hand* interaction effect plotted against Degrees of Radial or Ulnar Deviation from a neutral position. Means contrasts are in text.

Table 4.7

Results for t-tests performed that the means of effects = 0. * indicates the mean for that effect was significantly different from neutral at a level of significance of $p<0.05$. R/U represents radial-ulnar deviation.

Effect	Mean	t-obs	Significance
Height (-10)	-5.8045	5.8342	*
Height (-5)	-9.6021	8.8531	*
Height (0)	-14.0164	11.9716	*
Height (5)	-17.7318	14.903	*
Height (10)	-20.7462	17.2139	*
Slope (-45)	-32.3562	42.328	*
Slope (-22)	-24.1061	29.886	*
Slope (0)	-14.0575	16.9367	*
Slope (22)	-3.4982	4.646	*
Slope (45)	6.1171	8.3784	*
H/S (-10,-45)	-22.3686	15.9536	*
H/S (-10,-22)	-14.5326	10.44	*
H/S (-10,0)	-6.0972	3.97	*
H/S (-10,22)	3.4515	2.5493	*
H/S (-10,45)	10.5248	7.2355	*
H/S (-5,-45)	-28.2547	22.41	*
H/S (-5,-22)	-19.0217	11.943	*
H/S (-5,0)	-8.7148	5.6246	*
H/S (-5,22)	-.7933	0.4763	
H/S (-5,45)	8.7741	5.585	*
H/S (0,-45)	-34.1245	25.632	*
H/S (0,-22)	-25.5164	16.142	*
H/S (0,0)	-14.0471	8.2785	*
H/S (0,22)	-3.2336	2.2135	*
H/S (0,45)	6.8397	4.3959	*
H/S (5,-45)	-37.5624	23.7481	*
H/S (5,-22)	-28.6535	18.696	*
H/S (5,0)	-19.2549	11.7157	*
H/S (5,22)	-6.5455	4.094	*
H/S (5,45)	3.3573	2.0047	
H/S (10,-45)	-39.4707	23.4818	*
H/S (10,-22)	-32.8064	20.2346	*
H/S (10,0)	-22.17362	12.3068	*
H/S (10,22)	-10.3698	6.279	*
H/S (10,45)	1.0897	0.6933	

4.4 Pronation-Supination

4.4.1 Analysis of Variance

For the wrist movement direction pronation-supination, the main effects *Height* and *Slope* were significant at $p<.0001$, and the interaction effect *Height* x *Slope* was significant at $p<.05$. The ANOVA summary table for this analysis is shown in Table 4.8. The significant main effect *Height* revealed that pronation was the largest when the keyboard was positioned -10 cm below subject elbow height. As height increased, pronation became smaller and reached a minimum value when the keyboard was positioned +10 cm above subject elbow height. This trend is shown in Figure 4.7. Orthogonal polynomial contrasts were performed on the main effect *Height* to test for any linear, quadratic, or cubic trends. The analysis revealed that *Height* had a significant ($p<.0001$) linear effect. Table 4.9 shows the results from the Orthogonal Polynomial Contrast analysis.

The main effect *Slope* ($p<.0001$) indicated that pronation was the smallest when the keyboard was -45 degrees from horizontal, and became increasingly larger as keyboard slope was increased. The largest value for pronation was observed when the keyboard was +45 degrees from horizontal. This trend is illustrated in Figure 4.8. Orthogonal polynomial contrasts were performed on *Slope* to test for any linear, quadratic, or cubic effects. This analysis revealed that *Slope* had a significant ($p<.0001$) effect of linear function. The results of this analysis are shown in Table 4.10.

The *Height* x *Slope* interaction ($p<.05$) indicated that for *Height* conditions +10 cm and +5 cm, pronation was the same at -45 degrees from horizontal and -22 degrees from horizontal. Means contrast showed that

Table 4.8

ANOVA Summary Table for degrees from neutral for pronation-supination.

Source	df	SS	MS	F	P	Greenhouse-Geisser P
Between-Subjects						
Gender (G)	1	32553.4479	32553.4479	.5758	.4560	
Subjects/G	22	1243792.0149	56536.0007			
Within-Subjects						
Height (H)	4	31467.0543	7866.7636	21.5055	.0001	.0001
HxG	4	3482.3426	870.5856	2.3799	.0577	.0821
HxSubjects/G	88	32190.6636	365.803			
		Greenhouse-Geisser Epsilon = .7019				
Slope (S)	4	306287.7812	76571.9453	91.7628	.0001	.0001
SxG	4	1256.6125	314.1531	.3765	.8249	.6724
SxSubjects/G	88	73432.0797	834.4555			
		Greenhouse-Geisser Epsilon = .4624				
Hand (HA)	1	120489.5583	120489.5583	3.6082	.0707	.0707
HAxG	1	77506.208	77506.208	2.321	.1419	.1419
HAxSubjects/G	22	734653.0502	33393.3205			
		Greenhouse-Geisser Epsilon = 1.000				
HxS	16	9457.9211	591.1201	2.7257	.0004	.0139
HxSxG	16	3575.9562	223.4973	1.0306	.4232	.4097
HxSxSubjectsG	352	76337.1606	216.8669			
		Greenhouse-Geisser Epsilon = .3955				
HxHA	4	779.1	194.775	.9112	.4611	.4295
HxHAxG	4	766.8545	191.7136	.8969	.4694	.436
HxHAxSubjects/G	88	18811.1654	213.7632			
		Greenhouse-Geisser Epsilon = .6468				
SxHA	4	3314.2498	828.5625	2.0996	.0876	.1376
SxHAxG	4	1413.0819	353.2705	.8952	.4704	.4113
SxHAxSubjects/G	88	34727.0455	394.6255			
		Greenhouse-Geisser Epsilon = .4739				
HxSxHA	16	1988.2603	124.2663	.8451	.6337	.5334
HxSxHAxG	16	1558.7042	97.419	.6625	.8306	.6734
HxSxHAxSubjects/G	352	51759.6108	147.0443			
		Greenhouse-Geisser Epsilon = .3590				

