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FINAL PERFORMANCE REPORT

Title: **AN ERGONOMICS STUDY OF ALTERNATIVE KEYBOARD DESIGNS**

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A. SIGNIFICANT FINDINGS

This study was an investigation into whether fundamental designs of three commercially-available alternative QWERTY keyboards, namely split and vertically-inclined, are beneficial to keyboard users with respect to one occupational risk factor of upper extremity work-related musculoskeletal disorders, wrist and forearm posture. The experimental methodology of this study improved upon previous studies by testing more clerical typists (90 subjects) and also requiring each subject to practice typing on the alternative keyboard assigned to him/her for at least 10 hours before testing in the laboratory.

The significant findings from this study are the following:

- When set up correctly, the three commercially-available split QWERTY keyboards reduced mean ulnar deviation of the wrist from approximately 10 deg. to within 2.5 deg. of a neutral position compared to a conventional QWERTY keyboard. This finding reduces one occupational risk factor of work-related musculoskeletal disorders, namely ulnar deviation of the wrist. However, since the origins of WMSDs, which include carpal tunnel syndrome (CTS), tenosynovitis, tendinitis, lateral epicondylitis, etc., tend to be multifactorial, the extent to which split keyboards could reduce the frequency or severity of WMSDs is unknown.
- A commercially-available vertically-inclined QWERTY keyboard, in which the keyboard halves were tilted 30 deg. (like a drawbridge), reduced average forearm pronation by approximately 20 deg. compared to a conventional QWERTY computer keyboard (60 to 40 deg.). This finding is advantageous, at least theoretically, to the keyboard user because the forearm is closer to an anatomically-neutral position of the forearm. However, the extent to which vertically-inclined keyboards could reduce the frequency or severity of WMSDs is also unknown.
- Wrist position was found to differ between the right and left upper extremities with both the conventional and alternative keyboards, with the left wrist typically showing greater ulnar deviation and extension than the right wrist.
- No appreciable functional differences were noted in the kinematics of the wrist and forearm between alphabetic and alphanumeric typing tasks for either the conventional or alternative keyboards.
- There were no appreciable differences in performance between the conventional and alternative keyboard conditions after the subjects had practiced for 10 or more hours on the alternative keyboards.

B. USEFULNESS OF FINDINGS

A prospective purchaser of a computer keyboard will find a multitude of different designs of keyboards in the current marketplace, both in layout of keys (QWERTY and chorded) and in overall shape of keyboard. An ergonomist or keyboard user can recommend or buy a conventional computer keyboard based essentially on the 1981 IBM 101 PC keyboard (named for its 101 keys) or one of many specific designs of alternative keyboards. Some examples of alternative QWERTY keyboards are the following:

1) Keyboards that have their halves split or separated and angled to each other -*split.*

2) Keyboards that have their halves tilted like a drawbridge -- *vertically-inclined.*

3) Keyboards that have concave wells for fingers.

4) Keyboards that have their halves separated and mounted on the forearm posts of an office chair.

Since there is an overall lack of thorough scientific research into the efficacy of specific alternative keyboard designs with respect to upper extremity WMSDs, an ergonomist or keyboard user is often confused as to which type of keyboard to recommend or purchase. The fundamental question that this research study addressed was to determine if some of the commercially-available alternative QWERTY keyboards, namely split and vertically-inclined, are beneficial with respect to one occupational risk factor of upper extremity WMSDs, wrist and forearm posture. The results from this study show that the split and vertically-inclined keyboards that were tested do substantially reduce ulnar deviation and forearm pronation, respectively. To the extent that less ulnar deviation and less forearm pronation can lessen the risk of upper extremity WMSDs, the split and vertically-inclined QWERTY keyboards are advantageous to keyboard users, when compared to the conventional keyboard. The postural findings from this study can assist ergonomists and individual keyboard users in their efforts to reduce the frequency and severity of upper extremity WMSDs in office environments. Ergonomists can use this information in their evaluation and recommendation of office equipment, and individual keyboard users can use this study's postural findings to aid them in their selection of a computer keyboard. Additionally, for those with concerns about the impact of alternative keyboards on productivity, this study indicated that there were no appreciable productivity differences between conventional and alternative keyboards after users had 10 or more hours of practice on the alternative keyboards.

Other findings from this research may aid researchers who conduct studies of computer keyboards. First, since there was a statistically significant and practical difference in wrist posture between the left and right hands, future researchers should measure wrist posture of both hands. Second, the lack of a significant and practical difference in wrist and forearm posture between typing alphabetic and alphanumeric texts suggests that future researchers may need to measure the kinematics of subjects while they type from either alphabetic or alphanumeric texts, and not necessarily both.

C. ABSTRACT

Upper extremity work-related musculoskeletal disorders (WMSDs), such as carpal tunnel syndrome, tenosynovitis, tendinitis, etc., have increased substantially within the last decade, as evinced by the increase in the number of illnesses due to repeated trauma reported to the U.S. Bureau of Labor Statistics (BLS). The number of illnesses due to repeated trauma, which include upper extremity WMSDs, increased from 37,000 in 1985 to 332,000 in 1994 (BLS, 1994). Within the last two decades of published literature, upper extremity WMSDs have been often attributed to computer keyboard use. In a study of 250 visual display terminal (VDT) users at four newspapers and one insurance company, Smith et al. (1981) found that at least 25% of the VDT users reported swollen muscles or joints, painful or stiff arms, legs, neck, or shoulders. In 1991, Sauter et al., conducted a study on 539 data entry VDT users, and found that 13% of the subjects reported almost constant discomfort in their right wrist.

While the exact cause of occupationally-induced upper extremity WMSDs in computer keyboard users is not known, it appears that the deviated wrist and forearm posture (ulnar deviation and pronation) dictated by the design of the conventional flat computer keyboard is implicated in the etiology of upper extremity WMSDs. Within the past decade, manufacturers of several new alternative computer keyboard designs have entered the market. The apparent supposition of the design of these alternative keyboards is that the user can assume a more anatomically-neutral wrist and forearm posture, which according to biomechanical theory would reduce the risk of upper extremity WMSDs. Typically, these alternative computer keyboards are split into halves and rotated in the horizontal plane to reduce ulnar deviation and are inclined in the vertical plane (much like a draw bridge) to lessen forearm pronation. However, little quantitative data are available on whether the fundamental design of these commercially-available alternative computer keyboards actually reduce non-neutral wrist and forearm posture.

The specific aim of this research study was to investigate whether commercially-available alternative computer keyboards are beneficial from a biomechanical perspective -- i.e. whether users of alternative computer keyboards have kinematic motion patterns in the forearms, wrists, and fingers that pose less risk of upper extremity WMSDs (according to biomechanical theory) than users of the conventional computer keyboards.

The practice protocol and number of subjects tested in this study on alternative computer keyboards overcomes two major limitations of previous studies. First, 90 experienced clerical

subjects participated in this study, which is almost twice as great as previously published studies (Swanson et al., 1997; Honan et al., 1995). Second, each subject practiced typing on the commercially-available alternative keyboard assigned to him/her for at least 10 hours in his/her own workplace office during a period of two weeks before testing in the laboratory. Previous studies have typically provided practice time to the subject on the day of testing (Chen et al., 1994; Honan et al., 1995, 1996). Each of the 90 subjects in this study were full-time clerical workers between the ages of 21 and 55 who typed for at least two hours daily on a computer keyboard as part of his/her job. All subjects also were capable of typing at least 40 words per minute using the standard ten finger 'touch' method taught in business and secretarial schools, were asymptomatic of any pain or discomfort that would interfere with typing on a computer keyboard, had been typing for more than five years, and typed on a conventional computer keyboard for at least two hours per day at their workplace.

Three fundamentally different designs of commercially-available computer keyboards were tested in this study: A) a split fixed-angle keyboard, B) a split adjustable-angle keyboard, and C) a vertically-inclined keyboard, which resembles a drawbridge.

Each subject used one of the three alternative computer keyboards, which was randomly assigned to him/her, in his/her office for a two week period while performing regular work activities. While each subject was required to use the alternative keyboard for a minimum of 10 hours, 90% of the 90 subjects practiced typing on the alternative keyboard for at least 20 hours. Testing took place in a laboratory at Marquette University, where electromechanical goniometers were used to measure wrist, forearm, and finger angles. Fifteen samples of 30 seconds of data were collected over a 24-minute period as the subject typed text that appeared on the VDT screen. Each subject was tested using their assigned alternative computer keyboard and a conventional computer keyboard (in order to serve as their own control). The presentation order of the alternative and conventional keyboards was randomized for each subject.

The results show that all three fundamental designs of commercially-available alternative computer keyboards placed at least one component of wrist and forearm posture in a more neutral position than the conventional computer keyboard. Both split computer keyboards (fixed-angle and adjustable-angle) significantly reduced ulnar deviation in both wrists by about 8 deg. compared to the conventional keyboard (from approximately 10 deg. to 2 deg. for the right wrist; $p < 0.001$). Compared to the conventional keyboard, the vertically-inclined keyboard, which resembles a drawbridge, significantly reduced pronation of both forearms by about 20 deg. (from approximately 60 deg. to 40 deg.; $p < 0.001$). Only small differences were noted in the extension angle of the wrists between the conventional and alternative computer keyboards. Based on the results from this study, it appears that commercially-available alternative computer keyboards of the type used in this study place the wrist and forearm in a more neutral posture than a conventional keyboard. The beneficial effect of alternative computer keyboards enabling users to adopt more anatomically-neutral wrist and forearm postures on the incidence and severity of upper extremity WMSDs is yet unknown.

D. BODY OF REPORT

D.1. BACKGROUND

D.1.1. Work-Related Musculoskeletal Disorders (WMSDs) and Keyboard Users

Upper extremity WMSDs have increased substantially within the last decade, as evinced by the increase in the number of illnesses due to repeated trauma reported to the U.S. Bureau of Labor Statistics (BLS). The number of illnesses due to repeated trauma, which include upper extremity WMSDs, increased from 37,000 in 1985 to 332,000 in 1994 (BLS, 1994). The increase in number of illnesses as a percentage of the previous year's number averaged over 20% in 1990, 1991, and 1992, but tended to flatten out to about 7 to 10% for the years 1993 and 1994. Although this percentage decreased in 1993 and 1994, a 7 to 10% increase in number of illnesses due to repeated trauma from the previous year is still substantial and merits investigation into the occupational causes of illnesses due to repeated trauma.

Upper extremity WMSDs have been troublesome in the clerical service sector in the U.S., which has an employment base of over 18,000,000 (Statistical Abstract of the U.S., 1992). Many of the workers in the clerical sector use a computer keyboard during a majority of their working hours, resulting in 50,000 to 100,000 key strokes a day. In 1993 the BLS started to record the number of injuries and illness due to repetitive motion according to case characteristics, as reported by the employers. For cases whose primary work was *repetitive typing or key entry,* the number of injuries and illnesses that involved repetitive motion and resulted in days away from work was approximately 13,500 in 1993 and 1994. In approximately 90% of those cases, the site of injury was the upper extremity; moreover, the wrist was reported as the site for 75% of the cases. Approximately 65% of the cases were between the ages of 25 to 44, and about 85% were in the classification of Technical, Sales, and Administrative Support (which includes secretaries).

Within the last two decades of published literature, upper extremity WMSDs have been often attributed to mechanical and electronic keyboard use. Of 90 workers who operated teleprinters, Duncan and Ferguson (1974) found that 10 to 30% of the operators complained of musculoskeletal pain throughout the right upper extremity. The percentage for the left upper extremity ranged from 4 to 16%. These authors attribute the high percentage of symptoms to adverse postures of the upper extremity, which they observed on the shoulder and wrist on at least half of the 90 operators. In a similar study summarized by Grandjean (1984), Hunting et al. (1981) found a positive relationship between pain and joint angle for 119 accounting machine operators. At least 40% of the operators who held their neck at an angle 56 deg. or more reported neck stiffness and pain, and at least half of the operators who ulnarly deviated their wrists more than 9 deg. reported pain and cramping.

In a study of 250 visual display terminal (VDT) users at four newspapers and one insurance company, Smith et al. (1981) found that at least 25% of the VDT users reported swollen muscles or joints, painful or stiff arms, legs, neck, or shoulders. In 1987, Rossignol et al. conducted a cross-sectional epidemiological study of 1545 Massachusetts clerical workers in the private and public sectors on the relationship between VDT use and self-reported health symptoms. These researchers found a positive dose-response relationship between hours of VDT use and prevalence of pain, stiffness, and soreness in the shoulders and back. The prevalence of pain in the shoulders could be attributed to muscular fatigue from static contraction of the shoulder musculature. Hagberg and Sundelin (1986) found that six VDT wordprocessors averaged about 3.0% maximum voluntary contraction (MVC) in the upper trapezius muscle while they were typing during work periods of 3 to 5 hours.

In a study of 539 data entry VDT users, Sauter et al. (1991) found that 13% of the subjects reported almost constant discomfort in their right wrist. A statistical regression analysis indicated that ulnar deviation was the best predictor of right arm discomfort, which was the dominant arm for most subjects. Moreover, work station design factors explained 38% of the variance in discomfort at different body sites. While changes in workstation equipment (extrinsic ergonomic factors) may help those suffering from WMSDs, it may not be adequate, according to Pascarelli and Kella (1993). In a study of 53 disabled keyboard operators who complained of musculoskeletal pain from the shoulders to the hands, Pascarelli and Kella (1993) urged the recognition of intrinsic ergonomic factors such as retraining in keying technique and conditioning in the etiology of WMSDs due to typing.

In a study of 353 office workers, Bergqvist (1995) measured musculoskeletal discomfort and VDT work and how this relationship was affected by changes in office equipment and work organization. In general, Bergqvist (1995) found that increased use of the keyboard increased the reporting of hand/wrist problems. However, he found that new keyboards alleviated the musculoskeletal problems in the upper extremity of some subjects. A description of these new keyboards was not provided in the article.

In summary, it appears that the design of the keyboard is implicated in the etiology of upper extremity WMSDs among keyboard users for the following two reasons:

1) The often-cited occupational risk factors of repetitive movements and deviated posture of the wrist are an inherent part of typing on a computer keyboard.
2) There are a multitude of cross-sectional studies that have shown a strong positive relationship between musculoskeletal discomfort or pain and keyboard usage. However, it must be noted that, to the knowledge of the authors, there has not been a longitudinal study conducted and published in the literature that has established a direct cause and effect between keyboard usage and upper extremity WMSDs.

D.1.2. Design of Conventional Computer Keyboard

The computer keyboard has been the primary input device for computers and telecommunication, and it appears that it will continue to be a major input device in the future. The conventional computer keyboard (QWERTY) is a flat keyboard that has a two-dimensional matrix of alphanumeric keys that require one stroke for each character of the source document. The QWERTY keyboard (QWERTY is the arrangement of keys along the row above the left hand's home keys) was developed in the 1870s by Christopher Latham Sholes and is still the primary key layout, despite the development of alternative key configurations (Beeching, 1974). The DVORAK configuration, which was designed in 1936 and is probably the best known alternative key configuration, arranged the keys based on letter frequency and finger capacities (Kroemer, 1972). (A General Services Administration study failed to show any significant advantage of the DVORAK configuration (Klemmer, 1971)). The conventional QWERTY keyboard is an efficient data entry device in that the number of keystrokes per eight hour shift that a data entry clerk or office worker can enter ranges from 50,000 to 100,000 (Kroemer, 1972).

The conventional flat keyboard requires the operator to hold hands and forearms in a relatively awkward position. With this keyboard, the operator needs to pronate his/her forearms almost to the anatomical limit of the available range of motion in order to hold his/her palms almost horizontal (maximal pronation angle ranges from 80 to 100 degrees from the midposition

(Schoenmarklin and Marras, 1993)). In addition, the operator must deviate both hands in the ulnar direction in order to rest his/her fingers on the home keys, as shown in Figure 1.

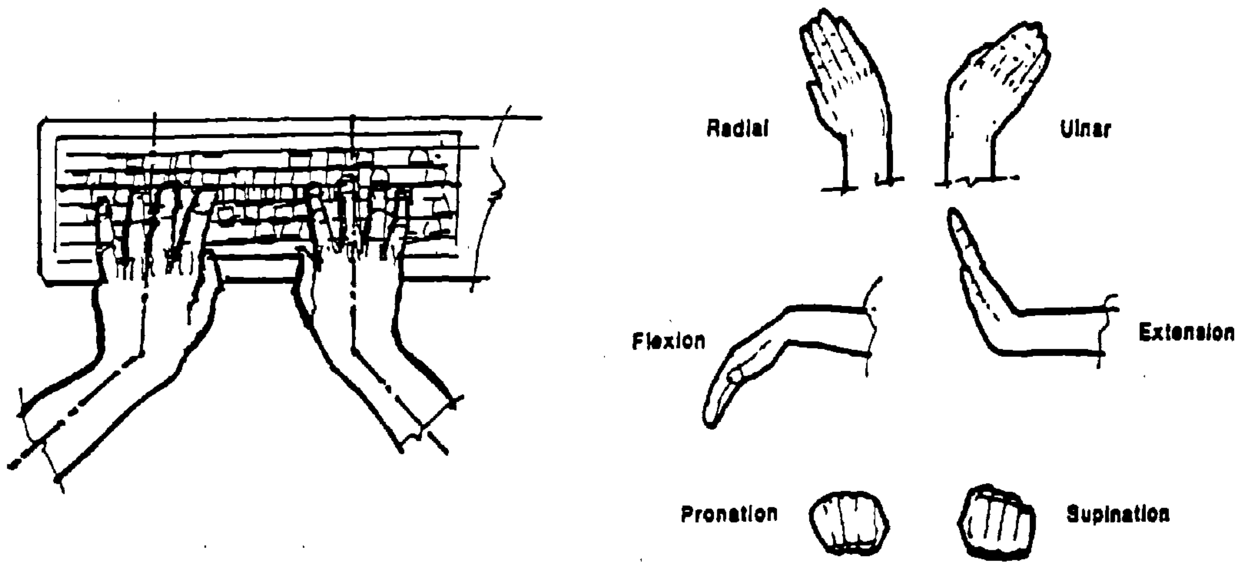


Figure 1. Top view of a conventional keyboard layout on the left. This layout requires ulnar deviation of the wrist, as well as pronation of the forearm near the forearm's anatomical limit of motion. On the right side of the figure, the planes of movement for wrist and forearm motion of the right upper extremity are illustrated.

In order to relieve tension from forearm pronation, the operator may tend to lift the elbows by abducting the shoulders (Kroemer, 1972). However, shoulder abduction has the consequence of exacerbating the ulnar deviation in the wrists, thereby producing a biomechanical tradeoff between excessive pronation of the forearm and excessive ulnar deviation of the wrist.

D.1.3. Biomechanical Aspects of Computer Keyboard Usage and WMSDs

Deviated wrist posture observed in the operation of conventional keyboards has been cited often as a risk factor for carpal tunnel syndrome (CTS) and upper extremity WMSDs overall (Alexander and Pulat, 1985; Armstrong, 1983, 1986; Armstrong and Chaffin, 1979; Armstrong et al, 1982; Armstrong et al, 1986; Browne et al., 1984; Charasch, 1989; Eastman Kodak Co., 1986; Fraser, 1989; Greenberg and Chaffin, 1975; Tichauer, 1966, 1978). Wrist flexion and extension are associated with CTS and tenosynovitis of the flexor tendons (Phalen, 1966), and wrist radial and ulnar deviation are associated with tenosynovitis and De Quervain's disease (Armstrong, 1983). The association between wrist posture and upper extremity WMSDs can be explained by biomechanical theory.

When the wrist is maintained in a neutral position, the tendons of the flexor and extensor muscles, which pass through the wrist, are "well-separated, run straight, and can operate efficiently" (Tichauer, 1978, p. 67). When the wrist is in extreme deviated posture, the net reaction force and friction applied to the tendons from the carpal bones and ligaments can irritate and inflame the tendon sheaths, causing tenosynovitis (Tichauer, 1978). Figure 2 illustrates the net reaction force on the tendons of the wrist joint. Once irritated, the inflamed flexor tendons, such as the flexor digitorum superficialis (FDS) and profundus (FDP), would occupy more space in the carpal tunnel, thus compressing the median nerve and contributing to CTS. In a static biomechanical model of the wrist, Armstrong and Chaffin (1979) showed how deviation of the wrist in the flexion/extension plane increased the net reaction force (**Fr** in Figure 2) from adjacent structures on the flexor tendons in the carpal tunnel. Similarly, in the radial/ulnar plane, the net reaction force on the tendons passing through the carpal tunnel would theoretically increase as the wrist is ulnarly deviated. As shown in Figure 2, as the tendon force (**Ft**) increases, so does **Fr**, the net reaction force. Therefore, with respect to conventional keyboards, the resulting elevated forces in the forearm muscles due to prolonged static contractions in deviated wrist postures could lead to tendinitis, tenosynovitis and CTS. Tendinitis could develop in the tendons that ulnarly deviate the wrist (flexor and extensor carpi ulnaris). Tenosynovitis could develop in the major tendons that pass through the carpal tunnel (FDS and FDP) and also the extensor digitorum communis. CTS could develop from the median nerve being compressed by the inflamed sheaths surrounding the FDS and FDP tendons.

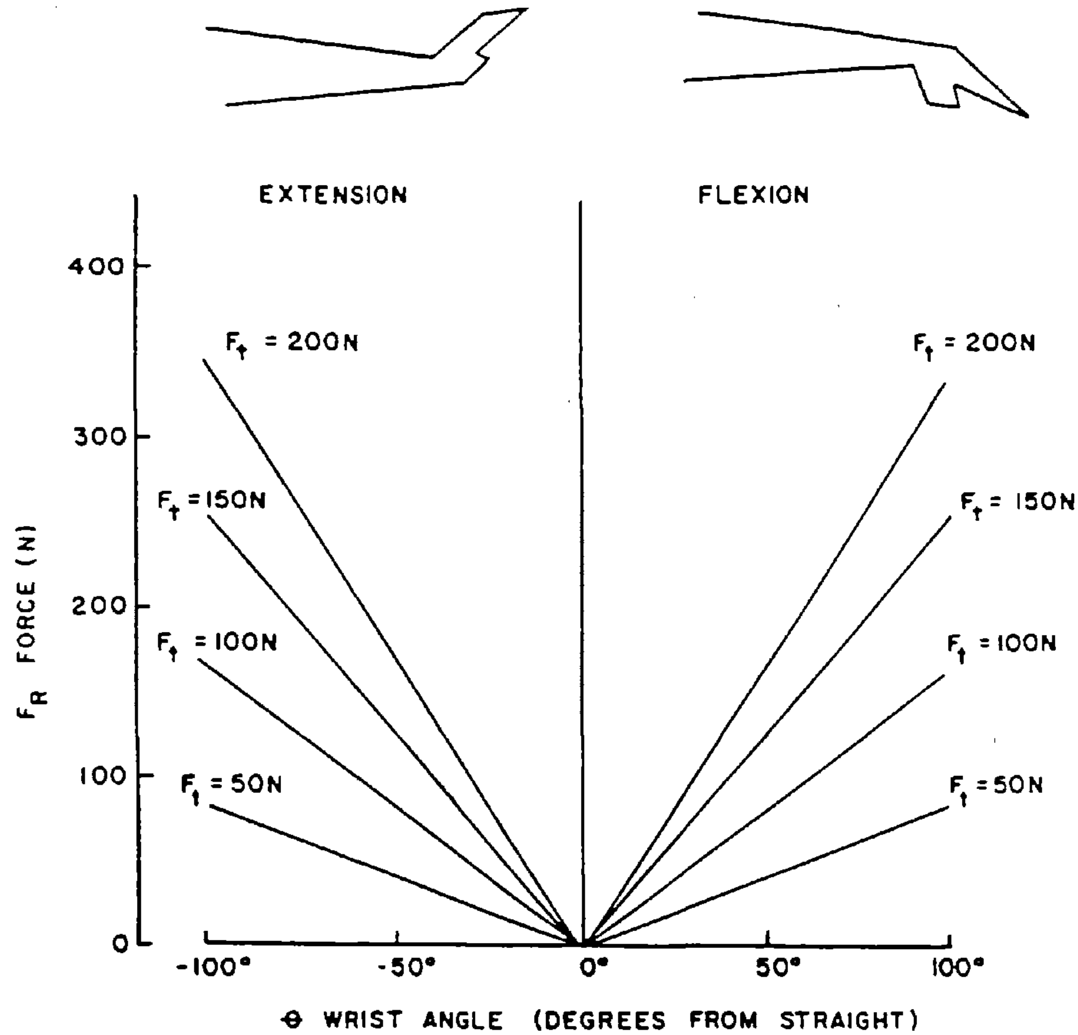


Figure 2. Net reaction forces (**Fr**) on the wrist joint as the wrist is flexed or extended. Adapted from Chaffin and Andersson (1991).

Development of upper extremity WMSDs from keyboard use could possibly be explained by studies of carpal tunnel pressure (CTP). Weiss et al. (1995) measured the pressure within the carpal tunnel of the wrist at a neutral posture and deviated at several angles in the radial/ulnar and flexion/extension planes. They found the lowest CTP was at a neutral position in both the radial/ulnar and flexion/extension planes. When the wrist was deviated from neutral, the CTP increased parabolically with the position of the wrist. CTP was approximately 20 mm Hg at 10 deg. ulnar deviation and about 15 mm Hg at 15 deg. wrist extension, which is the typical wrist posture of a user typing on a conventional keyboard.

Sommerich (1994) measured the CTP of four typists while they were typing, and she found that split keyboards did reduce CTP concomitantly with reductions in ulnar deviation. However, she found wide variations in CTP among her four subjects. Only one subject recorded CTP exceeding 30 mm Hg for a substantial period of time, which is the pressure threshold that can block fast axonal transport, resulting in morphological changes in the body of the nerve cell (Dahlin, 1990; Szabo et al., 1992). However, pressures as low as 20 mm Hg can retard blood flow within the nerve (Rydevik et al., 1981). Widely-varying CTPs between subjects from Sommerich's CTP study may explain why some keyboard users develop WMSDs while others do not.

In 1926, Klockenberg (cited in Kroemer, 1972) noticed the unnatural posture required for a flat keyboard and suggested a keyboard tilted in the vertical plane in order to relieve stress from forearm pronation. In an attempt to reduce the stress on the forearms and wrists, Kroemer (1972) tested an experimental keyboard that was not only tilted in the vertical plane, but also separated in the middle to reduce ulnar deviation, as illustrated in Figure 3a. Based on his results, Kroemer (1972) suggested the following improvements to the conventional flat keyboard:

1) to reduce ulnar deviation, separate the keyboard into two halves and angle the halves to facilitate positioning of fingers with the wrist in a neutral posture in the radial/ulnar plane.
2) to reduce forearm pronation, incline the keyboard halves in the vertical plane to align the forearms in a neutral position.

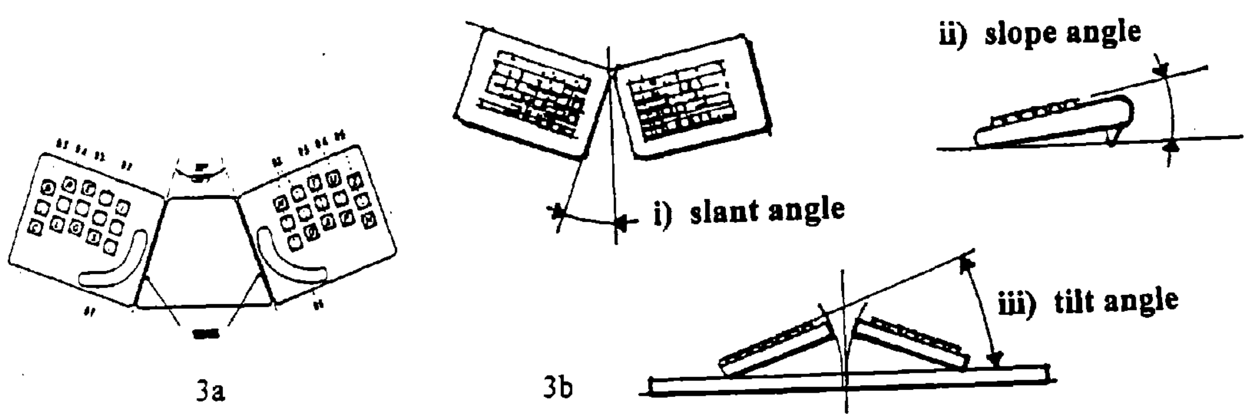


Figure 3. a) Top view of an experimental keyboard tested by Kroemer (1972). The keyboard is split into halves and rotated to minimize ulnar deviation. The rows of keys are curved to reflect the natural orientation of the fingers. b) The slant (i), slope (ii), and tilt (iii) angles of an alternative keyboard.

The total separation angle between the keyboard halves of Kroemer's (1972) is twice that of the slant angle, as shown in Figure 3b. The slant angle is typically the angular metric that is used to describe the amount of separation of split keyboards. Rotation of the keyboard in the other two orthogonal planes is referred to as the slope and tilt angles ((ii) and (iii) in Figure 3b). Keyboards that are tilted above the horizontal, which resemble the movement of a drawbridge, are called vertically-inclined in this report.

Nakaseko et al. (1985) tested a split keyboard like Kroemer's (1972) and found that subjects reported less pain and an increased feeling of relaxation when operating split keyboards. The split keyboards, angled at 25 degrees to each other, decreased ulnar deviation by 10 degrees as compared to the conventional keyboard (20 to 10 deg. ulnar deviation). In addition, more than 70% of the subjects preferred a split keyboard that was tilted (vertically-inclined).

A split and inclined keyboard is advantageous from a biomechanical and physiologic point of view. A conventional keyboard produces static tension in the muscles that pronate the forearm and the muscles that extend and ulnarly deviate the wrist. This static tension could lead to unnecessary muscle forces and localized muscular fatigue (Rohmert, 1960). Zipp et al. (1983) measured the electromyographic activity (EMG) of the upper extremity muscles of subjects typing on a conventional flat keyboard and a split and inclined keyboard, and they found that the split and inclined keyboard decreased the EMG activity of the muscles that pronate the forearm and ulnarly deviate the wrist. Moreover, a reduction of ulnar deviation also reduced the strain of most of the neck, shoulder, and arm muscles. These authors inferred that the decreased EMG levels from the more neutral posture of the forearm and wrist represented a genuine reduction in muscle tension. Based on these EMG results, Zipp et al. (1983) recommended a keyboard that was split, sloped at an angle of 10 to 20 deg., and tilted about 10 to 20 deg.

The results from Zipp et al. (1983) lend insight into why the unnatural wrist and forearm posture dictated by the conventional flat keyboard could cause CTS or upper extremity WMSDs. The muscles that Zipp et al. (1983) monitored -- pronator teres, which pronates the forearm, and flexor and extensor carpi ulnaris, which deviate the wrist ulnarly -- do not pass through the carpal tunnel. However, the flexor carpi ulnaris muscle run approximately parallel to the muscles whose tendons do pass through the carpal tunnel, the FDS and FDP. Because of their similar geometry and orientation, an increase in static tension in the flexor carpi ulnaris muscles from a pronated and ulnarly deviated posture would probably indicate an increase in the force of the flexor digitorum muscles. These additional force levels would occur during the entire time that a typist has his/her forearms pronated and wrist deviated ulnarly. The additional force in the flexor digitorum tendons would increase the reaction and shear forces against the tendons and could cause breakdown of the tendons' sheaths (tenosynovitis) or compress the median nerve, possibly causing CTS.

The repetitive movements required for depressing keys could also explain why keyboard users develop upper extremity WMSDs. Silverstein et al. (1986, 1987) conducted two epidemiological studies that provided evidence for a crude dose-response relationship between jobs that required highly repetitive hand/wrist movements and incidence of CTS and upper extremity WMSDs overall. After controlling for potential confounders, Silverstein et al. (1987) reported that the odds ratios in high-force/high-repetition industrial jobs compared to low-force/low-repetition jobs were more than 14 and 30 for CTS and upper extremity WMSDs, respectively. The odds ratios for jobs requiring high-repetitions, but low-force, had odds ratio of 1.9 and 3.6 for CTS and upper extremity WMSDs, respectively, compared to low-repetition/low-force jobs. Although typing on a computer keyboard would be considered a high-repetition/low-force job, the odds ratios for CTS and upper extremity WMSDs calculated in Silverstein's et al. studies (1986, 1987) may not apply to typing because Silverstein's classification of jobs did not include typing on keyboards.

The frequency of a task (repetition) may be a form of another risk factor, namely tendon force. Technically, repetition can be defined in biomechanical terms as cyclic angular acceleration, peak velocity, and deceleration about a joint. The tendons that flex the fingers, FDS and FDP, originate in the forearm and pass through the wrist. In order to accelerate the finger to depress a key, the respective FDS and FDP muscles in the forearm have to generate force according to Newton's second law of motion, $F = M * A$. Based on this law, the force that the extrinsic muscles in the forearm have to exert is proportional to the acceleration of the finger or wrist. Schoenmarklin and Marras (1990) developed a dynamic biomechanical model of the wrist joint that explained how angular acceleration of the wrist theoretically increases the net reaction force on the nerves and tendons passing through a joint, thereby increasing the risk of CTS and upper extremity WMSDs overall. Moreover, there was an interaction between acceleration and joint angle that exacerbated the net reaction force, as indicated in Figure 4. If an operator's wrist were deviated (even slightly) while typing, there would be a net reaction force on the tendons and nerves passing through the wrist. The faster the typing rate (i.e. greater acceleration), the greater the force in the tendon, and consequently, the greater net reaction force. Repetitive motions of the fingers and wrist could have a profound impact on the biomechanical forces in the tendons passing through the wrist and the resulting reaction forces.

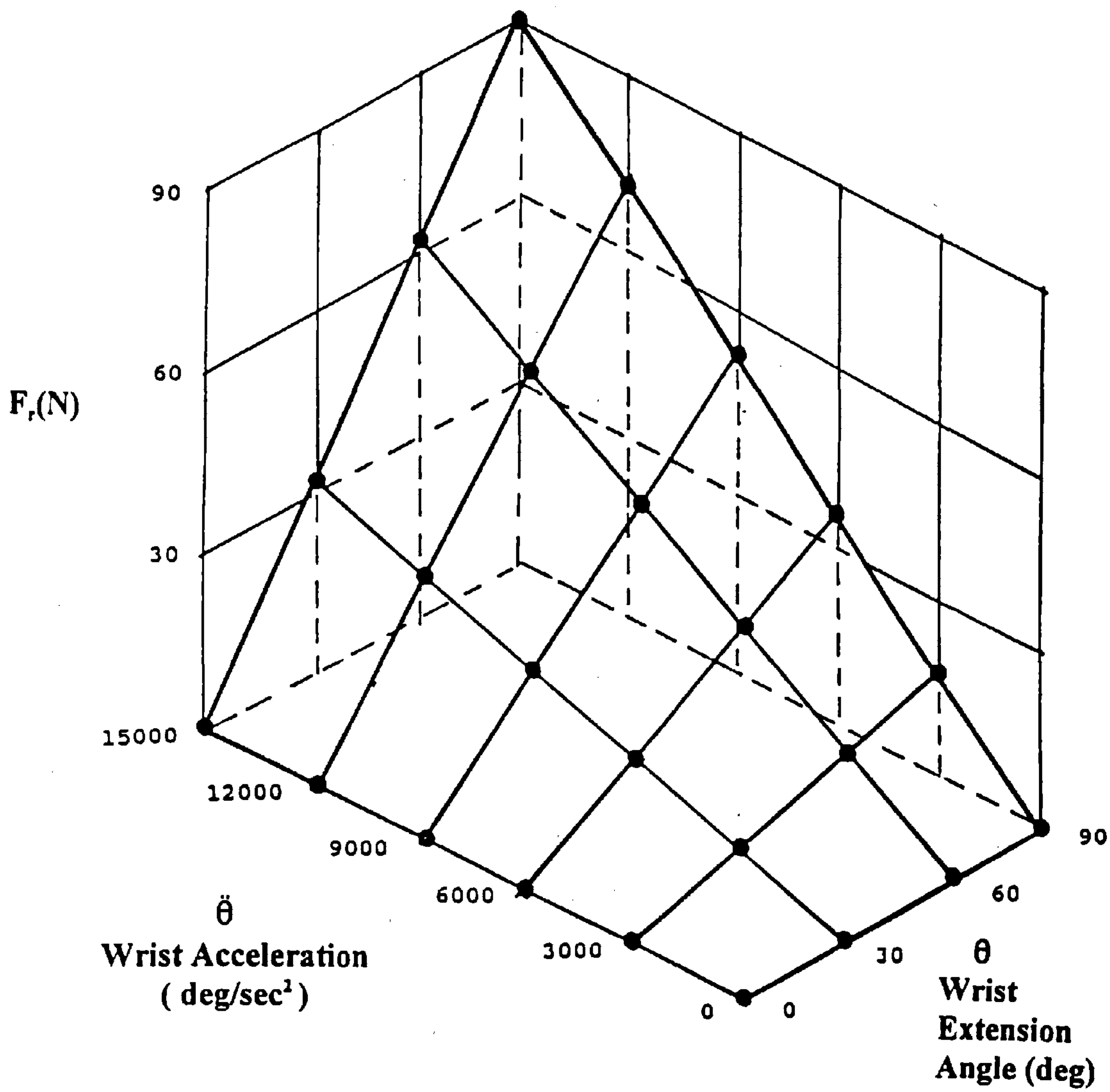


Figure 4. Net reaction force (**Fr**) on the wrist joint as a function of wrist acceleration and angle. Adapted from Schoenmarklin and Marras (1990).

During repetitive movements either in the fingers or wrist, part of the tendon force generated by the extrinsic muscles in the forearm will be lost to friction between the tendons and their adjacent structures. As the tendon is moved inside their sheaths in the wrist and finger joints, frictional energy is generated. This frictional energy, which is absorbed by the tendons and possibly their surrounding tissues, could deteriorate and inflame the tendons, thereby contributing to CTS and upper extremity WMSDs. Tanaka and McGlothlin (1989) hypothesized frictional work as a major cause of WMSDs.. Moore et al. (1991) found that friction between the tendons and adjacent structures was the mechanical parameter that best supported Silverstein's et al. (1986, 1987) dose-response relationships.

D.1.4. Studies of Alternative Computer Keyboard Designs

Many new computer keyboard designs featuring split halves that are rotated in the horizontal plane and/or inclined in the vertical plane have been introduced to the marketplace within the last decade. Several of these commercially-available keyboards comprise three categories of fundamentally different designs, which are described as follows and illustrated in Figures 5a through 5c.

The split fixed-angle keyboard is a flat keyboard that has the matrix of keys divided into halves that are rotated at a fixed separation angle of 20 to 30 deg. to each other (depending on the specific brand).

The split adjustable-angle keyboard is a split keyboard in which the separation angle between key halves can be adjusted.

The vertically-inclined keyboard is split into halves that can incline in the vertical plane, much like a drawbridge.

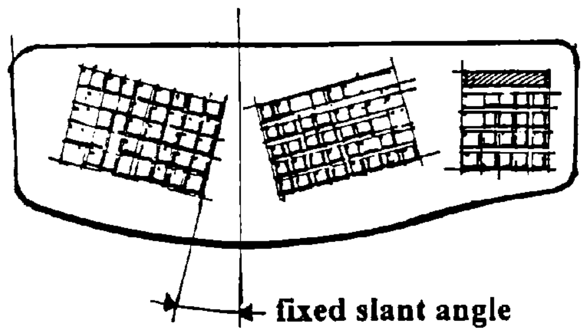


Figure 5a. Sketch of a commercially-available split fixed-angle computer keyboard.

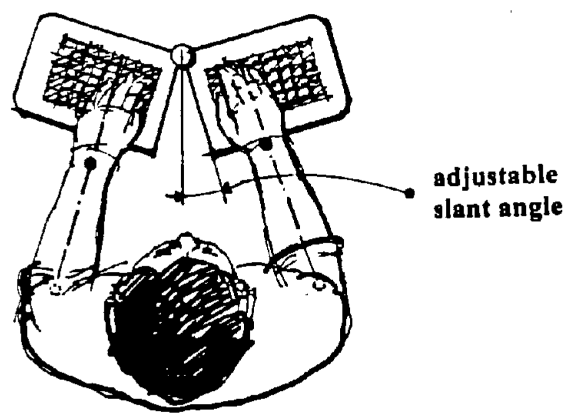


Figure 5b. Sketch of a commercially-available split adjustable-angle computer keyboard.

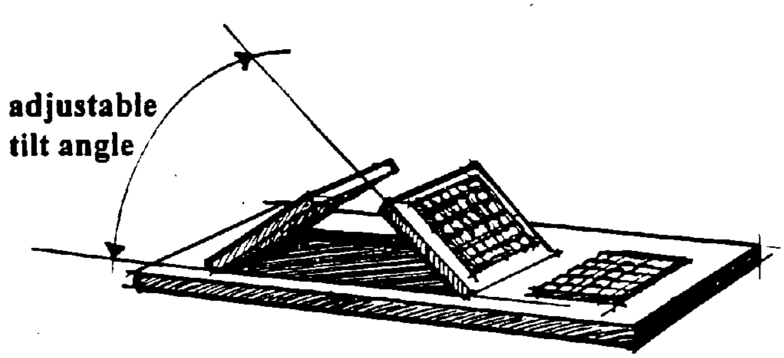


Figure 5c. Sketch of a commercially-available vertically-inclined computer keyboard.

D.1.4.1. Studies of Commercially-Available Alternative Keyboards
-- Subjective Ratings, Productivity, and Physiological Measures

Since 1990 many studies have been conducted as to whether commercially-available keyboards are optimal with respect to subjective ratings of comfort, productivity, and physiological measures, such as electromyography (EMG). In 1990 Thompson et al. used a split adjustable-angle keyboard called the Tony! Keyboard to determine the optimal keyboard slant and tilt angles. These researchers measured the EMG of the forearm flexors and extensors along with subjective preferences of the Tony! compared to the conventional keyboard. According to this study, the optimal slant angle was 9 deg. (separation angle of 18 deg.) and the optimal tilt angle ranged from 30 to 60 deg. for their eight subjects. However, one should treat the EMG data from this study with caution since the EMG data were analyzed as millivolts and were not normalized to % MVC (maximum voluntary contraction), which is the preferred method of analyzing EMG data (NIOSH, 1992).

Similar to Thompson et al. (1990), Marek et al. (1992) evaluated the use of a split keyboard with EMG activity. The muscle groups these researchers measured were the trapezius and forearm extensors. They found that among their 16 subjects the split keyboard significantly reduced muscular loading of the trapezius muscle and subjective feelings of muscular tension in the shoulder-neck region. The EMG results from this study must be treated with caution, again, since EMG recordings were analyzed as millivolts and not % MVC. The split keyboard that Marek et al. (1992) tested had a slant angle of 13 deg. (separation angle of 26 deg.), a slope of 10 deg., and a tilt angle of 5 deg. The authors do not state whether their subjects, who typed for 15 minutes on each keyboard during testing, were allowed to practice typing on the keyboards before testing.

Cakir (1995) investigated whether a split adjustable-angle Macintosh keyboard, whose slant angle can be adjusted up to 15 deg. (30 deg. separation angle), is advantageous to a split fixed-angle keyboard with a 12.5 deg. slant angle (which was tested prior and results unpublished) and a conventional keyboard. Cakir (1995) tested the split adjustable-angle and conventional keyboards on 26 subjects, and he found no significant difference in typing performance. However, compared to the conventional keyboard, the subjects rated the split adjustable-angle keyboard favorably with respect to its design and its impact on postural comfort. One of the purposes of this study was to determine how long it would take a typist to become familiar with the split adjustable-angle keyboard, and Cakir (1995) concluded that the seven hour familiarization results from a study on the concave well-design keyboard (Smith and Cronin, 1993) are consistent with his findings. Cakir (1995) does not report the familiarization period of his subjects, whom he tested in his previous unpublished work, to the split fixed-angle keyboard.

In 1993 Douglas et al. conducted a study of an IBM PS/2 keyboard compared to two split QWERTY keyboards. They found that the typing speed and number of errors from their nine subjects typing on the IBM PS/2 keyboard was significantly higher and lower, respectively, than the split keyboards. In addition, they found the subjects preferred the conventional IBM PS/2 keyboard to the split keyboard. Douglas's et al. (1993) experimental protocol provided each subject a ten minute "warmup" practice session at the start of each day. Each subject typed for three hours during each of three days, and each subject typed on only one keyboard each day. The authors do not state whether the subjects were allowed to practice on the alternative keyboards more than the ten minute "warmup" at the start of the day.

In 1995 Morelli et al. tested three commercially-available keyboards on 34 experienced telemarketers, each of whom typed on each alternative keyboard for a week. One of the three alternative keyboards was composed of three highly-adjustable modules, while the other two keyboards were non-adjustable alternative keyboards. After using each keyboard, subjects completed a questionnaire of seven psychophysical attributes relating to comfort and use of the keyboard. Morelli et al. (1995) found that the subjects rated the three alternative keyboards better in 'posture required for keying' and overall comfort than the conventional keyboard, although there were no significant differences among the three alternative keyboards themselves.

In a self-reported surveillance conducted over the Internet, Wright (1996) surveyed over 200 users of alternative keyboards. He found that the primary reason these users bought alternative keyboards is to help recover from injuries and avoid future musculoskeletal impairments. The predominant reason for selecting the commercially-available split keyboards was to improve keying posture and enhance comfort.

Swanson et al. (1997) tested three split keyboards and a conventional keyboard among 50 subjects who were recruited from a temporary employment agency. These researchers had 10 subjects test a keyboard under one of the following five conditions:

1) conventional keyboard
2) a split keyboard setup with no slant angle and no tilt angle
(setup like a conventional keyboard)
3) a split keyboard setup with no slant angle but a tilt angle of 12 deg.
4) a split keyboard with a slant angle of 12.5 deg. (separation angle of 25 deg.)
and a tilt angle of 45 deg.
5) a keyboard that separated the halves approximately shoulder width apart
and featured concave wells for each hand's fingers.

'Note: Conditions 2) and 3) were two different setups of the same keyboard.

Swanson et al. (1997) required each subject to type on the conventional keyboard for one day and then on one of the five keyboard conditions described above for two subsequent days. Subjects typed for 300 minutes each day, separated into four 75-minute work periods. The results from this study show that there were no significant differences in musculoskeletal discomfort and fatigue among the five keyboard conditions described above. There was a significant increase in discomfort and fatigue as the workday progressed, though. With regard to typing performance, the subjects typed significantly slower during the second day of testing with the concave-well design (keyboard condition 5) and with the split keyboard tilted at 45 deg. (keyboard condition 4), compared to other keyboard conditions. However, the performance decrement disappeared on the third day of testing for keyboard conditions 4) and 5).

Overall, commercially-available split keyboards received mixed results in terms of musculoskeletal comfort, both measured physiologically and recorded as perceived subjective ratings, from the literature review described above. Thompson et al. (1990), Marek et al. (1992), and Morrelli et al. (1995) all found the split keyboard to be favorable to the conventional keyboard physiologically or subjectively. On the contrary, Douglas and Happ (1993) and Swanson et al. (1997) found either no differences between the two keyboard designs or the conventional keyboard superior.

In order to interpret the mixed results of conventional vs. commercially-available split keyboards, one must look carefully at the experimental protocols and data analysis. Thompson et al. (1990) and Marek et al. (1992) analyses of EMG data were flawed in the sense they did not analyze EMG as %MVC, which is the preferred method (NIOSH, 1992). If these researchers had used %MVC as their dependent measure, it is not known whether the results would have been the same or different. In Douglas and Happ's (1993) study, it appears the subjects were not given any time to practice and become familiar with the two alternative keyboards, other than the ten minute 'warmup' period. Consequently, it is not surprising that the subjects' typing performance was greater for conventional keyboard and the conventional keyboard was preferred to the alternative keyboards, given the brief acclimatization time of ten minutes. Swanson's et al. (1997) results showing no significant difference in comfort between conventional and alternative keyboards over a two day period do not mean the alternative keyboards are not advantageous, but rather the two day period may not have been long enough for subjects to detect a difference in subjective comfort. If Swanson et al. (1997) had required their subjects to type on the assigned keyboard for a week, then maybe Swanson's et al. (1997) subjective comfort measures would have resulted in significantly higher comfort ratings (or lower discomfort ratings) for alternative keyboards over the conventional keyboard, which would have been consistent with Morelli's et al. (1993) findings. Although Morelli et al. (1993) did not measure subjective comfort but rather preferences of keyboards, they found subjects preferred the split keyboard over the conventional keyboard after one week of practice typing on the split keyboard. In summary, it is difficult to make inferences about the beneficial effects of conventional vs. commercially-available alternative keyboards based on physiological and subjective ratings of comfort and preference because practice and testing protocols have varied so much in the literature.

D.1.4.2 Studies of Commercially-Available Alternative Keyboards -- Wrist Posture

A few studies have investigated whether commercially-available alternative keyboards place the wrist in a more neutral posture than a conventional keyboard. According to Buesen (1984), the first truly 'ergonomic' keyboard for modern VDTs was shown to the public in April 1983. This keyboard was a split design that had a slant angle of 12.5 deg. (separation angle of 25 deg.), slope angle of 10 deg., and a tilt angle of 10 deg. Buesen said that the angular deviations built into the three planes of the keyboard were determined by feedback from prospective 600 customers, of whom 55% preferred the split over the conventional keyboard. The author does not state in this article whether these customers were experienced typists nor whether they actually typed on the split keyboard.

In 1985 Naseko et al. conducted a study on a split keyboard with a 12.5 deg. slant (separation angle of 25 deg.) and a 10 deg. tilt with 31 subjects, all of whom were trained typists. Although this keyboard was not a commercially-available keyboard, it was a functional prototype that was durable enough for experimental testing in the laboratory. Each typist typed for 45 minutes for each of the following three conditions, with a 30 minute rest between conditions.

1) conventional keyboard with a large forearm-wrist support
2) split keyboard described above with a small forearm-wrist support
3) split keyboard described above with a large forearm-wrist support

The authors do not state whether the subjects practiced typing on the split keyboards before testing. Using an oil-damped goniometer, Naseko et al. (1985) found that the subjects typed with about half the ulnar deviation dictated by the conventional keyboard (10 to 12 degrees of ulnar deviation for the two split keyboard conditions and 20 degrees of ulnar deviation for the conventional keyboard), independent of size of forearm-wrist support. The authors conclude that the decrease in ulnar deviation is definitely due to the split keyboard's slant angle of 12.5 deg.

In 1994 Chen et al. conducted a study of the conventional and three alternative keyboards on 11 subjects who worked at the Lawrence Livermore National Laboratory. The three alternative keyboards that were tested were the Apple adjustable, Kinesis, and Comfort keyboards. Wrist radial/ulnar and flexion/extension position were measured by the MacReflex 3D motion analysis system. Each subject was allowed to setup each of the three alternative keyboards to a position that was comfortable. The mean slant angle selected by the subjects for the Apple keyboard was 5 deg (s.d. = 6 deg.) (total separation angle of 10 deg.). The mean wrist ulnar deviation angle for the Apple, Comfort, and conventional keyboards was about 15 to 17 deg., while the mean wrist ulnar deviation angle for the Kinesis was approximately 5 deg. Subjects' typing speed on the Kinesis keyboard was about 66% of the other keyboards. Overall subjective ratings reveal that the three alternative keyboards were preferred to the conventional keyboard. The practice time allowed for each subject was three minutes before testing on each of the four keyboards.

In a study investigating the Apple adjustable keyboard, Sommerich (1994) measured the wrist ulnar deviation angle of four right-handed females who typed on a conventional keyboard and an Apple keyboard with a slant angle of 7.5 deg. (15 deg. separation angle) for three of her four subjects (the fourth subject had a separation angle of 22.5 deg.). The mean range of wrist ulnar deviation position for the four subjects who used the Apple keyboard was about 5 deg. less than for the conventional keyboard (10 to 20 deg. for the split and 15 to 25 deg. for the conventional keyboard). The subjects' wrist extension for both keyboards was approximately the same (0 to 15 deg.). The author did not report the duration of testing and whether subjects were allowed to practice on the split keyboard before testing.

In a study of 50 subjects, Honan et al. (1995) measured the wrist and forearm posture of a Microsoft Natural keyboard, a Natural keyboard with a leveler, and a conventional keyboard. Each subject typed on each keyboard that was adjusted to three different heights, thereby resulting in nine experimental conditions for each subject. Subjects practiced on each keyboard configuration for ten minutes before radial/ulnar, flexion/extension, and pronation/supination data were collected for ten minutes during the respective condition. These researchers found that the Microsoft Natural keyboard, with or without the leveler, reduced mean ulnar deviation 7 to 10 deg. less than the conventional (15 to 6 deg. for the right wrist and 16 to 9 deg. for the left). Wrist extension angle ranged between 20 to 28deg.

The wrist ulnar deviation position of 12 experienced typists working on a conventional keyboard, a keyboard mounted on the forearm support of a chair, and a conventional keyboard with a negative slope of 12 deg. were recorded by Hedge and Powers (1995). Although the chair-mounted keyboard was split, it appears from the article that the two halves were not angled towards each other. The subjects were allowed to configure the chair-mounted keyboard themselves to a position where it felt comfortable. Hedge and Powers (1995) found that the amount of wrist ulnar deviation was comparable among all three keyboard conditions, and the right and left wrists averaged 13 and 15 deg. of ulnar deviation, respectively. The negatively-sloped keyboard reduced wrist extension from 13 deg. of extension to one deg. of flexion, as compared to the conventional and chair-mounted keyboards. With regards to the experimental protocol, the 12 subjects typed a five minute 'pre-training' session and then three sessions of 50 minutes (one for each keyboard condition). The authors do not state whether the subjects practiced on the chair-mounted keyboard before testing in the laboratory.

As a follow-up to their previously mentioned work, Hedge and Shaw (1996) measured wrist position of 12 proficient typists who typed on a Floating Arms Keyboard (FAK) and a conventional keyboard. Each subject typed for 80 minutes on each keyboard, and their wrist ulnar deviation and extension angles were measured with an Exos Gripmaster system during the last 10 minutes of the 80 minute typing session. The authors do not state whether the subjects were allowed to practice on the FAK before testing. Hedge and Shaw (1996) found that the FAK reduced mean wrist ulnar deviation to 1.7 deg. as compared to 8.5 deg. of ulnar deviation for the conventional keyboard. In addition, these researchers measured the time the wrist was deviated greater than 15% of their mean wrist ulnar deviation *or* 15% of their mean wrist extension angle. For the FAK the subjects spent 27.5% of the time greater than 15% of their mean ulnar or mean extension position, significantly less than the conventional keyboard's 38.9%. There was no difference in mean wrist extension angle between the FAK (9.7 deg.) and the conventional keyboard (10.8 deg.).

In a study of 20 experienced typists, Honan et al. (1996) investigated whether wrist or forearm postures change for either a split or conventional keyboard over a four hour period of intensive keyboard use. The ten subjects randomly assigned to the split keyboard did not have any practice typing on the split keyboard, the Microsoft Natural Keyboard with Leveler, prior to testing. The researchers in this study did not find wrist and forearm postures changing significantly over the four hour period for the split keyboard, but some changes in posture occurred for the conventional keyboard. For the split keyboard, ulnar deviation averaged approximately 2 to 5 deg. for the right wrist and 0.6 to 3 deg. for the left wrist over the four hour period. Ulnar deviation dictated by the conventional keyboard ranged from 10 to 12 deg. for the right wrist and 12 to 15 deg. for the left wrist over the four hour period. Wrist extension ranged from 20 to 30 deg. for both keyboards, and pronation ranged from 65 to 75 deg. for both keyboards.

The literature review of studies that measured wrist posture of commercially-available split keyboards can be categorized into three groups, which vary in the amount of ulnar deviation measured while subjects typed on a split keyboard. First, there are two studies (Chen et al., 1994; Sommerich, 1994) who allowed their subjects to select an opening angle that was comfortable to them, which averaged about 10 to 15 deg. for subjects from both studies. The resulting ulnar deviation from subjects typing on a split keyboard with a 10 to 15 deg. separation angle was about 15 deg., which was either not different nor slightly less than the ulnar deviation from the conventional keyboard. The lack of a significant difference in ulnar deviation between the split and conventional keyboards may be due to the small difference in separation angles between the split and conventional keyboards (10 to 15 deg. vs. 0 deg.).

The second category was Naseko's et al. (1985) study of a split keyboard. This keyboard had a fixed slant angle of 12.5 deg. (separation angle of 25 deg.), and subjects typing on this keyboard reduced their ulnar deviation to about half of the ulnar deviation from a conventional keyboard (from 20 to 10 deg.). The third category consisted of Hedge and Shaw's (1996) and Honan's et al. (1996) studies where they found that wrist deviation in the radial/ulnar plane of subjects typing on the adjustable Floating Arms and the Microsoft Natural keyboards, which has a fixed separation angle of 25 deg., approached a neutral position within 2 to 3 deg.

In summary, it appears that if a commercially-available split keyboard has an opening angle of approximately 25 deg. (12.5 slant angle), then ulnar deviation is reduced to almost a neutral position in the radial/ulnar plane. The ulnar deviation from subjects typing on a conventional keyboard is typically at least 10 degrees.

D.1.5 Research Voids

After an extensive review of the literature on alternative QWERTY computer keyboards, the following research voids became apparent:

1) *Generally, small number of subjects in studies that measured physical metrics, such as posture.* Except for one study (Honan et al., 1995), the number of subjects in studies that measured wrist posture ranged from 4 to 20, which may be large enough to make statistical inferences (in some cases) and see trends occurring, but not large enough to generalize results -- whether the effects are beneficial or nonexistent -- to the large population of keyboard users. Results from Honan's et al. (1995) sample of 50 subjects, which is more than twice as great as other studies reported in the literature, are more reliable in generalizing results from laboratory studies to the large population of keyboard users, who can vary greatly in anthropometry and typing performance.

2) Amount of time provided to subjects to practice on the alternative keyboards. The subjects who participated in the studies where wrist posture was measured were given a paucity of time to practice on the alternative keyboard, sometimes as short as three minutes and not exceeding 30 minutes in those articles where the practice time was stated. In several publications, the practice time was not reported, which can lead one to think that practice time was not substantial and not an important part of the study. When one considers that typical subjects have been typing on the conventional keyboard at least five years and sometimes as long as two or three decades, it would appear that practice time for an alternative keyboard, albeit QWERTY, would not only be allowed, but required.

3) General absence of measurement of pronation/supination of the forearm. The pronation/supination angle of the forearm was measured in only two studies that were part of our literature review (Honan et al., 1995, 1996). Since pronation of the forearm is often cited as a major theoretical cause of physical pain and discomfort for conventional keyboard users (Kroemer, 1972; Zipp et al., 1983), its measurement would certainly bolster our knowledge of the working postures if typists and possibly enhance our understanding of the etiology of upper extremity WMSDs afflicting keyboard users.

The thrust of the research presented in this report was to address the research voids outlined above and to investigate, as thoroughly as possible, whether commercially-available split computer keyboards are actually beneficial from a biomechanical point of view, namely, do they place the wrist and forearm in a more neutral posture than a conventional keyboard? In this study, 90 subjects, all of whom were experienced keyboard users who could type over 45 words/min using the standard ten finger 'touch' method, were required to practice at least 10 hours during a two week period in their work place on the alternative keyboard assigned to them. After practicing on the alternative keyboard, subjects came to the laboratory for testing, where pronation/supination (pron/supin) of the forearms was measured along with wrist radial/ulnar (rad/uln) and flexion/extension (flex/ext) position while they were typing both alphabetic and alphanumeric texts.

D.2 SPECIFIC AIMS

The specific aim of this research was to determine if commercially-available QWERTY computer keyboards that have fundamental designs different than the conventional flat keyboard would influence wrist and forearm position while typing. Secondary aims of this project were to determine if the influence would be the same for both the left and right wrists and forearms and similar for tasks that involve typing mostly alphabetic characters versus alphanumeric texts.

D.3. PROCEDURES

In this study, 90 professional touch typists were recruited to test how alternative QWERTY computer keyboards influence wrist and forearm position while typing. In order to optimize the validity of the kinematic results, we conducted the study in a manner that provided the subjects with ample practice time on the alternative keyboard before data collection. Our strategy was to have each subject type on an alternative keyboard, which was randomly-assigned to the subject from a set of three fundamentally-different designs, in their workplace (performing actual work) for a period of one to two weeks (or a minimum of 10 hours of typing). After the one to two week practice period, each subject came to the laboratory for testing. Since the practice time was extensive for each subject, each subject was tested on only one of the three alternative keyboards, resulting in a total of 30 subjects using each one of the three alternative keyboards.

Testing was conducted during a three hour session in a controlled laboratory setting at Marquette University. Upon arrival at the laboratory, subjects were asked to sign a human subject consent form, which is shown in Appendix 1. Then, they were asked to fill-out a questionnaire that queried them on background demographics as well as their subjective perception of the alternative keyboard. The subjects were asked to rate the alternative keyboard in terms of its comfort and ease of use compared to the conventional keyboard. Following the questionnaire, anthropometric dimensions and physical characteristics recording sensory function, strength, and range of motion were measured. A copy of these data collection forms are attached in Appendix 2.

Following all measurements, the subject was seated at an adjustable computer work station, consisting of an adjustable office chair, adjustable desk, a footrest (if needed), a keyboard, and a tilt-adjustable VDT. The workstation was adjusted so the gross posture of the subject met the posture criteria for VDT operators in the ANSI Standard (ANSI-HFS 100-1988). Chair height was set so that the subject had both feet on the floor with a knee angle slightly less than 90 degrees. In this position, the subjects knees were slightly lower than the hips in order to maintain some lordosis in the lumbar spine. Once the chair height was properly adjusted, the table supporting the monitor was adjusted such that the center of the VDT screen was approximately at a 20 degree angle below a horizontal line passing through the subject's eye-level. The shelf supporting the keyboard was adjusted so the subject's elbow angle was approximately 90 deg.

and the forearm was horizontal. The adjustability of the workstation provided the necessary standardization of typing posture to minimize the effect of the subject's gross posture on the variables of interest in this study, namely, wrist and forearm posture.

After the work station was properly positioned, a set of wrist, forearm and finger electrogoniometers used to measure joint angle were attached to both upper extremities in a specific sequence described later in the methodology section (D.4.5). Once the subject was fully instrumented, each electrogoniometer was calibrated following a standard procedure also described later in the methodology section (D.4.5). Following the calibration procedure, the subject sat at the workstation and any final adjustments in the chair and work station were made before testing started.

Testing consisted of having each subject type both on a conventional computer keyboard and their assigned alternative keyboard they had practiced on for the previous one to two weeks. For each keyboard, three typing tasks of eight minutes duration were performed by the subject. A short rest period was given between each of the typing tasks. For each keyboard, the first two typing tasks were alphabetic typing tasks since the text that was typed consisted primarily of letter characters with very few numeric and symbolic (special function keys) characters being used. The third typing task was referred to as alphanumeric since the text included a large number of numeric and symbolic keys (a short text sample for each typing task is included in Appendix 3). The presentation order of the conventional and alternative keyboards was randomized for each subject and balanced over the entire group of subjects.

The texts that were typed in the two eight-minute alphabetic typing periods for each keyboard were selected from a list of eight possible standard texts. Each subject typed a different text during each eight-minute alphabetic typing period in order to minimize any benefit from learning previously-typed text. Throughout the study, texts were assigned so that their frequency of usage was the same for each alternative keyboard and each conventional keyboard. While this assignment of text required a significant a priori effort and planning, it ensured that no differences in wrist posture found among keyboards could be due to the text typed.

Whereas each of the alphabetic texts were from 7th-grade social science material, the alphanumeric typing tasks resembled word problems from a high school physics book that contained statistics, mathematical formulae, dates, and other numeric text. These texts do contain English words and sentences, though the alphanumeric texts themselves do not lend to easy interpretation by the subject. Again, the selection of which alphanumeric text the subject was to type on each keyboard was balanced in such a way that each text was used the same number of times for each alternative and conventional keyboard.

Testing followed the following sequence:

1. The subject typed a three-minute practice session on either the conventional or alternative keyboard, depending on which one was assigned first to him/her. A standard text, not used for the tests themselves, was used by all subjects for this three minute practice trial.

2. After a short rest break of approximately one minute, the subject was provided with the first assigned alphabetic text and was instructed to type for a full eight minute period without pauses. Following the typing task, the subject was given a short rest break of approximately one minute.

3. The subject was provided with the second assigned alphabetic text and was instructed to type for a full eight minute period without pauses. Following the typing task, the subject was given a short rest break again of approximately one minute.

4. The subject was provided with an assigned alphanumeric text and was instructed to type for a full eight minute period without pauses. Following this third typing task with the first keyboard, the subject was given a short rest break of approximately five minutes in order for the experimenter to switch keyboards.

5. Sequence 1 to 4 was then repeated for the keyboard (conventional or alternative) not previously tested in the first half of the session. The subject typed different sets of text with the second keyboard, including different text for the three minute practice session.

For both keyboards, kinematic data were collected for five periods of 30 seconds during each of the three eight-minute typing tasks using electrogoniometers attached to both wrists and forearms and the right index finger. These five periods of 30 seconds were at the following time intervals after the start of the eight minute task: 1 minute, 2.5 minutes, 4 minutes, 5.5 minutes, and 7 minutes. Testing was conducted in a manner that did not interrupt the subject's typing and the subject was not aware of the time periods when kinematic data were collected. This data collection protocol ensured that the collected data were representative of the subject's upper extremity posture throughout the entire eight minute session.

In addition to the kinematic data, typing performance data were collected while the subject was typing during the test sessions. Typing Tutor 6.0 software was used to calculate typing speed and accuracy for each of the eight minute typing tasks.

Immediately following data collection, post-testing calibration of the electrogoniometers was repeated (for purpose of comparison with the pre-test calibration data). At a later date, customized software was used to analyze all kinematic data, which included wrist radial/ulnar deviation, wrist flexion/extension and forearm pronation/supination for both upper extremities from all 90 subjects and metacarpophalangeal joint flexion/extension of the right index finger on 20 of the subjects.

D.4. METHODOLOGY

In this section, we first describe terms related to keyboard geometry in order to set a common ground for terminology used later in the report. Then, a description of the particular geometry of the keyboards tested in this study is provided. Finally, each of the specific procedures mentioned in section D.3 is described in detail.

D.4.1. Keyboard Geometry: Definition of Terms

There are five characteristics that are typically used to describe conventional and alternative QWERTY keyboard geometry. Three of three characteristics are illustrated in Figure 3b: slant, slope, and tilt angles. The remaining two characteristics, key spacing and distance between keyboard halves, are shown in Figure 6.

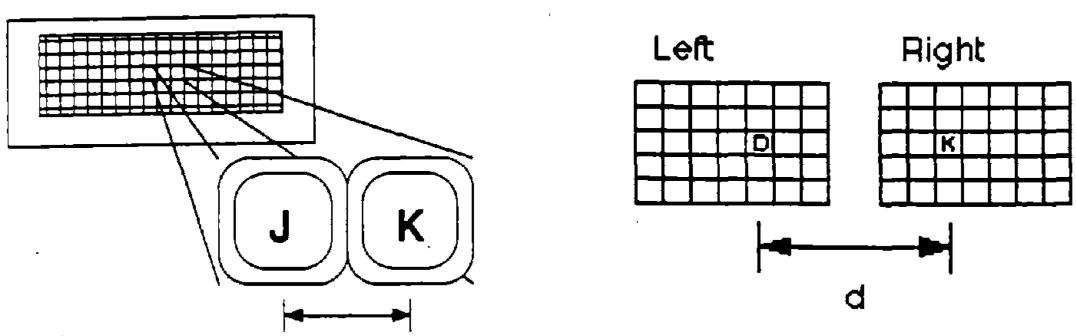


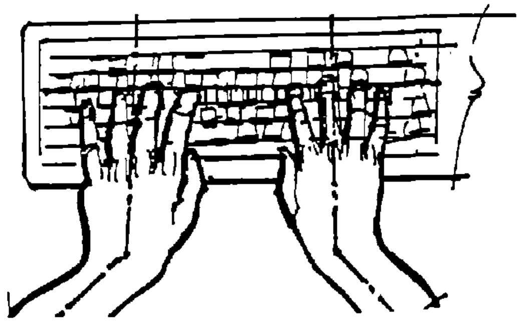
Figure 6. Diagrams of key spacing and distance between keyboard halves.

As shown in Figure 3b, the slant angle is defined as the angle that each keyboard half rotates from a center line that bisects the keyboard. It is determined by measuring the total separation angle in the horizontal plane between the two keyboard halves and dividing this angle by two. The slope angle is defined as the angle of the surface of the keys (from the bottom row to the top row of keys) in relationship to the surface that supports the keyboard. Typically this supporting surface is horizontal. A positive slope occurs when the top row of keys is elevated higher than the bottom row of keys. A negative slope occurs when the top row of keys is lower than the bottom row of keys. The tilt angle is defined as the angle formed by the keyboard halves rotated vertically above the surface supporting the keyboard. The tilt angle is measured along the home row of keys. The tilt angle is considered positive when the center of the keyboard ('g' and 'h' keys) is elevated higher than the right and left edges of the keyboard ('a' and ';' keys).

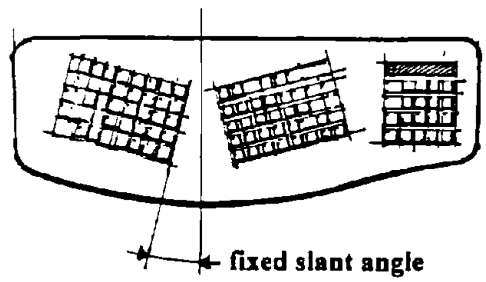
Key spacing is defined as the distance between the center of one key and the center of an adjacent key on the same row, as shown in Figure 6, and distance between keyboard halves is defined as the distance between the 'd' and 'k' keys, which are home row landmarks on each keyboard half. Typically, this geometric characteristic is used to describe the distance between halves of split keyboards and not the conventional keyboard.

D.4.2. Keyboard Geometry for Keyboards Used in the Study

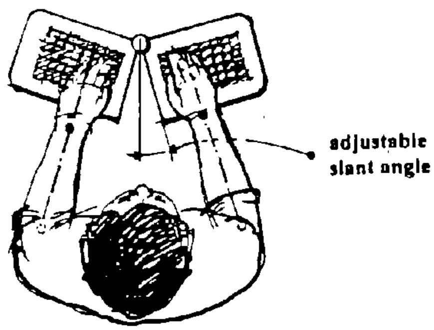
In this study, we investigated commercially-available QWERTY keyboards based on differences in fundamental design. Each design of keyboard is referred to in terms of its fundamental design and not the manufacturer of the one brand of keyboard we tested of each design type. Although there is more than one manufacturer of each basic design, we selected keyboards for testing that had high visibility within their specific design type and were readily available, either at a retail store or through a catalog. Each of four fundamental keyboard designs tested in this study are illustrated in Figure 7.



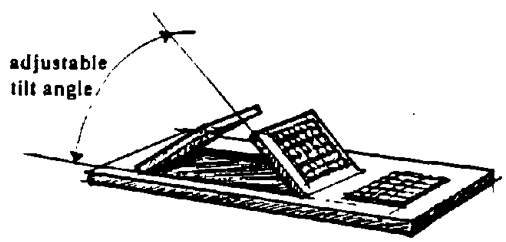
7a



7b



7c



7d

Figure 7. The four fundamental designs of QWERTY computer keyboards tested in this study: 7a) conventional, 7b) split fixed-angle, 7c) split adjustable-angle, and 7d) vertically-inclined.

Conventional Keyboard: The conventional computer keyboard design is the flat keyboard that has been in use in personal computer (PC) work stations since the introduction of the IBM PC in 1981. Tens of millions of these keyboards have been sold since the early 1980s. Most, if anot all, of the 101 keys in the conventional keyboard are aligned in straight rows. The conventional flat keyboard used in this study had a slant angle of 0°, a tilt angle of 0° and a slope angle of 5°. The spacing between adjacent keys was 1.905 cm (0.75 inch).

Split Fixed-Angle Keyboard: This design separates, at a fixed angle, its QWERTY layout of keys into halves. Some commercially-available split fixed-angle keyboards have a slight tilt angle molded into the plastic housing, while others do not. The split fixed-angle keyboard tested in this study had a slant angle of 12.5°, a slope angle of 6°, and a tilt angle of 7°. The key spacing was 1.905 cm (0.75 inch).

Split Adjustable-Angle Keyboard: As illustrated in Figure 6, these five characteristics are slant, slope, and tilt angles; key spacing; and distance between keyboard halves. The split adjustable-angle keyboard is similar to its fixed-angle relative except that the slant angle of the adjustable-angle keyboard can vary from 0 to 90°. Some split adjustable-angle keyboards allow the user to unhinge the pivot point and separate the two halves, which was a feature on the keyboard tested in this study. However, the keyboard tested in this study had the keyboard halves remain connected at the pivot point. The slant angle of the keyboard used in this study was adjusted to each subject's anthropometry, specifically his/her forearm length and elbow width. While the slant angle varied among subjects, the slope and tilt angles were constant at 5° and 1°, respectively. The spacing between adjacent keys was 1.905 cm (0.75 inch).

The split adjustable-angle keyboard was instrumented with a potentiometer at the keyboard's pivot point in order to measure the exact slant angle at which the keyboard was set for each subject. The keyboard was calibrated using a linear regression of voltage data from the potentiometer and slant angle of the keyboard. The slant angle was measured at six points between 0 and 20° using a protractor. For each of these angles, voltage from the potentiometer was recorded and stored. A linear regression of measured slant angle and potentiometer voltage resulted in equation (1).

$$\text{slant angle (deg.)} = (-6.77 * \text{volts}) + 53.45 \tag{1}$$

where volts is the voltage recorded on the potentiometer for a specific slant angle.

In this study, the investigator adjusted the split adjustable-angle keyboard to the subject at the time the keyboard was setup at his/her workplace for practice. As illustrated in Figure 8, the slant angle was adjusted so the radio-ulnar angle of each wrist was neutral (0 degree) when the subject was sitting with his/her elbows at the sides of the trunk and fingers placed on the home row of the keyboard. When the subject came to the laboratory for testing, the keyboard slant angle was set to the same slant angle used during the one to two week practice session.

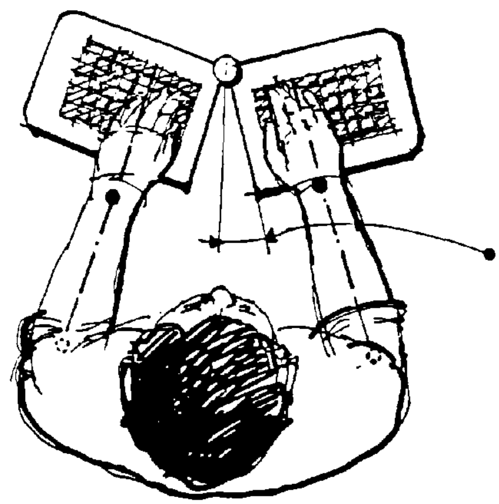


Figure 8. The slant angle of the split adjustable-angle keyboard was adjusted to each subject so his/her wrists had a neutral angle in the radial/ulnar plane when the subject's elbows were placed at the sides of the trunk.

Vertically-Inclined Keyboard: The vertically-inclined keyboard combines tilt and slant adjustability by a single control knob on the side of the keyboard. As the knob is turned, the slant and and tilt angles of each keyboard half change simultaneously. For the vertically-inclined keyboard tested in this study, the tilt and slant angles were coupled; thus, we were not able to adjust the tilt and slant angles independently of each other. While a single adjustment knob controls both halves of the keyboard, measurements of slant and tilt were slightly different for the left and right halves of the keyboard used in this study. (Due to the vertical rotation of the keyboard halves, a slope angle is difficult to measure.) The key spacing for the keyboard tested in this study was 1.905 cm (0.75 inch).

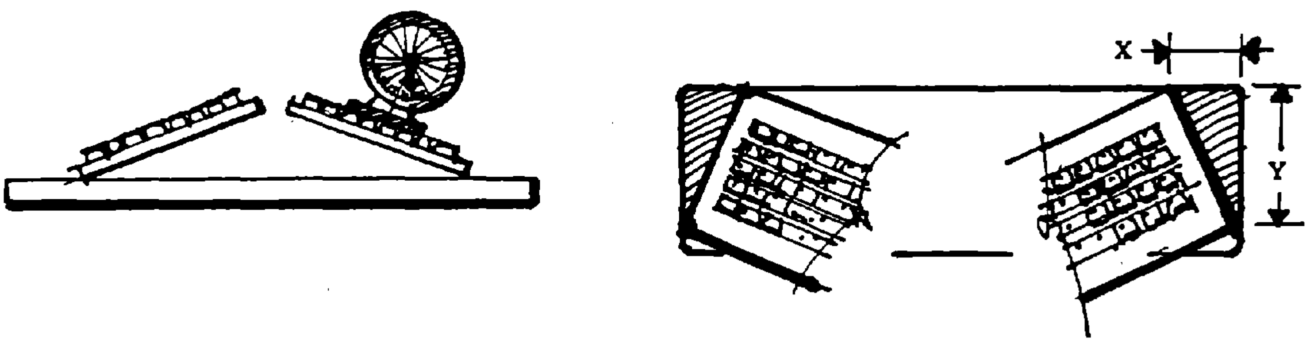
In order to determine the exact setting of tilt and slant angles selected by our subjects, we instrumented the control knob of the keyboard with a 12-turn rotary potentiometer. The vertically-inclined keyboard was calibrated using a linear regression of voltage and angle data. The tilt angle was measured using a hanging magnetic protractor positioned on the home row of the keyboard at 18 different tilt angles, as shown in Figure 9a. At each location, the protractor's angle for both the left and right side was recorded along with the voltage from the potentiometer. The relationship between the tilt angles and the voltages from the potentiometer was characterized by linear regression, as shown in equations (2) and (3).

tilt angle (deg.) for right half of keyboard = (-2.00 * volts) + 43.54 (2)

tilt angle (deg.) for left half of keyboard = (-2.05 * volts) + 38.80 (3)

where volts is the voltage recorded on the potentiometer for the specific tilt angle.

Similarly, the slant angle for each of the 18 tilt positions was determined by measuring two lengths along the keyboard halves and calculating the angle between them. The first measurement was the distance (Figure 9b--length X) that the top edge of the keyboard traveled as its tilt angle was adjusted. This measurement was perpendicular to the length of the side of the keyboard in the closed position (Figure 9b--length Y). The slant angle was the inverse tangent of lengths X/Y.



9a 9b

Figure 9. Sketches of how tilt angle (a) and slant angle (b) were measured on the vertically-inclined keyboard.

The slant angle was found to change equally for each side of the keyboard when adjusting the tilt angle. A linear regression of measured slant angle and potentiometer voltages resulted in equation (4).

slant angle (deg.) = (-0.94 * volts) + 11.99 (4)

where volts is the voltage recorded on the potentiometer for the specific slant angle.

In this study, each subject was allowed to set the keyboard at the tilt angle at which they felt comfortable. When each subject was tested in the laboratory, the tilt and slant angles of the vertically-inclined keyboard were measured by the potentiometer.

D.4.3. Keyboard Geometry for Selected Keyboards Not Used in the Study

There were two additional alternative keyboard designs that we initially intended to investigate in this study. However, due to difficulties described below, we abandoned these designs for inclusion in this study.

Concave-Well Design Keyboard: As shown in Figure 10, the concave-well design keyboard separates the keys into two concave wells and two small areas for the thumbs. There was no adjustability with the concave-well brand that we initially selected for this study. The distance between the wells (between keys 'd' and 'k') was approximately 25.65 cm (10.1 inches) and the key spacing was 1.905 cm (0.75 inch).

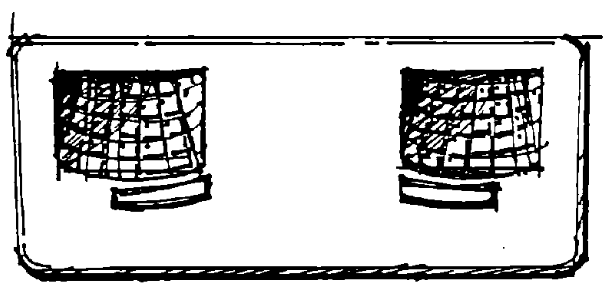


Figure 10. Sketch of concave-well keyboard.

We had difficulty recruiting subjects to use this keyboard because of the extended learning curve that is necessary to get accustomed to this alternative design. Since we recruited our subjects from the work environment, it was not possible for them to have the necessary reduction in work load that would have allowed them to get comfortable with the keyboard. The lower typing performance, and therefore reduction in work productivity, associated with learning how to type on this keyboard was unacceptable to most of the potential subjects who were asked to use this keyboard. If our subjects had undergone a special training program to use this keyboard, then their typing speeds may have been greater and close to normal typing speed, and possibly would have made it feasible to include this keyboard design in our study.

For the concave-well keyboard, a total of nine subjects were recruited to participate in the study. Of the nine subjects, only two were able to practice typing on the keyboard for a minimum of 10 hours. The results of the typing performance for these two subjects are presented in Table 1.

Table 1. Typing performance analysis for two subjects who typed on the concave-well design keyboard at their work place for a minimum of 10 hours. The typing performance of both the alphabetic and alphanumeric typing tasks were averaged.

Variables	Subject number/keyboard type			
	06/conventional	06/concave-well	22/conventional	22/concave-well
Words per minute	76	54.3	64	52
Number of errors	442	891	2	2
Characters typed	9173	5781	7724	6322
Accuracy (%)	95.6%	85%	100%	100%

For subject 06, who typed on the alternative keyboard for 32 hours prior to the testing session, the typing speed was approximately 29% lower when typing on the concave-well keyboard as compared to the conventional keyboard. In addition, the number of errors made while typing on this alternative keyboard was more than twice the number of errors made while typing on the conventional keyboard (891 errors vs. 442 errors). The large number of errors for subject number 06 typing on the concave-well keyboard as compared to subject number 22 is due to the fact that subject number 06 chose not to correct the errors as she was typing on the Typing 6.0 program. The option to correct errors is available to the subject but the use of the backspace to correct errors does impact negatively on the typing speed (see section D.4.7. for a complete explanation). Therefore, if subject 06 had chosen to correct her errors, typing speed would have been much lower compared to the conventional keyboard than the 29% observed.

For subject 22, who used the alternative keyboard for 64 hours prior to the testing session, the typing speed was approximately 19% lower when typing on the concave-well keyboard as compared to the conventional keyboard. Since subject 22 chose to correct her errors as she was typing, both tasks were relatively free of errors.

We approached seven additional subjects to try the concave-well keyboard for the study. One of the subjects tried the keyboard for three days before complaining that she was unable to reach all of the keys on the keyboard. One subject tried the keyboard for one day and could not adjust her work schedule to account for the decrease in productivity. A third subject tried the keyboard for two days and was also unable to reach all of the keys, especially the 'c' key. A fourth subject tried the keyboard for five minutes and asked to be assigned a different keyboard since the concave-well keyboard would slow her down too much. Three additional subjects (co-workers of the fourth subject) simply refused to use the keyboard since they were present when their co-worker attempted to use it.

Split Chair-Mounted Keyboard: The split chair-mounted keyboard design separates the QWERTY keyboard into halves that mount on the forearm posts of a conventional office chair. This design allows for a great amount of adjustability in the slant, slope, and tilt planes. As illustrated in Figure 11, the slant, slope, and tilt angles can be adjusted independently for each keyboard half throughout a range approaching 360 degrees. The spacing between adjacent keys was 1.905 cm (0.75 inch). Due to difficulty with subjects' acceptability of this unique design, only one subject was able to complete the minimum 10 hours of practice.

Figure 11. Sketch of split chair-mounted keyboard.

One subject typed on the split chair-mounted keyboard for approximately 40 hours at her work place. At the end of this familiarization period, typing performance on the alternative keyboard was very similar to the typing performance on the conventional keyboard, as indicated in Table 2.

Table 2. Typing performance analysis for one subject who used the split chair-mounted keyboard at her work place for approximately 40 hours. The typing performance of both the alphabetic and alphanumeric typing tasks were averaged.

Variables	Subject number/keyboard type	
	03/conventional	03/chair-mounted
Words per minute	55	51
Number of errors	2	8
Characters typed	4435	4141
Accuracy (%)	100%	100%

Three additional subjects were offered to use the split chair-mounted keyboard for the study. Both subjects used the keyboard for about two days. While both subjects were quite complimentary of the design and the keyboard itself, they stopped using it because it was too cumbersome to type in their work place. Because the keyboard must be attached to the arms of a specialized chair, it requires more space then is typically available at computer work stations and desks. In the work places that we visited, virtually no subjects had office space that would be adequate to contain such a chair/keyboard combination.

The comments from other subjects who tried using the split chair-mounted keyboard in their work environments were that they could not reach their phone or desk, as they felt somewhat trapped inside the chair when the keyboard halves were in position for typing. To get up from the chair, the subject needed to lift the keyboard halves up, and then reposition them to resume typing upon return. Employees who visit other offices on a frequent basis viewed the requisite repositioning of the keyboard halves as cumbersome, and therefore did not agree to practice on the split chair-mounted keyboard.

D.4.4. Subjects

Inclusion Criteria: Professional touch-typists who typed on a computer keyboard were the targeted population for research subjects. All subjects were required to be healthy in general and asymptomatic of any acute or chronic musculoskeletal disorder or pain that would interfere with typing. As indicated in Table 3, subjects were required to be able to type at least 40 words per minute, to have at least two years of experience in jobs that required computer keyboard typing as a regular part of the job, and to have the ability to complete at least 10 hours of typing on one alternative keyboard at their work place within approximately five to ten working days.

Table 3. Inclusion criteria for the subjects in the study.

Variables	Requirements
Age (years)	20 - 55
Typing speed (words per minute)	>40
Number of years having a job that required typing as a regular part of the job (years)	>2
Typed using the ten finger 'touch' method	Yes
Free of musculoskeletal disorders or pain in the upper extremities that would interfere with typing	Yes

Recruitment of Subjects: Recruitment of subjects was done through personal contacts and advertisements in local media. Since we aimed to recruit individuals who used a computer keyboard on a daily basis, we recruited subjects from a variety of sources, including county government, hospitals, teaching institutions, medium to large corporations, and small businesses. Most of the recruitment was made through an initial contact with the supervisor of a department who employed clerical workers. Only after proper approval from management was recruitment of individual potential subjects initiated. In many cases, management personnel themselves identified and approached likely candidates.

The initial contact with the potential subject, either by telephone or in person, determined the subject's suitability for the research. The subject was given a brief background history of the research study and was informed of the pertinent details of the study. After accepting to participate in the study, the subject signed a consent form and one of the three alternative keyboards was assigned to the subject. This keyboard was installed on the subject's office computer at the subject's desk in his/her work place. Instructions were given to the subject as to the operation of the alternative keyboard.

During the one to two week period that the subjects were given to practice with the alternative keyboard, they were free to call our office with any concerns or questions regarding the operation of the keyboards. Despite the near universal compatibility of the alternative keyboards with existing computer systems (both IBM-compatible and Macintosh), there were numerous instances where specific applications, particularly function keys, created some difficulties. In most cases, these problems were easily solved by a visit from one of the investigators or their staff. After the minimum practice time of at least ten hours was achieved, the subject made an appointment for a half day testing in the laboratory at Marquette University. The duration of the testing required a time commitment of three hours, which included setup, calibration, collection of data, anthropometric measurements, and completion of subjective surveys. For a great majority of subjects, testing was performed, with the permission of the subject's supervisor, during the 8 am to 5 pm work hours.

D.4.5. Questionnaires, Anthropometry, and Physical Characteristics of Subjects

Demographic Data: As indicated in Appendix 2, demographic data such as age, years of typing experience, and the number of hours the subject was able to practice on the keyboard were collected from each subject.

Anthropometry and Physical Parameters: Anthropometric measurements were made using a set of calipers. The measurements included height, weight, forearm-hand length, middle finger length, elbow to elbow width, shoulder width, forearm to finger length, and forearm to wrist length. A copy of the anthropometry data collection sheet is included in Appendix 2.

In addition, a number of physical parameters were measured on each subject. Cutaneous sensory function of both hands was measured using Semmes-Weinstein monofilaments; hand strength was measured with a Jamar hand dynamometer and with a pinch dynamometer for palmar, lateral, and 3-jaw chuck pinches; range of motion of the wrist and forearms was measured using a mechanical goniometer. Subjects were screened for carpal tunnel syndrome with a combination of Tinel's and Phalen's tests. A copy of the evaluation sheet is in Appendix 2.

Subjective Questionnaire on Comfort: Each subject was asked to fill out a subjective questionnaire on ease of use of the alternative keyboard that he/she practiced on, comfort with the alternative keyboard, and perceived speed and accuracy with the alternative keyboard as compared to the conventional keyboard. A copy of the evaluation sheet is in Appendix 2.

D.4.6. Electrogoniometers

Custom-made electrogoniometers were used to collect wrist and forearm position data in the radial/ulnar (rad/uln) and flexion/extension (flex/ext) planes of the wrist and the pronation/supination (pron/sup) plane of the forearm. A commercially-available Penny & Giles uniaxial strain gage electrogoniometers was used to measure flexion angle of the metacarpophalangeal (MCP) joint of the right index finger.

The subject's right upper extremity was instrumented first. The electrogoniometric devices were attached in the following order: (1) index finger goniometer, (2) wrist rad/uln goniometer, (3) wrist flex/ext goniometer, and (4) forearm pron/sup device. This sequence was repeated on the subject's left upper extremity.

Wrist Monitor: The wrist monitor was developed at the Biodynamics Laboratory of The Ohio State University to collect on-line data of wrist angle position in the rad/uln and flex/ext planes simultaneously and independently of each other (Marras and Schoenmarklin, 1993; Schoenmarklin and Marras, 1993). As illustrated in Figure 12, the wrist monitor was composed of two segments of thin metal feeler stock joined by a rotary potentiometer. The potentiometer measured the angle between the two segments of metal. The maximum angle between the two metal segments was 325°. The potentiometers were placed on the center of the wrist in the rad/uln and flex/ext planes according to the anatomical protocol described in the next section. The wrist monitor is lightweight (approximately 0.05 kilograms) and small enough to be unobtrusive to the typist wearing the monitors while she/he types..

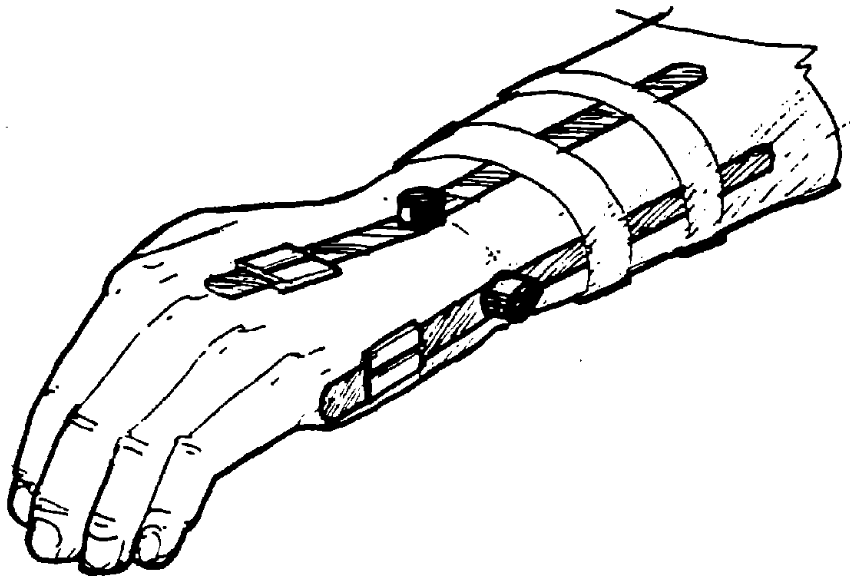


Figure 12. Wrist monitor that measured radial/ulnar deviation and flexion/extension of the wrist.