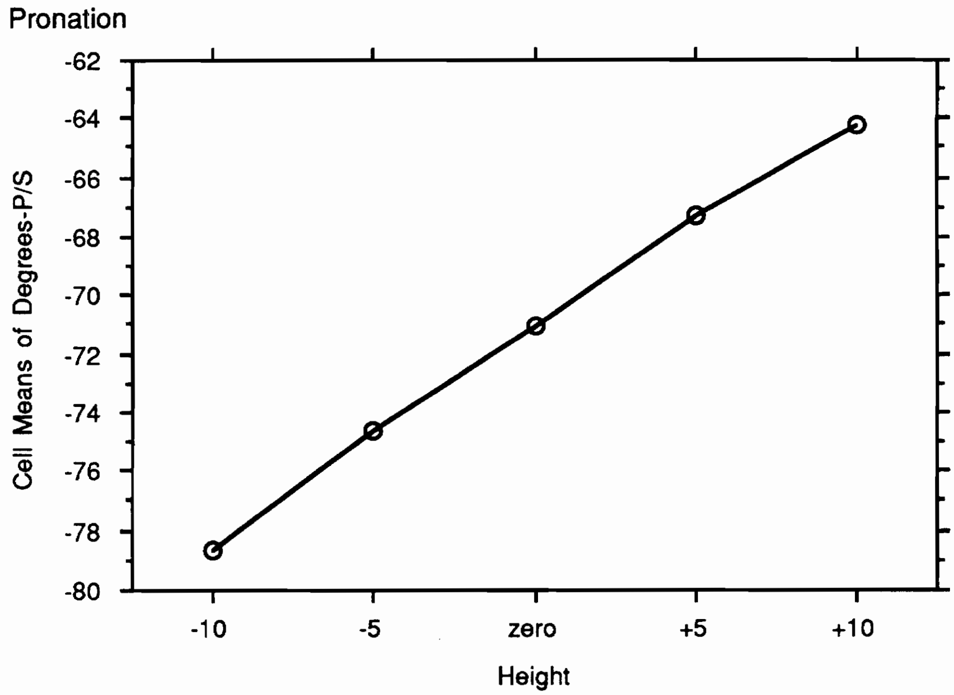


Figure 4.9 Significant main effect *Height* plotted against Degrees of Pronation or Supination from a neutral position.

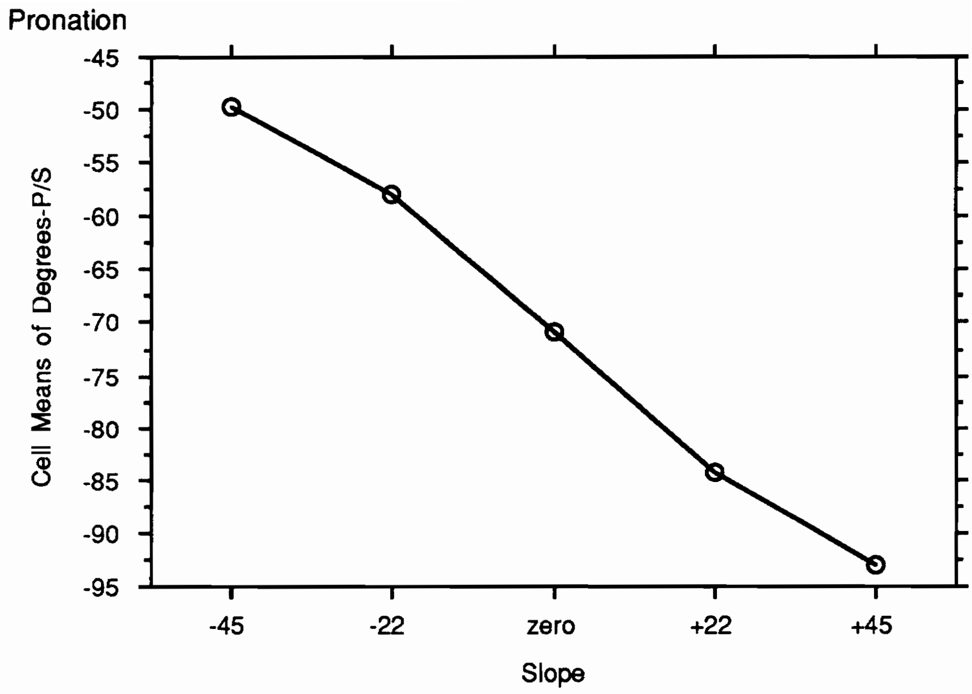


Figure 4.10 Significant main effect *Slope* plotted against Degrees of Pronation or Supination from a neutral position.

Table 4.9

Orthogonal Polynomial Contrast analysis on main effect *Height.*

Fit	df	SS	MS	F	p
Linear	1	31413.3574	31413.3574	85.8751	.0001
Quadratic	1	44.5244	44.5244	.1217	.728
Cubic	1	1.5033	1.5033	.0041	.949

Table 4.10

Orthogonal Polynomial Contrast analysis on main effect *Slope.*

Fit	df	SS	MS	F	p
Linear	1	304183.9324	304183.9324	364.5299	.0001
Quadratic	1	52.4463	52.4463	.0629	.8026
Cubic	1	2050.6483	2050.6483	2.4575	.1206

the values of pronation for each *Height* condition at both slopes were not significantly different from one another. As slope was increased from -22 degrees to +45 degrees from horizontal, the pronation values for both height conditions became increasingly larger. For *Height* conditions 0 cm and -5 cm, the pronation values were smallest at -45 degrees from horizontal and became increasingly larger as slope was increased to +45 degrees from horizontal. For the *Height* condition -10 cm, pronation was the smallest at -45 degrees from horizontal and became increasingly larger as slope was increased to +22 degrees from horizontal. At +45 degrees from horizontal, pronation then decreased. Figure 4.9 illustrates the *Height* x *Slope* interaction effect for pronation/supination.

4.4.2 Student's t-tests

For the wrist movement direction pronation-supination, all *Height*, *Slope*, and *Height* x *Slope* treatment means were significantly different from the neutral pronation/supination position. This analysis is shown in Table 4.11.

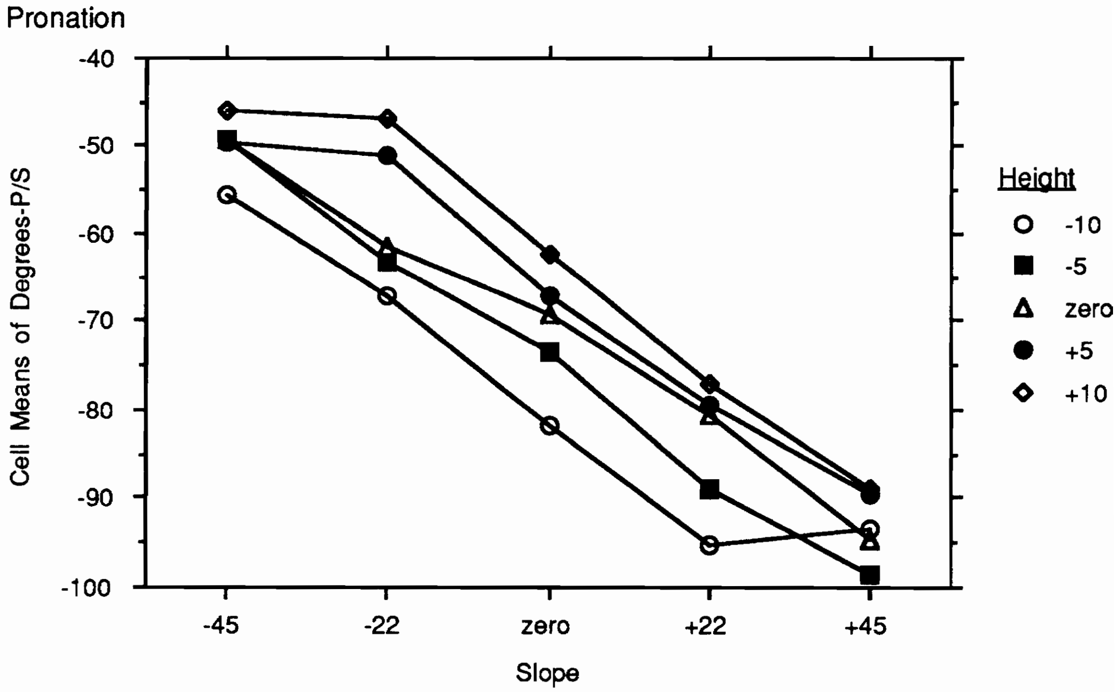


Figure 4.11 *Height* x *Slope* interaction effect plotted against Degrees of Pronation or Supination from a neutral position.