The wrist monitor was calibrated to each subject by recording the voltages of the rad/uln and flex/ext potentiometers while the subject's wrist was placed on a calibration table in the neutral position in the rad/uln and flex/ext planes. The bony landmarks shown in Figure 13 (Schoenmarklin, 1991) were used as reference points to align the wrist in the rad/uln and flex/ext planes. In the rad/uln and flex/ext planes, the wrist is in the neutral position when the longitudinal axis of the radius is parallel to the third metacarpal bone (Taleisnik, 1985; Palmer et al., 1985). Neutral position in the rad/uln plane was established by aligning marks placed on the third MCP joint (middle finger knuckle), the center of the wrist, and lateral epicondyle of the elbow (Taylor and Blaschke, 1951; Knowlton and Gilbert, 1983). The center of the wrist on the dorsal side is the "palpable groove between the lunate and capitate bones, on a line with the third metacarpal bone" (Webb Associates, 1978, p. IV-61). The wrist was aligned in a neutral position in the flex/ext plane when the center of the second metacarpal head, radial styloid, and olecranon process were collinear (Brumfield and Champoux, 1984).

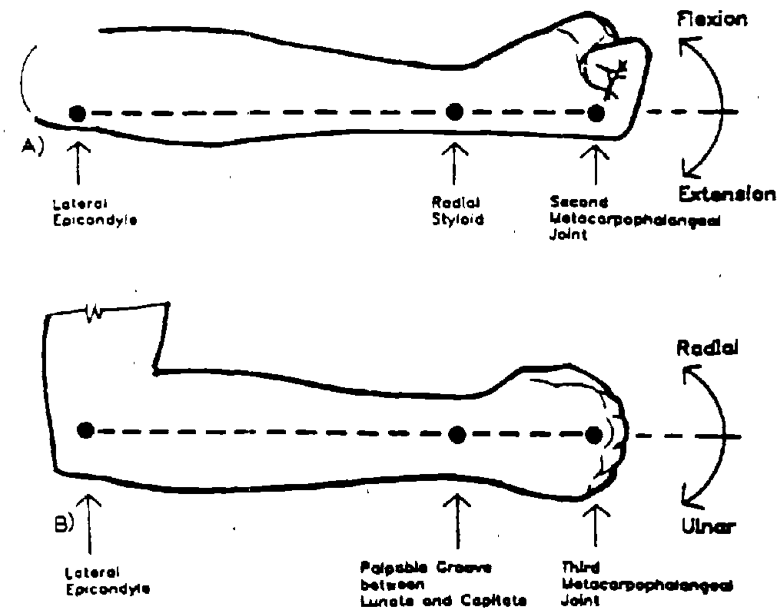


Figure 13. Bony landmarks on the elbow, wrist, and hand that were used to align the wrist in a neutral position in the radial/ulnar and flexion/extension planes (Schoenmarklin, 1991).

The angular deviation of the wrist in the rad/uln and flex/ext planes was determined according to equation (5).

$$\Theta_i = (V_{ij} - V_{nj}) * (16.25° / \text{volt}) \qquad (5)$$

where:

Θ_i = angular deviation in degrees at time *i* from the neutral angle in plane *j*. Plane *j* corresponds to potentiometer *j*.
V_{ij} = voltage recorded at time *i* from potentiometer *j*.
V_{nj} = voltage recorded at the neutral angle from potentiometer *j*.
16.25 = the ratio between angular deviation and change in voltage (16.25 = 325°/20 V).

Only the neutral voltages in the rad/uln and flex/ext planes were needed to provide reference voltages in each plane. Once these references voltages were known, wrist angles during the trials were calculated according to equation (5). All calibration data were recorded at 100 hz for one second and the average value of these 100 data points was used as the calibration value. Calibration values were recorded both prior to the testing session and immediately the session. The final calibration value was the average of these two values.

The sign conventions for angles in the rad/uln and flex/ext planes were as follows:

rad/uln: positive = radial deviation; negative = ulnar deviation
flex/ext: positive = flexion; negative = extension

Pronation/Supination Monitors. The pronation/supination device recorded the pron/supin angle of the forearm. The pron/supin device consists of a rod that remains parallel to the forearm during rotation. The rod was attached to a bracket affixed to the proximal end of the forearm with a velcro cuff. On the distal end of the forearm, the rod was connected to a potentiometer that was attached to a bracket. As the forearm rotated, the potentiometer rotated with respect to the fixed rod, and voltages from the potentiometer recorded the angular displacement of the forearm, as shown in Figure 14.

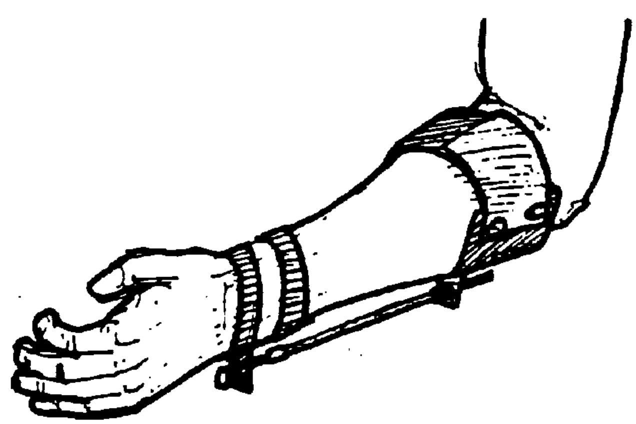


Figure 14. Pronation/supination apparatus (Schoenmarklin, 1991).

The ratio between angular deviation and change in voltage was not constant for subjects in the pron/supin plane, thus the ratio needed to be calculated for each subject. The pron/supin device was calibrated by the use of a pron/supin dial. While a subject held his/her elbows at 90° next to the trunk and with the forearms parallel to the ground, the experimenter adjusted the height of the calibration dial. The subject grasped the handle on the dial with a power grip. When the handle was aligned vertically (0°), his/her position was defined as the neutral pron/supin angle. Voltages were collected from the pron/supin potentiometers for both arms when the forearms were aligned in a neutral position. The subject was asked to pronate his/her forearms at pronation angles of 70°, 50° and 25° and at a supination angle of 70°. (Note: the first 35 subjects had calibration data recorded at only three points: 0°, 70° supination and the subject's maximal position of pronation (up to 85°)).

Based on the set of angular and voltage data, a best-fitting regression line was calculated for each subject's forearm. The relationship between pron/supin and voltage data was linear, as shown by squared coefficients of determination that averaged about .98 (Schoenmarklin, 1991).

The pron/supin angle was calculated according to regression equation (6):

$$\Theta_i = B_0 + B_1 * V_i \qquad (6)$$

where:

Θ_i = pronation/supination angle at time *i*
B_0 = regression intercept
B_1 = regression slope
V_i = voltage at time *i*

The sign convention for angles in the pron/supin plane was as follows:

pron/supin: positive = pronation, negative = supination

Finger Goniometer: Finger flexion was measured using a single axis Penny & Giles electrogoniometer placed over the subject's right index finger MCP joint (knuckle joints). Figure 15 shows the finger flexion goniometer placed over the index finger of a hand.

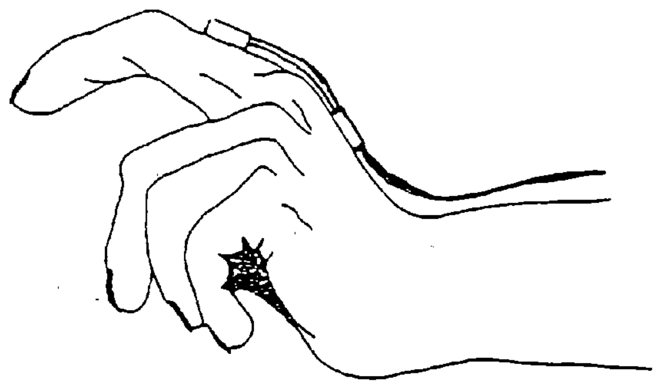


Figure 15. Finger goniometer that measured flexion of the right index MCP joint.

Neutral calibration voltages for the finger goniometer were collected at the same time as the neutral calibration voltages for rad/uln and flex/ext wrist monitors. The subject held their fingers out in a neutral flex/ext position. The angular deviation of the finger in the flex/ext plane was determined according to equation (7).

$$\Theta_i = (V_i - V_n) * (18.0° / \text{volt}) \tag{7}$$

where:

Θ_i = angular MCP flexion in deg. at time *i* from the neutral angle
V_i = voltage recorded at time *i* from finger goniometer
V_n = voltage recorded at the neutral angle from finger goniometer
18.0 = the ratio between angular deviation and change in voltage (18.0 = 360° / 20 V).

The sign convention for angular deviation of the MCP joint in the flex/ext plane was:

flex/ext: positive = flexion; negative = extension

D.4.7. Sampling Frequency and Data Processing

During the 30 second data collection trials, data from each of the electrogoniometers were collected at 300 Hz by a 12 bit analog to digital system and then stored on a PC. The kinematic data were subsequently filtered by a 7 Hz low pass Butterworth filter to remove noise and smooth the signal. Custom-written software was used to obtain the variables of interest for all joints.

D.4.8. Visual Record of Testing

A high-speed videocamera was used to provide a visual record of the subjects while they were typing in the laboratory. The camera was positioned in order to obtain a view of the subject in the sagittal plane from the subject's right side. In addition to providing a visual record of the subjects, a set of eight reflective markers were placed on the subject in order to quantify head, shoulder, and lower extremity posture. Markers were placed in positions that provided information on knee angle, hip angle, shoulder angle, and head position in the sagittal plane.

After proper calibration and adjustment of the videocamera, subjects were filmed during the entire typing tasks. A full view of the subject was obtained for the first alphabetic task. For the second alphabetic task, the view of the subject was limited to the torso, head and upper extremities. For the alphanumeric task, the camera was zoomed to include only the forearm and wrist motion.

While geometric analysis of the markers on videotape is possible, it would have required an inordinate amount of time well beyond the scope of the project. Furthermore, analysis of posture would not lead to important additional information since the subject's posture while typing was controlled by chair and work station adjustment. Thus, each subject's gross posture was recorded on video solely to provide a visual record of each subject's testing session.

D.4.9. Typing Tutor Software

The commercially available Typing Tutor 6.0 program was used to record typing performance during typing tasks. This program allowed subjects to type custom text, such as 7th grade social science material. The text to be typed was displayed directly on the VDT, and the subject was instructed to type the displayed text from the VDT on the keyboard. Instructions were given to the subjects to familiarize themselves with the Typing Tutor 6.0 program. The subject was instructed to type as he/she normally would type, which included backspacing to correct errors. At the end of the initial three minute typing practice period, the subject was asked if anything should be changed to create a more comfortable work setting, such as the keyboard position, VDT tilt angle, or lighting. Changes were made as requested.

Typing Performance Data: Subjects completed two eight-minute typing tasks (the alphabetic tasks) of mainly alphabetic text on both the conventional keyboard and the one alternative keyboard they had previously practiced on. Subjects also completed one typing task (the alphanumeric task) that consisted of a blend of numeric characters with alphabetic text on both the conventional keyboard and the alternative keyboard.

The Typing Tutor 6.0 software generated performance data in four areas:

1 - Speed in words per minute

2 - Accuracy percentage

3 - Total characters typed

4 - Total errors left in the typed document

Typing Speed: A 'word' is defined as five typed characters, which include spaces between words, and typing speed is defined as words per minute. Words per minute were calculated according to equation (8).

$$\text{Speed (words per minute)} = (\text{total characters} / 5) / \text{minute} \qquad (8)$$

The total cumulative time was the time measured between each successive keystroke and corresponded to the time set for the typing task (8 minutes in this experiment). The only exception to this rule occurred when the time between two consecutive keystrokes was greater than one second. In this case, the time between these two keystrokes was calculated as one second. Therefore, if a person needed to interrupt their typing task for a few seconds or minutes, the "clock" essentially stopped until typing resumed again. In this study, no subject was interrupted in the middle of their typing task; therefore, this feature of the program was not used.

Striking the backspace key did not enter into the total number of characters typed. When the backspace key was struck, the character that was overwritten was then deleted from the total characters typed. The time to backspace and correct, however, was part of the cumulative typing time.

Typing Accuracy: Accuracy was defined as the difference between the total number of characters typed and the total number of errors left in the document, divided by the total number of characters, as shown in equation (9).

$$\text{accuracy (\%)} = (\text{total characters - error characters}) / \text{total characters} \qquad (9)$$

Backspacing could be used if the subject so desired, but it was not required. Most subjects did backspace, however, which led to a high percentage of accuracy in the typed text at the end of the eight minute period. Although backspacing helped increase typing accuracy, it decreased the typing speed since the use of the backspace costs two characters (the backspace itself and the character being replaced). The high percentage of accuracy could also be explained by the extensive typing experience of the subjects.

Total Number of Characters Typed: Total number of characters was defined as the number of characters the subject reached at the end of the eight minute typing task. Total characters did not include hitting the backspace key, and the character that was overwritten was removed from the total character count.

Total Number of Errors: Total errors was defined as the number of mistaken keystrokes left in the document at the end of the eight minute period.

D.4.10. Independent Variables

The independent variables and their levels in this study were the following:

1. Keyboard design (4 levels: conventional, split fixed-angle, split adjustable-angle, vertically-inclined)
2. Hand (2 levels: right and left wrist and forearm)
3. Typing task (2 levels: alphabetic and alphanumeric).

D.4.11. Dependent Variables

The dependent variables in this study were categorized into three groups: kinematic measures, typing performance measures, and subjective ratings of keyboard designs.

Kinematic measures. Kinematic data were collected every sampling period. For the alphabetic task, 5 samples of data of 30 seconds in duration were collected for each of two 8-

minute typing tasks (for a total of ten 30-second data sampling periods). For the alphanumeric task, 5 samples of data of 30 seconds in duration were collected for a single 8-minute typing task.

Mean angular position for any of the kinematic dependent variables was calculated as the mean position of the joint of interest over 300 seconds of data for the alphabetic task and over 150 seconds of data for the alphanumeric task.

Minimum angular position for any of the variables of interest was calculated as the average of the minimum angular position of the joint for each of the 30 second sampling periods. Therefore, for the alphabetic task, the minimum angular value for each of the ten 30-second samples were averaged. For the alphanumeric task, the minimum angular value of the five 30-second samples were averaged.

Maximum angular positions were calculated according to the same methods employed for minimum angular positions.

In addition, the variance of the angular position was used as an index of the "dynamic" nature of typing. A small variance value (about the average angular position) would indicate that the joint of interest was held in a relatively fixed and static position over the overall typing task. A large variance would indicate that the joint of interest moved often during the typing task. For the alphabetic task, the variance for each of the five 30-second periods corresponding to each of the 8-minute typing tasks were averaged according to the statistical formula to average variance across groups (Glass and Hopkins, 1984). Then, the mean of these two values was taken as the overall variance. For the alphanumeric task, the variance for each of the five 30-second periods sampled during the 8-minute typing task were averaged according to the same Glass and Hopkins (1984) formula.

The following kinematic variables were measured and analyzed:

- mean, minimum, maximum and variance for wrist angular position in flex/ext
- mean, minimum, maximum and variance for wrist angular position in rad/uln deviation
- mean, minimum, maximum and variance for forearm angular position in pron/sup
- mean, minimum and maximum for right index MCP joint angular position in flex/ext

Typing Performance. For each keyboard (two keyboards for each subject) and typing tasks (alphabetic and alphanumeric), four dependent variables were obtained: typing speed in words per minute, accuracy percentage, total characters typed and total errors left in the typed document. Values for these four variables were obtained for each of the 8-minute typing periods and accounted for the entire eight minutes of typing. For the alphabetic typing task, the values for the two 8-minute typing periods were averaged together. The typing performance values for the alphanumeric task was from the single 8-minute typing task.

Subjective ratings of keyboard design. The following subjective ratings of keyboard designs were recorded from each subject, plotted, and then interpreted descriptively:

- subjective comfort of alternative keyboard compared to the conventional
- subjective ease of use of alternative keyboard compared to the conventional
- subjective accuracy of alternative keyboard compared to the conventional
- subjective typing speed of alternative keyboard compared to the conventional

D.4.12. Research Design

The experimental study was designed to test three fundamentally-different designs of alternative keyboards and the conventional flat keyboard. Because of the need for extensive practice time with the alternative keyboard, each of the subjects recruited in the study was tested on only one alternative keyboard in addition to the conventional keyboard (in order for each subject to serve as his/her own control). Therefore, all comparisons between conventional and alternative keyboards are made for each of the three alternative keyboards. In addition, the kinematic data from each alternative keyboard were compared to the other alternative keyboards in order to determine which alternative keyboard placed the wrist and forearm in the most neutral posture.

D.4.13. Statistical analysis

Descriptive statistics were first used to describe the demographic, anthropometric, and physical characteristics of the subjects who participated in the study. Second, inferential analyses were performed on all these characteristics in order to determine if there were any differences among the groups of subjects who typed on the various alternative keyboards.

Analysis of the kinematic data included both descriptive and inferential statistics. Descriptively, the data were presented in tabular as well as graphical formats in order to visualize the effects of each alternative keyboard on wrist, forearm, and finger kinematics. Inferential statistics were used to determine if any apparent descriptive differences were statistically significant. In order to determine the difference between the conventional keyboard and each alternative keyboard, a separate three-way analysis of variance (ANOVA) for repeated measures was performed on each independent variable of interest. Therefore, for each keyboard, the three factors for the three-way ANOVA were: keyboard design (2 levels--conventional versus alternative), hand (2 levels--right versus left) and typing task (2 levels--alphabetic versus alphanumeric). For each three-way ANOVA, main effects as well as interactions were tested statistically.

To determine the difference among the three alternative keyboards, a mixed-design three-way analysis of variance (ANOVA) was performed. The three factors for the three-way ANOVA were: keyboard design (3 levels--split fixed-angle, split adjustable-angle, vertically-inclined), hand (2 levels--right versus left) and typing task (2 levels--alphabetic versus alphanumeric). Keyboard design was a between-subject factor while both hand and typing task were within-subject factors. For each three-way ANOVA, main effects as well as interactions were tested statistically.

D.5. RESULTS

D.5.1. Demographics and Anthropometry

Source of Subject Group: Subjects were recruited through local media, university newsletters, university postings, personal contacts, and contacts to local businesses where typing jobs were performed. Subjects who participated in the research were employed in a wide variety of occupations, including secretarial, administrative, clerical, word processing, and managerial. As indicated in Table 4, the subjects came from employment sources including both the private (71 subjects) and public sectors (19 subjects).

Table 4. Type and number of employers where the subjects were recruited. The total number of subjects was 90.

Employers (*)	Number of subjects
Educational institutions (2)	28
Health-related industries (4)	20
County governments (2)	13
Manufacturing industries (3)	12
Large corporations (2)	8
Police departments (2)	6
Small business (1)	3

* The number between parentheses indicate how many employers in the respective category contributed subjects to the study.

Gender: Although the investigators tried assiduously to recruit males for this study, only two of the total of 90 subjects were men. Although several men expressed an interest in participating in the study, their inability to type with the standard ten finger 'touch' method made them ineligible.

Ethnicity: The group of participants was composed of eighty-one Caucasians, four African-Americans, two Hispanics, one Native-American, one Asian and one Pacific-Islander.

Age: The mean age of all subjects (n=90) was 37.8 ± 9.34 years, ranging from 21 to 58 years. Table 5 provides descriptive statistics for the entire group as well as for each of the three groups of 30 subjects using a specific design of alternative keyboard.

Table 5. Age of the subjects in years.

Keyboards	Mean ± s.d.	Minimum	Maximum
All subjects (n=90)	37.8 ± 9.34	21	58
Split fixed-angle (n=30)	38.6 ± 8.54	25	53
Split adjustable-angle (n=30)	40.7 ± 10.2	21	58
Vertically-inclined (n=30)	34.1 ± 7.84	22	55

Results of a one-way ANOVA indicates that age was statistically different among the three groups who used the alternative keyboards ($p = 0.02$). A Tukey's post-hoc pairwise comparison test determined that the age of those subjects using the split adjustable-angle keyboard was significantly greater than the age of the subjects using the vertically-inclined keyboard. While this difference in age is statistically significant, the investigators do not believe that this difference is a practical difference with regards to the results from this study. With this exception, no other statistically significant differences ($p < 0.05$) were found among the three groups.

Typing Experience: Subjects were asked their years of experience in employment that required typing. Table 6 presents the years of experience that subjects reported. Data are incomplete on the years of career experience for all subjects because the first 14 subjects were not specifically asked to report this information on the survey. However, these 14 subjects were all experienced touch typists and met the minimum requirement of two years experience, which was determined through personal interview at the time they received the alternative keyboard in their workplace.

Table 6. Subjects' years of experience in a job requiring typing.

Keyboards	Mean ± s.d.	Minimum	Maximum
All subjects (n=76)	14.4 ± 8.8	2	45
Split fixed-angle (n=24)	14.7 ± 7.4	5	30
Split adjustable-angle (n=26)	17.4 ± 10.7	2	45
Vertically-inclined (n=26)	11.2 ± 6.3	2	26

Results of a one-way ANOVA followed by a Tukey's post-hoc pairwise comparison test determined that the career experience of those subjects using the split adjustable-angle keyboard was significantly greater than the career experience of the subjects using the vertically-inclined keyboard ($p < .05$). The significantly greater career experience of subjects using the split adjustable-angle keyboard may be due in part to the older age of this subject group. Given the fact that each subject group had over ten years of experience typing, it is not believed that the difference in experience would influence the results from this study.

Other physical characteristics: Table 7 provides summary statistics for a few selected variables of anthropometry and functional characteristics measured on the participants in the study. A complete list of anthropometric and functional measurements is included in Appendix 4. Overall, the three groups of subjects corresponding to the three alternative keyboards were very similar in terms of anthropometric characteristics, strength, and range of motion of the wrists and hands. The only variables measured for which a statistically significant difference were found ($p < .05$) are listed in Table 7. These include range of motion for right and left wrist extension and range of motion for left wrist ulnar deviation. While these differences are statistically significant, they are within 6 degrees and are not considered to be of functional significance.

Table 7. Descriptive statistics (mean ± s.d.) for selected anthropometric and functional characteristics of subjects.* The number of subjects was 30 for each of the three keyboard groups.

Variables	Vertically-inclined	Split adj.-angle	Split fixed-angle
Height (m)	1.64 ± 0.05	1.63 ± 0.09	1.64 ± 0.06
Weight (kg)	67.1 ± 17.2	72.5 ± 18.0	68.6 ± 14.1
Shoulder width (cm)	38.4 ± 2.0	38.5 ± 2.7	38.4 ± 1.8
Right grip strength (kg)	27.2 ± 6.1	28.4 ± 6.2	27.8 ± 6.1
Left grip strength (kg)	25.2 ± 5.5	27.5 ± 6.0	25.0 ± 6.1
Right wrist extension (deg)**	60.7 ± 10.3	61.0 ± 6.9	66.0 ± 7.5
Left wrist extension (deg)**	62.6 ± 8.1	61.8 ± 5.2	68.4 ± 8.4
Right wrist ulnar deviation (deg)	35.1 ± 5.0	35.1 ± 5.5	36.1 ± 6.2
Left ulnar deviation (deg)***	35.6 ± 6.5	33.8 ± 4.5	37.9 ± 6.5

* A full list of anthropometric measurements is included in Appendix 2. The number of subjects is equal to 30 for each keyboard group.

** Variable found to have a significantly greater ($p < .05$) mean value for the split fixed-angle keyboard group compared to both the split adjustable-angle and vertically-inclined keyboard groups using a one-way ANOVA followed by a Duncan's multiple range test post-hoc analysis.

*** Variable found to have a significantly greater ($p < .05$) mean value for the split fixed-angle keyboard group compared to the split adjustable-angle keyboard group using a one-way ANOVA followed by a Duncan's multiple range test post-hoc analysis.

Based on reported history, none of the subjects who participated in the study had symptoms of upper extremity pain, either currently or in the past. In addition, none of the subjects had signs of carpal tunnel syndrome as tested with the Phalen's and Tinel tests on the day the subjects came to the laboratory for testing. Sensory testing of the palmar aspect of both hands, with the Semmes-Weinstein monofilaments, confirmed normal sensory function bilaterally on all subjects.

D.5.2. Practice Time Typing on the Alternative Keyboards

Subjects were asked to report the number of hours they spent typing on the keyboard at their workplace before testing in the laboratory. Table 8 provides summary statistics of the number of hours subjects reported.

Table 8. Number of hours subjects typed on the alternative keyboard in the workplace before testing in the laboratory, and the number of subjects categorized into three ranges of practice times.

Keyboards	Mean ± s.d.	10 to 19 hrs	20 to 40 hrs	> 40 hrs
All subjects (n=90)	27.0 ± 15.3	14*	61	15
Split fixed-angle (n=30)	29.1 ± 20.4	5	19	6
Split adjustable-angle (n=30)	26.2 ± 10.6	5	20	5
Vertically-inclined (n=30)	25.7 ± 12.8	4	22	4

Results of a one-way ANOVA indicate that the time spent practicing on the alternative keyboards was not statistically different among alternative keyboard groups ($p > 0.05$).

The investigators' initial goal was to have all subjects practice a minimum of 20 hours on the alternative keyboard assigned to him/her before testing, and the majority of the subjects (n = 76) achieved this goal. Of the 14 who did not practice 20 hours, seven practiced between 15 and 20 hours and the other seven practiced between 10 and 15 hours. The reasons given for not being able to complete the 20 hours of practice were varied and included sickness, vacation, changes in work schedule, etc. In all cases, subjects indicated that they felt comfortable enough with the alternative keyboard assigned to him/her for testing in the laboratory. While no strict upper limit in hours of practice was imposed, it was our goal to keep practice time below 40 hours in order to keep the group as homogeneous as possible. Sixty-one of the 90 subjects practiced at least 20 hours but less than 40 hours before testing in the laboratory. Fifteen subjects, relatively well distributed across the three keyboards, exceeded 40 hours of practice. The reason for exceeding forty hours was typically that the subject was too busy at work to be able to schedule a half-day for testing within two weeks after the keyboard was delivered to her/his office. In these 15 cases, the subject was discouraged from typing on her/his conventional keyboard after practicing on the alternative keyboard and before being tested in the laboratory so the subject's familiarity with the alternative keyboard would not diminish. Practice time above 40 hours most probably did not impact the results from the study because one can usually learn how to type at a normal rate on an alternative keyboard after approximately 10 hours of practice (Swanson et al,, 1997).

D.5.3. Subjective Ratings of Alternative Keyboards

Perceived Typing Speed on the Alternative Keyboard: Subjects were asked if they felt they reached the same level of typing speed using the alternative keyboard as they had when typing on a conventional keyboard. If the subject did feel that she/he reached the same level of typing speed using the alternative keyboard, the perceived speed value was recorded as 100%. If the subject did not feel she/he reached the same level of speed on the alternative keyboard as on the conventional keyboard, the subject reported what percentage of typing speed relative to the conventional keyboard that he/she reached during the practice time at their workplace.

Approximately one third of the subjects (37 of 90) reported that they felt they reached 100% of their typing speed using the alternative keyboard as compared to the speed with the conventional keyboard. Of these 37, 12 used the split fixed-angle, 15 used the split adjustable-angle, and 10 used the vertically-inclined keyboard. Of the three alternative keyboards, the vertically-inclined keyboard had the fewest number of subjects reporting having reached 100% typing speed (n = 10), but the overall percentages among the three keyboard groups are fairly comparable, as shown in Table 9. The column labeled '100%' is the number of subjects who reported that they typed on the alternative keyboard at 100% of their typing speed on a conventional keyboard. Note that all subjects felt that they reached a typing speed on the alternative keyboards that was 70% or greater of their speed on the conventional keyboard.

Table 9. Perceived speed of typing on the alternative keyboard as a percentage of speed typing on the conventional keyboard, and the number of subjects who felt their perceived speed of typing on their respective alternative keyboard was 100% of the conventional keyboard .

Keyboards	Mean ± s.d.	Minimum	Maximum	100%
All subjects (n=90)	90% ± 10.5	70%	100%	37
Split fixed-angle (n=30)	92% ± 7.9	75%	100%	12
Split adj.-angle (n=30)	91% ± 11.1	70%	100%	15
Vertically-inclined (n=30)	86% ± 11.2	70%	100%	10

The results of a one-way ANOVA indicated that the perceived typing speed using the alternative keyboards was not statistically different among alternative keyboard groups ($p > .05$). A one-tail t-test for each of the keyboards using the hypothesis that the mean perceived typing speed for subjects using each of the three alternative keyboards is 100% (the conventional keyboard is considered 100%) found that all three alternative keyboards had a perceived typing speed that was statistically less ($p < 0.0001$) than the conventional keyboard (100%).

Perceived Accuracy on the Alternative Keyboard: Subjects were asked if they felt they reached the same level of typing accuracy using the alternative keyboard as they had when using the conventional keyboard. (Typing accuracy was defined as the number of errors made while typing.) If the subject did feel that she/he reached the same level of typing accuracy using the alternative keyboard the perceived accuracy value was recorded as 100%. If the subject did not feel she/he reached the same level of typing accuracy on the alternative keyboard as on the conventional keyboard the subject reported what percentage of accuracy it was thought she/he reached during the practice time at their workplace.

Table 10 provides the perceived level of typing accuracy that subjects reported. The column labeled '100%' is the number of subjects who reported that they reached 100% of the typing speed that they had using the conventional keyboard.

Approximately one third of the subjects (36 of 90) reported that they felt they reached 100% of their typing accuracy using the alternative keyboard as compared to the accuracy they had using the conventional keyboard. Of these 36, 12 used the split fixed-angle keyboard, 14 used the split adjustable-angle keyboard, and 12 used the vertically-inclined keyboard. Of the three alternative keyboards, the vertically-inclined keyboard had the fewest number of subjects reporting having reached 100% typing accuracy, but again it was relatively close among keyboards.

Table 10. Perceived typing accuracy on the alternative keyboard as a percentage of typing accuracy on the conventional keyboard, and the number of subjects who felt their perceived typing accuracy on their respective alternative keyboard was 100% of the conventional keyboard.

Keyboards	Mean ± s.d.	Minimum	Maximum	100%
All subjects (n=90)	87% ± 11.66	70%	100%	36
Split fixed-angle (n=30)	89% ± 10.39	70%	100%	12
Split adj.-angle (n=30)	89% ± 11.62	70%	100%	14
Vertically-inclined (n=30)	84% ± 12.43	70%	100%	10

The result of a one-way ANOVA determined that the perceived typing accuracy using the alternative keyboards was not statistically different among alternative keyboard groups ($p > 0.05$). A one-tail t-test for each of the three keyboard subject groups hypothesizing that the mean perceived typing accuracy for subjects using each of the three alternative keyboards is 100% (the conventional keyboard is considered 100%) found that all three alternative keyboards had a perceived typing accuracy that was statistically less ($p < 0.0001$) than the typing accuracy on the conventional keyboard (100%).

Perceived Difficulty of Alternative Keyboard Usage: Subjects were asked to subjectively rate the perceived difficulty of using the alternative keyboard as compared to the conventional keyboard. Subjects were given a choice from one to five, with one being 'much harder to use', three being 'the same level of difficulty', and five being 'much easier to use'. Table 11 presents the results of perceived level of difficulty for the alternative keyboards, using the one to five scale. An average less than 3 indicates that the keyboard was subjectively harder to use than the conventional keyboard. An average greater than 3 indicates that the alternative keyboard was subjectively easier to use than the conventional keyboard. The data in Table 11 are shown in Figure 16 as a frequency distribution.

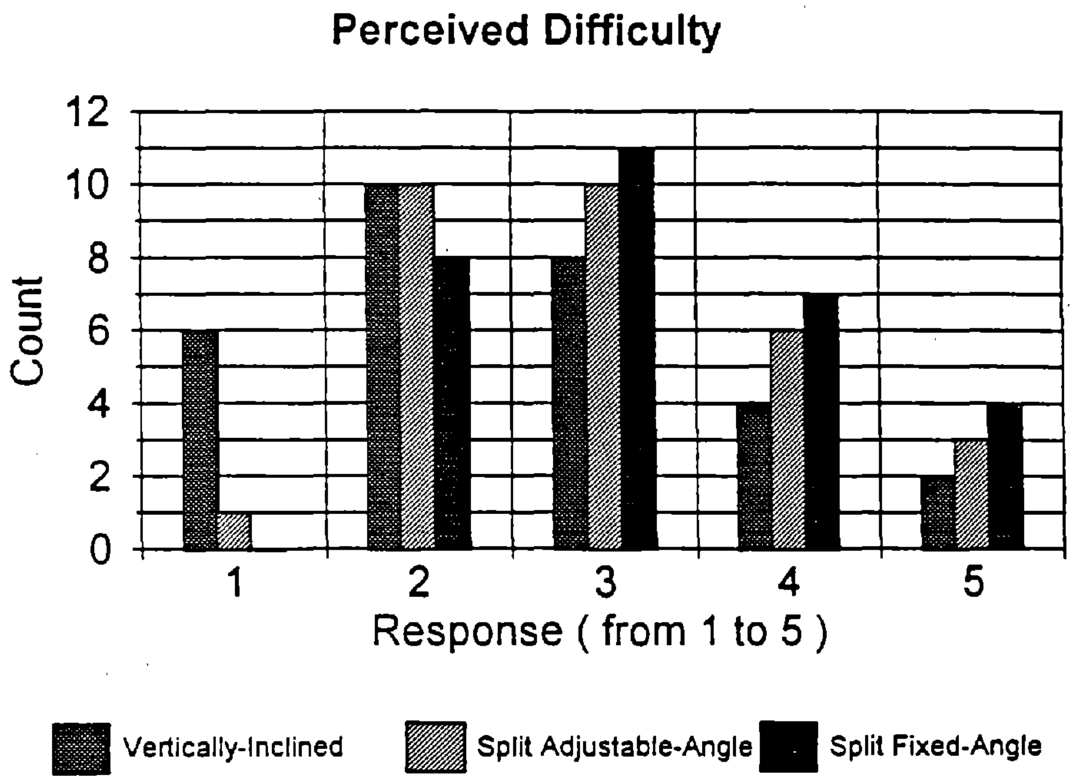


Figure 16. Frequency distribution of the perceived level of difficulty of use of the alternative keyboard as compared to the use of a conventional keyboard. The ratings range from 1 to 5, with 1 being 'much harder to use' and 5 being 'much easier to use'.

Table 11. Perceived level of difficulty of use of the alternative keyboard as compared to the use of a conventional keyboard. The ratings range from 1 to 5, with 1 being 'much harder to use' and 5 being 'much easier to use'.

Keyboards	Mean ± s.d.	Minimum	Maximum
All subjects (n=90)	2.9 ± 1.10	1	5
Split fixed-angle (n=30)	3.2 ± 0.99	2	5
Split adjustable-angle (n=30)	3.0 ± 1.03	1	5
Vertically-inclined (n=30)	2.5 ± 1.15	1	5

As shown in Figure 16 and Table 11, none of the keyboards was universally accepted as being easier to use. Similarly, none of the keyboards was universally accepted as being harder to use. Overall, subjects were split in their decision as to whether an alternative keyboard felt harder to use.

Split fixed-angle keyboard: Eleven of 30 subjects found the split fixed-angle keyboard to be either easier or much easier to use. Only eight subjects found this keyboard to be harder to use than the conventional..

Split adjustable-angle keyboard: Ten of 30 subjects found the split adjustable-angle keyboard to be as easy to use as the conventional keyboard. Nine of these 10 subjects found it to be either easier or much easier to use. Ten subjects found this keyboard to be harder to use than the conventional, and one subject felt that the keyboard was much harder to use.

Vertically-inclined keyboard: Eight of 30 subjects found the vertically-inclined keyboard to be as easy to use as the conventional keyboard. Only six subjects found it to be either easier or much easier to use. Sixteen subjects found this keyboard to be harder or much harder to use.

Comfort of Alternative Keyboards: Subjects were asked to subjectively rate the perceived comfort while using the alternative keyboard as compared to the conventional keyboard. Subjects were given a choice from one to five, with one being 'much less comfortable', three being 'the same' level of comfort, and five being 'much more comfortable.' An average less than 3 indicates that the keyboard was subjectively less comfortable than the conventional keyboard. An average greater than 3 indicates that the alternative keyboard was subjectively more comfortable to use than the conventional keyboard. The results of perceived comfort are presented in Table 12 and in Figure 17.

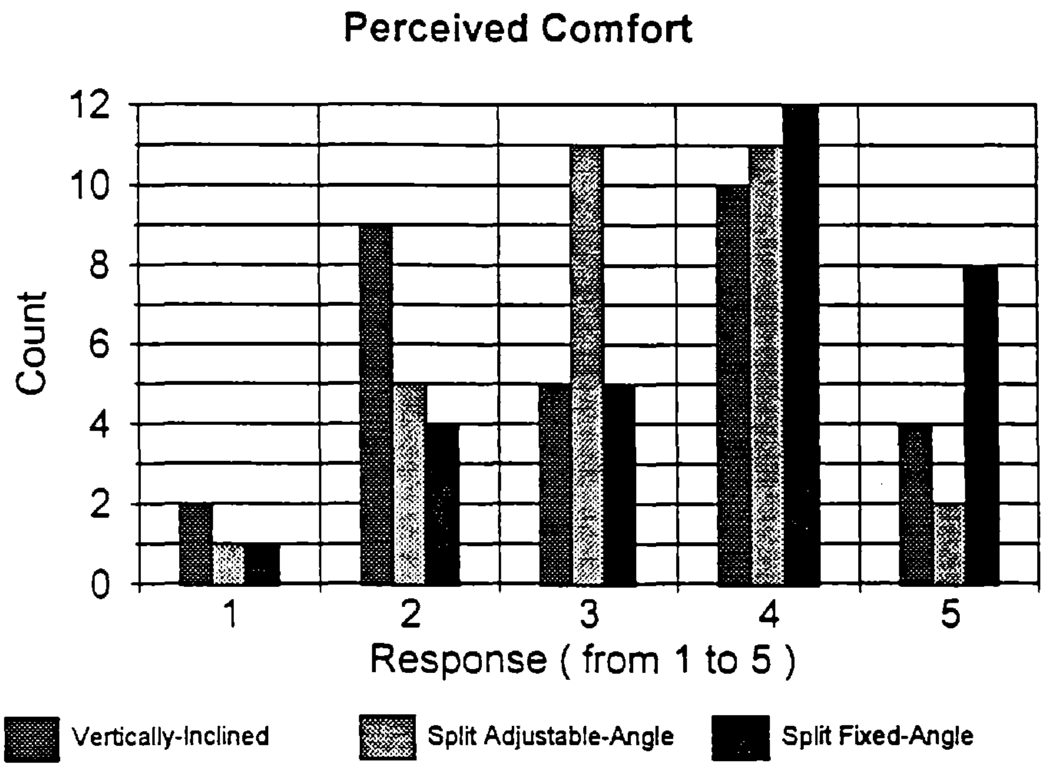


Figure 17. Perceived level of comfort using the alternative keyboard as compared to the use of a conventional keyboard. The ratings range from 1 to 5, with 1 being 'much less comfortable' and 5 being 'much more comfortable.'

Table 12. Perceived level of comfort using the alternative keyboard as compared to the use of a conventional keyboard. The ratings range from 1 to 5, with 1 being 'much less comfortable' and 5 being 'much more comfortable'.

Keyboards	Mean ± S.D.	Minimum	Maximum
All subjects (n=90)	3.4 ± 1.10	1	5
Split fixed-angle (n=30)	3.7 ± 1.09	1	5
Split adjustable-angle (n=30)	3.3 ± 0.93	1	5
Vertically-inclined (n=30)	3.2 ± 1.18	1	5

The mean comfort scores for the alternative keyboards show that subjects generally found the split fixed-angle keyboard to be more comfortable than the conventional keyboard and the split adjustable-angle keyboard to be as comfortable as the conventional keyboard. The comfort scores for vertically-inclined show that subjects either felt it was more comfortable or less comfortable, with very few subjects rating it with a middle score.

Split fixed-angle keyboard: Five of 30 subjects found the split fixed-angle keyboard to be as comfortable as the conventional keyboard. Twenty found it to be either more comfortable or much more comfortable to use. Only five subjects found this keyboard to be less or much less comfortable to use.

Split adjustable-angle keyboard: Eleven of 30 subjects found the split adjustable-angle keyboard to be as comfortable as the conventional keyboard. Thirteen subjects found it to be either more comfortable or much more comfortable to use. Six subjects found this keyboard to be less or much less comfortable to use.

Vertically-inclined keyboard: The distribution of the comfort ratings from this group of subjects is bimodal where a substantial number rated this keyboard as either a less comfortable (rating of 2 or less) or more comfortable (rating of 4 or greater), and a much smaller group rating it as same comfort (rating of 3).

D.5.4. Typing Performance

Typing Speed: A 'word' is defined as five typed characters, and typing speed is defined as the number of words typed per minute (WPM). Tables 13, 14 and 15 present the summary statistics for typing speed for each alternative keyboard as compared to the conventional keyboard. For each table, comparisons were made for both typing tasks, alphabetic and alphanumeric.

Table 13. Words per minute (WPM) for the 30 subjects who used the split fixed-angle keyboard.

	Typing Task			
	Alphabetic		Alphanumeric	
Keyboard	Mean ± s.d.	(Range)	Mean ± s.d.	(Range)
Conventional	60.53 ± 10.36	(42 - 80)	44.47 ± 9.21	(37 - 54)
Split fixed-angle	57.32 ± 8.68	(41 - 74)	41.83 ± 7.55	(31 - 62)

Data analysis for comparison of typing speed on the split fixed-angle keyboard was performed using a two-way ANOVA for repeated-measures. The two factors were keyboard design (2 levels--conventional and split fixed-angle) and typing task (2 levels--alphabetic and alphanumeric). A significant main effect was found for both factors ($p < 0.01$ for typing task and $p < 0.02$ for keyboard). No statistically significant interactions were found between factors.

Although statistically significant, mean typing speed was only approximately 3 words per minute greater with the conventional keyboard as compared to the split fixed-angle keyboard. As expected, due to the added difficulty with the text used, speed of typing with the alphanumeric typing task was much lower than for the more customary alphabetic task.

Table 14. Words per minute (WPM) for 29 subjects who used the split adjustable-angle keyboard.

	Typing Task			
	Alphabetic		Alphanumeric	
Keyboard	Mean ± s.d.	(Range)	Mean ± s.d.	(Range)
Conventional	63.11 ± 13.86	(43 - 96)	47.86 ± 14.23	(28 - 81)
Split adj.-angle	60.30 ± 13.31	(41 - 95)	44.00 ± 9.21	(29 - 61)

Data analysis for comparison of typing speed on the split adjustable-angle keyboard was performed using a two-way ANOVA for repeated-measures. The two factors were keyboard design (2 levels--conventional and split fixed-angle) and typing task (2 levels--alphabetic and alphanumeric). A significant main effect was found for both factors ($p < 0.01$ for typing tasks and for keyboards). No statistically significant interactions were found between factors.

Although statistically significant, mean typing speed was only approximately 3 words per minute greater with the split adjustable-angle keyboard compared to the conventional. As expected, typing speed in the alphanumeric typing task was much lower than for the alphabetic task.

Table 15. Words per minute (WPM) for 30 subjects who used the vertically-inclined keyboard.

	Typing Task			
	Alphabetic		Alphanumeric	
Keyboard	Mean ± s.d.	(Range)	Mean ± s.d.	(Range)
Conventional	58.67 ± 12.08	(28 - 87)	44.10 ± 10.20	(23 - 73)
Vert. Inclined	54.12 ± 9.01	(25 - 77)	40.34 ± 9.01	(23 - 54)

Data analysis for comparison of typing speed on the vertically-inclined keyboard was performed using a two-way ANOVA for repeated-measures. The two factors were keyboard (2 levels--conventional and vertically-inclined) and typing task (2 levels--alphabetic and alphanumeric). A significant main effect was found for both factors ($p < 0.01$ for typing tasks and for keyboard). No statistically significant interactions were found between factors.

Although statistically significant, mean typing speed was only approximately 4 words per minute greater with the conventional keyboard. As expected, speed of typing with the alphanumeric typing task was much lower than for the alphabetic task.

Overall, for each of the keyboards investigated, the subjects had reached a comfortable mean typing speed that was only 3 to 4 words per minute slower than when typing on the conventional keyboard. Note that the measured typing speed (95% for the split fixed-angle keyboard compared to the conventional keyboard, 96% for the split adjustable-angle keyboard and 92% for the vertically-inclined keyboard) compares favorably to the perceived typing speed of the subjects presented in Table 9 (92%, 91%, and 86%, respectively for the three alternative keyboards).

Typing accuracy: Accuracy was defined as the difference between the total number of characters typed and the total number of errors left in the document, divided by the total number of characters. Backspacing could be used if the subject so desired, but it was not required. Most subjects did backspace, which led to a high percentage of accuracy in the type text at the end of the eight minute period. However, while backspacing helped increase the typing accuracy, it decreased the typing speed since the use of the backspace costs two characters (the backspace itself and the character being replaced). The experience of the subjects at typing can also be viewed as a major factor in the high accuracy results.

Tables 16, 17 and 18 present the summary statistics for typing accuracy for each of the alternative keyboard as compared to the conventional keyboard. For each table comparisons were made for both typing tasks, alphabetic and alphanumeric.