Table 4.11

Results for t-tests performed that the means of effects = 0. * indicates the mean for that effect was significantly different from neutral at a level of significance of $p<0.05$. P/S represents pronation-supination.

Effect	Mean	t-obs	Significance
Height (-10)	-78.6417	23.658	*
Height (-5)	-74.6468	23.2305	*
Height (0)	-71.0774	23.086	*
Height (5)	-67.311	22.5898	*
Height (10)	-64.2204	20.7189	*
Slope (-45)	-49.8309	16.3139	*
Slope (-22)	-57.9746	19.8495	*
Slope (0)	-70.8894	24.6323	*
Slope (22)	-84.1881	28.3509	*
Slope (45)	-93.0143	30.0394	*
H/S (-10,-45)	-55.439	8.4718	*
H/S (-10,-22)	-67.0504	10.4557	*
H/S (-10,0)	-81.9246	11.4518	*
H/S (-10,22)	-95.2583	12.7575	*
H/S (-10,45)	-93.5365	11.6084	*
H/S (-5,-45)	-49.1413	7.3264	*
H/S (-5,-22)	-63.2494	9.3248	*
H/S (-5,0)	-73.5639	11.6594	*
H/S (-5,22)	-88.8413	12.8346	*
H/S (-5,45)	-98.4381	13.8044	*
H/S (0,-45)	-49.1676	7.159	*
H/S (0,-22)	-61.5898	9.3987	*
H/S (0,0)	-69.2627	11.1211	*
H/S (0,22)	-80.6318	12.7964	*
H/S (0,45)	-94.7353	13.9134	*
H/S (5,-45)	-49.4695	7.1216	*
H/S (5,-22)	-51.0765	8.2362	*
H/S (5,0)	-67.1945	11.112	*
H/S (5,22)	-79.3072	12.9752	*
H/S (5,45)	-89.5071	14.3	*
H/S (10,-45)	-45.9373	6.311	*
H/S (10,-22)	-46.9069	7.2273	*
H/S (10,0)	-62.5012	9.9255	*
H/S (10,22)	-76.9017	12.3933	*
H/S (10,45)	-88.8547	13.8549	*

4.5 Analysis of Input Performance Data

A repeated measures analysis of variance was conducted on the input performance data. The dependent variable that was used for the ANOVA was corrected words per minute. Corrected words per minute was calculated as (gross words per minute - the number of errors)/ number of minutes. The ANOVA summary table for this analysis is shown in Table 4.12. The main effects *Slope* and the *Height* x *Slope* interaction were significant at $p<.0001$. The significant main effect *Slope* indicated that correct words typed per minute was the highest when the keyboard was 0 degrees from horizontal. Means contrasts were performed on the main effect *Slope* to determine any statistical differences between means. The next two highest values, which were not significantly different from one another, were observed at -22 degrees and +22 degrees from horizontal. The two lowest values for correct words typed per minute, which were not significantly different from one another, were observed at -45 degrees and +45 degrees from horizontal. This trend is shown in Figure 4.10. Orthogonal means comparisons were performed to test for any linear, quadratic, cubic, or quartic effects. The summary table for this analysis is shown in Table 4.13. The analysis revealed that *Slope* had a significant quadratic effect ($p<.0001$).

The significant ($p<.0001$) *Height* x *Slope* interaction indicated that at slope conditions 0 degrees, +22 degrees, and -22 degrees, there was no statistical difference in correct words typed per minute for all height conditions. At the slope condition -45 degrees, subjects typed the most correct words per minute at -10 cm. They made significantly ($p<.0001$) more errors at +5 cm than -10 cm, and significantly ($p<.0001$) more errors at +10 than +5 cm. At the slope condition +45 degrees, subjects made the least amount of errors at +10 cm. Their performance decreased significantly at 0 cm, and then at -5 cm, and -10 cm. This effect can be seen in Figure 4.11

Table 4.12

ANOVA Summary Table for text data (correct words typed per minute).

Source	df	SS	MS	F	P	Greenhouse-Geisser P
Between-Subjects						
Subject	24	90051.1416	3752.1309			
Within-Subjects						
Height (H)	4	144.7976	36.1994	1.8936	.1178	.1365
HxSubject	96	1835.2024	19.1167			
		Greenhouse-Geisser Epsilon = .7703				
Slope (S)	4	4823.1776	1205.7944	26.1099	.0001	.0001
SxSubject	96	4433.4224	46.1815			
		Greenhouse-Geisser Epsilon = .7430				
HxS	16	1786.9864	111.6866	5.6591	.0001	.0001
HxSxSubject	384	7578.5136	19.7357			
		Greenhouse-Geisser Epsilon = .4510				

Table 4.13

Orthogonal Polynomial Contrast analysis on main effect *Slope*.

Fit	df	SS	MS	F	p
Linear	1	33.62	33.62	.728	.3957
Quadratic	1	4756.1287	4756.1287	102.98778	.0001
Cubic	1	31.205	31.205	.6757	.4131
Quartic	1	2.22403	2.22403	.04816	.8268

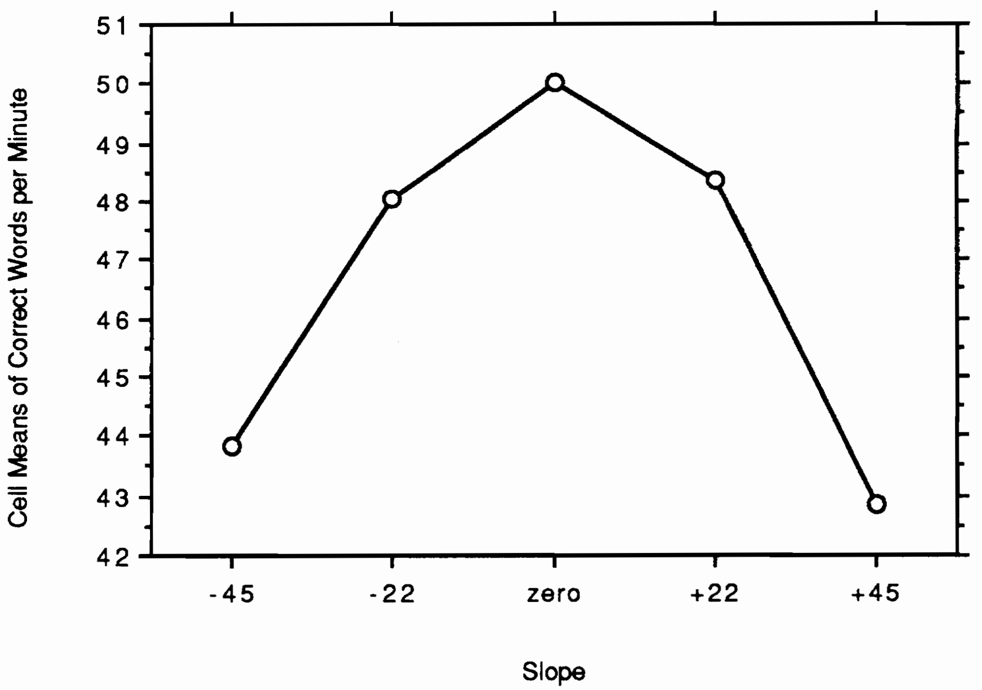


Figure 4.12 Main effect of *Slope* plotted against Correct Words Typed per Minute.

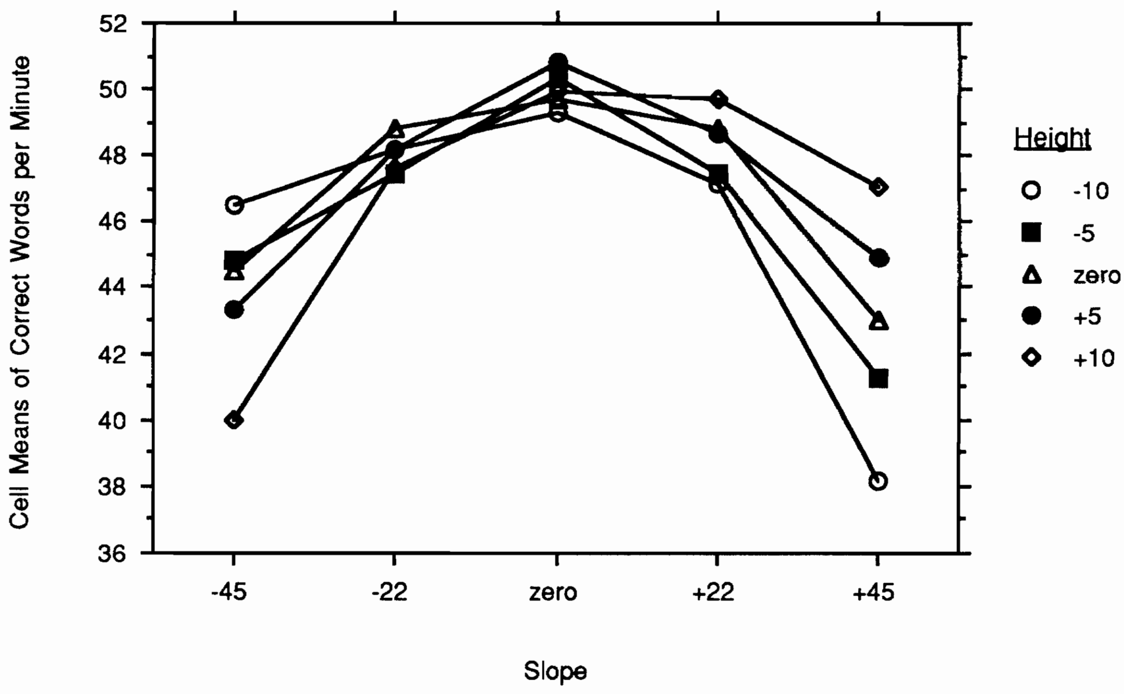


Figure 4.13 Interaction effect *Height* x *Slope* plotted against Correct Words Typed per Minute.

5. DISCUSSION

5.1 Flexion-Extension

The results of this study indicated that *Slope* of keyboard significantly ($p<.0001$) affected the dependent variable, degrees of flexion-extension from a neutral position. The least amount of wrist flexion was observed when the keyboard was +45 degrees from horizontal. Wrist extension was not observed at this condition as might have been expected, however. This may have been due to the fact that the keyboard support surface moved with the keyboard rather than remaining horizontal while the keyboard slope was adjusted. The support surface was designed this way to allow the keyboard to be easily adjusted in all *Height/Slope* conditions. Means comparisons revealed that wrist flexion was not significantly ($p<.0001$) different for *Slope* conditions +22, 0, and -22 degrees. As expected, when the keyboard was -45 degrees from horizontal, the largest value for wrist flexion was observed. In order for subjects to type in this *Slope* condition, they had to keep their wrists flexed the entire time.

An interesting result was observed by the significant ($p<.0001$) *Hand* effect. On the average for flexion-extension, the left hand demonstrated extension ($\bar{x}$= 29.325 degrees) while the right hand demonstrated flexion ($\bar{x}$ = -41.718 degrees). This effect may be related to the position of the alphanumeric keys on the extreme left side of the keyboard. Subjects were seated in center of the keyboard, and the alphanumeric keys were positioned the left side of the keyboard. Because subjects used only the alphanumeric keys for the experimental tasks, they probably had to shift their hands to the left side of the keyboard to perform the experimental tasks.

As mentioned in the previous chapter, two-tailed t-tests were performed independently on the means for the main effects of *Height* and *Slope* and the interaction *Height* x *Slope* for flexion-extension, radial-ulnar deviation, and pronation-supination. These tests detected any significant differences between the wrist movement values for the treatment means and the neutral wrist positions.

For the wrist movement direction flexion-extension, the *Height* means for 5 cm and 10 cm were significantly different than the neutral position for flexion-extension. Although the Analysis of Variance did not find a significant *Height* effect, the t-test was more powerful and therefore more capable of finding a significant difference if it existed. The t-test was a more powerful test because it was comparing only two means, whereas the F-tests used in the analysis of variance were comparing 10 means. These results suggest that at high keyboard heights, it may be more difficult to keep wrists in a neutral position with respect to flexion-extension than at low keyboard heights.

The *Slope* means for -22 degrees and -45 degrees from horizontal were significantly different from the neutral position for flexion-extension. This effect probably occurred because when the keyboard was at negative slopes, subjects were forced to keep their wrists flexed in order to reach the keys. The fact that the *Slope* means for 0, 22, and 45 degrees from horizontal were not significantly different from neutral might have occurred due to the design of the keyboard support surface, which moved with the keyboard. If the support surface had not moved with the keyboard, subjects may have collapsed their wrists onto the support surface and extended their wrists. The design of the apparatus may have encouraged subjects to hold their forearms so that their wrists were in a neutral position with respect to flexion-extension when the keyboard was at positive slopes.