Similar to the analysis performed with typing speed, data analysis for comparison of typing accuracy was performed using a two-way ANOVA for repeated-measures for each keyboard. The two factors were keyboard design (2 levels--conventional and alternative) and typing task (2 levels--alphabetic and alphanumeric). A separate analysis was performed for each keyboard.

Table 16. Mean typing accuracy for 30 subjects who used the split fixed-angle keyboard.

	Typing Task			
	Alphabetic		Alphanumeric	
Keyboard	Mean ± s.d.	(Range)	Mean ± s.d.	(Range)
Conventional	99.52 ± 1.06	(96 - 100)	99.63 ± 0.84	(97 - 100)
Split fixed-angle.	99.80 ± 0.70	(96 - 100)	99.80 ± 0.79	(96 - 100)

Table 17. Mean typing accuracy for 29 subjects who used the split adjustable-angle keyboard.

	Typing Task			
	Alphabetic		Alphanumeric	
Keyboard	Mean ± s.d.	(Range)	Mean ± s.d.	(Range)
Conventional	99.72 ± 0.69	(97 -100)	99.48 ± 1.33	(94 - 100)
Split adj.-angle	99.49 ± 1.22	(93 - 100)	99.52 ± 1.55	(92 - 100)

Table 18. Mean typing accuracy for 30 subjects who used the vertically-inclined keyboard.

	Typing Task			
	Alphabetic		Alphanumeric	
Keyboard	Mean ± s.d.	(Range)	Mean ± s.d.	(Range)
Conventional	99.62 ± 1.23	(94 - 100)	99.69 ± 0.99	(95 - 100)
Vert. Inclined	99.53 ± 1.51	(92 - 100)	99.69 ± 1.29	(93 - 100)

For all three alternative keyboards, no statistically significant main effect or interactions were found ($p < .05$) in typing accuracy for the two factors of keyboard design and typing task. Typing accuracy was extremely high in all cases.

Number of characters typed: Total number of characters typed was defined as the number of characters the subject reached at the end of the eight minute typing task. This variable does not include hitting the backspace key. In addition, the character that was backspaced is removed from the total character count.

Tables 19, 20 and 21 present the summary statistics for characters typed for each of the alternative keyboard as compared to the conventional keyboard. For each table, comparisons were made for both the alphabetic and alphanumeric typing tasks..

Similar to the analysis performed with typing speed, data analysis for comparison of characters typed was performed using a two-way repeated-measures ANOVA for each keyboard. The two factors were keyboard design (2 levels--conventional and alternative) and typing task (2 levels--alphabetic and alphanumeric). A separate analysis was performed for each keyboard.

Table 19. Total number of characters typed for 30 subjects who used the split fixed-angle keyboard during eight minute typing sessions.

	Typing Task			
	Alphabetic		Alphanumeric	
Keyboard	Mean ± s.d.	(Range)	Mean ± s.d.	(Range)
Conventional	2439 ± 336.6	(1705 - 3235)	1797 ± 366.0	(1204 - 2811)
Split fixed-angle	2311 ± 334.4	(1674 - 3000)	1690 ± 299.2	(1241 - 2493)

Table 20. Total number of characters typed for 29 subjects who used the split adjustable-angle keyboard during eight minute typing sessions.

	Typing Task			
	Alphabetic		Alphanumeric	
Keyboard	Mean ± s.d.	(Range)	Mean ± s.d.	(Range)
Conventional	2545 ± 556.1	(1747 - 3879)	1954 ± 558.8	(1148 - 3300)
Split adj. angle	2433 ± 533.9	(1647 - 3810)	1781 ± 367.5	(1172 - 2461)

Table 21. Total number of characters typed for 30 subjects who used the vertically-inclined keyboard during eight minute typing sessions.

	Typing Task			
	Alphabetic		Alphanumeric	
Keyboard	Mean ± s.d.	(Range)	Mean ± s.d.	(Range)
Conventional	2368 ± 485.1	(1144 - 3492)	1781 ± 410.2	(926 - 2938)
Vert. inclined	2184 ± 463.3	(1002 - 3092)	1634 ± 360.8	(947 - 2186)

With regards to all three alternative keyboards (refer to Tables 19, 20, and 21), a significant main effect was found for both factors ($p < 0.01$ for typing task and $p < 0.02$ for keyboard design). No statistically significant interactions were found between factors. These results are expected since total number of characters typed is directly related to typing speed in words per minute, which did not result in a significant interaction between keyboard design and task. Similar to typing speed, the number of characters typed was slightly greater with the conventional keyboard. In addition, more characters were typed in the alphabetic task compared to the alphanumeric task.

Total number of errors: Total number of errors is defined as the number of mistaken keystrokes left in the document at the end of the eight minute period.

Tables 22, 23 and 24 present the summary statistics for total errors for each alternative keyboard as compared to the conventional keyboard. For each table, comparisons were made for both alphabetic and alphanumeric typing tasks.

Similar to the analysis performed with typing speed, data analysis for total number of errors was performed using a two-way repeated-measures ANOVA for each keyboard. The two factors were keyboard design (2 levels--conventional and alternative) and typing task (2 levels--alphabetic and alphanumeric). A separate analysis was performed for each keyboard.

Table 22. Total number of errors for 30 subjects who used the split fixed-angle keyboard during eight minute typing sessions.

	Typing Task			
	Alphabetic		Alphanumeric	
Keyboard	Mean ± s.d.	(Range)	Mean ± s.d.	(Range)
Conventional	15.05 ± 27.77	(0 - 105)	10.93 ± 17.41	(0 - 68)
Split fixed-angle	8.17 ± 19.99	(0 - 106)	6.83 ± 8.51	(0 - 62)

Table 23. Total number of errors for 29 subjects who used the split adjustable-angle keyboard during eight minute typing sessions.

	Typing Task			
	Alphabetic		Alphanumeric	
Keyboard	Mean ± s.d.	(Range)	Mean ± s.d.	(Range)
Conventional	11.12 ± 19.88	(0 - 91)	13.62 ± 23.99	(0 - 92)
Split adj. angle	17.68 ± 41.90	(0 - 263)	13.14 ± 38.38	(0 - 209)

Table 24. Total number of errors for 30 subjects who used the vertically-inclined keyboard during eight minute typing sessions.

	Typing Task			
	Alphabetic		Alphanumeric	
Keyboard	Mean ± s.d.	(Range)	Mean ± s.d.	(Range)
Conventional	14.80 ± 39.55	(0 - 237)	11.76 ± 24.50	(0 - 101)
Vert. inclined	18.13 ± 47.38	(0 - 230)	11.72 ± 32.56	(0 - 159)

As indicated for all three alternative keyboards in Tables 22, 23, and 24, no statistically significant main effect or interactions were found ($p < .05$). Interestingly, fewer errors were left in the alphabetic document when using the split fixed-angle keyboard as compared to the conventional. However, given the several thousand number of characters typed, a difference of about 7 characters is actually very small (8 vs. 15 errors for the split fixed-angle and conventional keyboards, respectively; refer to Table 22).

D.5.5. Conventional Keyboard: Descriptive Results of Wrist and Forearm Position

Since all subjects who participated in this study were tested on the conventional keyboard, a descriptive analysis for all 90 subjects is presented in this section. In addition, a two-way ANOVA for repeated measures was performed to determine any statistically significant differences between the position of the left versus the right wrist and between the alphabetic and alphanumeric typing tasks. Table 25A presents the mean wrist and forearm position data for both hands and both typing tasks performed. Table 25B presents the results of the statistical analysis.

As a group, the 90 subjects typed on the conventional keyboard with a mean upper extremity typing posture which consisted of extended and ulnarly deviated wrists and pronated forearms (Table 25A and Figures 18 to 21). A statistically significant ($p < 0.01$) and possibly practical difference was present between the mean left and right wrist radial/ulnar and flexion/extension posture. The 90 subjects using the conventional keyboard tended to place the left wrist in a mean position which was more ulnarly deviated than the right wrist. The difference in mean wrist ulnar position was approximately 5 deg. (10 deg. for the right hand and 15 deg. for the left hand), as shown in Table 25A and Figures 18 and 19. The difference in mean wrist extension angle between the right and left side was about 3-4 deg. (approximately 17 deg. for the right wrist and 21 deg. for the left), which was also statistically significant ($p < 0.01$, Table 25B). Similarly, as shown in Table 25A and Figures 20 and 21, the difference in mean pronation angle of the forearm was about 4 deg. between the right and left sides (66 deg. for the right forearm and 62 deg. for the left) ($p < 001$, Table 25B). However, unlike the greater ulnar deviation and extension of the left wrist over the right wrist, it was the right forearm that was pronated more than the left forearm.

Table 25A. *Mean* wrist and forearm position in degrees when typing on a conventional computer keyboard (n = 90 for both wrists, n = 73 for left forearm and n = 81 for right forearm). Wrist radial deviation, wrist flexion and forearm pronation are indicated by positive values. Wrist ulnar deviation, wrist extension and forearm supination are indicated by negative values.

Typing task	Wrist radial/ulnar deviation	Wrist flexion/ extension	Forearm pronation/ supination
Left hand			
Alphabetic	-15.0 ± 7.7	-21.2 ± 8.8	62.2 ± 10.6
Alphanumeric	-16.8 ± 8.0	-20.8 ± 8.4	62.3 ± 10.1
Right hand			
Alphabetic	-10.1 ± 7.2	-17.0 ± 7.4	65.6 ± 8.3
Alphanumeric	-10.8 ± 7.2	-17.4 ± 7.6	66.3 ± 8.4

Table 25B. P- values of the 2-way analysis of variance for the *mean* wrist and forearm position for the conventional keyboard. The two factors are hand (right and left) and typing task (alphabetic and alphanumeric).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Hand (H)	1	0.000 **	0.000 **	0.001 **
Typing Task (T)	1	0.000 **	0.953	0.186
H x T	1	0.000 **	0.009 **	0.326

** Significant at p < 0.01 level; * significant at p < 0.05 level.

While a statistically significant difference ($p < 0.01$) for typing task was found for wrist radial/ulnar deviation, this difference was less than two degrees and likely not functionally significant. Similarly, despite the statistical significance for hand x task (HxT) interaction for wrist radial/ulnar and wrist flex/ext position ($p < .01$), these differences were minor in terms of degrees.

The number of subjects who had data for the left and right forearm pronation was 73 and 81, respectively. Data from 17 subjects for the left forearm and nine subjects for the right forearm were discarded due to a lack of consistency between pre and post-testing calibration data. Because of the difficulty in fixing the goniometers in proper position, some "slippage" must have occurred for this small group of subjects. The data lost in this manner is not problematic in this study since we had a large number of subjects and since the data loss was distributed relatively evenly among the three alternative keyboard users.

Tables 26A and 26B present the maximum joint position data and the results of the subsequent statistical analysis. While a number of statistically significant differences ($p < 0.05$) are present, an overview of the values in Table 26A indicate that all these differences are less than 3 degrees, and therefore are likely to be of no functional difference (Table 26A and Figures 18 through 21). The average maximum wrist ulnar deviation for all subjects was about 25 deg. (refer to Table 26A and Figures 18 and 19); similarly, the average maximum wrist extension was approximately 25 deg. (refer to Table 26A and Figures 18 and 19). The average maximum forearm pronation for all 90 subjects was about 72 deg. (refer to Table 26A and Figures 23 and 24).

Table 27A and 27B present the minimum joint position and the results of the subsequent statistical analysis. A statistically significant hand main effect was present for forearm pronation only ($p < 0.01$, Table 27B). Despite the statistically significant difference between typing tasks found for wrist radial/ulnar and wrist flex/ext minimum position, these differences were functionally minimal ($p < .01$, Table 27B). The average minimum wrist ulnar deviation across all 90 subjects was about 4 deg., and the average minimum wrist extension angle was about 10 deg. (refer to Table 27A and Figures 18 and 19). The average minimum pronation of the forearm was approximately 55 deg. (refer to Table 27A and Figures 20 and 21).

In summary, there are statistically significant as well as potentially functionally significant differences between the posture of the right and left wrist and forearm when typing on a conventional computer keyboard. But, no practical difference in position existed between the two typing tasks, alphabetic and alphanumeric. Regardless of whether wrist and forearm position were expressed as the mean, minimum, or maximum, the difference in position between the two typing tasks was generally within 0 to 3 degrees, as indicated in Tables 25A, 26A and 27A and Figures 18 through 21. .

Table 26A. *Maximum* wrist and forearm position in degrees when typing on a conventional computer keyboard (n = 90 for both wrists, n = 73 for left forearm and n = 81 for right forearm). Wrist radial deviation, wrist flexion and forearm pronation are indicated by positive values. Wrist ulnar deviation, wrist extension and forearm supination are indicated by negative values.

Typing task	Wrist radial/ulnar deviation	Wrist flexion/ extension	Forearm pronation/ supination
Left hand			
Alphabetic	-23.5 ± 7.0	-26.1 ± 8.8	70.2 ± 10.3
Alphanumeric	-26.2 ± 6.8	-26.6 ± 8.6	71.3 ± 10.2
Right hand			
Alphabetic	-24.7 ± 6.0	-25.2 ± 7.9	72.1 ± 9.1
Alphanumeric	-25.2 ± 6.2	-26.2 ± 8.3	73.4 ± 9.4

Table 26B. P- values of the 2-way analysis of variance for the *maximum* wrist and forearm position for the conventional keyboard. The two factors are hand (right and left) and typing task (alphabetic and alphanumeric).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Hand (H)	1	0.000 **	0.000 **	0.091
Typing Task (T)	1	0.035 *	0.000 **	0.002 **
H x T	1	0.000 **	0.123	0.729

** Significant at $p < 0.01$ level; * significant at $p < 0.05$ level.

Table 27A. *Minimum* wrist and forearm position in degrees when typing on a conventional computer keyboard (n = 90 for both wrists, n = 73 for left forearm and n = 81 for right forearm). Wrist radial deviation, wrist flexion and forearm pronation are indicated by positive values. Wrist ulnar deviation, wrist extension and forearm supination are indicated by negative values.

Typing task	Wrist radial/ulnar deviation	Wrist flexion / extension	Forearm pronation/ supination
Left hand			
Alphabetic	-5.3 ± 9.0	-14.9 ± 9.0	54.6 ± 11.7
Alphanumeric	-6.5 ± 9.5	-13.3 ± 8.9	53.3 ± 11.4
Right hand			
Alphabetic	-2.3 ± 7.6	-7.5 ± 8.0	57.0 ± 10.7
Alphanumeric	-1.9 ± 7.9	-6.5 ± 8.4	56.8 ± 11.3

Table 27B. P- values of the 2-way analysis of variance for the *minimum* wrist and forearm position for the conventional keyboard. The two factors are hand (right and left) and typing task (alphabetic and alphanumeric).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Hand (H)	1	0.924	0.420	0.011
Typing Task (T)	1	0.000 **	0.003	0.067
H x T	1	0.000	0.090	0.077

** Significant at $p < 0.01$ level; * significant at $p < 0.05$ level.

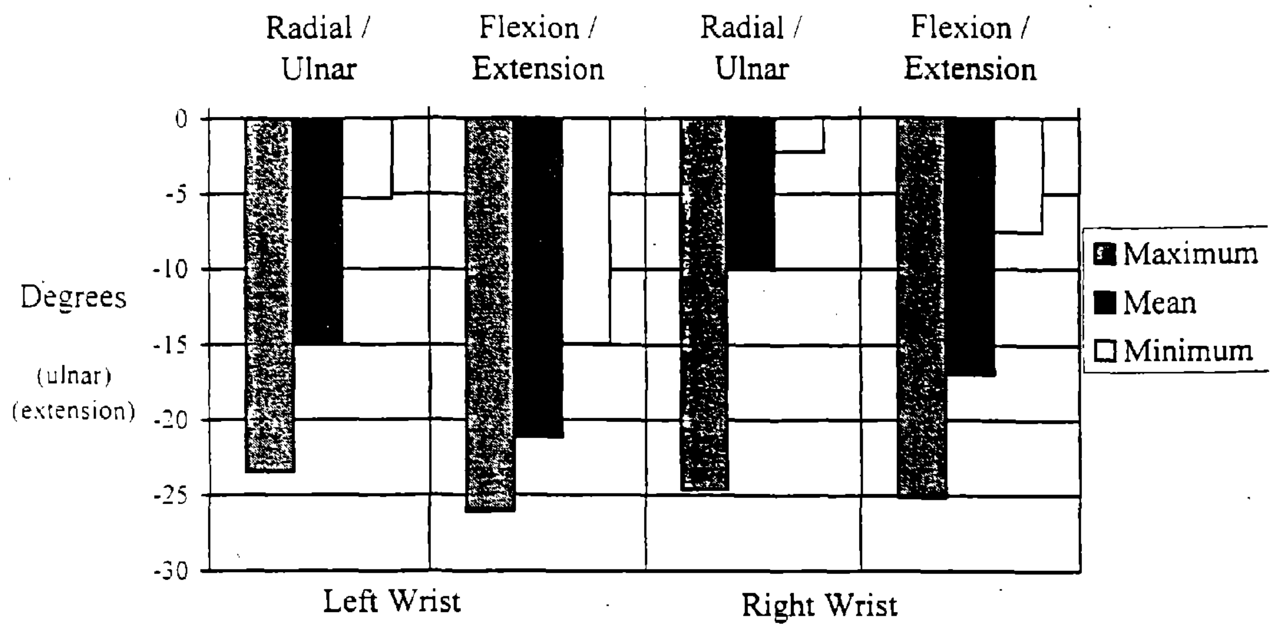


Figure 18. Mean, maximum and minimum wrist position when typing an *alphabetic* task on the conventional computer keyboard (n = 90).

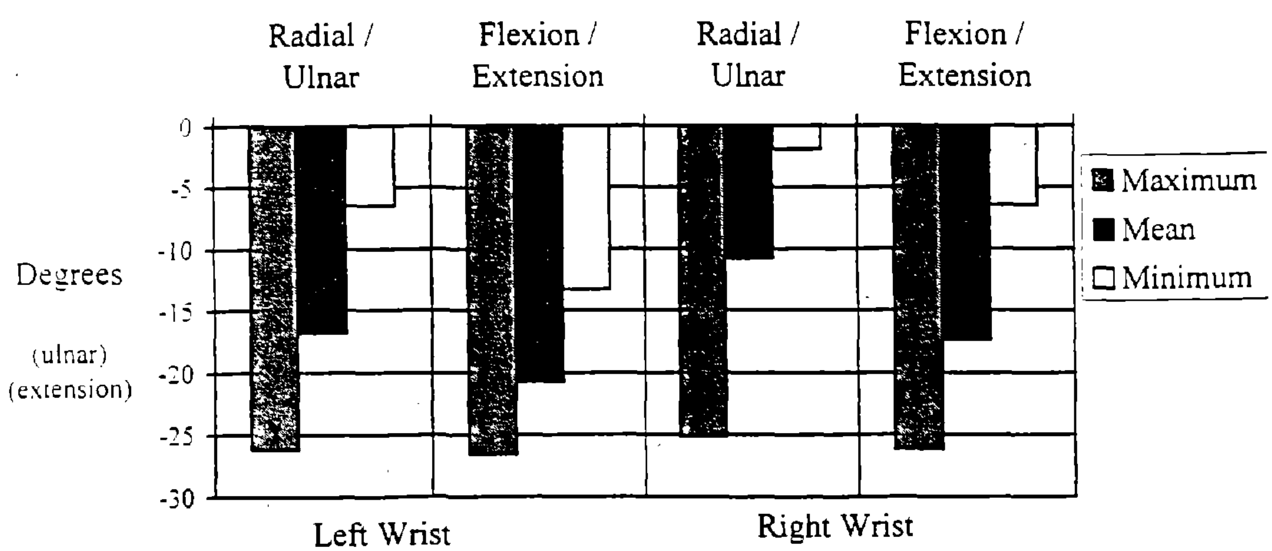


Figure 19. Mean, maximum and minimum wrist position when typing an *alphanumeric* task on the conventional computer keyboard (n = 90).

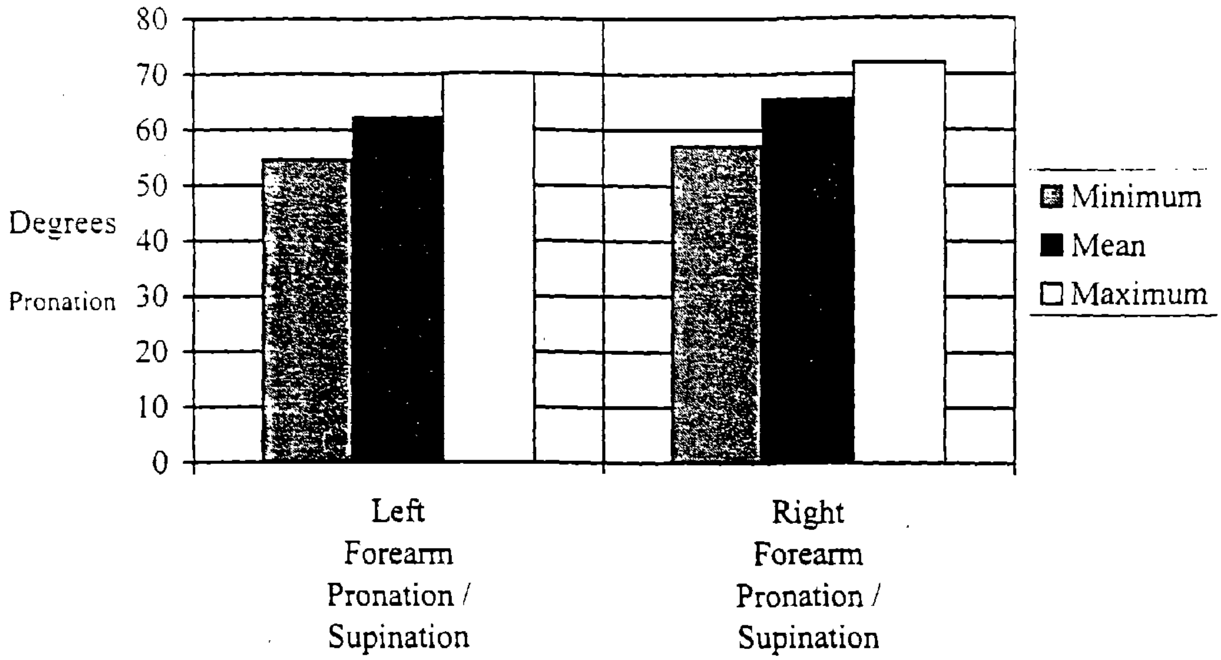


Figure 20. Mean, maximum and minimum forearm position when typing an *alphabetic* task on the conventional computer keyboard (n = 73 for left forearm and n = 81 for the right forearm).

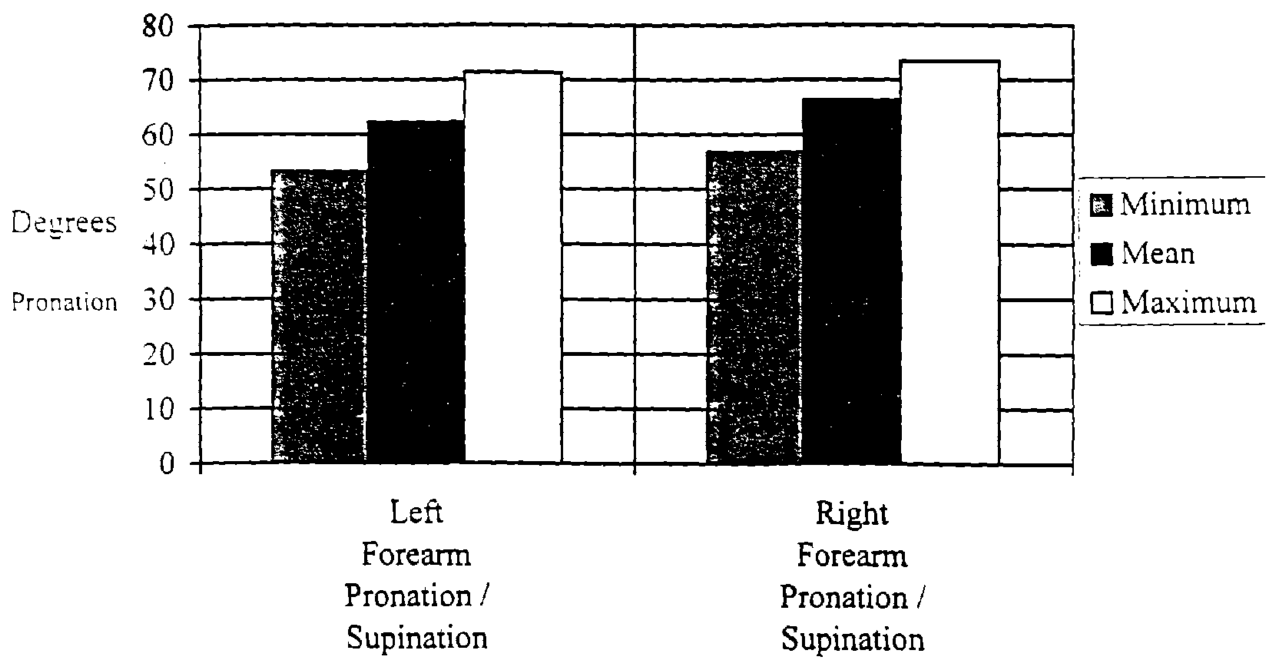


Figure 21. Mean, maximum and minimum forearm position when typing an *alphanumeric* task on the conventional computer keyboard (n = 73 for left forearm and n = 81 for the right forearm).

D.5.6. Split Fixed-Angle Keyboard: Analysis of Wrist and Forearm Position

In this study, 30 subjects were tested on both the conventional and a split fixed-angle keyboard in order to establish the effect of these two keyboard designs on wrist and forearm position. Tables 28A, 28B and 28C, which list a summary of ANOVA p-values, show statistically significant effects for keyboard design (split fixed-angle vs. conventional) across all three planes of wrist and forearm position. Compared to the conventional keyboard, the 30 subjects who practiced using the split fixed-angle alternative keyboard placed their upper extremity in significantly less wrist ulnar deviation, wrist extension, and forearm pronation ($p < 0.01$). Each plane of movement will be discussed separately. The results for the mean position data will be discussed in detail, followed by a summary of the minimum and maximum position data.

Wrist Radial/Ulnar Position. As shown in Figure 22, mean wrist ulnar deviation of the 30 subjects was significantly lower when the subjects typed on the split fixed-angle keyboard compared to the conventional keyboard ($p < 0.01$). For the alphabetic task, the reduction in mean ulnar deviation was approximately 10.7 deg. (16.5 deg. to 5.8 deg.) for the left wrist and approximately 9.1 deg. (7.9 deg.of ulnar deviation to 1.2 deg. of radial deviation) for the right wrist. The fact that the alternative keyboard affected wrist ulnar deviation with a different magnitude between the right and left side is indicated by the statistically significant keyboard and hand interaction (KxH) (refer to Table 28A and Figure 23). It is noteworthy that a greater decrease in ulnar deviation was present on the side where the ulnar deviation with the conventional keyboard was initially larger. Also, note that while the keyboard has a slant angle of 12.5 degrees for each hand, the reduction in ulnar deviation ranged from 9 to 11 deg.

A statistically significant main effect was also noted for hands ($p< 0.01$). Overall, the left hand was held in a greater mean ulnar deviation than the right hand while typing (by approximately 9.0 deg. for the conventional keyboard and 6.0 deg. for the split fixed-angle keyboard).

Typing task also had a statistically significant main effect ($p < 0.01$), but similar to the analysis done on all subjects for the conventional keyboard, this difference was only 1 or 2 deg. (refer to Table 29). Therefore, although the hand and task interaction (HxT) was statistically significant for ulnar deviation ($p < 0.05$), it did not result in a noteworthy difference. Figure 24 shows the minor differences in ulnar deviation among the various combinations of hand and tasks.

Table 28A. P- values of the 3-way analysis of variance for the mean wrist position when comparing the split fixed-angle keyboard to the conventional keyboard. The three factors are keyboard (conventional and split fixed-angle), hand (right and left) and typing task (alphabetic and alphanumeric).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Keyboard (K)	1	0.000**	0.000**	0.001**
Hand (H)	1	0.000**	0.001**	0.162
Typing Task (T)	1	0.000**	0.766	0.643
K x H	1	0.022*	0.598	0.053
K x T	1	0.418	0.735	0.922
H x T	1	0.027*	0.001**	0.904
K x H x T	1	0.443	0.259	0.330

** Significant at $p < 0.01$; * significant at $p < 0.05$.

Table 28B. P- values of the 3-way analysis of variance for the maximum wrist position from neutral when comparing the split fixed-angle keyboard to the conventional keyboard. The three factors are keyboard (conventional and split fixed-angle), hand (right and left) and typing task (alphabetic and alphanumeric).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Keyboard (K)	1	0.000 **	0.001 **	0.001 **
Hand (H)	1	0.198	0.318	0.120
Typing Task (T)	1	0.000 **	0.364	0.052
K x H	1	0.400	0.636	0.266
K x T	1	0.379	0.674	0.552
H x T	1	0.016 *	0.036 *	0.377
K x H x T	1	0.229	0.099	0.866

** Significant at $p < 0.01$; * significant at $p < 0.05$.

Table 28C. P- values of the 3-way analysis of variance for the minimum wrist position from neutral when comparing the split fixed-angle keyboard to the conventional keyboard. The three factors are keyboard (conventional and split fixed-angle), hand (right and left) and typing task (alphabetic and alphanumeric).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Keyboard (K)	1	0.000 **	0.000 **	0.002 **
Hand (H)	1	0.000 **	0.000 **	0.884
Typing Task (T)	1	0.006 **	0.035 *	0.118
K x H	1	0.004 **	0.830	0.042 *
K x T	1	0.620	0.229	0.784
H x T	1	0.006 **	0.004 **	0.102
K x H x T	1	0.168	0.618	0.100

** Significant at $p < 0.01$; * significant at $p < 0.05$.

Table 29. *Mean* wrist radial/ulnar position in degrees for the split fixed-angle and conventional keyboards (negative = wrist ulnar deviation; positive = wrist radial deviation) (n = 30).

	Keyboard	
Typing task	Conventional	Split fixed-angle
Left wrist		
Alphabetic	-16.5 ± 8.8	-5.8 ± 9.8
Alphanumeric	-18.7 ± 9.3	-7.3 ± 10.8
Right wrist		
Alphabetic	-7.9 ± 6.7	1.2 ± 6.8
Alphanumeric	-9.0 ± 7.0	0.2 ± 6.9

Table 30. *Maximum* wrist radial/ulnar position in degrees for the split fixed-angle and conventional keyboard (negative = ulnar deviation; positive = radial deviation) (n = 30).

	Keyboard	
Typing task	Conventional	Split fixed-angle
Left wrist		
Alphabetic	-25.0 ± 8.2	-14.7 ± 9.8
Alphanumeric	-27.3 ± 7.9	-17.0 ± 9.4
Right wrist		
Alphabetic	-23.7 ± 4.7	-13.7 ± 5.6
Alphanumeric	-24.0 ± 4.9	-14.9 ± 5.5

Table 31. *Minimum* wrist radial/ulnar position in degrees for the split fixed-angle and conventional keyboard (negative = ulnar deviation; positive = radial deviation) (n = 30).

	Keyboard	
Typing task	Conventional	Alternative
Left wrist		
Alphabetic	-7.3 ± 10.5	4.3 ± 10.4
Alphanumeric	-9.2 ± 11.2	3.3 ± 12.0
Right wrist		
Alphabetic	-0.4 ± 9.0	9.0 ± 7.6
Alphanumeric	-0.6 ± 8.8	8.5 ± 7.8

The results of the minimum and maximum ulnar deviation resembled the results for radial/ulnar position in that the maximum ulnar deviation from neutral was about 10 deg. less for the split fixed-angle keyboard than the conventional keyboard (25 to 15 deg.), as shown in Table 30 and Figure 25. The minimum ulnar deviation from neutral showed a change of about 10 deg. (from 4 deg. of ulnar deviation to 7 deg. of radial deviation), as shown in Table 31 and Figure 26.

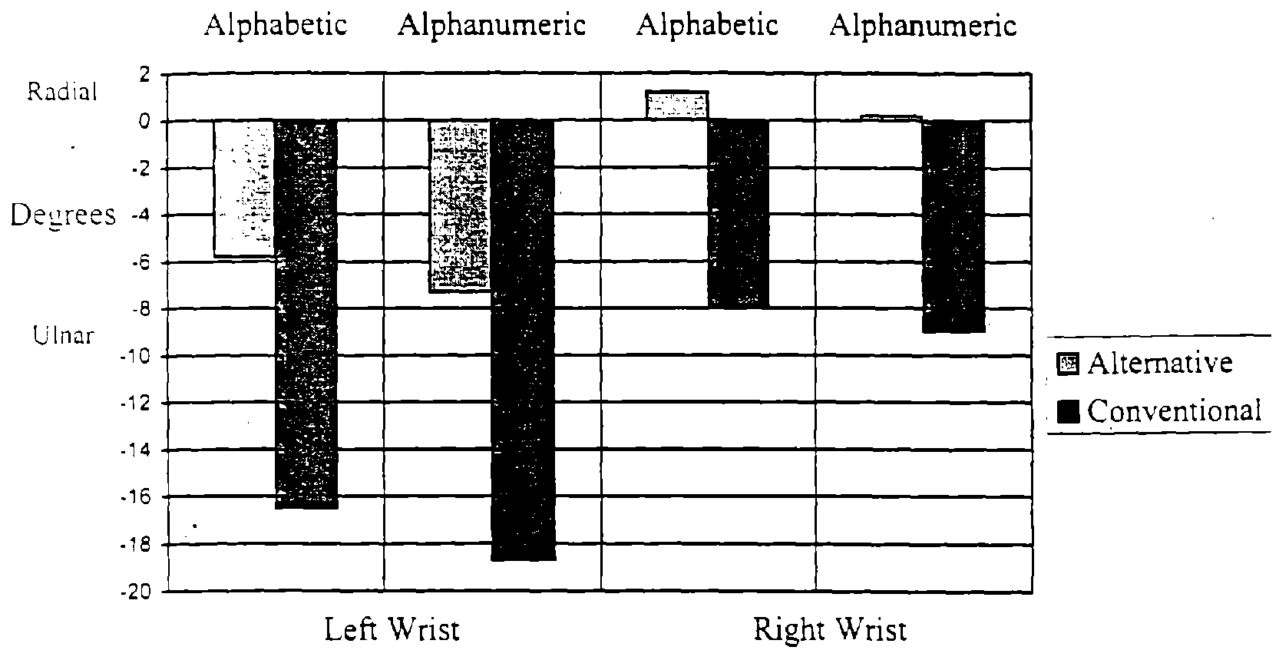


Figure 22. Mean wrist radial/ulnar position for the split fixed-angle and conventional keyboards for both typing tasks (n = 30).

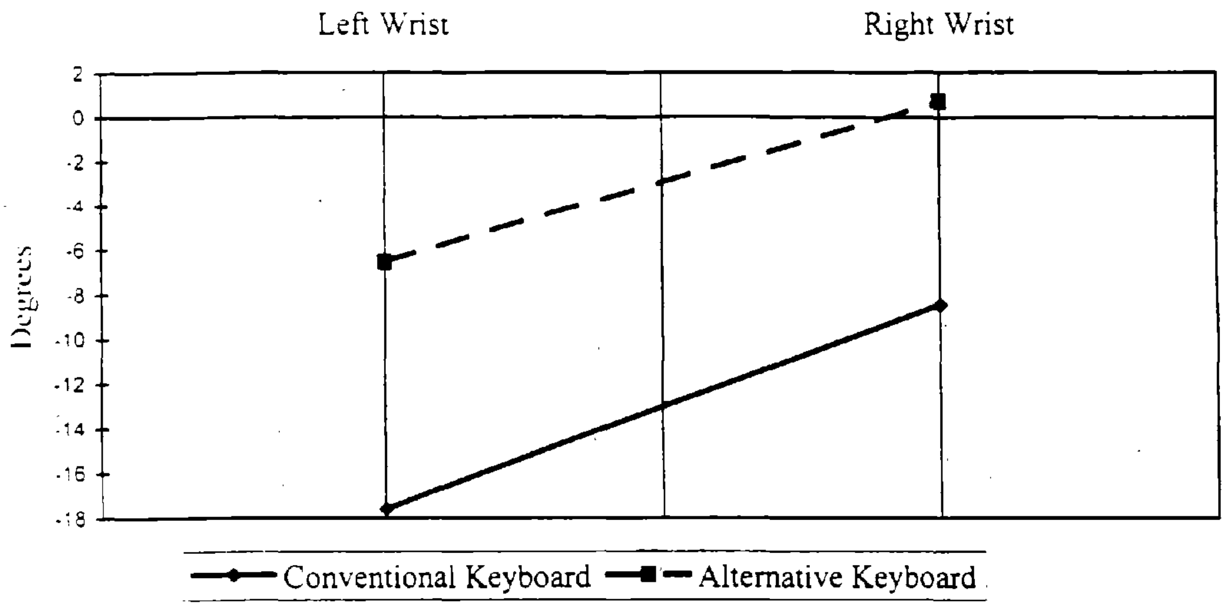


Figure 23. *Hand x Keyboard* interaction for mean wrist radial/ulnar position for the split fixed-angle and conventional keyboards (n = 30).

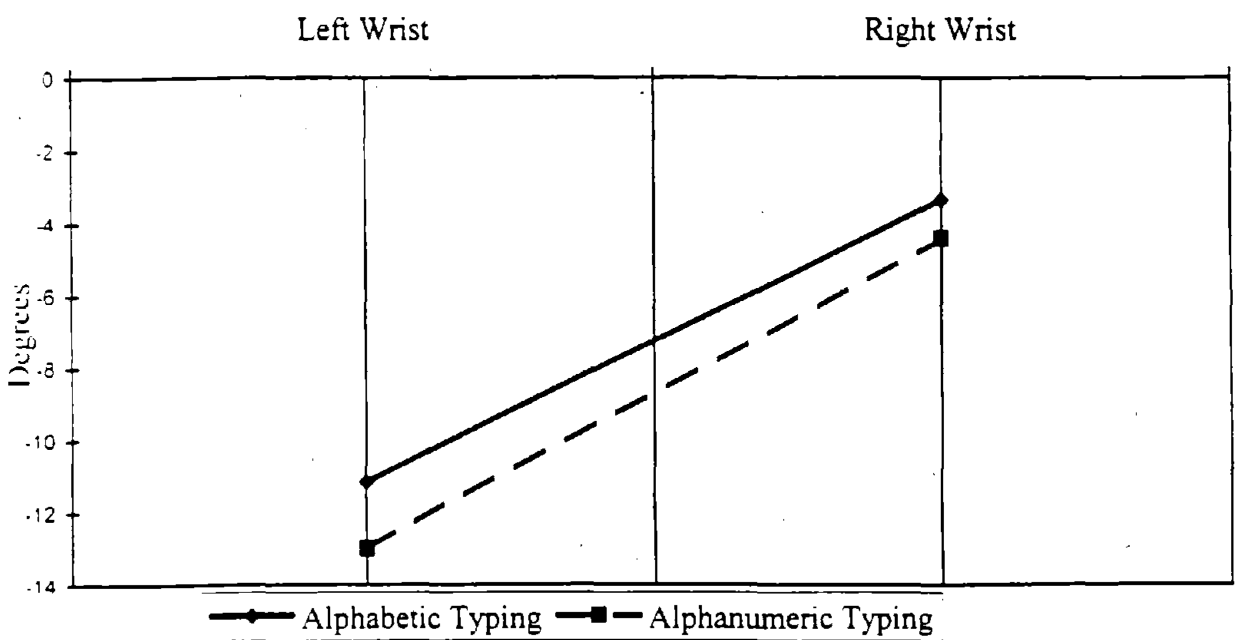


Figure 24. *Hand x Typing Task* interaction for mean wrist ulnar position for the split fixed-angle and conventional keyboards (n =30).

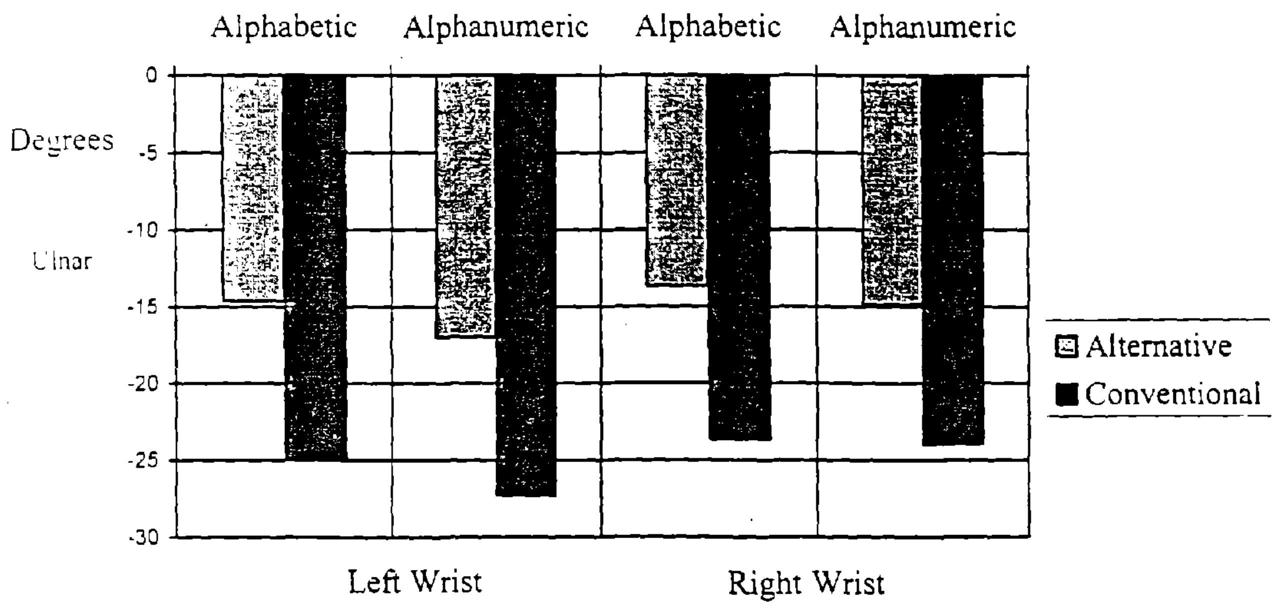


Figure 25. *Maximum* wrist ulnar position for the split fixed-angle and conventional keyboards for both typing tasks (n = 30).

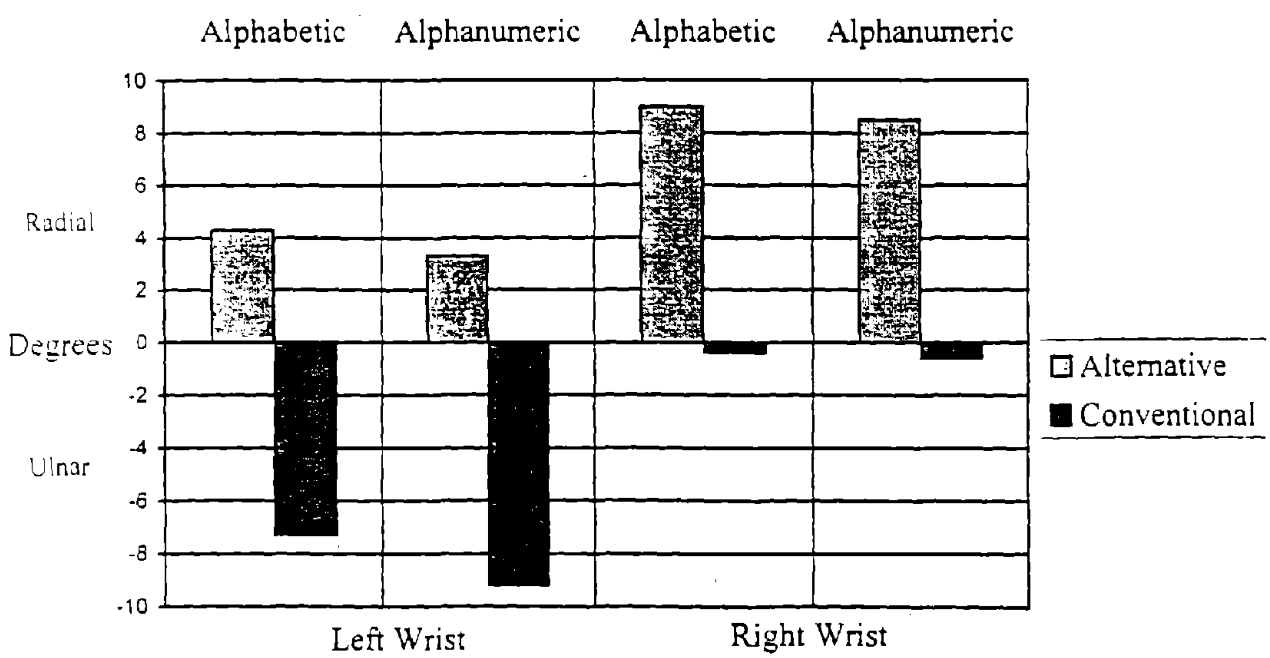


Figure 26. *Minimum* wrist radial/ulnar position for the split fixed-angle and conventional keyboards for both typing tasks (n = 30).

Wrist Flexion/Extension Position. Similar to ulnar deviation, mean wrist extension of the 30 subjects was less when using the split fixed-angle keyboard, compared to the conventional keyboard ($p < .01$, Table 28A). When using the split fixed-angle keyboard, the subjects extended their wrists by about 5 deg. less than when using the conventional keyboard (a change from approximately 18 to 13 deg. of extension for the right hand and from 23 to 18 deg. of extension for the left hand), as shown in Table 32 and Figure 27. A statistically significant lesser amount of wrist extension on the right as compared to the left is noted for both keyboards ($p < 0.01$, Table 28A). No significant main effect was noted for typing task ($p > 0.05$).