The following *Height* x *Slope* interaction means were significantly different from the neutral position for flexion-extension: (0 cm, -45 degrees), (5 cm, -45 degrees), (10 cm, -45 degrees). This analysis suggests that negative slopes cause wrist flexion significantly different from neutral only when coupled with high keyboard heights. At low keyboard heights, the arms may be able to reach the keys easier at negative slopes than at high keyboard heights.

Considering **only** the wrist movement direction flexion-extension, the following conclusions about keyboard height and slope can be made based on the results of this study:

- Keyboard positions with slope -45 degrees from horizontal may be undesirable because the largest values for wrist flexion were observed at this slope.
- Keyboard heights 5-10 cm above operator elbow height may be undesirable because they resulted in wrist flexion significantly ($p<.05$) different from the neutral flexion-extension position.
- Keyboard positions with slope conditions 0 and +22 degrees may be desirable because they did not cause wrist flexion significantly different from the neutral position.

5.2 Radial-Ulnar Deviation

For the wrist movement direction radial-ulnar deviation, the main effect

Height significantly ($p<.0001$) affected ulnar deviation. The smallest value of ulnar deviation was observed when the keyboard was -10 cm below operator elbow height and became increasingly larger as keyboard height was increased. Conceivably, low keyboard heights may have restricted ulnar deviation more than high keyboard heights.

Slope also significantly ($p<.0001$) affected radial-ulnar deviation. Ulnar deviation was maximum when the keyboard was -45 degrees from horizontal and decreased to its minimum value when the keyboard was +22 degrees from horizontal. When the keyboard was +45 degrees from horizontal, radial deviation was observed. Perhaps at the more negative keyboard slopes, more ulnar deviation was necessary to reach the keys.

The *Height x Slope* interaction demonstrated that as *Slope* was increased from -45 degrees to +45 degrees from horizontal, ulnar deviation decreased and radial deviation increased. In addition, ulnar deviation became smaller and radial deviation larger as *Height* was decreased from +10 cm to -10 cm below operator elbow height. This effect might have occurred because more ulnar deviation is necessary to reach the keys at negative slopes, particularly at high keyboard heights. Likewise, less ulnar deviation and more radial deviation may be necessary to reach the keys at positive slopes, particularly at low keyboard heights.

An interesting result was demonstrated in the *Height x Hand* interaction. At *Height* conditions -10 cm and -5 cm, the right hand demonstrated more ulnar deviation than the left hand. When the keyboard was at operator elbow height, the right hand still demonstrated more ulnar deviation than the left hand, but the values were more similar than for the higher *Height* conditions. When the keyboard was at 5 cm and 10 cm above operator elbow height, both hands demonstrated approximately the same amount of ulnar deviation. At low keyboard heights, it was seen that the right-handed subjects demonstrated more ulnar deviation with their right hand than their left. At high keyboard heights, where the most ulnar deviation was observed, no significant differences were noted in ulnar deviation between the two hands. This may have been because higher keyboard heights required more ulnar deviation to reach the keys, therefore it may have been harder to detect any difference for ulnar deviation between the hands.

Results of t-tests for the wrist movement direction radial-ulnar deviation indicated that all *Height* and *Slope* means were significantly different from the neutral radial-ulnar deviation position. Conceivably, a significant amount of ulnar or radial deviation may be necessary to effectively reach the keys when typing at any condition. The only three treatment conditions which were not significantly different from neutral were: (-5 cm, +22 degrees), (+5 cm, 45 degrees), and (+10 cm, +45 degrees). This result may have been due to the design of the keyboard support surface, which moved with the keyboard and did not provide a horizontal resting surface.

The following generalizations about keyboard height and slope can be made regarding **only** radial-ulnar deviation:

- Lower keyboard heights may be desirable because they resulted in the smallest values for ulnar deviation.
- Slope conditions +22 and +45 degrees may be desirable because they resulted in the smallest values for radial-ulnar deviation.

- The following three treatment conditions may be desirable because they yielded the smallest values of radial-ulnar deviation: (-5 cm, +22 degrees), (+5 cm, +45 degrees), and (+10 cm, +45 degrees).

5.3 Pronation-Supination

For the wrist posture pronation-supination, the main effect *Height* demonstrated that pronation was maximum when the keyboard was -10 cm below operator elbow height and decreased linearly as the keyboard height increased. One explanation for this effect is simply that more pronation may be required to reach the keys at low keyboard heights than at high keyboard heights.

The main effect *Slope* also affected the amount of pronation observed. Pronation was the smallest at negative slopes and increased linearly as keyboard *Slope* increased. Perhaps at negative slopes, less pronation was necessary to effectively reach the keys than at positive slopes.

The smallest values for pronation were observed at (+10 cm, -45 degrees) and the largest values for pronation were observed at (-5 cm, +45 degrees). This result suggests that minimal pronation may be necessary to effectively reach the keys at high keyboard heights coupled with negative slopes, and maximum pronation may be needed to effectively reach the keys at low keyboard heights coupled with positive slopes.

For the wrist movement direction pronation-supination, all *Height*, *Slope*, and *Height x Slope* treatment means were significantly different from the neutral pronation-supination position. These results suggest that pronation will occur while typing in any treatment condition, although the amount of pronation will vary according to the condition.

Regarding **only** the wrist movement direction pronation-supination, the following conclusions can be made:

- Higher keyboard heights may be desirable because they yielded the smallest values for pronation.
- Negative slopes may be desirable because they produced the smallest values for pronation.
- The treatment condition where pronation was minimum (+10 cm, -45 degrees) may be desirable.

5.4 Overall Upper Extremity Posture

When evaluating the results of this experiment, it is necessary to examine how the various components of wrist posture may have affected one another. As keyboard height was increased, it is likely that subjects were medially rotating their elbows and holding their arms elevated in order to compensate for the increased keyboard height. This type of compensatory behavior would help to explain why no significant *Height* effect was found for flexion-extension. As subjects rotated their elbows, smaller values of pronation and larger values of ulnar deviation would be expected. These effects, which were both observed, help to support this assumption.

Although this study did not examine whether or not this effect was present, electromyograms could have been used to measure the amount of force exerted by the trapezius muscles. This information would have helped to determine whether the subjects were "shrugging" their shoulders in order to hold their arms elevated. In addition, videotapes could have been used to determine whether this behavior was exhibited.

5.5 Input Performance Data

The analysis of input performance data indicated that subjects typed the most correct words per minute when the keyboard was 0 degrees from horizontal and +22 degrees from horizontal. This could be explained by the fact that most keyboards have slopes from 0 to 22 degrees, and subjects have practiced typing at these conditions. Subjects typed significantly ($p<.0001$) fewer correct words per minute at negative slopes and at +45 degrees from horizontal. A possible explanation for subjects performing poorly at +45 degrees from horizontal is that subjects commented they felt like their fingers were slipping off the keys in this condition. The fact that subjects typed fewer correct words per minute at negative slopes could be explained by subjects' comments which indicated that they forgot where their fingers were at negative slopes. Most subjects found negative slopes, especially -22 degrees, to be comfortable, however. One subject commented that practice at negative slopes would probably help his typing ability considerably. It should be noted that the keyboard used for this experiment was designed to be used for keyboard slopes 5 degrees from horizontal. This equipment design may have affected the data input performance at conditions other than 5 degrees from horizontal.

Means comparison performed on the significant ($p<.0001$) *Height* x *Slope* interaction indicated that at slope conditions 0 degrees, +22 degrees, and -22 degrees, there was no statistical difference in correct words typed per minute for all height conditions. The fact that at -45 degrees, subjects typed the most correct words per minute at -10 cm could be explained by the fact that this height may have made the keys easier to reach. As the height increased for this slope, the keys may have became more awkward to reach perhaps resulting in more errors. When the keyboard was positioned at +45 degrees, subjects made the least errors at +10 cm. This could be because at this height subjects may have been able to keep their fingers on the keyboard better. However, the very high positions may have caused subjects to hold their arms up, which would be quite fatiguing to subjects. As the height was decreased, subjects made more errors. Perhaps this was due to the subjects' fingers slipping off the keys more in these positions.

The following conclusions can be drawn about keyboard height and slope regarding **only** data input performance:

- Keyboard slopes 0 and +22 degrees may be desirable because they yielded the most correct words typed per minute.
- Practice at negative slope conditions is necessary before any meaningful conclusions can be made regarding input performance in these conditions.
- Keyboard slope condition +45 degrees may be undesirable because subjects typed significantly ($p<.0001$) less correct words per minute in this condition.
- At negative keyboard slopes, low keyboard heights yielded the most correct words per minute. Therefore, this combination of height and slope may be desirable.
- For positive keyboard slopes, high keyboard heights yielded the most correct words per minute. Therefore, this combination may

be desirable.

5.6 Subjective Data

Overall, subjects made the following comments regarding the treatment conditions:

- Treatment condition of -10 cm and +45 degrees was unbearably uncomfortable and interfered with typing ability. In this treatment condition, subjects felt like their fingers were slipping off the keys.
- Subjects felt that treatment conditions with low keyboard heights and -22 degrees were the most comfortable.
- Subjects felt that they forgot where their fingers were at negative slopes and found it hard to reach the row of keys with "p" and "q."
- Negative slopes felt uncomfortable only when coupled with high keyboard heights. These positions caused subjects to hold their forearms up to type and were fatiguing.
- In general, treatment conditions with +45 slopes were uncomfortable.

5.7 General Recommendations

In order to arrive at general recommendations concerning keyboard height and slope, the following factors were considered: flexion-extension data, radial-ulnar deviation data, pronation-supination data, overall upper extremity posture, and subjective data. Taking all these factors into account, recommendations concerning keyboard height and slope were made. According to the results of this study, the following keyboard conditions may be undesirable:

- Keyboard positions with slope -45 degrees from horizontal may be undesirable because significant wrist flexion was observed at these slopes.
- Keyboard positions with slope +45 degrees from horizontal may be undesirable. In general, this keyboard slope was painful to subjects' wrists, and the pain was intensified when this slope was combined with low keyboard heights.
- Keyboard heights 5-10 cm above operator elbow height may be undesirable because they resulted in wrist flexion significantly ($p<.05$) different from neutral. Positions with these keyboard heights coupled with negative slopes were especially fatiguing to subjects. Also keyboard heights less than -5 cm below elbow height may be undesirable due to interference with subjects' knees.

In general, the following keyboard conditions may be desirable:

- Keyboard positions with slope conditions 0, +22, or -22 may be desirable. For the slope conditions 0 and +22 degrees, flexion-extension and radial-ulnar deviation were not significantly different from neutral. Although the slope condition -22 degrees was significantly ($p<.05$) different from neutral for flexion-extension, subjects commented that it was very comfortable, especially when the keyboard was at elbow height or below. The slope condition +22 degrees may be desirable when the keyboard is at elbow height due to subjects' comments that positive slopes and low keyboard heights were very uncomfortable. When the keyboard slope is 0 degrees, keyboard height -5 cm below operator elbow height may be desirable.

- Lower keyboard heights may be desirable because they resulted in values for flexion-extension and radial-ulnar deviation which were not significantly different from neutral. However, keyboard heights less than -5 cm below operator elbow height should probably be avoided due to interference with the position of subjects' knees.

5.8 Limitations of Experiment

5.8.1 Limitation of Equipment

From this experiment, it can be concluded that the wrist monitors developed at The Ohio State University Biodynamics Laboratory are an effective means to measuring the following components of wrist movement: flexion-extension, radial-ulnar deviation, and pronation-supination. However, there were several difficulties with the experimental apparatus that may have detracted from the overall conclusions of this study. The first difficulty involved equipment problems with the wrist monitor which caused the elimination of one subject's data set. The problem encountered was a loose wire connection which prevented any data from being collected. In addition to this problem with the wrist monitor, the following limitations were noted:

- Interference with task. Parts of wrist monitor pressed keys when subjects did not. The monitor didn't allow subjects to maintain a natural position, especially when the keyboard was -45 or 45 degrees from horizontal. On subjects with small hands, the device interfered with typing by restricting motion of fingers.

- Subjects' skin may have moved while performing tasks. Thus, the potentiometers may not have stayed where they were initially positioned.
- The wrist monitor became uncomfortable, although not painful. This discomfort may have affected subjects wrist posture.
- The tape used to apply the wrist monitors restricted subjects' range of motion, even when the tape was applied loosely.
- The potentiometers on the wrist monitor may not have been placed over the true joint centers of rotation. This may have had an effect on the range and accuracy of the data collected.
- The wrist monitor was not calibrated in the same position as the position where subjects performed the experimental tasks. Thus, the posture data from the wrist monitors may not have accurately represented the subjects' true wrist postures.

5.8.2 Assumptions

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

- Subjects only typed for two minutes in each of the experimental conditions, therefore conclusions cannot be made about wrist posture while typing beyond the scope of this time period. Because this time period was extremely short, it is unknown whether wrist posture would change as the duration of the experimental task changed. Therefore, it is very important to consider this limitation of the study when interpreting the results.

- The experimental task only required subjects to copy a text passage from a document holder to the computer. In daily activities, typist's most likely perform many other keyboard tasks, which may affect their overall wrist posture.
- The assumption was made that the device was indeed positioned correctly and calibrated accurately.
- It was assumed that for a given keyboard height, the amount of height deviation due to the keyboard slope was negligible.

5.9 Future Research

The findings of this study indicate several areas for future research. Possible areas for future investigation are listed below:

- An analysis of the accuracy and range of values for the wrist monitor device dependent upon the positioning of its various components.
- Further extension of this study using a keyboard support surface which extends past the keyboard and remains horizontal despite the position of the keyboard itself.
- Further extension of this study using less extreme slopes and heights.
- An investigation of wrist posture when subjects set the keyboard at the height and slope they think is most comfortable.
- Further extension of this study using longer typing tasks.
- Further research to determine whether subjects rotated elbows

medially and help arms elevated when the keyboard was at high heights.