Unlike the analysis performed for ulnar deviation, there was no interaction between hand and keyboard design (KxH) for wrist extension ($p > 0.05$, Table 28A) but a statistically significant hand and typing task interaction (H X T) was present ($p < 0.01$, Table 28A). The data in Table 32 show that this statistically significant hand x task interaction (HxT) did not result in any noteworthy pattern.

Overall, the results from analyzing the minimum and maximum wrist extension data resembled the results from the mean position data (refer to Tables 33 and 34), where the split fixed-angle keyboard reduced minimum and maximum wrist extension position by about 4 deg.

While this keyboard was not specifically designed to reduce wrist extension while typing, a statistically (and possibly functionally) significant reduction in wrist extension occurred. The reason for this difference cannot be attributed to a difference in slope angle between keyboards since the slope angles were 5 degrees and 6 degrees for the conventional and split fixed-angle keyboards, respectively.

Table 32. *Mean* wrist flexion/extension position in deg. for the split fixed-angle and conventional keyboards (negative = wrist extension; positive = wrist flexion) (n = 30).

	Keyboard	
Typing task	Conventional	Split fixed-angle
Left wrist		
Alphabetic	-22.6 ± 10.4	-18.2 ± 8.6
Alphanumeric	-21.8 ± 9.8	-17.7 ± 9.3
Right wrist		
Alphabetic	-17.6 ± 8.1	-12.8 ± 5.7
Alphanumeric	-18.2 ± 8.5	-13.3 ± 5.9

Table 33. *Maximum* wrist flexion/extension position in deg. for the split fixed-angle and conventional keyboards (negative = wrist extension; positive = wrist flexion) (n = 30).

	Keyboard	
Typing task	Conventional	Split fixed-angle
Left wrist		
Alphabetic	-27.4 ± 10.6	-24.0 ± 9.1
Alphanumeric	-26.9 ± 9.9	-24.0 ± 9.0
Right wrist		
Alphabetic	-25.7 ± 8.9	-22.1 ± 6.2
Alphanumeric	-26.4 ± 9.4	-22.5 ± 6.3

Table 34. *Minimum* wrist flexion/extension position in deg. for the split fixed-angle and conventional keyboards (negative = wrist extension; positive = wrist flexion) (n = 30).

	Keyboard	
Typing task	Conventional	Split fixed-angle
Left wrist		
Alphabetic	-16.6 ± 10.6	-11.6 ± 9.3
Alphanumeric	-14.6 ± 10.7	-10.0 ± 10.5
Right wrist		
Alphabetic	-8.4 ± 8.9	-2.9 ± 6.7
Alphanumeric	-7.7 ± 8.8	-3.1 ± 7.5

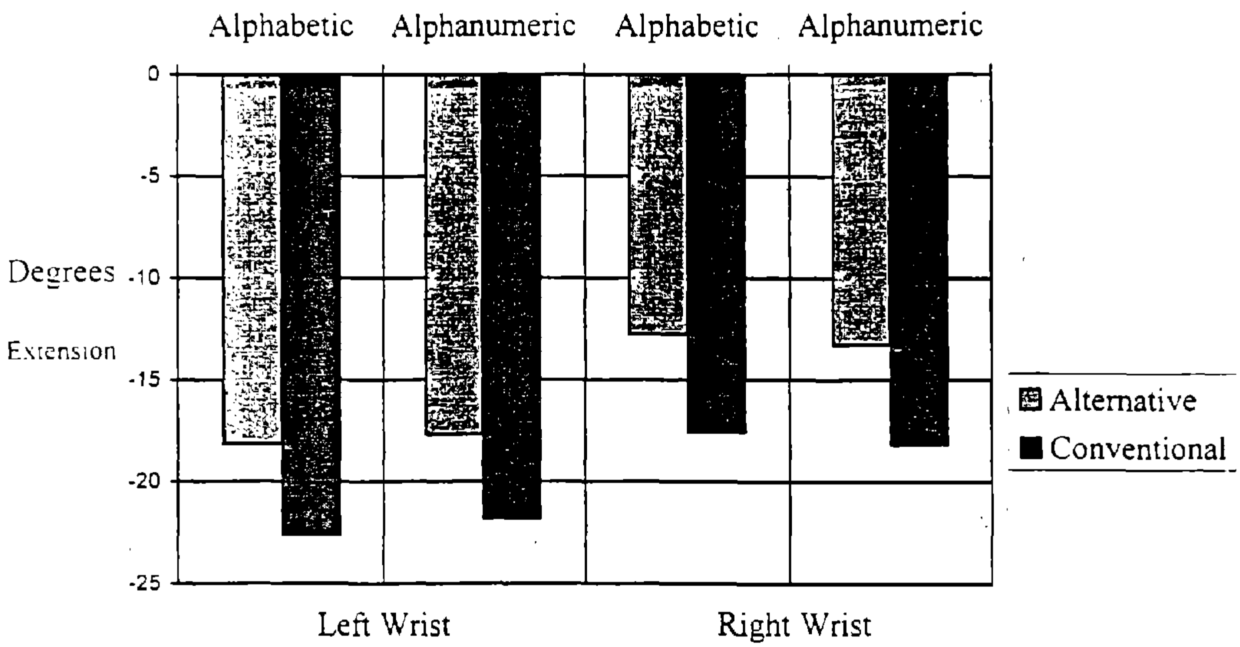


Figure 27. *Mean* wrist flexion/extension position for the split fixed-angle and conventional keyboards for both typing tasks (n = 30).

Forearm Pronation/Supination Position. As shown in Tables 28A and 35 and Figure 28, the only significant main effect for forearm pronation position was keyboard design where the split fixed-angle keyboard placed the forearm in a slightly less pronated posture than the conventional keyboard (approximately 62 vs. 66 deg.). As a percentage of maximum anatomical pronation (which is approximately 90 deg.), this reduction of 4 deg. represents less than 10% of maximum pronation and is probably not a practical difference. However, this reduction of 4 deg. pronation corresponds well to the 7 deg. tilt angle of split fixed-angle keyboard (as compared to a 0 degree tilt angle on the conventional keyboard). The results of the minimum and maximum pronation data are similar to the results from the mean positions, as revealed in Tables 36 and 37.

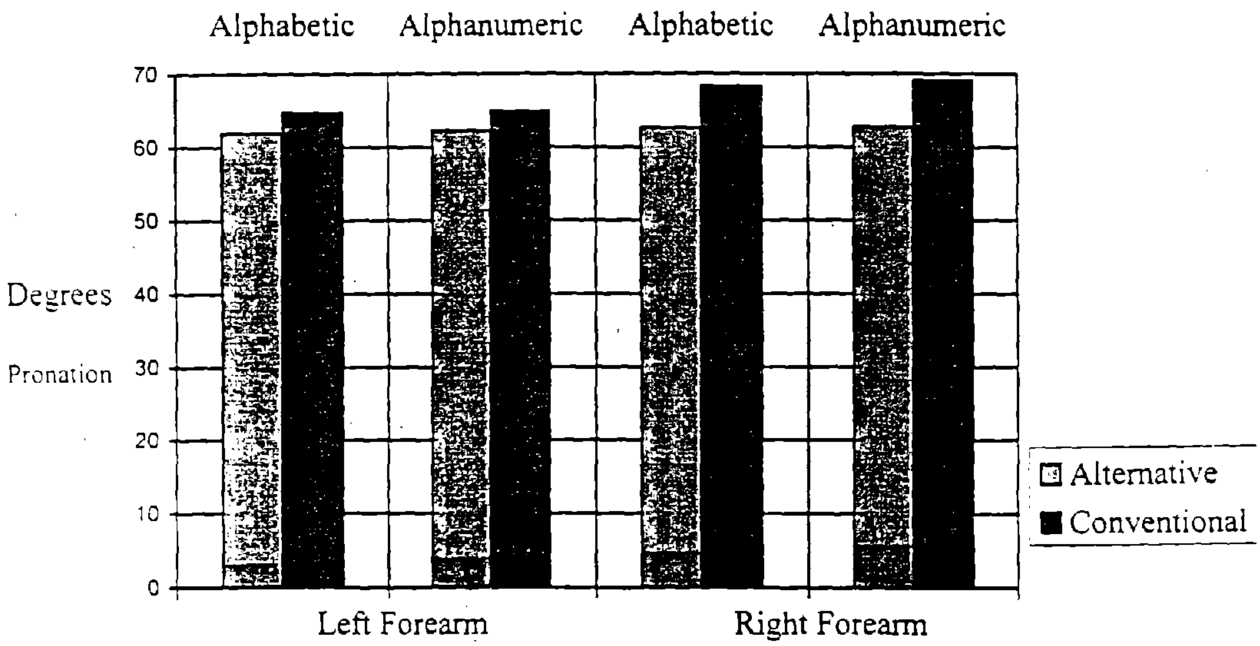


Figure 28. *Mean* forearm pronation for the split fixed-angle and conventional keyboards for both typing tasks (n = 24 for the left forearm and n = 25 for the right forearm).

Table 35. *Mean* forearm pronation/supination position in deg. for the split fixed-angle and conventional keyboards (negative = forearm supination; positive = forearm pronation) (n = 24 for the left forearm and n = 25 for the right forearm).

	Keyboard	
Typing task	Conventional	Split fixed-angle
Left forearm		
Alphabetic	64.7 ± 8.9	61.9 ± 9.2
Alphanumeric	64.8 ± 9.0	62.2 ± 9.1
Right forearm		
Alphabetic	68.3 ± 8.1	62.6 ± 6.9
Alphanumeric	69.1 ± 7.8	62.7 ± 7.0

Table 36. *Minimum* forearm pronation/supination position in deg. for the split fixed-angle and conventional keyboard (negative = forearm supination; positive = forearm pronation) (n = 24 for the left forearm and n = 25 for the right forearm).

	Keyboard	
Typing task	Conventional	Split fixed-angle
Left forearm		
Alphabetic	56.3 ± 10.0	53.4 ± 9.9
Alphanumeric	55.3 ± 11.5	52.0 ± 10.8
Right forearm		
Alphabetic	59.2 ± 11.2	53.3 ± 7.1
Alphanumeric	59.1 ± 11.2	53.0 ± 6.2

Table 37. *Maximum* forearm pronation/supination position in deg. for the split fixed-angle and conventional keyboards (negative = forearm supination; positive = forearm pronation) (n = 24 for the left forearm and n = 25 for the right forearm).

	Keyboard	
Typing task	Conventional	Split fixed-angle
Left forearm		
Alphabetic	73.1 ± 9.1	70.2 ± 10.5
Alphanumeric	74.2 ± 9.4	72.4 ± 12.6
Right forearm		
Alphabetic	75.1 ± 9.2	69.7 ± 8.6
Alphanumeric	76.5 ± 9.0	70.0 ± 8.5

D.5.7. Split Adjustable-Angle Keyboard: Analysis of Wrist and Forearm Position

Thirty subjects were tested both on a conventional and a split adjustable-angle keyboard in order to establish the effects of these two keyboard designs on wrist and forearm position. Tables 38A, 38B and 38C, which list a summary of ANOVA p-values, show statistically significant effects for keyboard design for both wrist radial/ulnar and flexion/extension position. Overall, the subjects placed their wrist in significantly less ulnar deviation and wrist extension when typing on the split adjustable-angle keyboard as compared to the conventional keyboard. The keyboard design did not influence forearm pronation ($p > 0.05$, Table 38A).

Each plane of movement will be discussed separately. The results for the mean position data will be discussed in detail, followed by a summary of the minimum and maximum position data.

Keyboard Setting for Slant Angle. The split adjustable-angle keyboard was set at a mean slant angle of 10.5 deg (s.d. of 3.6 deg. and range from 5 to 20 deg.). The slant angle was tailored to each subject so that his/her wrists were in a neutral rad/uln position when the elbows were placed at the subject's sides in proper typing posture.

Wrist Radial/Ulnar Position. Typing on the split adjustable-angle keyboard, compared to the conventional keyboard, reduced mean wrist ulnar deviation by approximately 8 deg. for both the right and left hands (11 to 3 deg. for the right hand and 14 to 6 deg. for the left hand), as shown in Table 39 and Figure 29. This 8 degree reduction is 2.5 degrees less than the average slant angle used by the subjects. This shift towards neutral in the radial/ulnar plane also carried over to the minimum and maximum ulnar deviation. The maximum ulnar deviation from neutral was reduced from about 21 to 15 deg., as shown in Table 40 and Figure 30. The minimum ulnar deviation from neutral changed from about 3 degrees of ulnar deviation to 5 deg of radial deviation, as shown in Table 41 and Figure 31. This significant reduction in ulnar deviation due to keyboard design was not affected by hand or task, as evinced by the absence of any keyboard and hand (KxH) and keyboard and task (KxT) interactions (refer to Tables 38A, B & C).

As shown in Figure 29 and Table 38A, a significant hand main effect for mean wrist radial/ulnar position was also established, with the wrist ulnar deviation for the right being 3 degrees less than for the left hand. Less ulnar deviation in the right wrist, as compared to the left wrist, is consistent with ulnar measurements of subjects using the conventional and split fixed-angle keyboards.

Table 38A. P-values for the 3-way analysis of variance for the *mean* wrist position when comparing the split adjustable-angle keyboard to the conventional keyboard. The three factors are keyboard (conventional and split adjustable-angle), hand (right and left) and typing task (alphabetic and alphanumeric).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Keyboard (K)	1	0.000 **	0.000 **	0.381
Hand (H)	1	0.011 *	0.071	0.034 *
Typing Task (T)	1	0.001 **	0.385	0.620
K x H	1	0.382	0.918	0.042 *
K x T	1	0.118	0.091	0.436
H x T	1	0.057	0.810	0.968
K x H x T	1	0.531	0.439	0.334

** Significant at $p < 0.01$; * significant at $p < 0.05$.

Table 38B. P-values for the 3-way analysis of variance for the *maximum* wrist position when comparing the split adjustable-angle keyboard to the conventional keyboard. The three factors are keyboard (conventional and split adjustable-angle), hand (right and left) and typing task (alphabetic and alphanumeric).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Keyboard (K)	1	0.000 **	0.000 **	0.348
Hand (H)	1	0.343	0.575	0.205
Typing Task (T)	1	0.000 **	0.077	0.174
K x H	1	0.054	0.352	0.177
K x T	1	0.318	0.045 *	0.213
H x T	1	0.008 **	0.722	0.514
K x H x T	1	0.531	0.247	0.413

** Significant at $p < 0.01$; * significant at $p < 0.05$.

Table 38C. P-values for the 3-way analysis of variance for the *minimum* wrist position when comparing the split adjustable-angle keyboard to the conventional keyboard. The three factors are keyboard (conventional and split adjustable-angle), hand (right and left) and typing task (alphabetic and alphanumeric).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Keyboard (K)	1	0.000 **	0.000 **	0.252
Hand (H)	1	0.331	0.000 **	0.167
Typing Task (T)	1	0.135	0.006 **	0.067
K x H	1	0.793	0.966	0.120
K x T	1	0.167	0.471	0.319
H x T	1	0.006 **	0.246	0.365
K x H x T	1	0.467	0.214	0.314

** Significant at $p < 0.01$; * significant at $p < 0.05$.

Table 39. *Mean* wrist radial/ulnar position in degrees for the split adjustable-angle and the conventional keyboard (negative = ulnar deviation; positive = radial deviation) (n = 30).

	Keyboard	
Typing task	Conventional	Split adjustable-angle
Left wrist		
Alphabetic	-13.3 ± 7.7	-5.7 ± 6.8
Alphanumeric	-14.8 ± 7.1	-7.0 ± 6.3
Right wrist		
Alphabetic	-10.7 ± 7.4	-2.5 ± 6.5
Alphanumeric	-11.7 ± 7.2	-2.9 ± 6.8

Table 40. *Maximum* wrist radial/ulnar position in degrees for the split adjustable-angle and conventional keyboards (negative = ulnar deviation; positive = radial deviation) (n = 30).

	Keyboard	
Typing task	Conventional	Split adjustable-angle
Left wrist		
Alphabetic	-21.6 ± 7.0	-14.9 ± 6.6
Alphanumeric	-24.1 ± 6.2	-17.4 ± 5.3
Right wrist		
Alphabetic	-24.5 ± 7.2	-16.1 ± 7.1
Alphanumeric	-25.7 ± 7.4	-16.6 ± 7.0

Table 41. *Minimum* wrist radial/ulnar position in degrees for the split adjustable-angle and conventional keyboards (negative = ulnar deviation; positive = radial deviation) (n = 30).

	Keyboard	
Typing task	Conventional	Split adjustable-angle
Left wrist		
Alphabetic	-3.4 ± 8.9	5.1 ± 7.4
Alphanumeric	-4.3 ± 8.7	3.9 ± 7.3
Right wrist		
Alphabetic	-2.8 ± 7.5	5.7 ± 5.8
Alphanumeric	-2.3 ± 7.3	5.4 ± 6.5

A statistically significant main effect for mean wrist radial/ulnar position was found for typing task, but this difference was within 1 to 2 degrees (Table 39) and is not likely functionally significant.

For both the minimum and maximum wrist radial/ulnar position, a statistically significant interaction ($p < 0.01$) exists between hand and typing task (H X T) (Table 38B and 38C and Figures 32 and 33). However, the magnitude of these differences in deg. does not seem to bear any practical consequences (Figures 32 and 33).

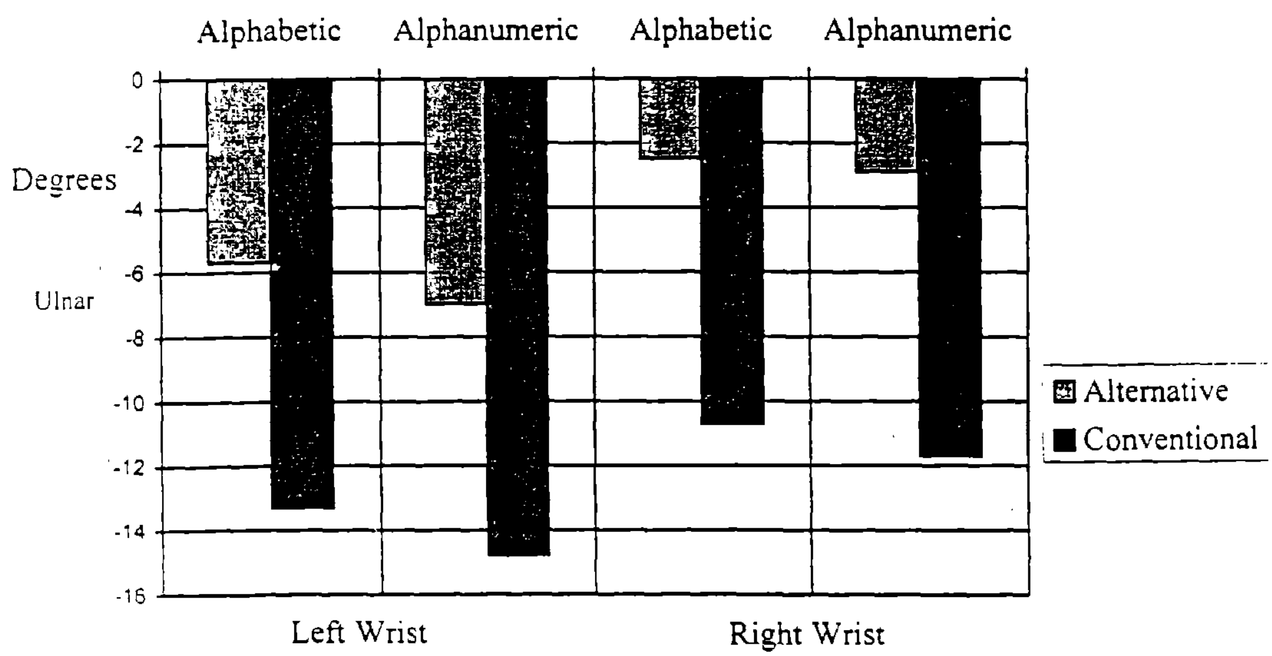


Figure 29. *Mean* wrist ulnar position for the split adjustable-angle and conventional keyboards for both typing tasks (n = 30).

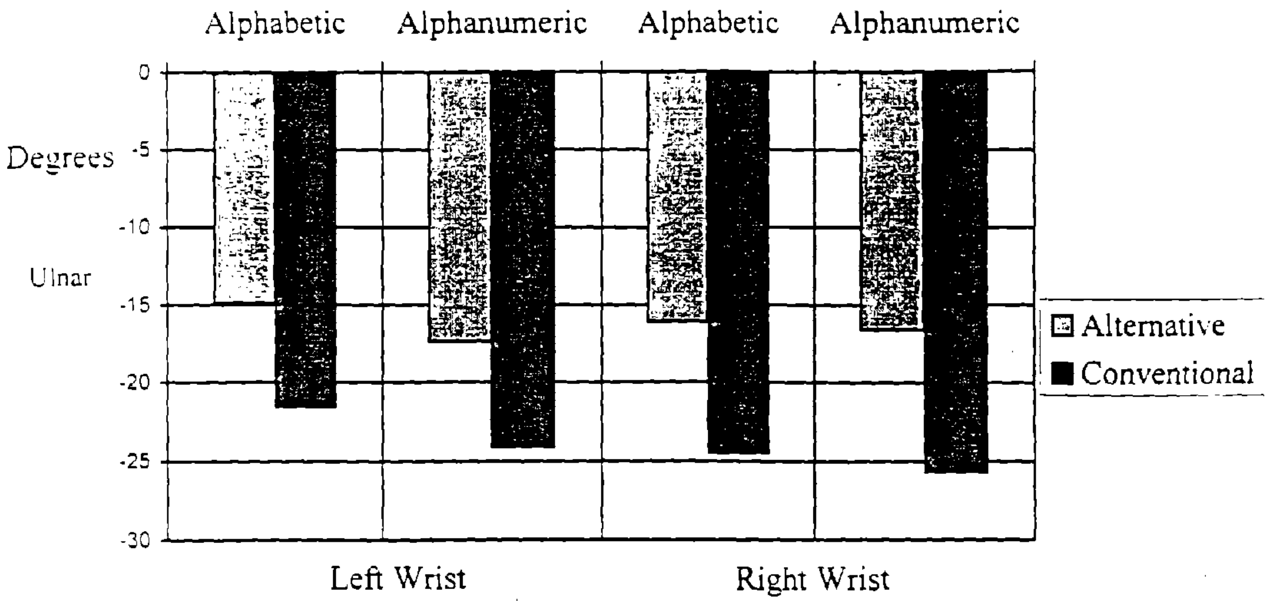


Figure 30. *Maximum* wrist ulnar position for the split adjustable-angle and the conventional keyboards for both typing tasks (n = 30).

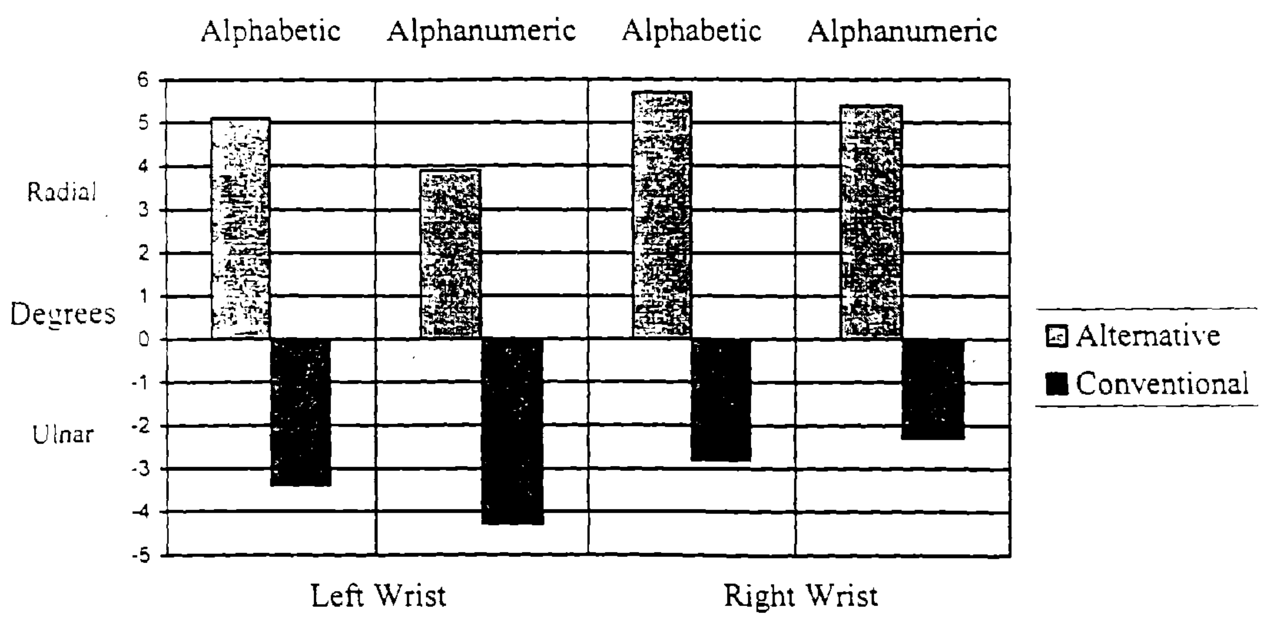


Figure 31. *Minimum* radial/ulnar position for the split adjustable-angle and the conventional keyboards for both typing tasks (n = 30).

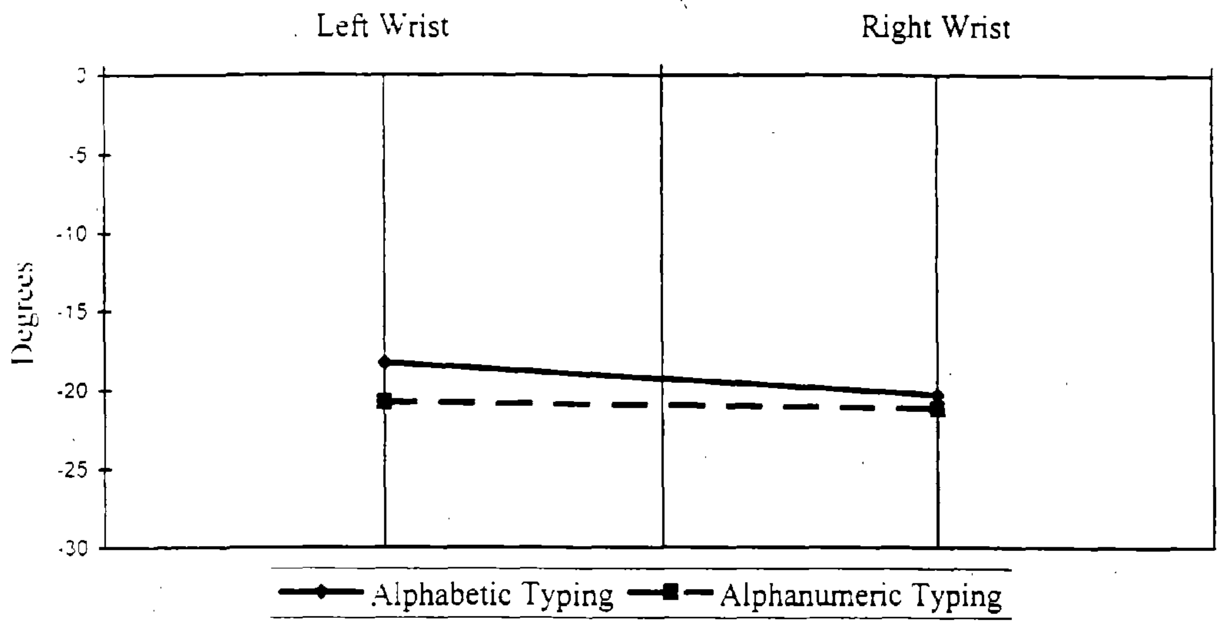


Figure 32. Hand x Typing interaction for the *maximum ulnar* position for the split adjustable-angle and conventional keyboards (n =30).

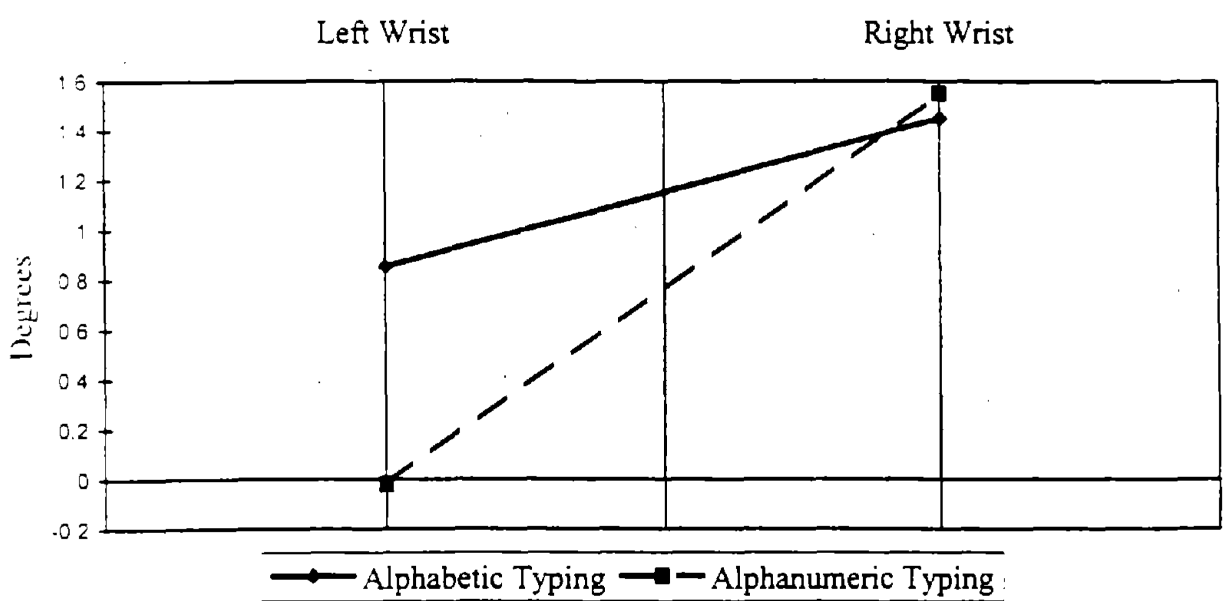


Figure 33. Hand x Typing interaction for the *minimum ulnar* position (which is radial in this figure) for the split adjustable-angle and conventional keyboards (n = 30).

Wrist Flexion/Extension Position. As indicated in Table 38A, the only significant main effect for the mean flex/ext position data was keyboard design, in which the split adjustable-angle keyboard placed the wrist in a slightly less extended position of about 4 deg. (18 to 14 deg. for the right hand and 21 to 17 deg. for the left hand) than the conventional keyboard (refer to Table 42 and Figure 34). Similar to the split fixed-angle keyboard, it is unclear why the split adjustable-angle keyboard reduced wrist extension since the slope angle of this keyboard is the same as the conventional keyboard (slope angle of both keyboards is 5 deg.).

The minimum wrist extension position revealed a significant hand effect in which the right hand was about 6 deg. closer to neutral than the left hand for both keyboards (3 to 9 deg. for the right and left hands, respectively, for split adjustable-angle keyboard; 7 to 13 deg. for the conventional keyboard) (refer to Table 44).

A statistically significant ($p < .05$) interaction was found for keyboard by task (K X T) for maximum wrist extension, but as for most interactions involving typing tasks, the difference in degrees does not appear to be functionally significant (Fig. 35).

Table 42. *Mean* wrist flexion/extension position in degrees for the split adjustable-angle and conventional keyboards (negative = wrist extension; positive = wrist flexion) (n = 30).

	Keyboard	
Typing task	Conventional	Split adjustable-angle
Left wrist		
Alphabetic	-20.4 ± 8.5	-16.9 ± 8.4
Alphanumeric	-20.6 ± 8.2	-16.1 ± 7.5
Right wrist		
Alphabetic	-17.9 ± 6.7	-14.1 ± 7.2
Alphanumeric	-18.0 ± 6.7	-13.7 ± 7.0

Table 43. *Maximum* wrist flexion/extension position in degrees for the split adjustable-angle and conventional keyboard (negative = wrist extension; positive = wrist flexion) (n = 30).

	Keyboard	
Typing task	Conventional	Split adjustable-angle
Left wrist		
Alphabetic	-25.5 ± 8.4	-22.3 ± 8.5
Alphanumeric	-26.9 ± 8.5	-22.1 ± 7.5
Right wrist		
Alphabetic	-26.2 ± 6.9	-23.3 ± 7.4
Alphanumeric	-27.0 ± 6.9	-23.3 ± 7.2

Table 44. *Minimum* wrist flexion/extension position in degrees for the split adjustable-angle and the conventional keyboards (negative = wrist extension; positive = wrist flexion) (n = 30).

	Keyboard	
Typing task	Conventional	Split adjustable-angle
Left wrist		
Alphabetic	-13.7 ± 9.3	-9.9 ± 8.4
Alphanumeric	-13.1 ± 8.6	-8.5 ± 7.7
Right wrist		
Alphabetic	-7.6 ± 7.7	-3.4 ± 7.8
Alphanumeric	-6.0 ± 8.5	-1.9 ± 7.1

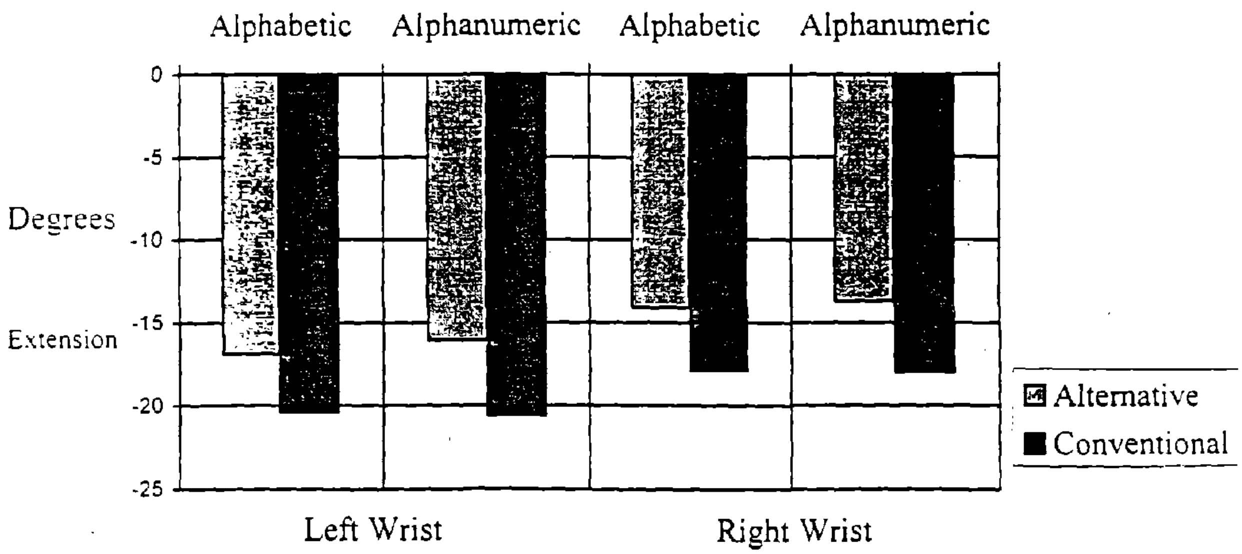


Figure 34. *Mean* wrist flexion/extension position for the split adjustable-angle and conventional keyboards for both typing tasks (n = 30).

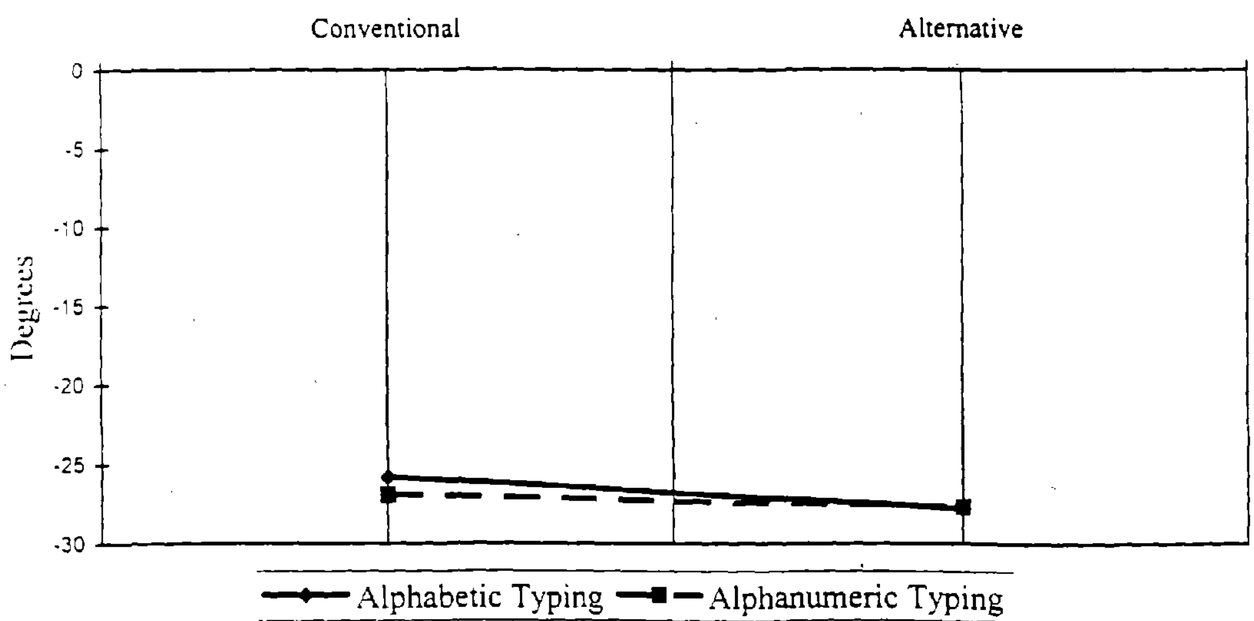


Figure 35. Keyboard x Typing task interaction for maximum wrist flexion/extension position for the split adjustable-angle keyboard and conventional keyboards.

Forearm Pronation/Supination Position. As indicated in Table 38A, the mean position data for forearm pronation/supination showed a significant hand effect and keyboard and hand interaction (KxH) ($p < 0.05$). When averaged across keyboards, the right hand was pronated about 5 deg. more than the left hand (65 to 60 deg.), as revealed in Table 45 and Figure 36. This difference of 5 deg. of pronation is probably insignificant compared to the maximum anatomical range of approximately 90 deg. pronation for healthy people. These data are in agreement with the pronation data from the conventional and split fixed-angle keyboards in that subjects pronated their right forearm more than their left when typing.

Although significant statistically as indicated in Table 38A and shown in Figure 37, the keyboard and hand interaction (KxH) interaction did not reveal a noteworthy difference. The minimum and maximum pronation data (Tables 46 and 47) did not show any significant main effects or interactions, as revealed in Tables 38B & C and Tables 46 and 47. In summary, the split adjustable-angle keyboard used in this study did not influence the amount of forearm pronation when compared to the conventional keyboard..

Table 45. *Mean* forearm pronation/supination position in degrees for the split adjustable-angle and conventional keyboards (negative = forearm supination; positive = forearm pronation) (n = 24 for the left forearm and n = 27 for the right forearm).

	Keyboard	
Typing task	Conventional	Split adjustable-angle
Left forearm		
Alphabetic	59.5 ± 9.8	60.0 ± 11.7
Alphanumeric	59.9 ± 8.5	60.2 ± 9.9
Right forearm		
Alphabetic	65.2 ± 8.6	64.1 ± 9.0
Alphanumeric	66.2 ± 9.1	63.6 ± 8.3

Table 46. *Minimum* forearm pronation/supination position in degrees for the split adjustable-angle and conventional keyboards (negative = forearm supination; positive = forearm pronation) (n = 24 for the left forearm and n = 27 for the right forearm).

	Keyboard	
Typing task	Conventional	Split adjustable-angle
Left forearm		
Alphabetic	52.6 ± 10.6	53.0 ± 11.4
Alphanumeric	51.8 ± 9.1	51.6 ± 9.9
Right forearm		
Alphabetic	56.0 ± 11.0	55.8 ± 10.8
Alphanumeric	55.8 ± 12.7	54.4 ± 10.6

Table 47. *Maximum* forearm pronation/supination position in degrees for the split adjustable-angle and conventional keyboards (negative = forearm supination; positive = forearm pronation) (n = 24 for the left forearm and n = 27 for the right forearm).

	Keyboard	
Typing task	Conventional	Split adjustable-angle
Left forearm		
Alphabetic	67.5 ± 9.5	67.8 ± 12.1
Alphanumeric	68.9 ± 8.9	68.9 ± 10.8
Right forearm		
Alphabetic	72.0 ± 8.7	70.7 ± 8.8
Alphanumeric	74.0 ± 9.5	70.4 ± 7.9

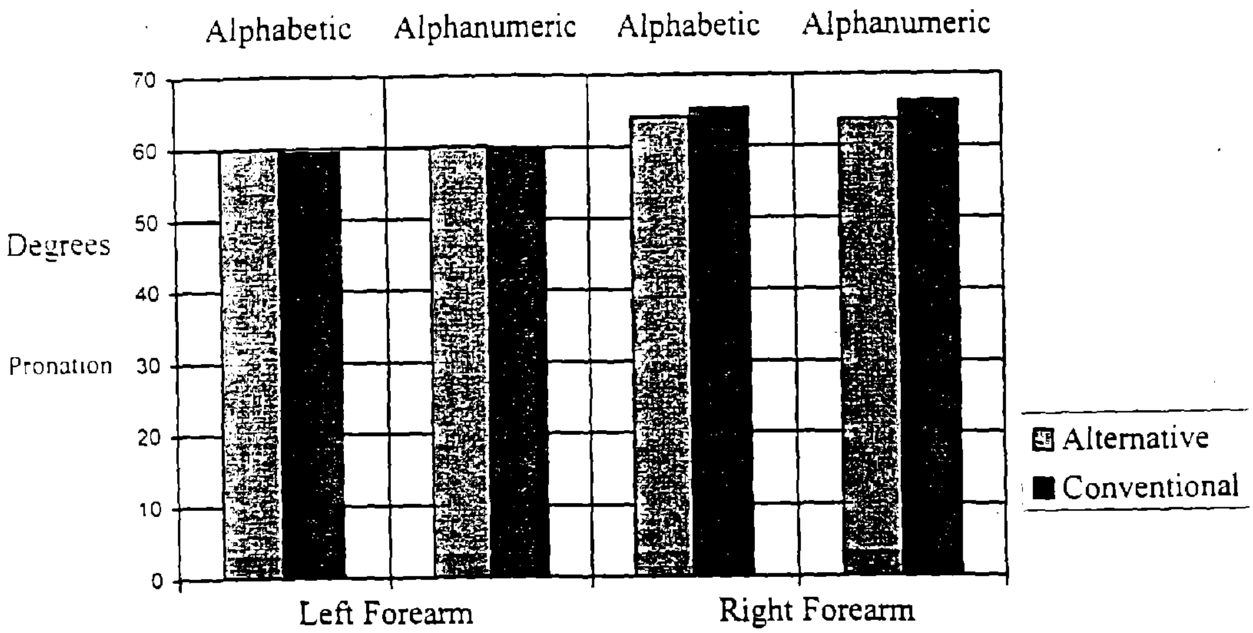


Figure 36. *Mean* forearm pronation/supination position for the split adjustable-angle and conventional keyboards for both typing tasks (n = 24 for the left forearm and n = 27 for the right forearm).

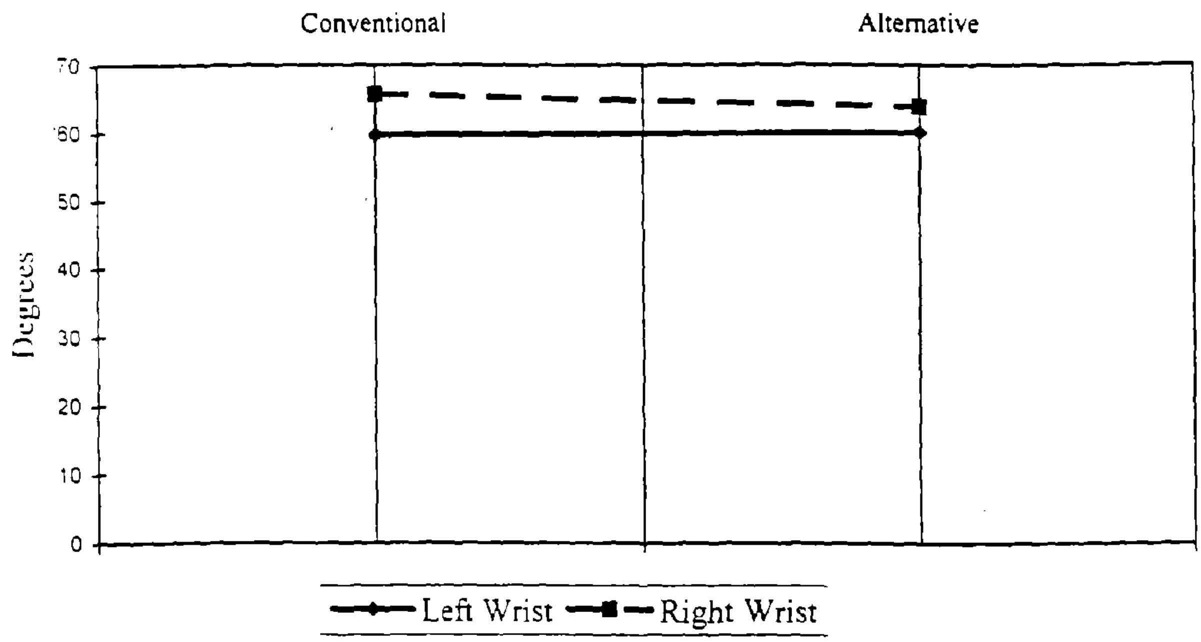


Figure 37. Keyboard x Hand interaction for mean forearm pronation/supination position for the split adjustable-angle and conventional keyboards.

D.5.8 Vertically-Inclined Keyboard: Analysis of Wrist and Forearm Position

In this study, 30 subjects were tested both on a conventional and a vertically-inclined keyboard in order to establish the effect of these two keyboard designs on wrist and forearm position. Tables 48A, 48B and 48C, which list a summary of ANOVA p-values, show statistically significant main effects for keyboard design ($p < 0.01$) for wrist rad/uln position and forearm pron/supin position ($p < 0.01$). Overall, the subjects reduced their forearm pronation considerably and also lessened their ulnar deviation to almost a neutral position in the rad/uln plane when using the vertically-inclined keyboard as compared to the conventional keyboard.

Each plane of movement will be discussed separately. The results for the mean position data will be discussed in detail, followed by a summary of the minimum and maximum data.

Keyboard Setting for Tilt and Slant Angles. The tilt and slant angles of the vertically-inclined keyboard used in this study cannot be adjusted independently. When the subject rotates the knob on the left side of the keyboard, the keyboard halves tilt upward like a drawbridge and slant outward in the horizontal plane. The 30 subjects who typed on the vertically-inclined keyboard adjusted the keyboard halves at mean tilt angles of 32.8 deg. (s.d. of 4.2 deg. and range from 24.5 to 42.0 deg.) for the right hand and 27.8 deg. (s.d. of 4.3 deg. and range from 19.3 to 37.2 deg.) for the left hand. (The difference in tilt angle between the right and left side is due to the design of the keyboard and is not controlled by the typist.) The concomitant slant angle of the keyboard halves adjusted at these tilt angles was 7.0 deg. (s.d. of 2.0 deg. and range from 3.1 to 11.3 deg.) for both keyboard halves.

Wrist Radial/Ulnar position. As compared to the conventional keyboard, the vertically-inclined keyboard reduced mean ulnar deviation by about 12 deg. (11 degrees of ulnar deviation to 2 degrees of radial deviation for the right hand and 16 to 3 degrees of ulnar deviation for the left hand), thereby moving both wrists within a few degrees of the neutral position in the rad/uln plane (refer to Tables 48A and 49 and Figure 38). This shift towards neutral in the rad/uln plane for the vertically-inclined keyboard carried over to the maximum and minimum positions in that maximum ulnar deviation was reduced from approximately 24 to 12 deg. and minimum ulnar deviation moved from about 5 deg. ulnar to about 7 deg. *radial*, as shown in Tables 50 and 51 as well as Figures 39 and 40. The significant main effect for hand is consistent with our earlier findings which showed greater ulnar deviation of the left. Although significant statistically, the main effects for hand and task (HxT) did not reveal any noteworthy practical differences.

Table 48A. P-values for the 3-way analysis of variance for the *mean* wrist position when comparing the vertically-inclined keyboard to the conventional keyboard. The three factors are keyboard (conventional and vertically-inclined), hand (right and left) and typing task (alphabetic and alphanumeric) (n = 30).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Keyboard (K)	1	0.000 **	0.238	0.000 **
Hand (H)	1	0.001 **	0.000 **	0.816
Typing Task (T)	1	0.000 **	0.084	0.017 *
K x H	1	0.139	0.243	0.008 **
K x T	1	0.599	0.022 *	0.013 *
H x T	1	0.040 *	0.022 *	0.645
K x H x T	1	0.028 *	0.572	0.872

** Significant at $p < 0.01$; * significant at $p < 0.05$.

Table 48B. P-values for the 3-way analysis of variance for the *maximum* wrist position when comparing the vertically-inclined keyboard to the conventional keyboard. The three factors are keyboard (conventional and vertically-inclined), hand (right and left) and typing task (alphabetic and aphanumeric) (n = 30).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Keyboard (K)	1	0.000 **	0.278	0.000 **
Hand (H)	1	0.558	0.172	0.920
Typing Task (T)	1	0.000 **	0.530	0.649
K x H	1	0.358	0.243	0.001 **
K x T	1	0.722	0.001 **	0.038 *
H x T	1	0.000 **	0.034 *	0.137
K x H x T	1	0.078	0.986	0.940

** Significant at $p < 0.01$; * significant at $p < 0.05$.

Table 48C. P-values for the 3-way analysis of variance for the *minimum* wrist position when comparing the vertically-inclined keyboard to the conventional keyboard. The three factors are keyboard (conventional and vertically-inclined), hand (right and left) and typing task (alphabetic and aphanumeric) (n = 30).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Keyboard (K)	1	0.000 **	0.415	0.000 **
Hand (H)	1	0.069	0.000 **	0.780
Typing Task (T)	1	0.299	0.001 **	0.003 **
K x H	1	0.257	0.092	0.142
K x T	1	0.385	0.348	0.026 *
H x T	1	0.023 *	0.039 *	0.638
K x H x T	1	0.073	0.951	0.920

** Significant at $p < 0.01$; * significant at $p < 0.05$.

Table 49. *Mean* wrist radial/ulnar position in degrees for the vertically-inclined and conventional keyboards (negative = ulnar deviation; positive = radial deviation) (n = 30).

	Keyboard	
Typing task	Conventional	Vertically-inclined
Left wrist		
Alphabetic	-15.2 ± 6.3	-3.1 ± 7.8
Alphanumeric	-16.8 ± 7.3	-4.0 ± 7.8
Right wrist		
Alphabetic	-11.5 ± 7.3	2.4 ± 7.3
Alphanumeric	-11.8 ± 7.1	1.7 ± 7.7

Table 50. *Maximum* wrist radial/ulnar position in degrees for the vertically-inclined and conventional keyboards (negative = ulnar deviation; positive = radial deviation) (n = 30).

	Keyboard	
Typing task	Conventional	Vertically-inclined
Left wrist		
Alphabetic	-23.9 ± 5.5	-12.0 ± 7.4
Alphanumeric	-27.2 ± 5.8	-14.5 ± 7.3
Right wrist		
Alphabetic	-25.8 ± 6.0	-14.2 ± 7.2
Alphanumeric	-25.8 ± 6.1	-14.7 ± 7.0

Table 51. *Minimum* wrist radial/ulnar position in degrees for the vertically-inclined and conventional keyboards (negative = ulnar deviation; positive = radial deviation) (n = 30).

	Keyboard	
Typing task	Conventional	Vertically-inclined
Left wrist		
Alphabetic	-5.1 ± 7.1	6.7 ± 7.5
Alphanumeric	-6.1 ± 8.0	6.0 ± 7.9
Right wrist		
Alphabetic	-3.7 ± 7.1	9.8 ± 6.9
Alphanumeric	-3.0 ± 7.6	9.5 ± 7.5

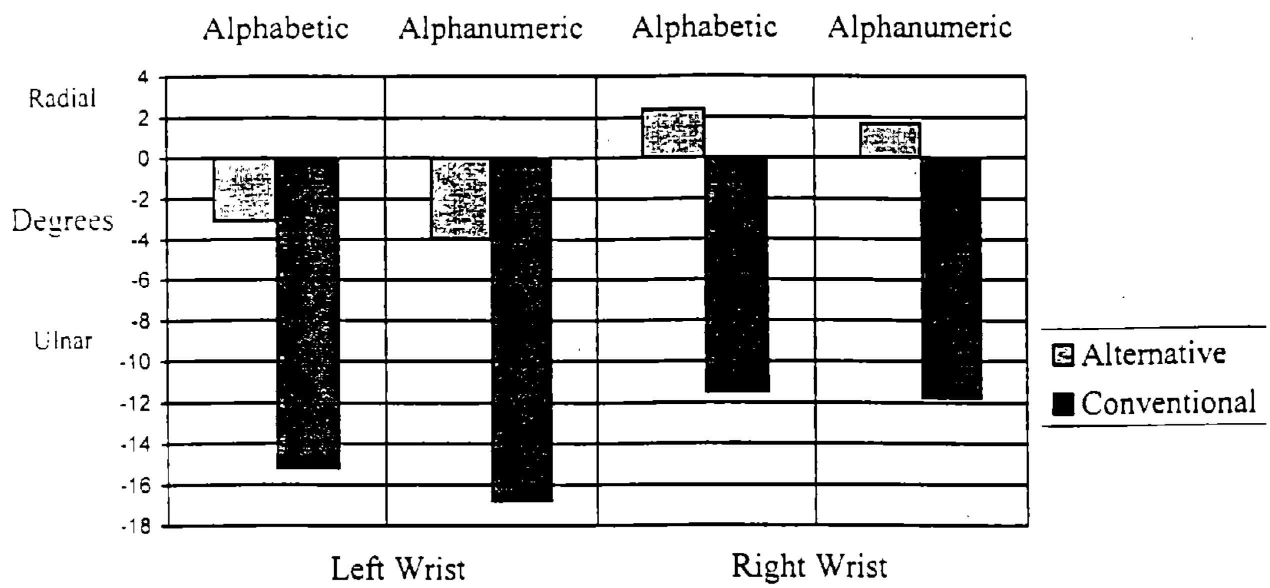


Figure 38. *Mean* wrist radial/ulnar position for the vertically-inclined and conventional keyboards for both typing tasks (n = 30).

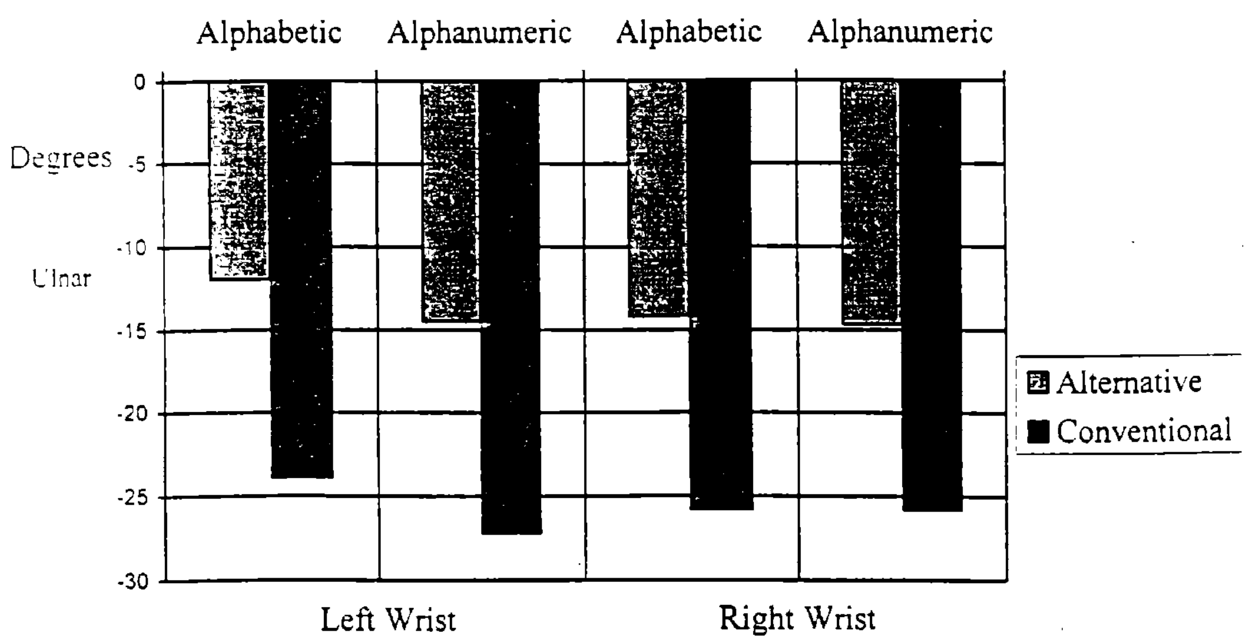


Figure 39. *Maximum* wrist radial/ulnar position for the vertically-inclined and conventional keyboards for both typing tasks (n = 30).

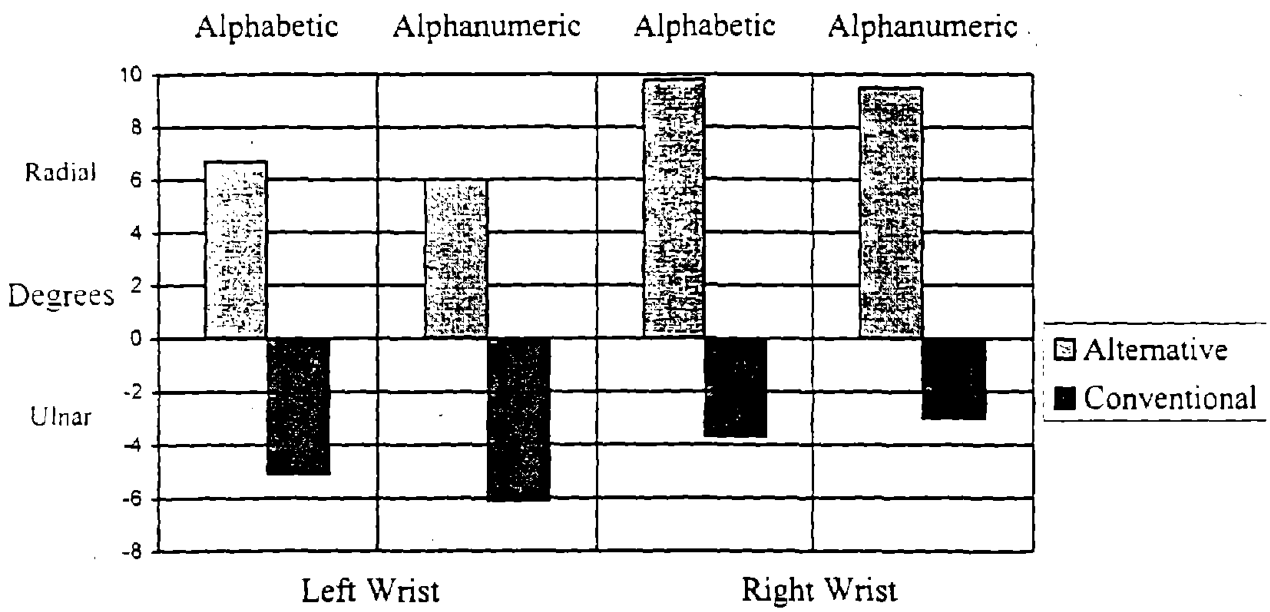


Figure 40. *Minimum* wrist radial/ulnar position for the vertically-inclined and the conventional keyboards for both typing tasks (n = 30).

Wrist Flexion/Extension Position. The vertically-inclined keyboard did not influence wrist flex/ext position as compared to the conventional keyboard. Mean wrist extension for the right side was approximately 5 degrees less than for the left side on both keyboards (Table 52 and Figure 41), which was significantly less than extension of the right wrist ($p < 0.01$, Table 48A).

Although indicated as significant statistically in Table 48A, the keyboard and task interaction (KxT) and hand x task interaction (HxT) did not reveal any practical differences. In general, the minimum and maximum position data followed the same patterns of the mean position data (refer to Tables 53 and 54).

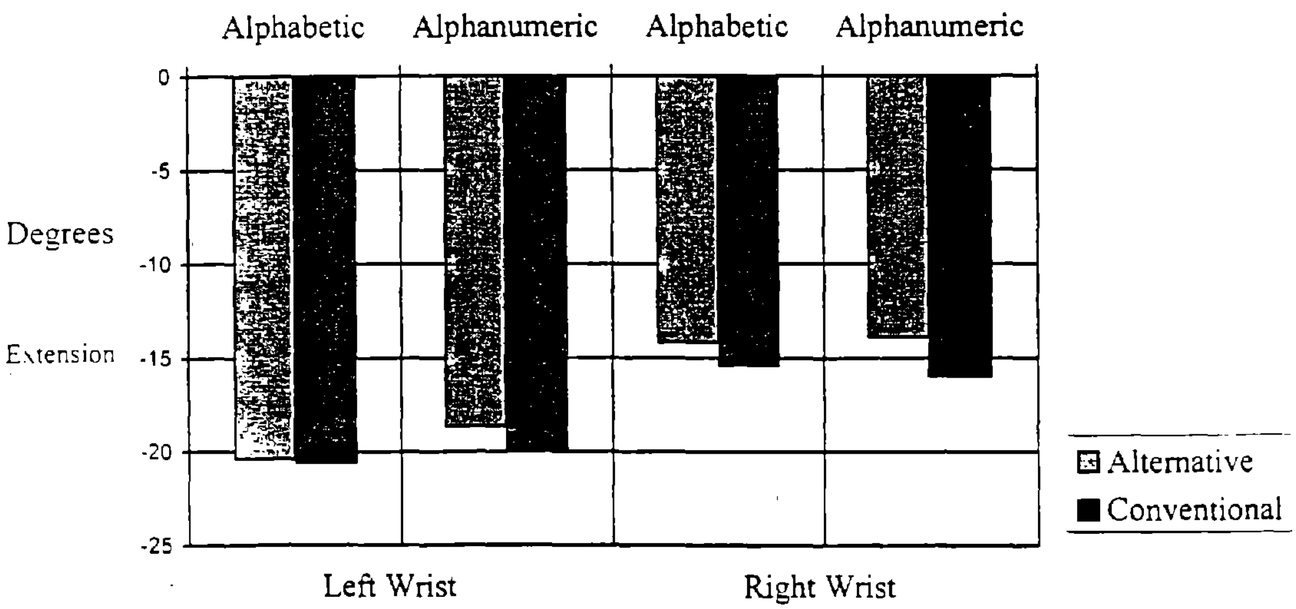


Figure 41. *Mean* wrist flexion/extension position for the vertically-inclined and conventional keyboard for both typing tasks (n = 30).

Table 52. *Mean* wrist flexion/extension position in degrees for the vertically-inclined and conventional keyboards (negative = wrist extension; positive = wrist flexion) (n = 30).

	Keyboard	
Typing task	Conventional	Vertically-inclined
Left wrist		
Alphabetic	-20.6 ± 7.2	-20.4 ± 5.5
Alphanumeric	-20.0 ± 7.0	-18.7 ± 6.1
Right wrist		
Alphabetic	-15.4 ± 7.2	-14.2 ± 7.4
Alphanumeric	-16.0 ± 7.7	-13.9 ± 7.6

Table 53. *Maximum* wrist flexion/extension maximum position in degrees for the vertically-inclined keyboard (negative = wrist extension; positive = wrist flexion) (n = 30).

	Keyboard	
Typing task	Conventional	Vertically-inclined
Left wrist		
Alphabetic	-25.5 ± 7.2	-25.7 ± 5.7
Alphanumeric	-26.0 ± 7.6	-24.7 ± 5.9
Right wrist		
Alphabetic	-23.8 ± 7.8	-23.0 ± 8.1
Alphanumeric	-25.1 ± 8.6	-22.9 ± 7.8

Table 54. *Minimum* wrist flexion/extension position in degrees for the vertically-inclined and conventional keyboards (negative = wrist extension; positive = wrist flexion) (n = 30).

	Keyboard	
Typing task	Conventional	Vertically-inclined
Left wrist		
Alphabetic	-14.5 ± 6.9	-14.5 ± 6.3
Alphanumeric	-12.1 ± 7.0	-11.7 ± 7.4
Right wrist		
Alphabetic	-6.5 ± 7.6	-5.3 ± 7.7
Alphanumeric	-5.8 ± 7.9	-4.1 ± 7.8

Forearm Pronation/Supination Position. The draw-bridge action of the vertically-inclined keyboard significantly reduced mean forearm pronation by approximately 20 deg. (60 to 40 deg. for the right forearm and 62 to 42 for the left forearm), as shown in Table 55 and Figure 42 ($p < 0.01$). The approximately 20 deg. decrease in pronation reduction also was evident in the maximum and minimum pronation position in that maximum pronation of about 70 deg. was reduced to 50 deg. and minimum pronation was decreased from about 55 deg. to 33 deg. (refer to Tables 56 and 57).

Other than the keyboard design effect, the significant main effects and interactions for the minimum and maximum position data did not reveal any noteworthy differences.

The reduction of 20 degrees in forearm pronation is approximately 7 to 12 degrees less than the difference in tilt angle between the conventional keyboard and the average tilt angles used by the subjects who typed with the vertically-inclined keyboard (27 and 32 deg. tilt angles for the left and right halves, respectively)..

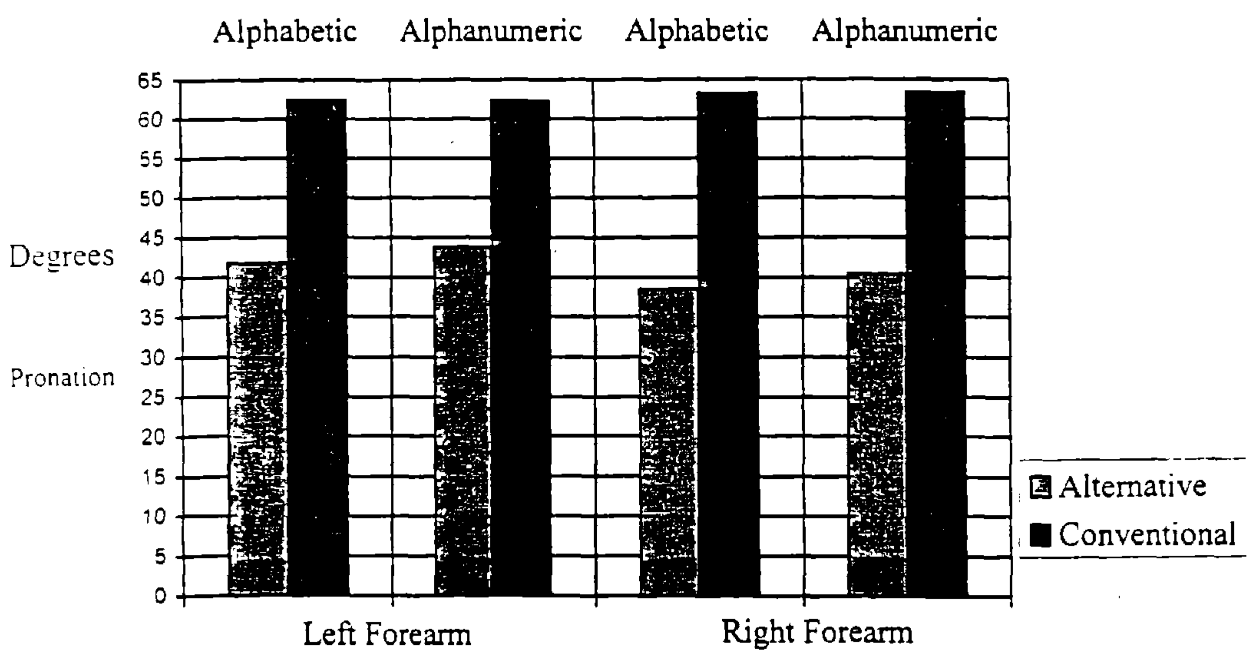


Figure 42. *Mean* forearm pron/sup position for the vertically-inclined and conventional keyboards for both typing tasks (n = 25 and n = 29 for the left and right forearm, respectively).

Table 55. *Mean* forearm pronation/supination position in degrees for the vertically-inclined and conventional keyboards (negative = forearm supination; positive = forearm pronation) (n = 25 for the left forearm and n = 29 for the right forearm).

	Keyboard	
Typing task	Conventional	Vertically-inclined
Left forearm		
Alphabetic	62.4 ± 12.4	41.8 ± 12.7
Alphanumeric	62.3 ± 12.3	43.8 ± 12.1
Right forearm		
Alphabetic	63.2 ± 7.6	38.5 ± 8.9
Alphanumeric	63.4 ± 7.5	40.4 ± 9.0

Table 56. *Minimum* forearm pronation/supination position in degrees for the vertically-inclined and conventional keyboards (negative = forearm supination; positive = forearm pronation) (n = 25 for the left forearm and n = 29 for the right forearm).

	Keyboard	
Typing task	Conventional	Vertically-inclined
Left forearm		
Alphabetic	54.9 ± 14.2	33.7 ± 13.1
Alphanumeric	52.7 ± 13.5	33.5 ± 12.3
Right forearm		
Alphabetic	55.7 ± 9.7	29.1 ± 9.0
Alphanumeric	55.4 ± 9.5	29.8 ± 8.9

Table 57. *Maximum* forearm pronation/supination position in degrees for the vertically-inclined and conventional keyboards (negative = forearm supination; positive = forearm pronation) (n = 25 for the left forearm and n = 29 for the right forearm).

	Keyboard	
Typing task	Conventional	Vertically-inclined
Left forearm		
Alphabetic	70.1 ± 11.8	50.2 ± 13.6
Alphanumeric	71.0 ± 11.9	53.3 ± 13.4
Right forearm		
Alphabetic	68.9 ± 8.8	46.2 ± 9.7
Alphanumeric	69.4 ± 8.5	48.6 ± 10.6

D.5.9. Analysis of Wrist and Forearm Position Among Three Alternative Keyboards

A mixed-design three-way ANOVA was performed on all wrist and forearm position data in order to compare the three alternative keyboards. The between-subjects variable was keyboard design (3 levels--split fixed-angle, split adjustable-angle, and vertically-inclined). The two within-subject factors were: hand (2 levels--right and left) and task (2 levels-alphabetic and alphanumeric).

Wrist Radial/Ulnar Position. As shown in Table 58A, there was no statistically significant effect (at the 0.05 level) on mean ulnar position among the three alternative keyboard designs. The mean position in the radial/ulnar plane ranged from approximately 3 deg. of ulnar deviation to 3 deg. of radial deviation for the right wrist, among the three keyboards (Table 59 and Figures 43 and 44).

In contrast to keyboard design, there were significant main effects for hand and typing task, as indicated in Table 58A. Across all 3 keyboards, wrist radial/ulnar deviation for the right hand was about neutral as compared to about 4 to 5 degrees of ulnar deviation for the left hand, as shown in Table 59 and Figures 43 and 44. Although statistically significant, the main effect for typing task was minimal, resulting in a difference of only about 1 to 2 deg. between the alphabetic and alphanumeric tasks, as revealed in Table 59. The significant hand x task interaction (HxT) indicated in Table 58A was also minimal (refer to data in Table 59).

The maximum wrist angle from neutral in the radial/ulnar plane revealed that the subjects moved their wrists to an extreme of approximately 15 deg. ulnar deviation, which was at least 10 deg. more ulnar deviation than the mean ulnar angle, as shown in Table 60. The minimum wrist angle in the radial/ulnar plane showed that the subjects crossed over the neutral angle to approximately 5 to 10 deg. of wrist radial deviation, as revealed in Table 61. Similar to the results of mean ulnar position, there were significant effects for hand and typing task and hand and task interaction (HxT), as revealed in Tables 58B and 58C for the minimum and maximum radial/ulnar data.

Table 58A. P-values for the 3-way ANOVA for the *mean* wrist position when comparing the three alternative keyboards. The three factors are keyboards (split fixed-angle, split adjustable-angle, vertically-inclined), hand (right and left) and typing task (alphabetic and alphanumeric).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Keyboard (K)	2	0.091	0.574	0.000 **
Hand (H)	1	0.000 **	0.000 **	0.663
Typing Task (T)	1	0.000 **	0.001 **	0.055
K x H	2	0.204	0.261	0.272
K x T	2	0.449	0.051	0.044 *
H x T	1	0.038 *	0.002 **	0.478
K x H x T	2	0.430	0.276	0.767

** Significant at $p < 0.01$; * significant at $p < 0.05$.

Table 58B. P-values for the 3-way ANOVA for the *maximum* wrist position when comparing the three alternative keyboards. The three factors are keyboards (split fixed-angle, split adjustable-angle, vertically-inclined), hand (right and left) and typing task (alphabetic and alphanumeric).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Keyboard (K)	2	0.283	0.721	0.000 **
Hand (H)	1	0.938	0.226	0.998
Typing Task (T)	1	0.000 **	0.406	0.125
K x H	2	0.410	0.190	0.249
K x T	2	0.829	0.128	0.144
H x T	1	0.000 **	0.070	0.394
K x H x T	2	0.604	0.531	0.800

** Significant at $p < 0.01$; * significant at $p < 0.05$.

Table 58C. P-values for the 3-way ANOVA for the *minimum* wrist position when comparing the three alternative keyboards. The three factors are keyboards (split fixed-angle, split adjustable-angle, vertically-inclined), hand (right and left) and typing task (alphabetic and alphanumeric).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Keyboard (K)	2	0.245	0.215	0.000 **
Hand (H)	1	0.000 **	0.000 **	0.607
Typing Task (T)	1	0.004 **	0.000 **	0.001 **
K x H	2	0.177	0.651	0.477
K x T	2	0.841	0.173	0.101
H x T	1	0.050 *	0.006 **	0.021 *
K x H x T	2	0.816	0.098	0.272

** Significant at $p < 0.01$; * significant at $p < 0.05$.

Table 59. *Mean* wrist radial/ulnar position in degrees for each alternative keyboard (negative = wrist ulnar deviation; positive = wrist radial deviation) (n = 30 for each keyboard).

	Keyboard		
Typing task	Vertically-inclined	Split adjustable-angle	Split fixed-angle
Left wrist			
Alphabetic	-3.1 ± 7.8	-5.7 ± 6.8	-5.8 ± 9.8
Alphanumeric	-4.0 ± 7.8	-7.0 ± 6.3	-7.3 ± 10.8
Right wrist			
Alphabetic	2.4 ± 7.3	-2.5 ± 6.5	1.2 ± 6.8
Alphanumeric	1.7 ± 7.7	-2.9 ± 6.8	0.2 ± 6.9

Table 60. *Maximum* wrist ulnar position in degrees for each alternative keyboard (negative = ulnar deviation; positive = radial deviation) (n = 30 for each keyboard).

	Keyboard		
Typing task	Vertically-inclined	Split adjustable-angle	Split fixed-angle
Left wrist			
Alphabetic	-12.0 ± 7.4	-14.9 ± 6.6	-14.7 ± 9.8
Alphanumeric	-14.5 ± 7.3	-17.4 ± 5.3	-17.0 ± 9.4
Right wrist			
Alphabetic	-14.2 ± 7.2	-16.1 ± 7.1	-13.7 ± 5.6
Alphanumeric	-14.7 ± 7.0	-16.6 ± 7.0	-14.9 ± 5.5

Table 61. *Minimum* wrist radial/ulnar position in degrees for each alternative keyboard design (negative = ulnar deviation; positive = radial deviation) (n = 30 for each keyboard).

	Keyboard		
Typing task	Vertically-inclined	Split adjustable-angle	Split fixed-angle
Left wrist			
Alphabetic	6.7 ± 7.5	5.1 ± 7.4	4.3 ± 10.4
Alphanumeric	6.0 ± 7.9	3.9 ± 7.3	3.3 ± 12.0
Right wrist			
Alphabetic	9.8 ± 6.9	5.7 ± 5.8	9.0 ± 7.6
Alphanumeric	9.5 ± 7.5	9.0 ± 7.6	8.5 ± 7.8

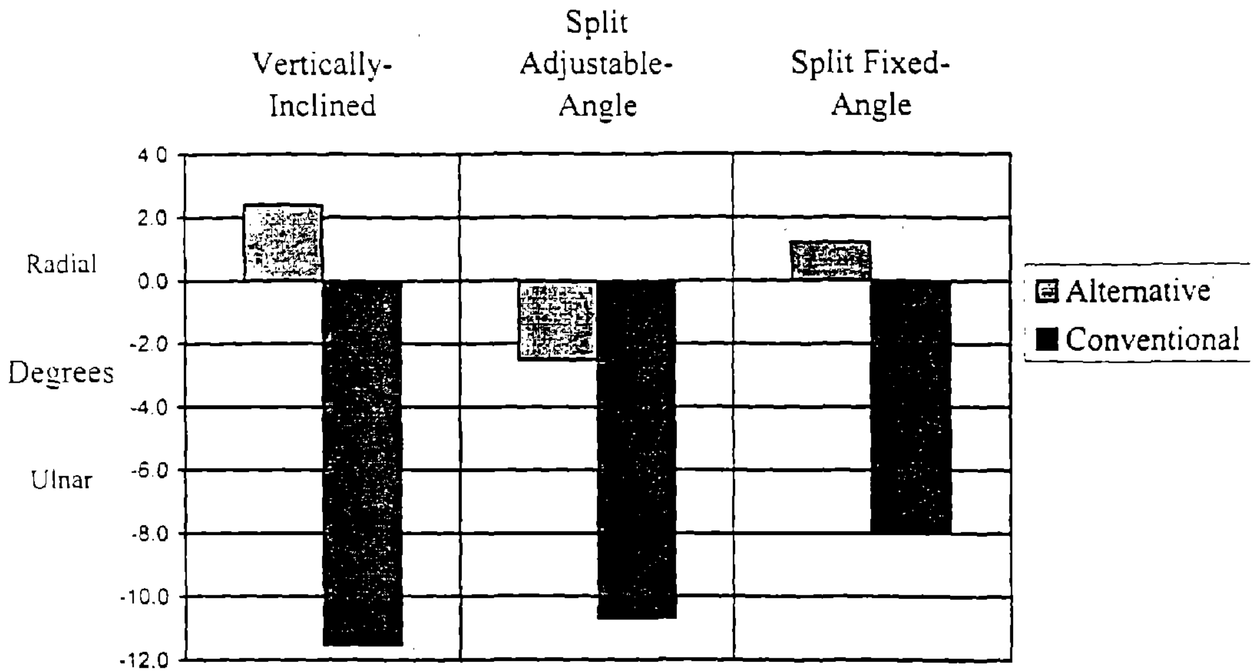


Figure 43. Mean radial/ulnar position for the *right* wrist for each alternative keyboard (n = 30 per keyboard).

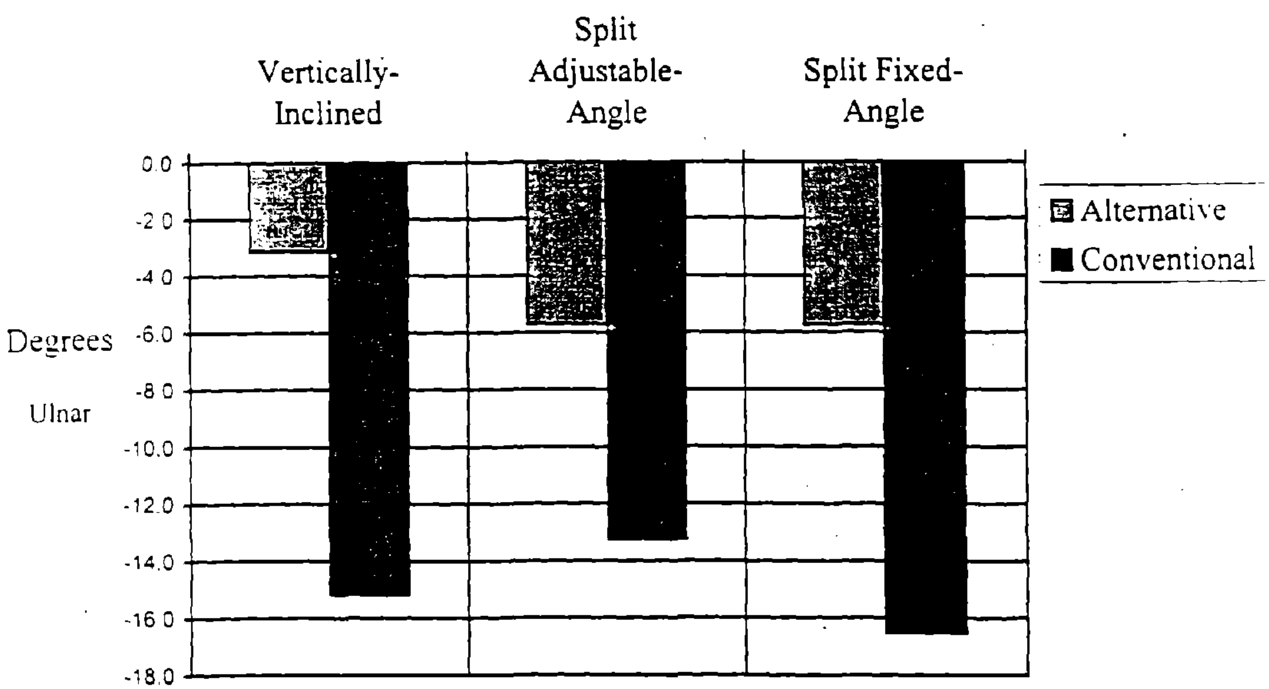


Figure 44. Mean radial/ulnar position for the *left* wrist for each alternative keyboard (n = 30 per keyboard).

Wrist Flexion/Extension Position. There was not a statistically significant main effect for mean extension angle, as evinced by the mean wrist extension data showing only about a 2 to 4 deg. difference among the three alternative keyboard designs within a hand (12 to 14 deg. for the right hand and 16 to 20 deg. for the left hand) (refer to Tables 58A and 62 and Figures 45 and 46). Similar to the ANOVA results for wrist radial/ulnar position, the ANOVA for flex/ext mean data showed significant hand and task main effects and hand and task interaction (HxT), as presented in Table 58A. As shown in Figures 45 and 46, the right hand was extended about 5 deg. less than the left hand (13 deg. for the right and 18 deg. for the left). This finding is consistent with results from the conventional keyboard as well as the alternative keyboards tested in this study. Despite the statistical significance, the typing task main effect and hand and task interaction (HxT) were minimal.

No statistically significant ($p > 0.05$) main effects or interactions were found for minimum wrist extension (Table 58B).

The minimum wrist extension angle from neutral followed the statistical pattern of the mean data, as revealed in Table 58C. As compared to the mean extension data, the subjects moved their wrist about 7 to 10 deg. closer to neutral, resulting in extension angles of approximately 4 deg. for the right hand and about 12 deg. for the left hand (refer to Table 64). The maximum extension angle from neutral showed the subjects moved their wrists to an extreme of approximately 20 to 25 deg. extension, regardless of the typing task, hand, and keyboard design (refer to Table 64).

Table 62. *Mean* wrist flexion/extension position in degrees for each alternative keyboard (negative = wrist extension; positive = wrist flexion) (n = 30 for each keyboard).

	Keyboard		
Typing task	Vertically-inclined	Split adjustable-angle	Split fixed-angle
Left wrist			
Alphabetic	-20.4 ± 5.5	-16.9 ± 8.4	-18.2 ± 8.6
Alphanumeric	-18.7 ± 6.1	-16.1 ± 7.5	-17.7 ± 9.3
Right wrist			
Alphabetic	-14.2 ± 7.4	-14.1 ± 7.2	-12.8 ± 5.7
Alphanumeric	-13.9 ± 7.6	-13.7 ± 7.0	-13.3 ± 5.9

Table 63. *Maximum* wrist flexion/extension position in degrees for each alternative keyboard (negative = wrist extension; positive = wrist flexion) (n = 30 for each keyboard).

	Keyboard		
Typing task	Vertically-inclined	Split adjustable-angle	Split fixed-angle
Left wrist			
Alphabetic	-25.7 ± 5.7	-22.3 ± 8.5	-24.0 ± 9.1
Alphanumeric	-24.7 ± 5.9	-22.1 ± 7.5	-24.0 ± 9.0
Right wrist			
Alphabetic	-23.0 ± 8.1	-23.3 ± 7.4	-22.1 ± 6.2
Alphanumeric	-22.9 ± 7.8	-23.3 ± 7.2	-22.5 ± 6.3

Table 64. *Minimum* wrist flexion/extension position in degrees for each alternative keyboard design (negative = wrist extension; positive = wrist flexion) (n = 30 for each keyboard).

	Keyboard		
Typing task	Vertically-inclined	Split adjustable-angle	Split fixed-angle
Left wrist			
Alphabetic	-14.5 ± 6.3	-9.9 ± 8.4	-11.6 ± 9.3
Alphanumeric	-11.7 ± 7.4	-8.5 ± 7.7	-10.0 ± 10.5
Right wrist			
Alphabetic	-5.3 ± 7.7	-3.4 ± 7.8	-2.9 ± 6.7
Alphanumeric	-4.1 ± 7.8	-1.9 ± 7.1	-3.1 ± 7.5

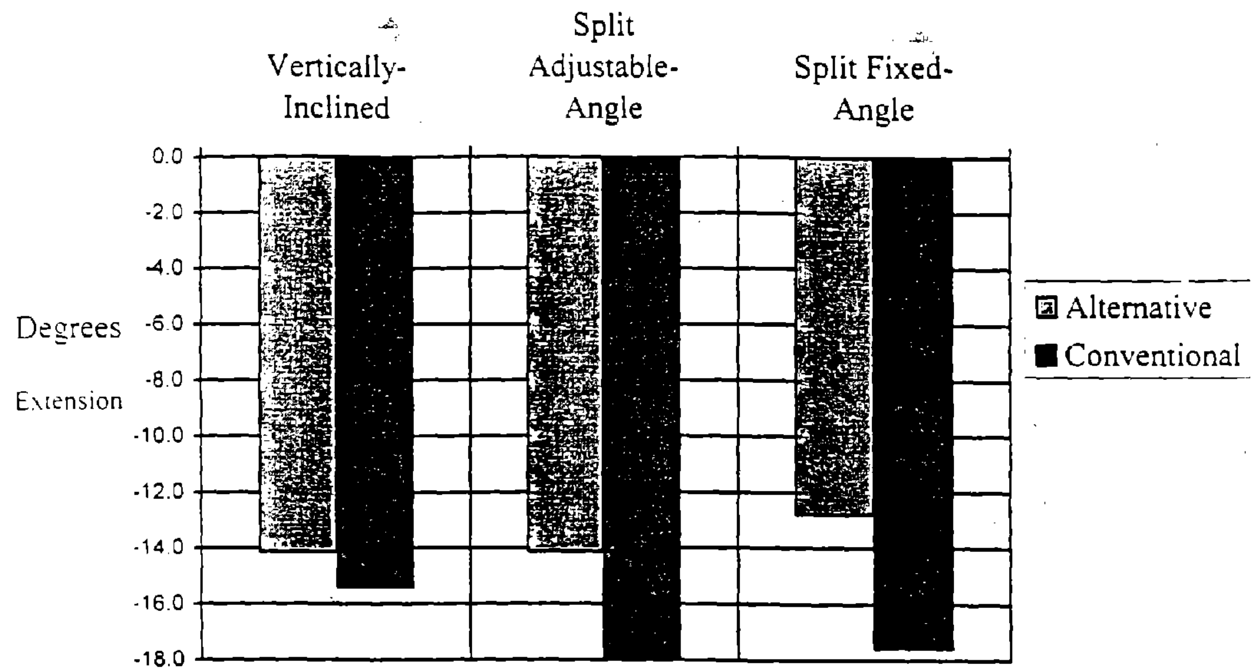


Figure 45. Mean flexion/extension position for the *right* wrist for each alternative keyboard (n = 30 per keyboard).

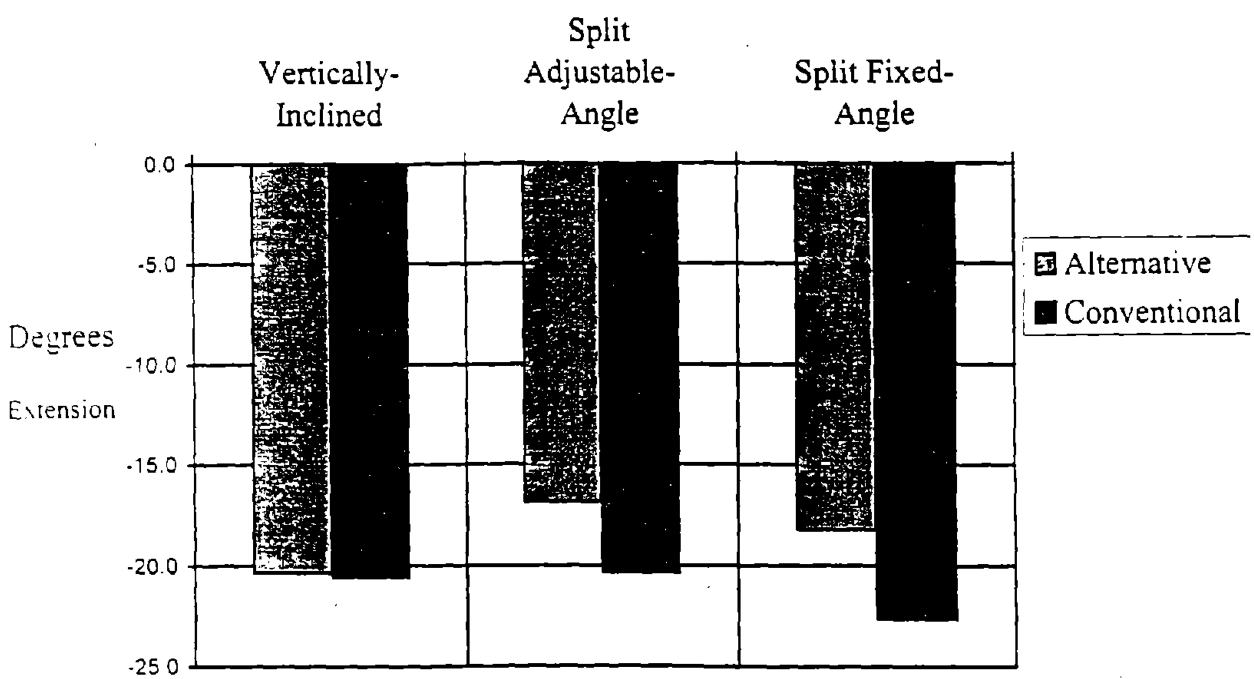


Figure 46. Mean flexion/extension position for the *left* wrist for each alternative keyboard (n = 30 per keyboard).

Forearm Pronation/Supination Position. As compared to the split fixed-angle and adjustable-angle keyboards, the vertically-inclined keyboard significantly reduced forearm pronation by 18 deg. (60 deg. to 42 deg. pronation) (refer to Tables 58A and 65 and Figures 47 and 48). The maximum pronation angle increased approximately 8 to 10 deg. for each respective keyboard (60 to 70 deg. for the split keyboards and 40 to 50 deg. for the vertically-inclined), as shown in Table 66. Likewise, the minimum pronation angle was about 8 deg. closer to neutral for each respective keyboard (60 to 53 deg. for the split keyboards and 40 to 32 deg. for the vertically-inclined), as shown in Table 67.