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Appendix A: Written Instructions for Experiment

Keyboard Height/Slope Study

Thank you for participating in this research. This study is being conducted by the Industrial Ergonomics Laboratory of the Human Factors Engineering Center at Virginia Tech. The experiment is being run by MaryAnn Jedrziewski as part of her Masters' Thesis work and is being supervised by Dr. Jeff Woldstad, a professor in Industrial and Systems Engineering.

As you may already know, the purpose of this study is to determine the optimal combination(s) of keyboard height and keyboard slope for computer operators. We are interested in determining how these variables affect wrist postures. This study will help establish guidelines for the adjustment of computer workstations to prevent cumulative trauma disorders of the wrist and hand.

This study will be conducted in one experimental session, lasting approximately three hours. You will be compensated at a rate of $5.00 per hour for an expected total of $15.00. First, you will be fitted with a wrist monitor apparatus on each hand. What this encompasses is having four thin metal strips positioned on your forearm and hand and secured with adhesive tape. You will then be positioned in an adjustable chair so that your knees and ankles are at right angles, and your "sitting elbow height from the floor" will be measured. Next, you will be asked to type a passage of text from a document holder onto an IBM PC for two minutes in each of 25 experimental conditions. While you are typing, if you need to see the next page, inform the investigator. Do not remove your hands from the keyboard and flip the page yourself. You may rest your hands as you normally would while typing. Do not remove your hands from the vicinity of the keyboard, however (i.e. don't rest them on your lap). Also, while typing, if you make a spelling error, do not go back and correct it- continue typing.

The data from the experiment should be analyzed by August 31, 1992, and the results made available to you should you desire to review them. The research team members for this experiment are:

MaryAnn Jedrziewski, Graduate Student
Dr. Jeff Woldstad, Professor, ISE

If you have concerns about the way in which you have been treated or the manner in which the experiment is being conducted and do not wish to express these concerns directly to the experimental team, you may contact the University's Institutional Review Board Chairperson Dr. Robert Beaton at (703) 231-5936.

Thank you once again for your participation. We hope that you will enjoy your experience in this experiment.

Appendix B: Informed Consent Form

Informed Consent Form

This form constitutes informed consent by you to participate in this study. Please read it carefully, as well as the attached sheet, and then sign it below.

Your Rights as a Subject are:

1.) It is your right as a subject to withdraw from the study at any time and for any reason.

2.) Any of the research team members will answer any questions that you may have, and you should not sign this consent form until you understand fully all of the terms involved.

3.) You have a right to see your data and withdraw it from the study if you so desire. Please inform the experimenter immediately of this decision, as the data will be handled anonymously and not possible to track once the session is over.

4.) You have the right to be informed of any risks or discomforts in this research. There is minimal risk associated with this experiment. You may experience some discomfort when the adhesive tape from the wrist monitors are removed. This discomfort should be short-lived and pose no further complication or discomfort to you.

5.) If you wish to receive a synopsis of the study, please include your address under the signature line below and a copy will be sent to you. Once you have read the synopsis, and if you wish for a more detailed report, please contact one of the team members and a full report will be made available to you.

6.) Should any further questions arise, please contact one of the team members. If you have any concerns about the way the experiment is being conducted or the way you are being treated, you may contact Dr. Stout at the phone number on the other page.

Your participation is greatly appreciated and we hope that you will find the study a pleasant and interesting experience. Your signature below indicates that you have read this document in its entirety, that your questions have been answered, and that you consent to participate in the study described.

Signature: ______________________________ Date ____________

Address: ____

____

Appendix C: Latin Square Design

LATIN SQUARE DESIGN

Subject

TC

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25
2	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25	O1
3	O25	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24
4	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25	O1	O2
5	O24	O25	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23
6	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25	O1	O2	O3
7	O23	O24	O25	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22
8	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25	O1	O2	O3	O4
9	O22	O23	O24	O25	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21
10	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25	O1	O2	O3	O4	O5
11	O21	O22	O23	O24	O25	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20
12	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25	O1	O2	O3	O4	O5	O6
13	O20	O21	O22	O23	O24	O25	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19
14	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25	O1	O2	O3	O4	O5	O6	O7
15	O19	O20	O21	O22	O23	O24	O25	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18
16	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25	O1	O2	O3	O4	O5	O6	O7	O8
17	O18	O19	O20	O21	O22	O23	O24	O25	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17
18	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25	O1	O2	O3	O4	O5	O6	O7	O8	O9
19	O17	O18	O19	O20	O21	O22	O23	O24	O25	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16
20	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10
21	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15
22	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11
23	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14
24	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12
25	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13

Appendix D: ANOVA Summary Tables for Time Factor

Table D.1

ANOVA Summary Table for degrees from neutral for flexion/extension.

Source	df	SS	MS	F	P	Greenhouse-Geisser P
Between-Subjects						
Gender (G)	1	10004.617	10004.617	.746	.3971	
Subjects/G	22	295052.096	13411.459			
Within-Subjects						
Hand (HA)	1	727418.936	727418.936	62.283	.0001	.0001
HAxG	1	10228.170	10228.170	.876	.3595	.3595
HAxSubjects/G	22	256942.094	11679.186			
	Greenhouse-Geisser Epsilon = 1.000					
Time (T)	2	255.066	127.533	5.191	.0095	**.0295**
TxG	2	27.373	13.687	.557	.5769	.4763
TxSubjects/G	44	1081.069	24.570			
	Greenhouse-Geisser Epsilon = .542					
HAxT	2	3.606	1.803	.083	.9206	.8003
HAxG	2	78.839	39.420	1.813	.1751	.1911
HAxTxSubjects/G	44	956.440	21.737			
	Greenhouse-Geisser Epsilon = .552					

Appendix E: Summary of Regression Analyses on Voltage/Degrees Conversion Data

Table E.1

Subject	Channel	β_0	β_1	R^2	Significance
1	Left F/E	-67.648	178.410	.99678	**
1	Right F/E	69.134	-155.506	.9739	**
1	Left R/U	-80.295	199.431	.99115	****
1	Right R/U	75.597	-201.273	.99315	****
1	Left P/S	464.868	-1517.263	.94589	*
1	Right P/S	-317.651	743.241	.96865	**

Coefficients, R^2 values, and significance levels for linear regressions on voltage/degree data for each channel for first three subjects. * indicates significance at p<0.01, ** indicates significance at p<0.005, *** indicates significance at p<0.001, **** indicates significance at p<0.0005, ***** indicates significance at p<0.0001. F/E represents flexion/extension, R/U represents radial/ulnar deviation, P/S represents pronation/supination.