As indicated in Tables 58A, 58C, 65, and 67, the other significant effects and interactions for the pron/supin data -- keyboard and task interaction (KxT) for mean data and task main effect and hand and task interaction (HxT) for minimum data from neutral -- were not noteworthy.

Table 65. *Mean* forearm pronation position in degrees for each alternative keyboard design (negative = forearm supination; positive = forearm pronation)
(n = 24 for the left forearm for the split fixed-angle and the split adjustable-angle keyboards, n = 25 for the left forearm for the vertically-inclined keyboard and the right forearm for the split fixed-angle keyboard, n = 27 for the right forearm for the split adjustable-angle keyboard and n = 29 for the right forearm for the vertically-inclined keyboard)

	Keyboard		
Typing task	Vertically-inclined	Split adjustable-angle	Split fixed-angle
Left forearm			
Alphabetic	41.8 ± 12.7	60.0 ± 11.7	61.9 ± 9.2
Alphanumeric	43.8 ± 12.1	60.2 ± 9.9	62.2 ± 9.1
Right forearm			
Alphabetic	38.5 ± 8.9	64.1 ± 9.0	62.6 ± 6.9
Alphanumeric	40.4 ± 9.0	63.6 ± 8.3	62.7 ± 7.0

Table 66. *Maximum* forearm pronation position in degrees for each alternative keyboard design (negative = forearm supination; positive = forearm pronation.

(n = 24 for the left forearm for the split fixed-angle and the split adjustable-angle keyboards; n = 25 for the left forearm for the vertically-inclined keyboard and the right forearm for the split fixed-angle keyboard, n = 27 for the right forearm for the split adjustable-angle keyboard and n = 29 for the right forearm for the vertically-inclined keyboard)

	Keyboard		
Typing task	Vertically-inclined	Split adjustable-angle	Split fixed-angle
Left forearm			
Alphabetic	50.2 ± 13.6	67.8 ± 12.1	70.2 ± 10.5
Alphanumeric	53.3 ± 13.4	68.9 ± 10.8	72.4 ± 12.6
Right forearm			
Alphabetic	46.2 ± 9.7	70.7 ± 8.8	69.7 ± 8.6
Alphanumeric	48.6 ± 10.6	70.4 ± 7.9	70.0 ± 8.5

Table 67. *Minimum* forearm pronation position in degrees for each alternative keyboard design (negative = forearm supination; positive = forearm pronation).

(n = 24 for the left forearm for the split fixed-angle and the split adjustable-angle keyboards, n = 25 for the left forearm for the vertically-inclined keyboard and the right forearm for the split fixed-angle keyboard, n = 27 for the right forearm for the split adjustable-angle keyboard and n = 29 for the right forearm for the vertically-inclined keyboard)

	Keyboard		
Typing task	Vertically-inclined	Split adjustable-angle	Split fixed-angle
Left forearm			
Alphabetic	33.7 ± 13.1	53.0 ± 11.4	53.4 ± 9.9
Alphanumeric	33.5 ± 12.3	51.6 ± 9.9	52.0 ± 10.8
Right forearm			
Alphabetic	29.1 ± 9.0	55.8 ± 10.8	53.3 ± 7.1
Alphanumeric	29.8 ± 8.9	54.4 ± 10.6	53.0 ± 6.2

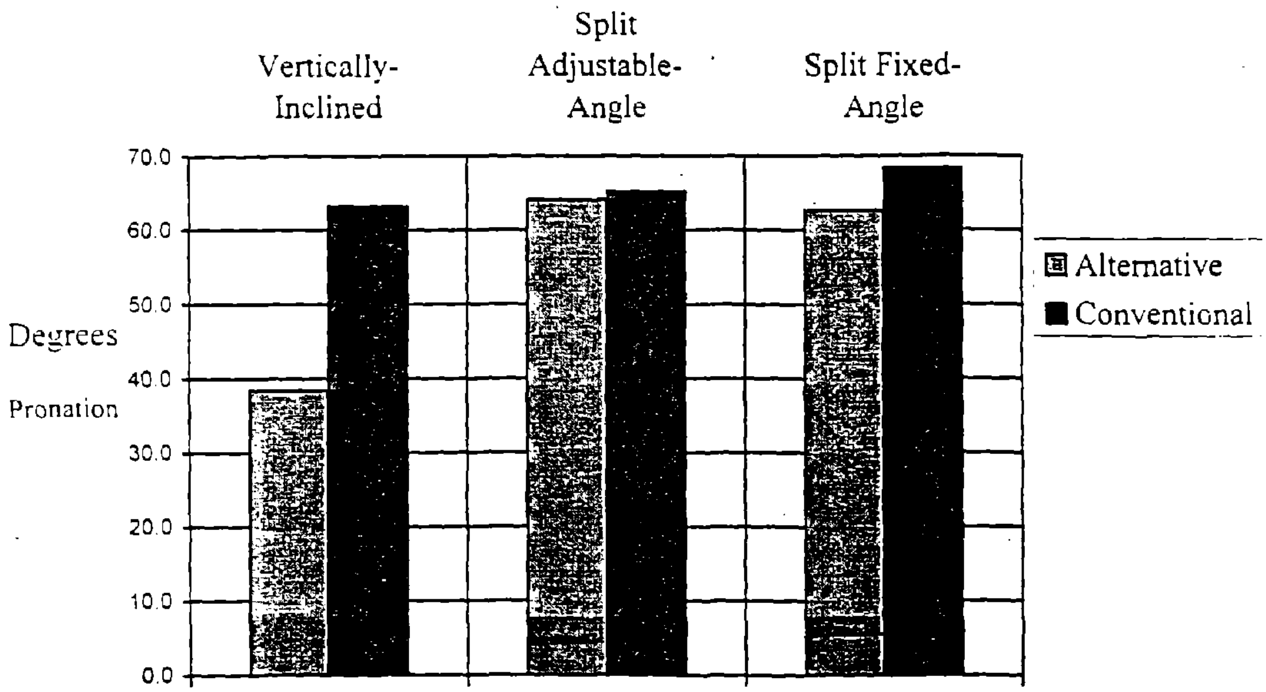


Figure 47. Mean pronation position for the *right* forearm for each alternative keyboard.

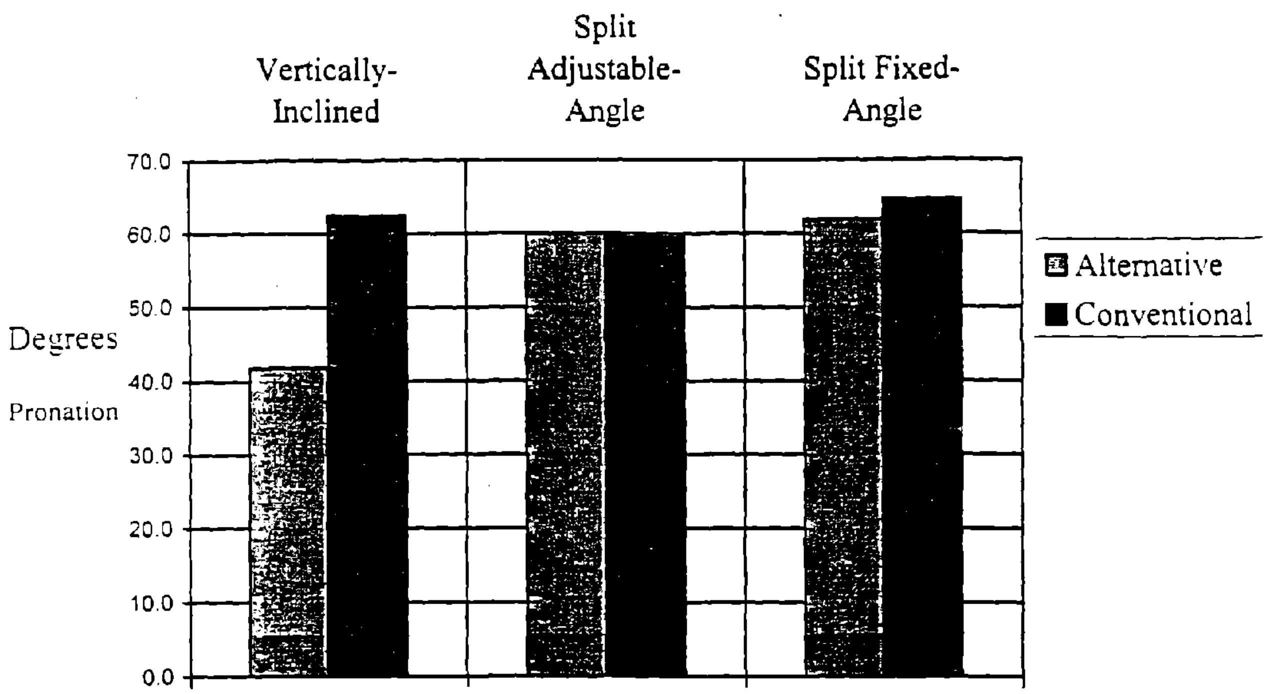


Figure 48. Mean pronation position for the *left* forearm for each alternative keyboard.

D.5.10. Analysis of Finger Data

Flexion angle of the metacarpophalangeal (MCP) joint of the right index finger was measured on 20 subjects and are presented in Figure 49 and Tables 68 to 71. Descriptive data for all 20 subjects typing on the conventional keyboard revealed the mean flexion angle was approximately 11 deg. with a range from 3 deg. extension to 35 deg. flexion (refer to Table 70). ANOVA results from Table 69 did not reveal a significant difference in mean flexion angle across the three alternative keyboards. Figure 49 and data from Table 71 show the mean flexion angle of the MCP joint ranged from 8 to 11 deg. for all three alternative keyboards. The MCP flexion angle for the conventional keyboard ranged from 10 to 11 deg., as shown in Figure 49 and Table 71. For both split keyboards, there were not significant differences in mean MCP flexion between the conventional and respective split alternative keyboard, but there was a significant difference for the vertically-inclined keyboard. However, as shown in Table 71 and Figure 49, the difference of two deg. flexion (8 to 10 deg.) between the vertically-inclined and conventional keyboards is minimal and not noteworthy.

Our initial intent was to measure flexion of the MCP joints of the index and ring fingers for both hands on all subjects. Due to the high rate of failure of the Penny & Giles goniometers and the prohibitive cost of replacement, we could only collect data for the right index finger of 20 subjects.

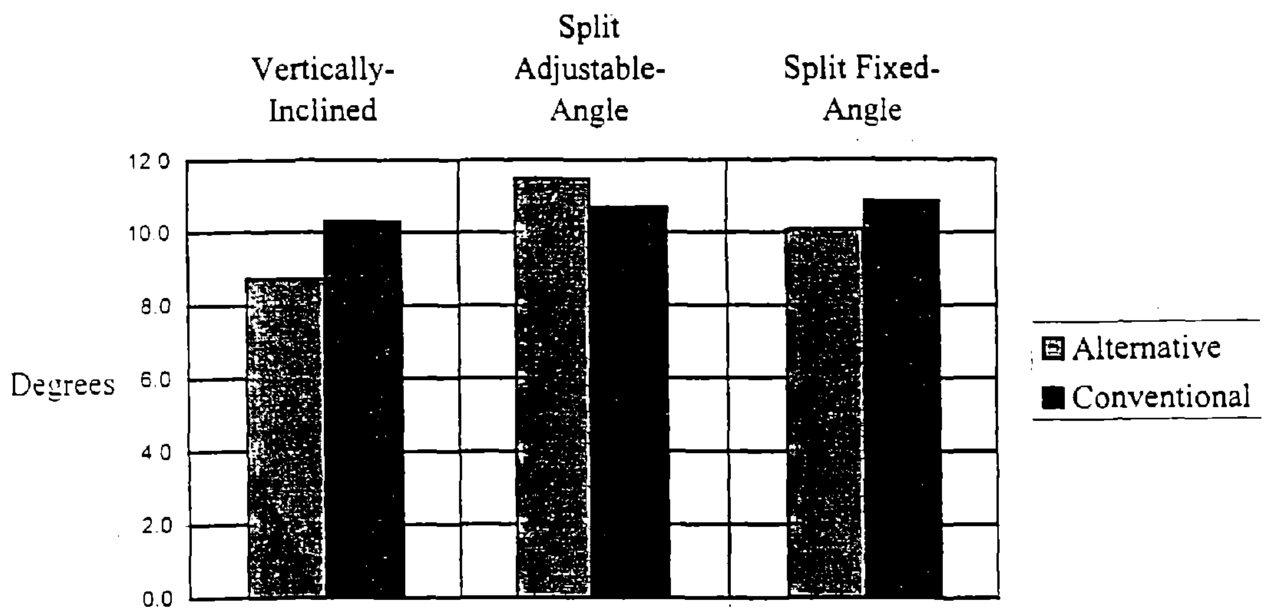


Figure 49. Mean flexion position of the MCP joint of the right index finger in deg. (n = 7 for the split adjustable-angle and vertically-inclined keyboards and n = 6 for the split fixed-angle keyboard).

Table 68. P-values for the main effects and interactions for mean flexion position of the metacarpophalangeal (MCP) joint of the right index finger for alternative versus conventional keyboard comparisons (n = 7 for the split adjustable-angle and the vertically-inclined keyboards and n = 6 for the split fixed-angle keyboard).

Main Effects and Interactions	DF	Vertically-Inclined	Split Adjustable-Angle	Split Fixed-Angle
Keyboard (K)	1	0.045*	0.383	0.145
Typing Task (T)	1	0.741	0.620	0.597
K x T	1	0.126	0.542	0.279

* $p < 0.05$

Table 69. P-values for the main effects and interactions for mean flexion position of the MCP joint of the right index finger among alternative keyboards and typing tasks.

Main Effects and Interactions	DF	P-value
Keyboard (K)	2	0.815
Typing Task (T)	1	0.617
K x T	2	0.610

Table 70. Mean flexion position in deg. of the metacarpophalangeal joint of the right index finger in degrees for the conventional keyboard (positive = finger flexion; negative = finger extension) (n=20 subjects).

Typing Task	Mean ± s.d.	Minimum	Maximum
Alphabetic	10.6 ± 8.3	-3.2	33.9
Alphanumeric	11.2 ± 8.5	-1.8	35.8

Table 71. Mean flexion position of the metacarpophalangeal joint of the right index finger in deg. for each keyboard.

	Vertically-Inclined (n=7)		Split Adjustable (n=7)		Split Fixed (n=6)	
Typing task	Conventional	Alternative	Conventional	Alternative	Conventional	Alternative
Alphabetic	10.3 ± 13.1	8.7 ± 13.7	10.7 ± 4.6	11.5 ± 5.5	10.9 ± 5.5	10.1 ± 6.8
Alphanumeric	10.7 ± 13.5	7.9 ± 14.3	11.4 ± 4.7	11.7 ± 4.8	11.6 ± 5.5	10.1 ± 6.0

D.5.11. Variance Analysis of Wrist and Forearm Position While Typing

In addition to the mean, minimum and maximum position for each subject while they were typing, we also measured the variance of wrist and forearm position. Variance was defined as the amount of variation that existed about the mean position of the joint, in a respective plane, for each subject. Variance, which is the square of the standard deviation, of the angular position of the wrist and forearm is used as an index of "dynamic motion" of the joints while typing. A small variance value about the mean angular position would indicate that the joint of interest was held in a relatively fixed and static position over the overall typing task. A large variance would indicate that the joint of interest moved considerably about its mean position during the typing task.

Calculation of Summary Statistics for Variance. The variances of wrist and forearm angle in the rad/uln, flex/ext, and pron/supin planes were measured on each subject according to the following procedure:

1) The position variance of each 30 second trial was computed for each respective plane of movement.

2) The position variances from each of the five trials during an alphabetic or alphanumeric typing session were pooled together, and a variance for the five trials was computed according to the statistical procedure reported in Glass and Hopkins (1984).

3) The variances computed in 2) from each of the two sets of five alphabetic trials were averaged.

4) The mean position variance for the alphabetic trials computed in 3) was recorded for each subject. The position variance for the five alphanumeric trials computed in 2) was recorded for each subject.

5) The two summary position variances for each subject from 4) (one for alphabetic and one for alphanumeric) were entered into a spreadsheet, and ANOVAs were performed on the data.

Position Variance of Conventional Keyboard. The position variances of wrist and forearm angles for the conventional keyboard across all 90 subjects, as shown in Table 72A and Figure 50, indicate that the variance ranged 14 to 24 deg. for wrist rad/uln deviation, 6 to 16 deg. for wrist flex/ext position, and 12 to 18 deg. for forearm pronation.

Overall, the mean position variance for the alphabetic task was approximately 3 to 6 deg. less than for the alphanumeric task. This difference was statistically significant ($p < 0.01$, Table 72B) for wrist rad/uln deviation, wrist flex/ext and forearm pron/sup. The increase in variance for the alphanumeric task is likely due to the greater need to use numeric and special function keys when typing alphanumeric text, resulting in greater movement of the wrist and forearm. In addition, right wrist flex/ext and rad/uln deviation mean position variance was significantly greater than the left wrist, as evinced by an additional 3 to 6 deg. of variance of the right hand over the left hand ($p < 0.01$, Table 72B).

These data clearly show that typing is not an absolutely static task and that dynamic movement takes place at the wrist and forearm. In addition, the amount and frequency of the motion seems to be different between hands and also based on the typing task.

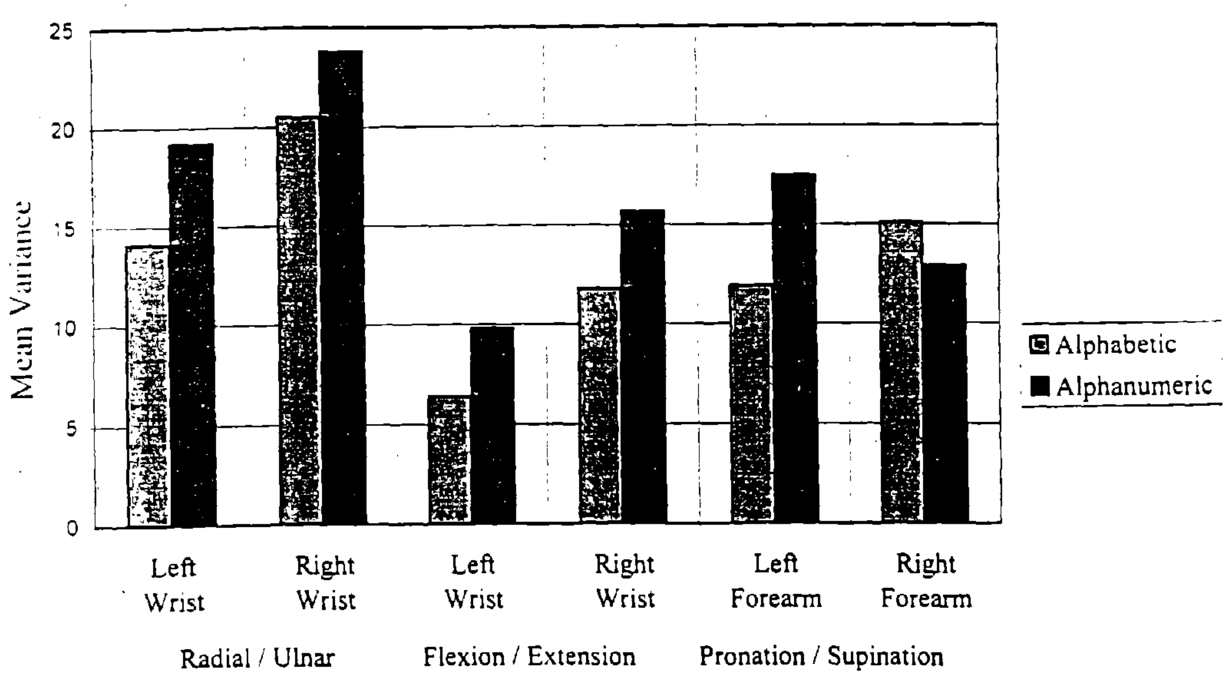


Figure 50. Mean variance in deg. for the conventional keyboard
(n = 90 for wrist data, n = 73 for left forearm data, and n = 81 for right forearm data).

Table 72A. Variance in deg. (mean ± s.d.) for the conventional keyboard (n = 90 for wrist data, n = 73 for left forearm data and n = 81 for right forearm data).

Typing task	Wrist radial/ulnar deviation	Wrist flexion/ extension	Forearm pronation/ supination
Left hand			
Alphabetic	14.1 ± 7.5	6.4 ± 5.4	11.9 ± 9.2
Alphanumeric	19.2 ± 10.9	9.8 ± 7.9	17.5 ± 14.8
Right hand			
Alphabetic	20.5 ± 9.3	11.8 ± 6.6	15.1 ± 16.5
Alphanumeric	23.8 ± 15.6	15.7 ± 11.1	12.9 ± 18.0

Table 72B. P- values of the 2-way ANOVA for the position variance of the wrist and forearm for the conventional keyboard. The two factors are hand (right and left) and typing task (alphabetic and alphanumeric).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Hand (H)	1	0.000**	0.000**	0.140
Typing Task (T)	1	0.000**	0.000**	0.000**
H x T	1	0.213	0.582	0.031

** Significant at $p < 0.01$ level; * significant at $p < 0.05$ level.

Position Variance of Split Fixed-Angle Keyboard. A three-way ANOVA (independent variables: keyboard design, hand, and typing task) was performed on the data from the 30 subjects who used the split fixed-angle and conventional keyboards to determine if there were differences in position variance between these two keyboards. The p-values results from this ANOVA are shown in Table 73. As shown in Table 73 and Figure 51, the split fixed-angle keyboard, as compared to the conventional keyboard, did not produce any significant differences in position variance in the three planes, as evinced by the lack of significant main effects for keyboard design. However, there were significant main effects for hand and typing tasks for rad/uln and flex/ext wrist angles, and a significant main effect for typing task for pron/sup (refer to Table 73 and Figure 51). The data from both keyboards are presented in Tables 74, 75, 76 and Figures 51 and 52. The significant hand and task interaction (HxT) is illustrated in Figure 53.

Table 73. P-values of the 3-way ANOVA for the variance of the wrist position comparing the split fixed-angle keyboard to the conventional keyboard. The three factors are keyboard (conventional and split fixed-angle), hand (right and left) and typing task (alphabetic and alphanumeric).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Keyboard (K)	1	0.202	0.092	0.780
Hand (H)	1	0.000 **	0.000 **	0.128
Typing Task (T)	1	0.000 **	0.002 **	0.028 **
K x H	1	0.469	0.427	0.577
K x T	1	0.674	0.177	0.099
H x T	1	0.268	0.996	0.008 **
K x H x T	1	0.826	0.722	0.958

** Significant at $p < 0.01$ level; * significant at $p < 0.05$ level.

Table 74. *Wrist ulnar* variance in deg.for the split fixed-angle and conventional keyboards (n = 30).

Typing task	Keyboard: Conventional	Keyboard: Split fixed-angle
Left wrist		
Alphabetic	13.0 ± 8.0	15.2 ± 8.1
Alphanumeric	16.6 ± 9.9	19.8 ± 11.1
Right wrist		
Alphabetic	22.0 ± 11.3	22.9 ± 12.4
Alphanumeric	24.6 ± 15.6	25.8 ± 13.4

Table 75. *Wrist extension* variance in deg.for the split fixed-angle and conventional keyboards (n = 30).

Typing task	Keyboard: Conventional	Keyboard: Split fixed-angle
Left wrist		
Alphabetic	5.3 ± 2.6	6.6 ± 3.1
Alphanumeric	8.1 ± 5.6	8.2 ± 4.2
Right wrist		
Alphabetic	11.5 ± 6.6	13.7 ± 9.5
Alphanumeric	14.1 ± 10.5	15.4 ± 11.0

Table 76. *Forearm pronation* variance in deg. for the split fixed-angle and conventional keyboards (n = 24 for the left hand and n = 25 for the right hand).

Typing task	Keyboard: Conventional	Keyboard: Split fixed-angle
Left forearm		
Alphabetic	14.2 ± 12.4	16.0 ± 15.6
Alphanumeric	21.7 ± 20.2	20.2 ± 14.4
Right forearm		
Alphabetic	13.9 ± 16.0	15.2 ± 13.6
Alphanumeric	17.0 ± 19.0	14.3 ± 12.9

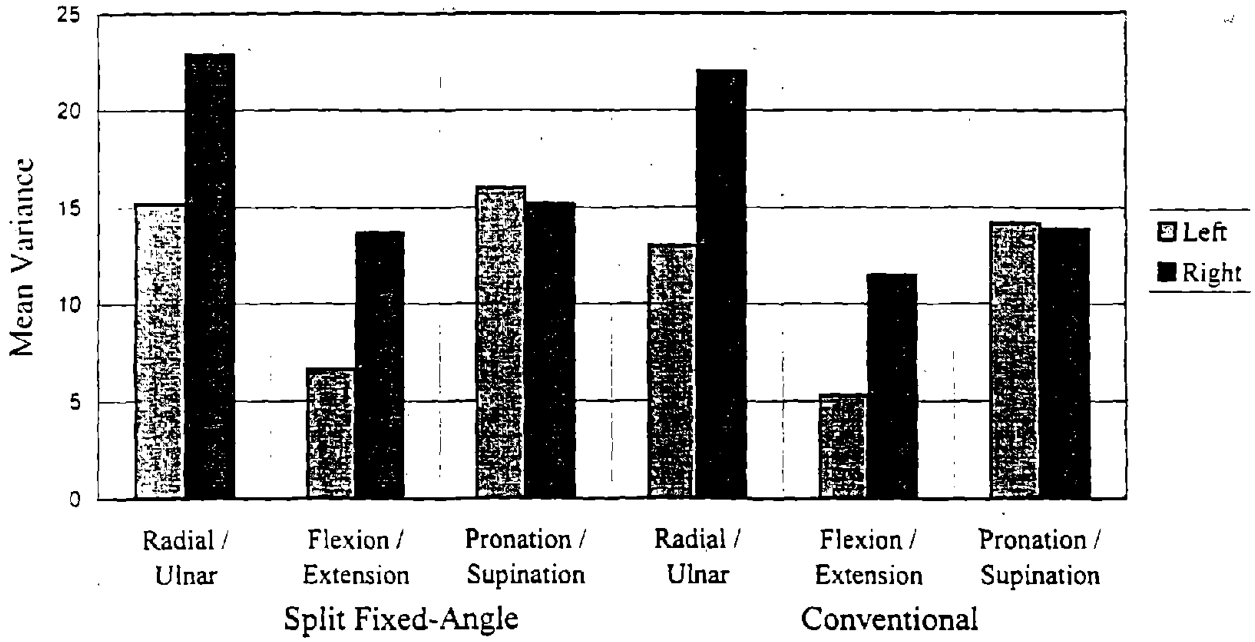


Figure 51. Mean variance in deg. for *each hand* for the split fixed-angle and the conventional keyboards (alphabetic typing task).

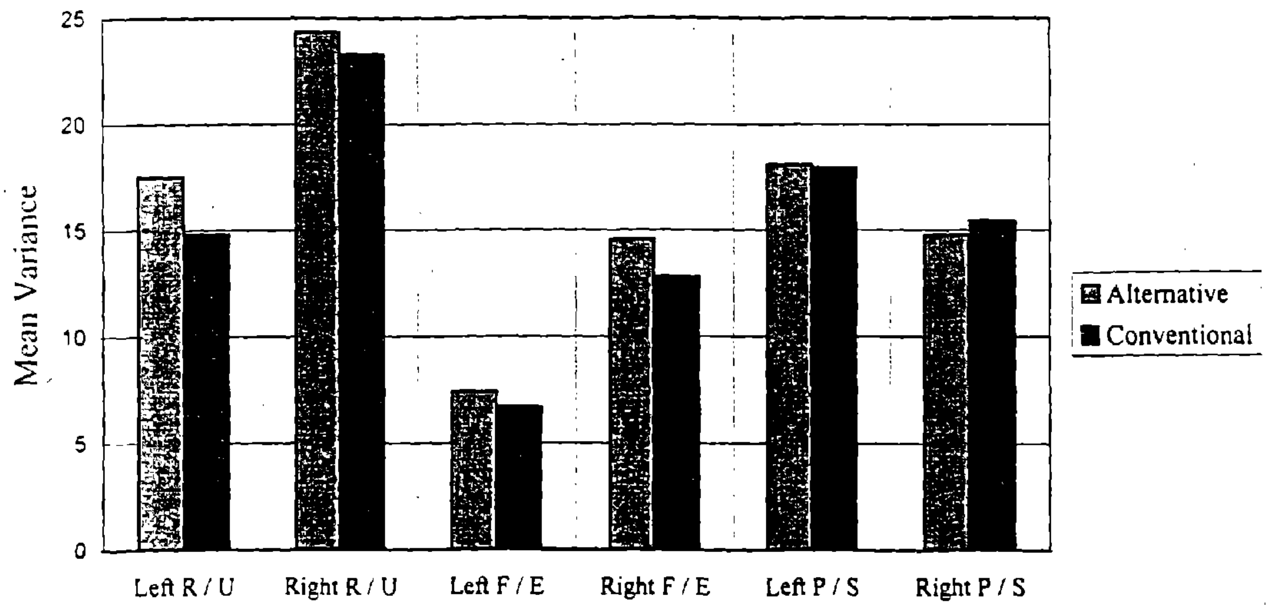


Figure 52. Mean variance in deg. for the split fixed-angle and conventional keyboards.

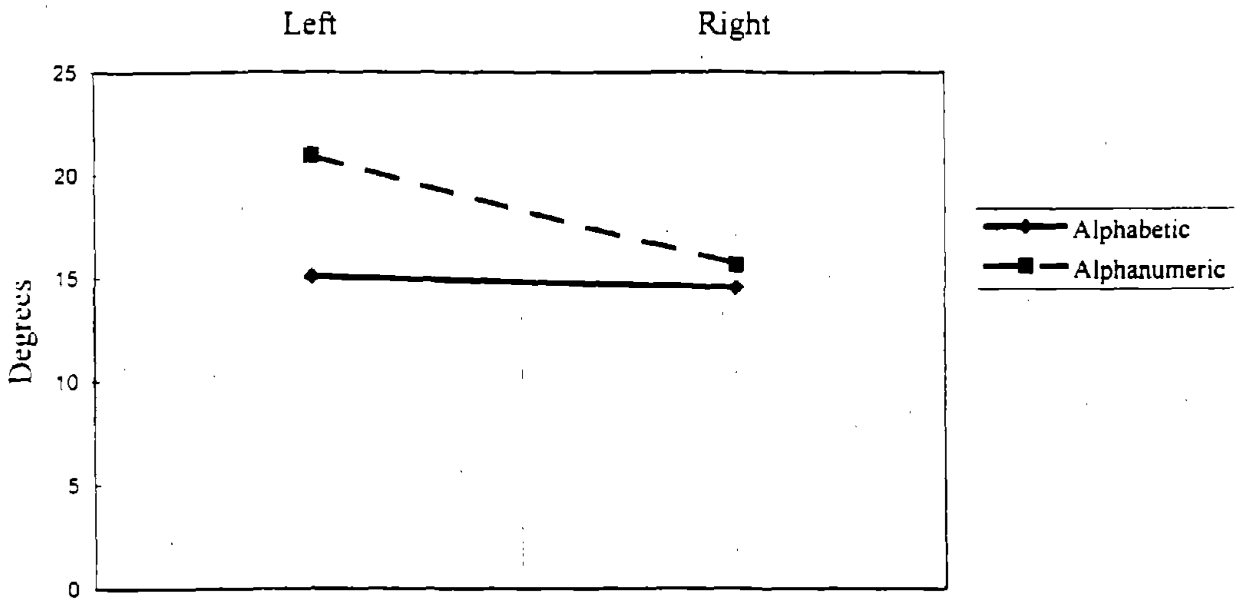


Figure 53. Hand and typing task interaction (HxT) on the mean pronation variance (in deg.) for the split fixed-angle keyboard.

Position Variance of Split Adjustable-Angle Keyboard. Similar to the split fixed-angle keyboard, the ANOVA results from the 30 subjects who used the split adjustable-angle keyboard revealed significant hand and typing task main effects for rad/uln and flex/ext wrist positions and significant typing task effect for pron/supin (refer to Table 77 and Figure 54). In addition, the wrist and forearm variance data did not show any significant differences in position variance between the alternative split adjustable-angle and conventional keyboards. The data for both keyboards are presented in Tables 78, 79, 80 and Figures 54 and 55. The significant keyboard and hand (KxH) and keyboard and task (KxT) interactions are illustrated in Figures 56 and 57, respectively.

While no significant differences existed between keyboards, the alphanumeric task resulted in greater variance for both wrists and forearms. Additionally, right wrist position variance was statistically greater for both position variables (rad/uln and flex/ext) than left wrist variance.

Table 77. P-values of the 3-way ANOVA for the variance of wrist position comparing the split adjustable-angle keyboard to the conventional keyboard. The three factors are keyboard (conventional and split adjustable-angle), hand (right and left) and typing task (alphabetic and alphanumeric).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Keyboard (K)	1	0.069	0.566	0.712
Hand (H)	1	0.048 *	0.000 **	0.780
Typing Task (T)	1	0.003 **	0.000 **	0.045 *
K x H	1	0.042 *	0.317	0.376
K x T	1	0.042 *	0.192	0.516
H x T	1	0.702	0.159	0.350
K x H x T	1	0.064	0.656	0.700

** Significant at $p < 0.01$ level; * significant at $p < 0.05$ level.

Table 78. *Wrist ulnar* variance in deg. for the split adjustable-angle and conventional keyboards (n = 30).

	Keyboard	
Typing task	Conventional	Split adjustable-angle
Left wrist		
Alphabetic	14.1 ± 7.6	16.8 ± 7.2
Alphanumeric	18.3 ± 8.7	21.3 ± 11.7
Right wrist		
Alphabetic	18.8 ± 9.1	21.0 ± 10.0
Alphanumeric	24.7 ± 19.9	22.0 ± 13.0

Table 79. *Wrist extension* variance in deg. for the split adjustable-angle and conventional keyboards (n = 30).

	Keyboard	
Typing task	Conventional	Split adjustable-angle
Left wrist		
Alphabetic	7.2 ± 5.3	8.0 ± 8.2
Alphanumeric	10.3 ± 7.1	9.2 ± 4.1
Right wrist		
Alphabetic	11.9 ± 6.5	13.4 ± 7.1
Alphanumeric	16.2 ± 8.1	16.7 ± 9.9

Table 80. *Forearm pronation* variance in deg. for the split adjustable-angle and conventional keyboards (n = 24 for the left forearm and n = 27 for the right forearm).

	Keyboard	
Typing task	Conventional	Split adjustable-angle
Left forearm		
Alphabetic	10.8 ± 6.5	13.5 ± 15.2
Alphanumeric	15.9 ± 12.6	16.4 ± 11.9
Right forearm		
Alphabetic	12.8 ± 20.6	12.7 ± 17.6
Alphanumeric	17.3 ± 18.0	13.9 ± 17.6

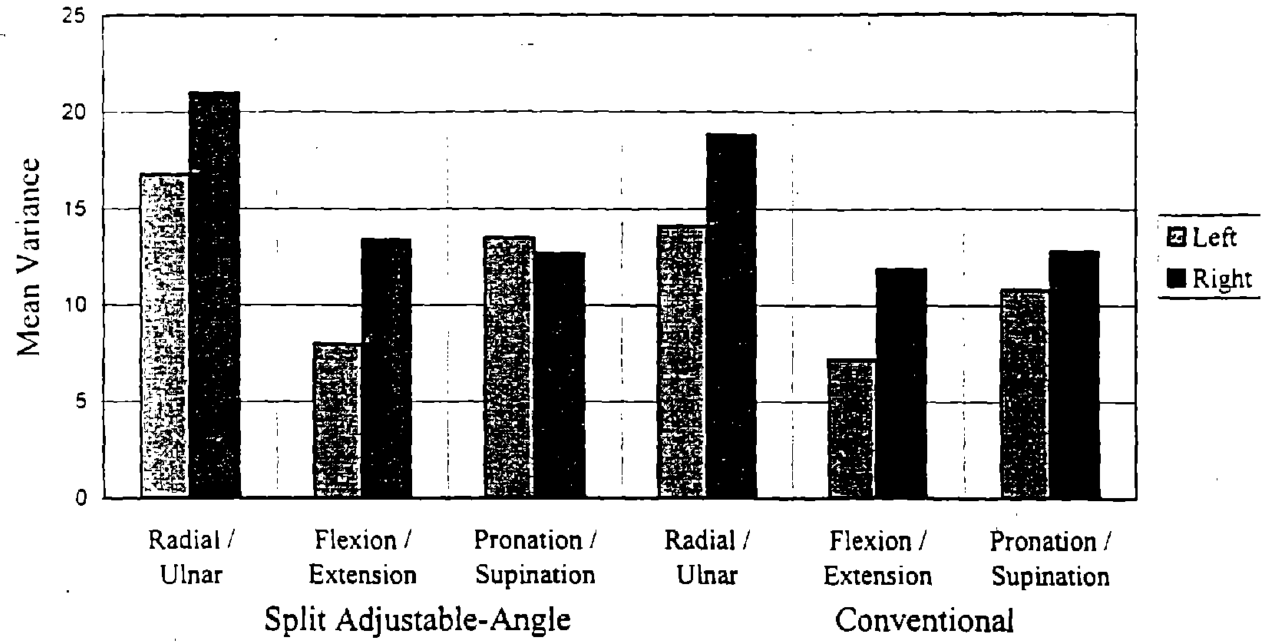


Figure 54. Mean variance in deg. for both hands for the split adjustable-angle and conventional keyboards (alphabetic typing task).

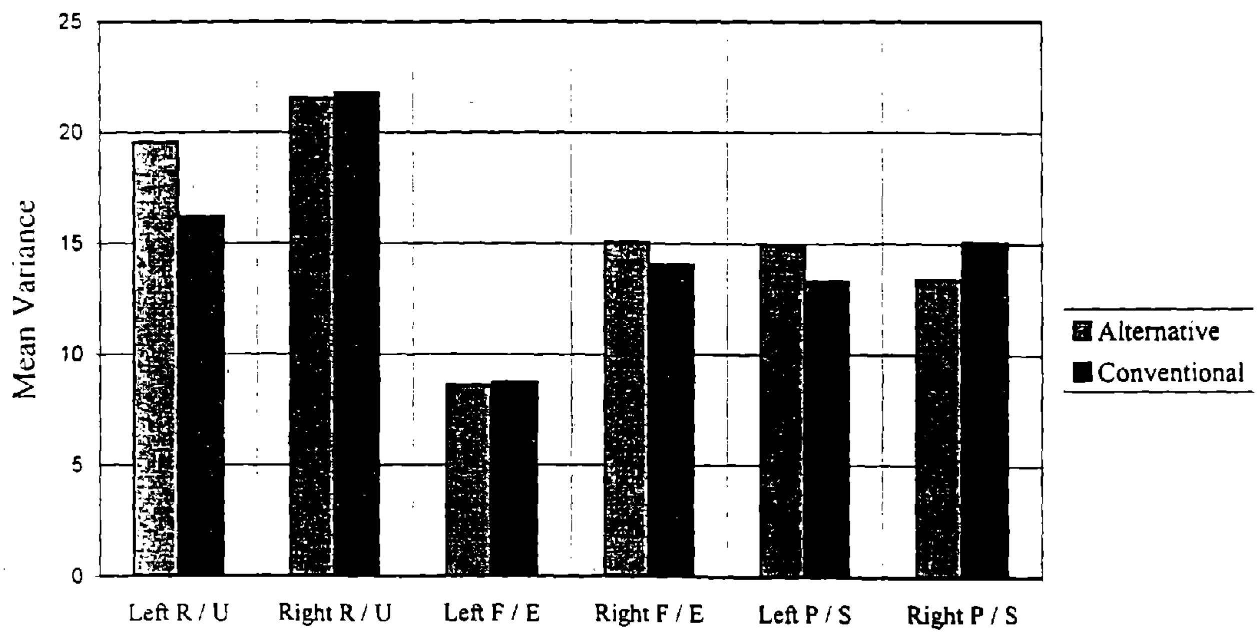


Figure 55. Mean variance in deg. for the split adjustable-angle and conventional keyboards.

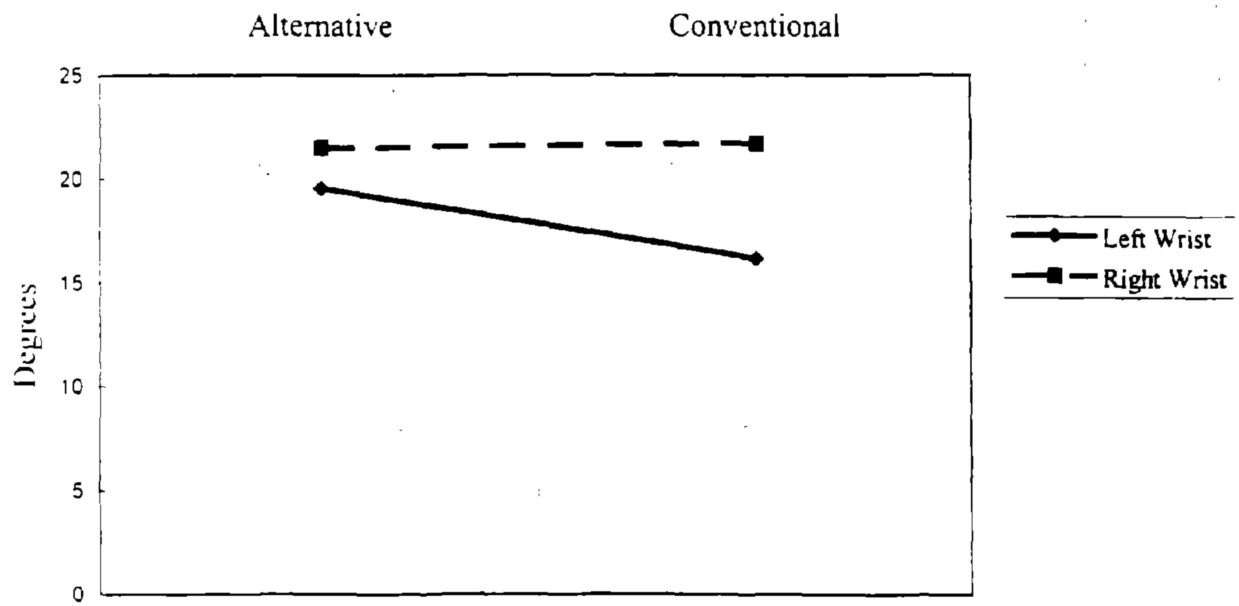


Figure 56. Keyboard and hand interaction (KxH) on the mean ulnar variance (in deg.) for the split adjustable-angle keyboard.

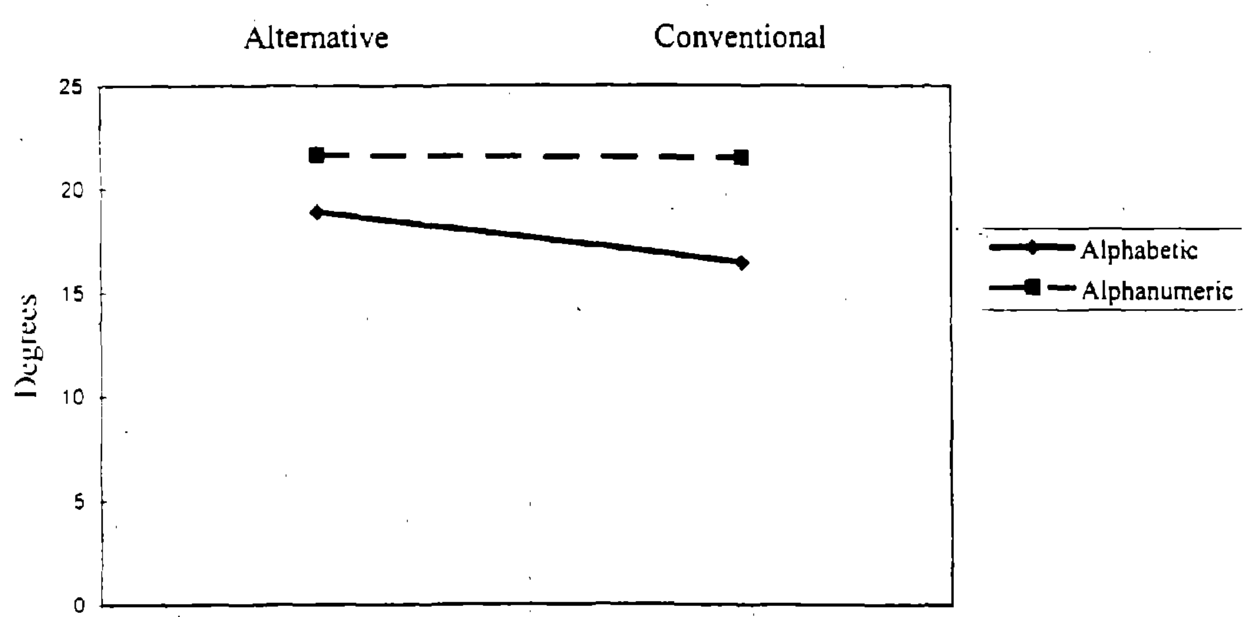


Figure 57. Keyboard and typing task interaction (KxT) on the mean ulnar variance (in deg.) for the split adjustable-angle keyboard.

Position Variance of Vertically-Inclined Keyboard. Similar to the two split keyboards, the results of ANOVA on the vertically-inclined keyboard variance data revealed significant hand and typing task effects for rad/uln and flex/ext wrist position and a significant task effect for pron/sup, as indicated in Table 81. As shown in Table 81 and Figure 58, the absence of a significant keyboard design effect shows that there was no difference in position variance data between the vertically-inclined and conventional keyboards. Data for both keyboards are presented in Tables 82, 83, 84 and Figures 58 and 59. The keyboard and hand (KxH) and keyboard and task (KxT) interactions are illustrated in Figures 60 and 61.