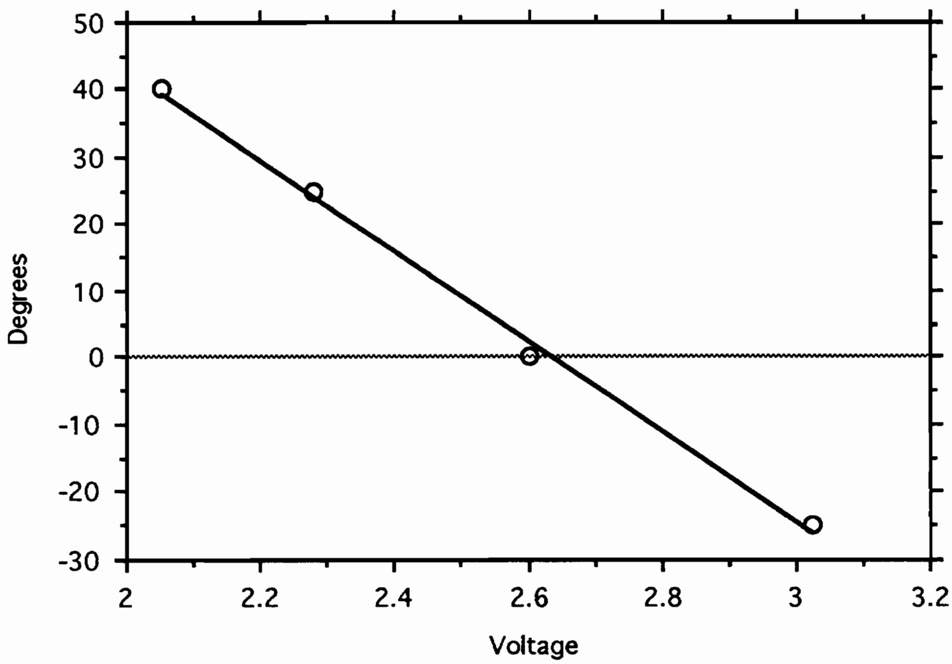

Figure E.1 Graph of linear regression for subject 1 left hand, flexion-extension channel.

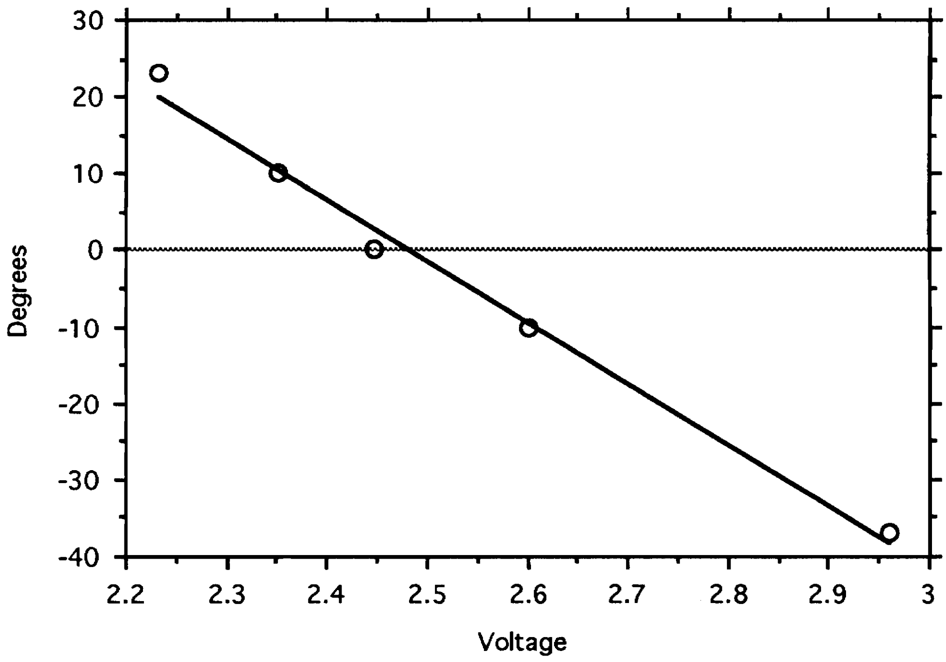

Figure E.2 Graph of linear regression for subject 1 left hand, radial-ulnar deviation channel.

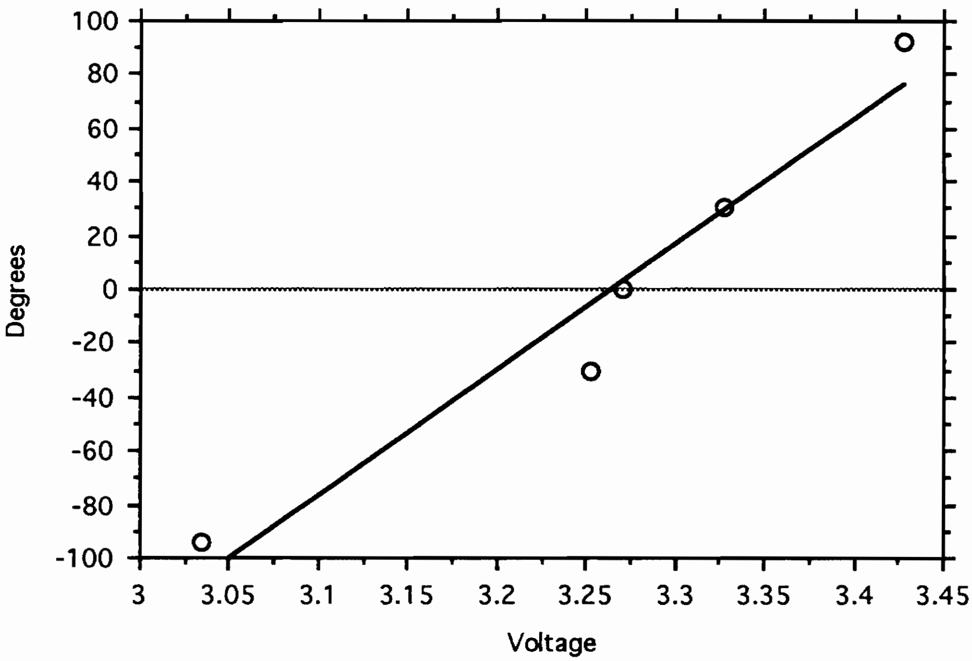

Figure E.3 Graph of linear regression for subject 1 left hand, pronation-supination channel.

VITA

MaryAnn Jedrziewski was born in Dayton, Ohio on May 9, 1968 and immediately moved to Alexandria, Virginia. She graduated from Fort Hunt High School in 1986 and completed her B.S. degree in Industrial Engineering and Operations Research from Virginia Tech in 1990. She entered the Human Factors graduate program at Virginia Tech in Fall 1990 and received her M.S. degree in September 1992. During the summer of 1991, she worked for Honeywell , Inc. in Minneapolis, Minnesota performing ergonomic and training tasks. Her areas of interest include: ergonomics, safety, systems design, and training. She is an active member of the Human Factors Society, the Institute of Industrial Engineers, and Alpha Pi Mu Industrial Engineering Honor Society.

MaryAnn Jedrziewski