Table 81. P-values of the 3-way ANOVA for the variance of the wrist position comparing the vertically-inclined keyboard to the conventional keyboard. The three factors are keyboard (conventional and vertically-inclined), hand (right and left) and typing task (alphabetic and alphanumeric).

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Keyboard (K)	1	0.167	0.292	0.057
Hand (H)	1	0.010 **	0.000 **	0.592
Typing Task (T)	1	0.000 **	0.000 **	0.000 **
K x H	1	0.002 **	0.304	0.065
K x T	1	0.243	0.166	0.093
H x T	1	0.002 **	0.835	0.207
K x H x T	1	0.684	0.803	0.998

** Significant at $p < 0.01$ level; * significant at $p < 0.05$ level.

Table 82. *Wrist ulnar* variance in deg. for the vertically-inclined and conventional keyboards (n = 30).

	Keyboard	
Typing task	Conventional	Vertically-inclined
Left wrist		
Alphabetic	15.1 ± 7.2	14.8 ± 6.2
Alphanumeric	22.7 ± 13.1	20.3 ± 8.6
Right wrist		
Alphabetic	20.6 ± 7.1	26.3 ± 11.5
Alphanumeric	22.0 ± 10.1	26.8 ± 13.0

Table 83. *Wrist extension* variance in deg. for the vertically-inclined and conventional keyboards (n = 30).

	Keyboard	
Typing task	Conventional	Vertically-inclined
Left wrist		
Alphabetic	6.8 ± 7.2	6.4 ± 6.5
Alphanumeric	11.0 ± 10.3	9.4 ± 10.7
Right wrist		
Alphabetic	12.0 ± 6.9	10.9 ± 5.8
Alphanumeric	16.8 ± 14.0	13.9 ± 8.2

Table 84. *Forearm pronation* variance in deg. for the vertically-inclined and conventional keyboards (n = 25 for the left hand and n = 29 for the right hand).

	Keyboard	
Typing task	Conventional	Vertically-inclined
Left forearm		
Alphabetic	10.8 ± 7.7	11.8 ± 7.7
Alphanumeric	14.9 ± 9.2	19.7 ± 16.2
Right forearm		
Alphabetic	11.8 ± 17.5	12.2 ± 8.9
Alphanumeric	10.3 ± 10.3	16.3 ± 14.2

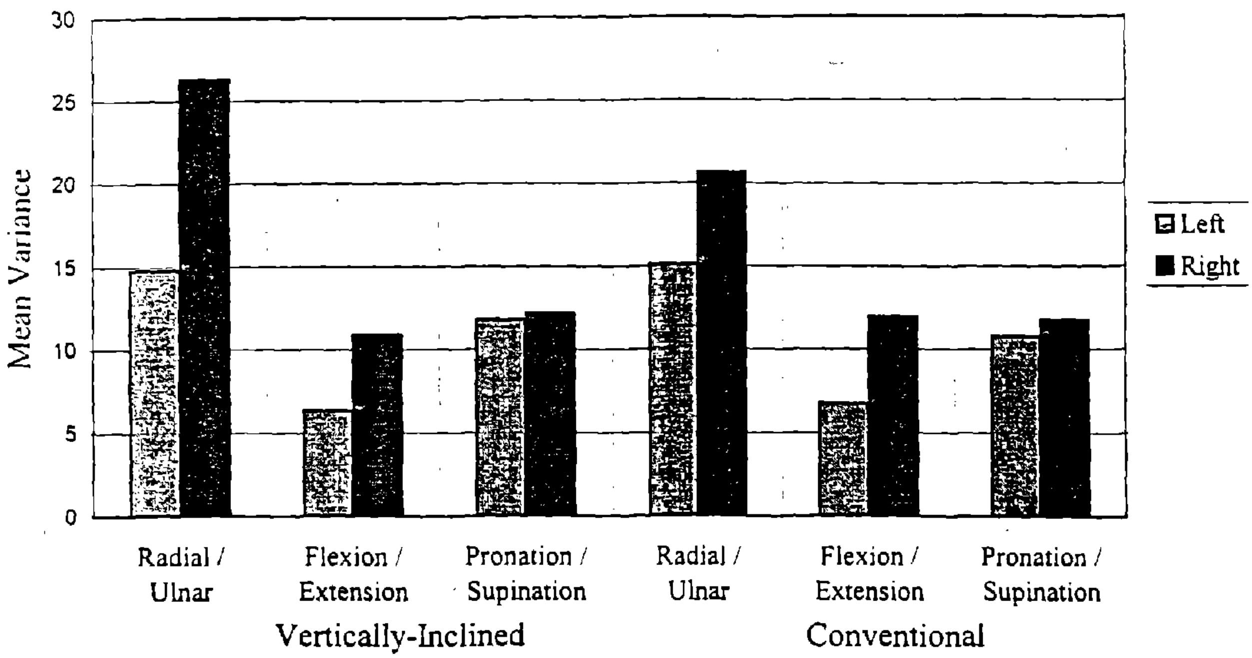


Figure 58. Mean variance in deg. for each hand for the vertically-inclined and conventional keyboards (alphabetic typing task).

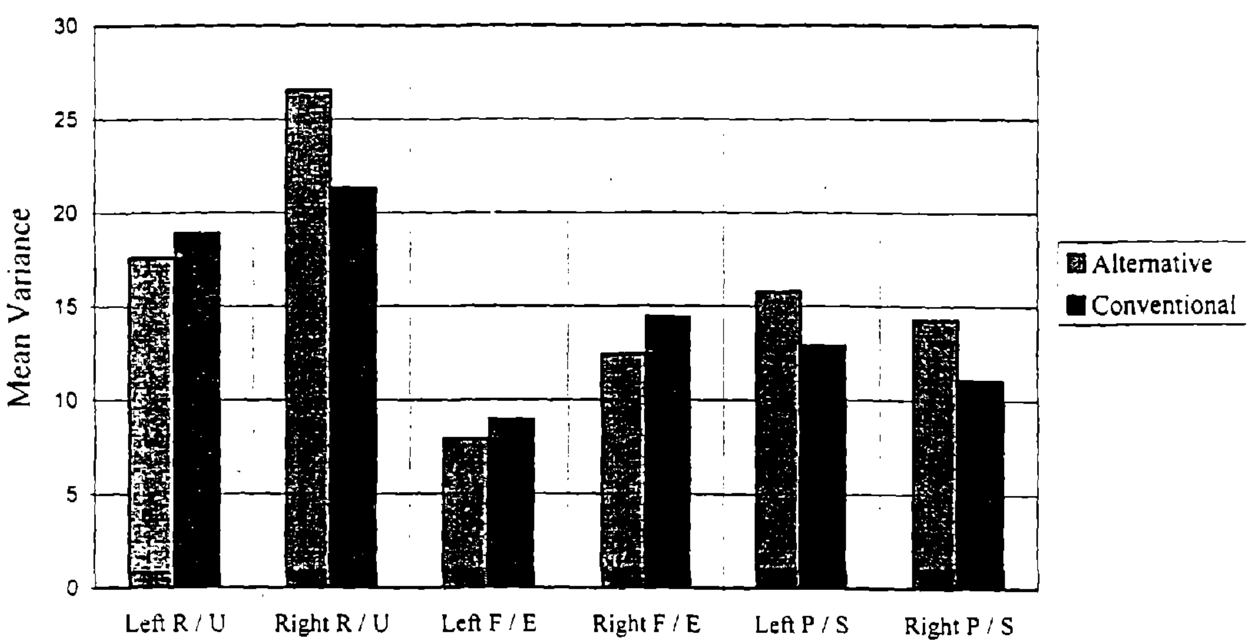


Figure 59. Mean variance in deg. for the vertically-inclined and conventional keyboards.

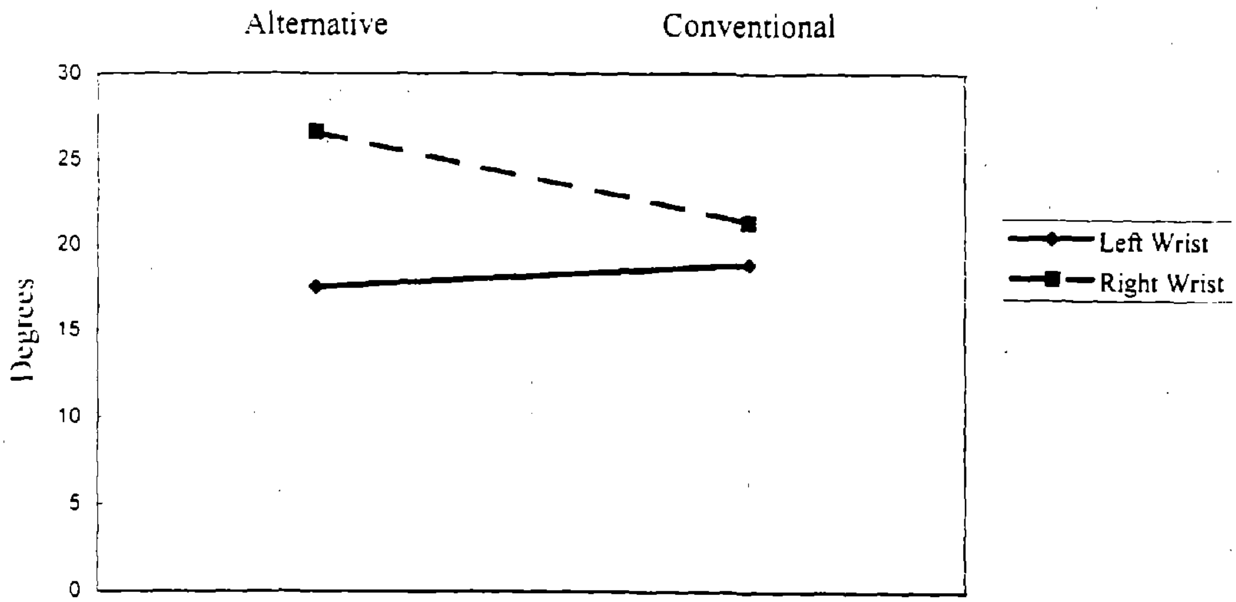


Figure 60. Keyboard and hand interaction (KxH) on the mean ulnar variance (in deg.) for the vertically-inclined keyboard.

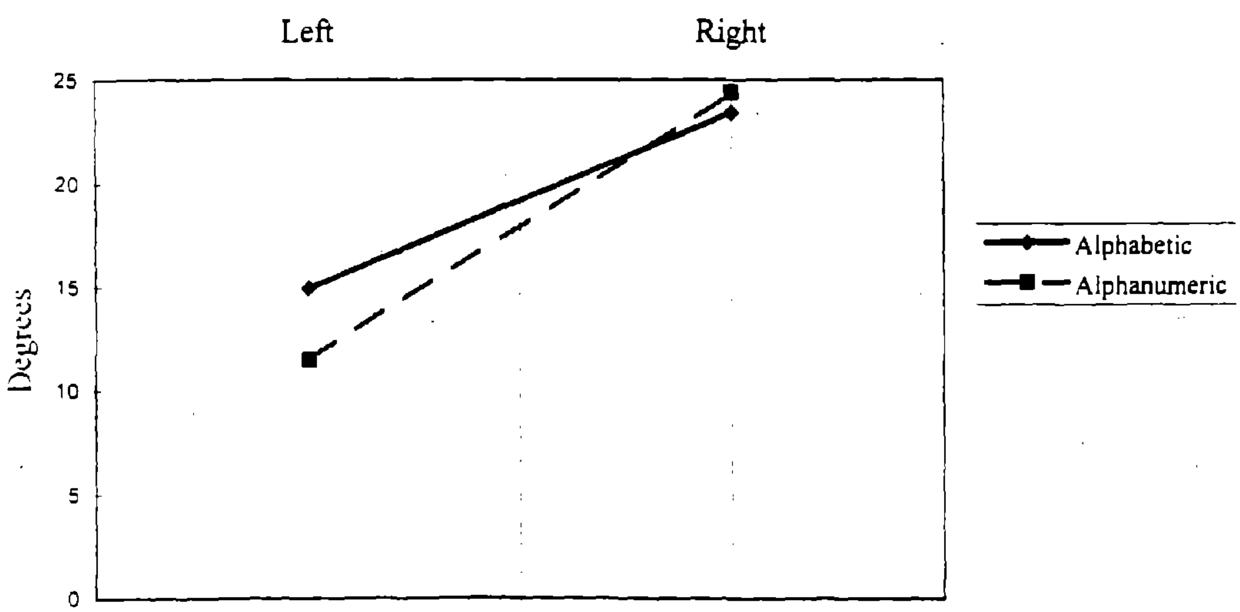


Figure 61. Hand and typing task interaction (HxT) on the mean ulnar variance (in deg.) for the vertically-inclined keyboard.

Position Variance Across Three Alternative Keyboards. A three-way ANOVA (independent variables: keyboard design, hand, and typing task) was performed to determine if there were significant differences and interactions in position variance across the three alternative keyboards. As shown in Table 85 and Figure 62, there were no significant differences in mean position variance across the three alternative keyboard designs. Variance data for the three keyboards are presented in Tables 86, 87, 88 and Figure 62.

As demonstrated earlier with the conventional and each alternative keyboard, greater variance around the mean is found for the right wrist in both planes of movement as compared to the left wrist. Also, the alphanumeric typing task consistently required greater movement (variance) about the mean position than the alphabetic typing task, regardless of the keyboard used.

The significant hand and typing task interaction (HxT) on ulnar deviation, as indicated in Table 85 and shown in Figure 63, shows relatively minor differences of 2 to 5 deg. ulnar deviation between the two typing tasks for all three keyboards.

Table 85. P-values of the 3-way ANOVA for the variance of the wrist and forearm position across the three alternative keyboards.

Main effects and interactions	DF	Radial/ulnar	Flexion/extension	Pronation/supination
Keyboard (K)	2	0.699	0.568	0.738
Hand (H)	1	0.000 **	0.000 **	0.406
Typing Task (T)	1	0.000 **	0.000 **	0.000 **
K x H	2	0.089	0.402	0.404
K x T	2	0.799	0.483	0.136
H x T	1	0.008 **	0.267	0.032
K x H x T	2	0.546	0.358	0.482

** Significant at $p < 0.01$ level; * significant at $p < 0.05$ level.

Table 86. *Wrist ulnar* variance in deg. for all three keyboard designs (n = 30 for each keyboard).

Typing task	Keyboard		
	Vertically-inclined	Split adjustable-angle	Split fixed-angle
Left wrist			
Alphabetic	14.8 ± 6.2	16.8 ± 7.2	15.2 ± 8.1
Alphanumeric	20.3 ± 8.6	21.3 ± 11.7	19.8 ± 11.1
Right wrist			
Alphabetic	26.3 ± 11.5	21.0 ± 10.0	22.9 ± 12.4
Alphanumeric	26.8 ± 13.0	22.0 ± 13.0	25.8 ± 13.4

Table 87. *Wrist extension* variance in deg. for all three keyboard designs (n = 30 for each keyboard).

Typing task	Keyboard		
	Vertically-inclined	Split adjustable-angle	Split fixed-angle
Left wrist			
Alphabetic	6.4 ± 6.5	8.0 ± 8.2	6.6 ± 3.1
Alphanumeric	9.4 ± 10.7	9.2 ± 4.1	8.2 ± 4.2
Right wrist			
Alphabetic	10.9 ± 5.8	13.4 ± 7.1	13.7 ± 9.5
Alphanumeric	13.9 ± 8.2	16.7 ± 9.9	15.4 ± 11.0

Table 88. *Forearm pronation* variance in deg. for all three alternative keyboard designs.

Typing task	Keyboard		
	Vertically-inclined	Split adjustable-angle	Split fixed-angle
Left forearm			
Alphabetic	11.8 ± 7.7	13.5 ± 15.2	16.0 ± 15.6
Alphanumeric	19.7 ± 16.2	16.4 ± 11.9	20.2 ± 14.4
Right forearm			
Alphabetic	12.2 ± 8.9	12.7 ± 17.6	15.2 ± 13.6
Alphanumeric	16.3 ± 14.2	13.9 ± 17.6	14.3 ± 12.9

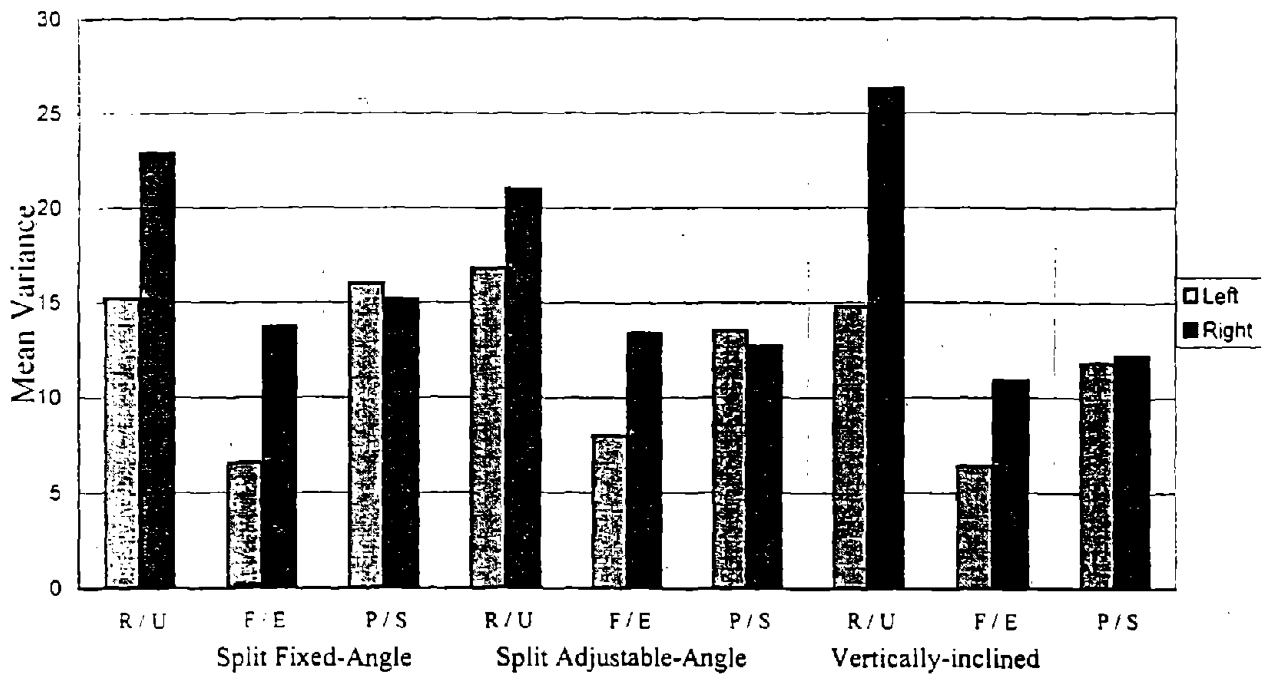


Figure 62. Mean variance in deg. among alternative keyboards (alphabetic typing task).

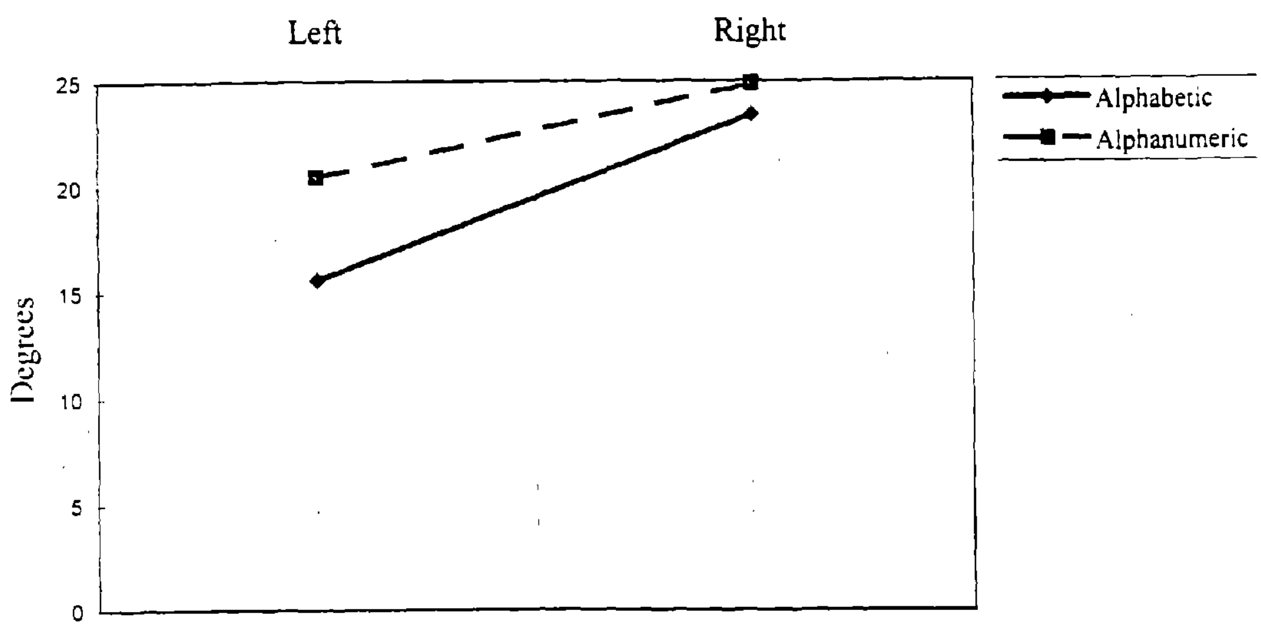


Figure 63. Hand and typing task interaction (HxT) on mean ulnar variance (in deg.) among alternative keyboards.

E. DISCUSSION

E.1. APPROACH AND UNIQUENESS OF STUDY

The object of this study was to compare the wrist and forearm position of subjects typing on a conventional keyboard and three types of commercially-available alternative keyboard (split fixed-angle, split adjustable-angle, and vertically-inclined). Although several investigators have studied alternative keyboards in the past and published their results, the study in this report is unique in two respects. First, the number of subjects tested in this study was 90 (who were all experienced clerical workers), which is almost twice as great as the number of subjects in published studies that measured physical metrics, such as wrist position. Except for Honan's et al. (1995) study that tested 50 subjects, most, if not all, published studies that measured wrist posture employed approximately 30 subjects or less (Naseko et al., 1985; Chen et al., 1994; Sommerich, 1994; Hedge and Powers, 1995; Hedge and Shaw, 1996). Theoretically, the results from a sample size of 90 would be more generalizable to the population of keyboard users than results from smaller sample sizes.

Second, each of the 90 subjects was required to practice on the alternative keyboard assigned to him/her for at least ten hours during a two week practice period before testing in the laboratory. This practice time of ten hours was substantially greater than practice periods in the published literature. Many published studies that measured wrist posture did not report whether the subjects were required or allowed to practice on the alternative keyboards before testing (Naseko et al., 1985; Sommerich, 1994; Hedge and Powers, 1995; Hedge and Shaw, 1996). One published study (Chen et al., 1994) stated each subject practiced for three minutes on each alternative keyboard before testing. When one considers that keyboard subjects have been typing on conventional keyboards for several years or possibly decades, then time adjusting to a new keyboard should be allowed, if not required for subjects.

With respect to wrist position, the authors of this study recommend the minimum amount of practice time should be approximately 20 to 30 minutes for subjects to familiarize themselves with alternative keyboards. Honan et al. (1996) measured the wrist and forearm position of subjects typing on alternative keyboards over a four hour period, and they found there were no overall significant changes in wrist and forearm posture in subjects typing on the alternative keyboards over the four hour period. The positions of the wrist and forearm measured in the first

20 minutes of typing were indicative of the postures during the four hour period. However, these authors caution that typing position may change after the four hour period.

E.2. WRIST AND FOREARM POSTURE AS A FUNCTION OF RIGHT/LEFT HANDS

Whether the subjects in this study were typing on conventional or alternative keyboards, they tended to place their left wrist in greater ulnar deviation (3 to 7 deg. more ulnar deviation for alternative keyboards and 2 to 8 deg. more ulnar deviation for conventional -- refer to Figures 43 and 44, pg. 115) and greater wrist extension (3 to 6 deg. more extension for both alternative and conventional -- Figures 45 and 46, pg. 118) than the right wrist. These results agree with Hedge and Powers (1995), who found that subjects ulnarly deviated their left wrists 2 deg. more than their right wrists (15 to 13 deg. ulnar for left and right, respectively) when they typed on conventional and chair-mounted keyboards. The results for forearm pronation from typing on the conventional keyboard indicated the right forearm was pronated approximately 1 to 5 deg. more than the left forearm. However, the pronation results from typing on alternative keyboards were mixed, as shown in Figures 47 and 48 (pg. 121). Compared to the left forearm, there was approximately 4 deg. less right forearm pronation for the vertically-inclined keyboard and approximately 5 deg. more right forearm pronation for the two split keyboards.

In theory, these differences in positioning between the right and left upper extremities during typing can be explained anatomically. Typists are taught to keep their hands parallel to the surface of the keyboard, whether it is conventional or alternative. Maintaining a parallel relationship between the keyboard surface and hand would require the wrist, in theory, to deviate ulnarly less and extend less, but the forearm to pronate more, than if the hand were angled to the keyboard surface. According to this theory and based on the lower forearm pronation for the left forearm, subjects in this study would have tended to keep their hands more angled (and less parallel) to the keyboard surface than their right hands. (However, since the geometric relationship between the keyboard surface and hand was not measured in this study, the authors are speculating on the relationship between the hand and keyboard surface.) As contrasted to the left hand, the right hand would have been more parallel to the plane of the keyboard, thereby resulting in less ulnar deviation, less wrist extension, but more forearm pronation. The reasons for the differences in wrist and forearm posture between the two upper extremities are not fully understood, and a detailed kinematic analysis of the geometric relationship between the hand and keyboard surface is needed to corroborate the theory postulated above. Perhaps the reason typists pronate less and deviate ulnarly more with the left upper extremity than the right could be that typists have to type more characters or special keys, such as the tab, with their left little finger than their right little finger, and it is easier to type these keys with reduced pronation and ulnar deviation. According to physiological findings from Zipp et al. (1983), less pronation in the left upper extremity than the right would be advantageous to the health of the operator. However, whether the small difference of only about 5 deg. of forearm pronation (refer to Figures 47 and 48) would result in an appreciable difference in health outcomes is questionable.

E.3. POSTURE AND TYPING TASK

There were no significant and appreciable differences in wrist and forearm posture between subjects typing alphabetic and alphanumeric tasks. (A sample of both texts is in Appendix 3.) The lack of typing task effect on wrist and forearm posture suggests that researchers of future studies probably need to test their subjects typing either alphabetic or alphanumeric texts, and not both. (The alphanumeric text used in this study was similar to word problems from a high school physics text and should not be construed to represent numeric data entry via the numeric keypad.)

E.4. WRIST AND FOREARM POSITION FROM TYPING

E.4.1. Conventional Keyboard

While the 90 subjects typed alphabetic text on an IBM PS-2 conventional keyboard, they placed their right and left wrists at mean ulnar deviation angles of 10 and 15 deg., respectively, and at mean wrist extension angles of 17 and 22 deg., respectively (refer to Figure 18, p. 78). The 90 subjects' forearm pronation averaged 62 to 65 deg. for the left and right forearms, respectively (refer to Figure 20, p. 79). The subjects' mean wrist and forearm position while typing alphanumeric text varied by only 2 to 3 deg. from their typing alphabetic text (refer to Figures 18 to20). According to the theory discussed in Section E.2, the 5 deg. difference between the right and left hands' ulnar deviation would have indicated differences in how the subjects placed their hands with respect to the keyboard (the right hand would have been more parallel to the keyboard than the left hand, theoretically resulting in more pronation and less ulnar deviation for the right upper extremity).

Measurements of 10 to 15 deg. ulnar deviation from the 90 subjects typing on a conventional keyboard agree well with the literature. Measurements of ulnar deviation from subjects typing on conventional keyboards as reported in the published studies reveal a range from 7 to 27 deg., with most reports in the 10 to 15 deg. range. (Hedge and Powers (1995) -- 13 to 15 deg. ulnar; Hedge et al. (1995) -- 7 to 10 deg. ulnar; Hedge and Shaw (1996) -- 8.5 deg. ulnar; Honan et al. (1996) -- 10 to 15 deg. ulnar; Smith and Cronin (1993) -- 12 to 27 deg. ulnar; Smutz et al. (1994) -- 25 deg. ulnar; Somerich (1994) -- 15 to 25 deg. of ulnar; Chen et al. (1994) -- 17 deg. ulnar; Grandjean (1983) -- more than 10 deg. ulnar (accounting maching operators)).

In addition, measurements of 17 to 22 deg. wrist extension from the 90 subjects typing on conventional keyboard agree well with the literature. Measurements of wrist extension from subjects typing on conventional keyboards as reported in published studies reveal a range of wrist extension from 11 to 30 deg., with most reports in the 20 to 25 deg. range (Hedge et al. (1995) -- 19.4 deg. extension; Hedge and Powers (1995) -- 13 deg. extension; Hedge and Shaw (1996) -- 10.8 deg. extension; Honan et al. (1996) -- 20.3 to 30.9 deg. extension Smutz et al. (1994) -- 20 deg. extension; Chen et al. (1995) -- 23 deg. extension).

The quantitative recordings of 62 to 65 deg. of mean pronation for the left and right forearms from the 90 subjects typing on a conventional keyboard agree well with the paucity of published studies that measured pronation. Honan et al. (1996) measured mean pronation angles of 65 to 73 deg. over a four hour period while 20 subjects typed on a conventional keyboard. In an earlier study, Honan et al. (1995) measured mean pronation angles ranging from 72 to 79 deg. from their 50 subjects typing on a conventional keyboard.

The variance of posture data showed that the ulnar deviation and extension of the right wrist varied significantly and appreciably more than the left wrist (refer to Figure 51, p. 129, and Table 72B, p. 126). These kinematic findings indicate clearly that typing is not a static task with respect to the wrist and forearm. The reason(s) why the right wrist and forearm move more frequently than the left side are not fully understood. Perhaps one major cause of the disparity in position variance is the location of frequently typed special keys such as 'enter' and 'back space' on the right side of the keyboard, thereby requiring the right hand to deviate more than the left hand from the home row. Additional analysis is needed to determine the exact cause(s) of the disparity in position variance between the right and left hands.

In addition to hand, the typing tasks had a significant and appreciable effect on variation on wrist and forearm position (refer to Table 72B, p. 126, and Figure 50, p. 125). The alphanumeric task resulted in greater variance of wrist and forearm position than the alphabetic typing task. Compared to the location of alphabetic keys, the location of the numeric keys two rows up from home row would be a likely explanation why the wrist and forearm moved more frequently from the home row.

E.4.2. Split vs. Conventional Keyboards

Compared to the conventional keyboard, the two split alternative keyboards reduced mean ulnar deviation significantly and substantially, as indicated in Tables 28A and 38A (pp. 81 and 92) and shown in Figures 22 and 29 (pp. 83 and 94). The split fixed-angle keyboard reduced mean ulnar deviation for the left wrist from 16 to 6 deg. and for the right wrist 8 deg. ulnar to 1 deg. radial. Similarly, the split adjustable-angle keyboard reduced mean ulnar deviation 15 to 6 deg. for the left wrist and 11 to 3 deg. for the right wrist. The results in ulnar deviation from this study agree well with Honan's et al. (1996) study, who found the ulnar deviation of 20 experienced typists who typed on a split fixed-angle keyboard (with a slant angle of 12.5 deg.) for four hours ranged from neutral (0 deg.) to 5 deg. ulnar. The results from this study do not agree with an earlier study of Honan (Honan et al., 1995 -- 5 to 10 deg. ulnar from typing on a split keyboard with fixed slant angle of 12.5 deg.) and Chen's et al. (1994). In the latter study, the researchers measured the ulnar deviation from subjects typing on a split adjustable-angle keyboard that was adjusted to a slant angle of only 5 deg. The resulting mean ulnar deviation from typing on the split keyboard was 15 deg., which was no different than the ulnar deviation from the same subjects who typed on a conventional keyboard. The lack of a difference in ulnar deviation may have been due to the small slant angle of 5 deg..

With respect to the aggregate data from the subjects who typed on both split keyboards, the ratio between slant angle and reduction in ulnar deviation was approximately 1.5:1.0 for both split keyboards (fixed-angle keyboard-- 12.5 deg. fixed slant angle led to a mean 8 deg. decrease in ulnar deviation; adjustable-angle keyboard --10.5 deg. slant angle led to a mean 8 deg. decrease in ulnar deviation). When analyzing only the mean aggregate data from the 30 subjects who typed on the split keyboards, the 1.5:1.0 ratio between slant angle and reduction in ulnar deviation may not hold for individual subjects. The ratio between slant angle and reduction in ulnar deviation for individual subjects will vary somewhat from 1.5:1.0 ratio, which was calculated from aggregate data, and future analysis is required to determine the variability of this ratio for individuals.

Although not as substantial of a reduction as for ulnar deviation, the two split keyboards reduced significantly mean wrist extension about 5 deg. for the fixed-angle keyboard and 3 to 4 deg. for the adjustable-angle keyboard (Tables 28A and 38A, pp. 88 and 92), compared to wrist extension posture from typing on the conventional keyboard. The resulting mean extension angles for both the fixed-angle and adjustable-angle keyboards ranged from approximately 13 to 18 deg. (Figure 27 and 34, pp. 88 and 99).

As compared to the conventional keyboard, the mean forearm pronation angle was significantly less for the split fixed-angle keyboard by approximately 3 to 6 deg. (Table 28A, p. 81; Figure 28, p. 89). The mean pronation angle for subjects typing on the fixed-angle keyboard ranged from 60 to 65 deg. There was no significant difference in pronation angle between the conventional and adjustable-angle keyboard (Table 38A, p. 92).

E.4.2. Vertically-Inclined vs. Conventional Keyboard

Compared to the conventional keyboard, the vertically-inclined keyboard reduced forearm pronation significantly and substantially, as indicated in Table 48A (p. 104) and shown in Figure 42 (p. 110). Mean forearm pronation for the conventional keyboard averaged about 62 deg. and decreased approximately 20 deg. to a pronation position of 42 deg. for the left forearm and decreased approximately 24 deg. to a position of 40 deg. or less pronation for the right forearm. The difference in pronation between the left and right forearms is most probably attributabale to the asymmetry of tilt angles of the two keyboard halves. The left keyboard half was tilted at a mean angle of 27.8 deg., which was 5 deg. less than the mean tilt angle of the right half (32.8 deg.). The disparity in tilt angles was not selected or controlled by the operator, but caused by the lack of precision of the keyboard's internal mechanism that tilted the keyboard like a drawbridge. (Anecdotally, the subjects reported the keyboard halves of the vertically-inclined keyboard tested in this study felt flimsy and jiggled slightly when they typed.)

To the authors' knowledge, there have been no studies conducted that measured the pronation angle of subjects typing on vertically-inclined keyboards. Therefore, no comparisons can be made between the results of this study and the literature.

The ratio between tilt angle and reduction in pronation angle was approximately 1.5:1.0, as calculated by the *mean* 30 deg. of tilt angle and the *mean* 20 deg. of reduction in forearm pronation for all 30 subjects. Similar to the ratio between slant angle and reduction in ulnar deviation, the ratio of 1.5:1.0 between tilt angle and pronation reduction may not hold true for individual subjects. Future analysis is necessary to discern whether the ratios for individuals varied from the aggregate ratio.

Similar to the split keyboards, the ulnar deviation of the subjects who typed on the vertically-inclined keyboard was significantly and dramatically reduced to a near neutral position in the radial/ulnar plane (Table 48A, p. 104). Mean ulnar deviation from typing on the vertically-inclined keyboard decreased approximately 12 deg., from 11 to 16 deg. for the conventional to 4 deg. ulnar to 2 deg. radial for the vertically-inclined, as shown in Figure 38 (p. 106). This decrease in ulnar deviation was expected somewhat because the tilt and slant angles are coupled in the commercially-available vertically-inclined keyboard tested in this study. However, the ratio between slant angle and reduction in ulnar deviation was approximately 1.0:1.5, as calculated by the mean slant angle of 7 deg. at 30 deg. of tilt for the vertically-inclined keyboard used in this study and the approximately 12 deg. of reduction in ulnar deviation. The ratio of 1.0:1.5 is the inverse of the ratio between slant angle and ulnar deviation reduction for split keyboards. Future analysis and research is needed to determine how the ratio between slant angle and ulnar deviation reduction is affected by tilt angle.

E.5. BIOMECHANICAL ISSUES OF KEYBOARDS

E.5.1. Net Reaction Force and Friction

Radial/Ulnar Plane. The results from this study corroborate Hedge and Shaw's (1996) and Honan's et al. (1996) findings that split and vertically-inclined keyboards, when used properly, do reduce ulnar deviation to almost a neutral position. In our study of commercially-available split and the vertically-inclined keyboards, the wrist was within 2.5 deg. of neutral in the radial/ulnar plane. The reduction of ulnar deviation to almost a neutral position minimizes, if not eliminates for all practical purposes, one of the occupational risk factors of WMSDs associated with typing (namely, ulnar deviation). According to biomechanical theory, typing in a near neutral posture in the radial/ulnar plane would benefit the operator because both the friction between tendons and adjacent structures in the wrist and the net reaction force on the tendons passing through the wrist would be less than if the wrist were deviated substantially in the radial/ulnar plane.

First, the flexor digitorum superficialis and profundus (FDS and FDP) tendons passing through the carpal tunnel within the wrist would have less friction against its adjacent structures, namely carpal bones and flexor retinaculum. Less friction could reduce the inflammation of the tendons and their sheaths, thereby reducing the risk of tenosynovitis. Less inflammation would also keep the tendons from pressing against the median nerve in the carpal tunnel, thereby reducing the risk of carpal tunnel syndrome.

Second, compared to substantial ulnar deviation, there would be less net reaction force exerted against the FDS and FDP tendons from the carpal bones and flexor retinaculum with a near neutral wrist posture, which would therefore reduce, theoretically, the risk of tenosynovitis and carpal tunnel syndrome. Static and dynamic modelling of the wrist by Armstrong and Chaffin (1979) and Schoenmarklin (1990) have shown theoretically that as the wrist is deviated from a neutral posture, the net reaction force exerted by the carpal bones and flexor retinaculum against the tendons passing through the carpal tunnel increase. (The carpal bone and flexor retinaculum keep the tendons from bowstringing from the wrist joint.) Net reaction forces against the tendons and their sheaths can deteriorate the health of tendons in the same manner as frictional forces described above.

Flexion/Extension Plane. Compared to the conventional keyboard, the small reduction of 3 to 5 deg. of wrist extension from typing on the two split keyboards would theoretically (as described above) reduce the friction between the tendons and the net reaction force from their adjacent supporting structures. However, whether a reduction of 3 to 5 deg. extension would have a practical beneficial effect is unknown.

Pronation/Supination Plane. Based on limited laboratory findings, less pronation of the forearm would be beneficial to keyboard users with respect to physical pain and comfort. Forearm pronation has been shown by Zipp et al. (1983) to increase tension of the muscles that pronate the forearm, namely the pronator teres and pronator quadratus (along with the flexor carpi radialis (FCR)). Compared to a conventional keyboard, tension measured by EMG in the pronator muscles can decrease 80% when a keyboard user types on a vertically-inclined keyboard tilted at 30 deg. (Zipp et al., 1983). Muscle forces required to pronate the forearm to almost its anatomical limit for conventional keyboards are long-duration static contractions that could possible cause muscle fatigue or pain. However, whether full forearm pronation can cause an upper extremity WMSD affecting the tendons or nerves is debatable, considering the muscles that Zipp et al. (1983) found strained at full pronation do not originate at the lateral epicondyle (site of lateral epicondylitis) or have tendons terminating at the wrist or passing through the wrist. When the forearm is pronated from a neutral position, the tendons passing through the wrist would twist rather than bend or wrap around supporting structures (bending occurs when the wrist is deviated in either the ulnar or extension directions). The fact that the tendons that are implicated in a few upper extremity WMSDs (FDS and FDP -- carpal tunnel syndrome, tenosynovitis; FCR -- tendinitis) do twist when the forearm is pronated may contribute to the etiology of some WMSDs. However, very little is known about the extent of twisting of tendons as a function of forearm pronation and how this might contribute to a WMSD.

Although there is a scarcity of data on the biomechanical etiology of WMSDs due to forearm pronation, a previous study has shown that when typists are given a choice, they prefer less forearm pronation than that required for typing on a conventional keyboard. In a study of 38 female typists, Kroemer (1972) found that the most preferred location of the arm when the forearm is pronated at 90 deg. is when the shoulder is abducted 90 deg. When Kroemer's (1972) subjects placed their arms at their sides (shoulder abduction angle of 0 deg.), the subjects preferred a forearm pronation angle no greater than 30 deg., which is about 1/2 the forearm pronation angle required to type on a conventional keyboard (as measured in the present study). Based in part on these findings, Kroemer (1972) developed a vertically-inclined keyboard that allowed for adjustments in tilt angle for laboratory testing. After having over 30 experienced typists try this new keyboard, he found that the most preferred tilt angle was 60 deg.

E.5.2. Carpal Tunnel Pressure

Radial/Ulnar and Flexion/Extension Planes. When the wrist is in a near neutral radial/ulnar posture, the pressure on the median nerve is less than when the wrist is deviated 10 to 20 deg. (Sommerich, 1994; Weiss et al., 1995). Less pressure on the median nerve would reduce, theoretically, the risk of carpal tunnel syndrome because carpal tunnel syndrome is defined, clinically, as compression of the median nerve as it passes through the carpal tunnel.

Weiss et al. (1995) conducted a study on how wrist position in the radial/ulnar and flexion/extension planes affected pressure in the carpal tunnel. These researchers found the lowest carpal tunnel pressure of about 8 mm of Hg when the wrist was deviated approximately 2 deg. ulnarly and 2 deg. extension, and the pressure increased to approximately 20 mm Hg and 50 mm Hg when the wrist was deviated 10 and 20 deg. ulnarly, respectively. The pressure in carpal tunnel was about 15 mm Hg when the wrist was radially deviated 10 deg. Pressures even as low as 20 mm Hg could reduce axonal transport in the neuron substantially, as demonstrated and reported by Dahlin et al. (1990). Axonal transport decreased 75% when pressure applied to the vagus nerve of a rabbit increased from 10 to 20 mm Hg. When the pressure on the nerve increased to 30 mm Hg, the nerve showed marked detrimental morphological changes, such as displacement of the neuron's nucleus and changes in the neuron's metabolism.

The findings from this study and other reported in the literature that conventional keyboards consistently require about 10 deg. or more of ulnar deviation could explain why typing on conventional keyboards has been problematic with respect to WMSDs. As Weiss et al. (1995) showed, 10 deg. of ulnar deviation resulted in an increase in carpal tunnel pressure that may lead to both temporary and permanent detrimental changes in the nerve. With regards to wrist extension required for typing on a conventional keyboard, whether a decrease in carpal tunnel pressure due to a reduction of about 5 deg. of wrist extension from typing on split keyboards would affect health outcomes is questionable.

Pronation/Supination Plane. Although the authors of this study could not find any published literàture investigating the relationship between forearm pronation angle and carpal tunnel pressure, one study conducted by Sommerich (1994) found that carpal tunnel pressure was very subject-specific in nature. She found that only one of her four subjects exhibited carpal tunnel pressure greater than 20 mm Hg while typing on a conventional keyboard. 20 mm Hg has been shown to be a pressure threshold above which could possibly cause temporary dysfunction in the nerve.

E.5.3. Acceleration of the Wrist

Compared to the conventional keyboard, the decreased magnitude of frictional force, net reaction force, and carpal tunnel pressure when the wrist is in a near neutral wrist posture might mitigate the risk factor of acceleration of the wrist, which has been shown by Marras et al. (1993) and Schoenmarklin et al. (1994) to be one of the best predictors of hand or wrist WMSDs from highly-repetitive tasks requiring hand and wrist motion. In essence, acceleration of the wrist is a risk factor that relates to the force the muscle exerts and the subsequent force transmitted through the tendons. According to Newton's second law ($F=M*A$ for linear movement and *Torque = Moment of Inertia * Angular Accel.* for rotational movement), the greater the acceleration of a joint, the more muscle force required. Consequently, acceleration of the wrist as a risk factor of hand or wrist WMSDs is really a risk factor of the muscle force required for moving the wrist.

Compared to the conventional keyboard, the benefits of typing on alternative keyboards in a near neutral posture in the radial/ulnar plane would decrease the force required of the muscles to accelerate the FDS and FDP tendons passing through the carpal canal. From typing on a conventional keyboard, which causes the wrist to ulnarly deviate 10 deg. or more, the forearm muscles have to exert force to accelerate the tendons that are bent around carpal bones on the radial and ulnar sides of the wrist. From typing on either a split or vertically-inclined keyboard, which places the wrist in a near neutral radial/ulnar position, accelerating the FDS and FDP tendons as they pass through the carpal tunnel *straight* would require, theoretically, less muscle and tendon force than if an operator where typing on a conventional keyboard. This reduced muscle and tendon force would result, theoretically, in less muscle fatigue and frictional wear against the tendons, and possibly WMSDs of the hand or wrist.

Note: The acceleration risk factor, which is affected directly by the speed of typing, was not confounded with typing performance in this study because typing performance (speed and accuracy) was similar between the conventional and alternative keyboards. Differences in mean typing speed between the conventional and alternative keyboards were about 3 WPM (refer to Tables 13 - 15, pp 66-67), and mean accuracy for all keyboards was 99% (refer to Table 16-18, pp 68-69).

F. PLANNED PUBLICATIONS

The authors of this report plan to publish the results from this study in the following journals:

Wrist, Forearm, and Finger Posture From Typing on a Conventional Computer Keyboard. Will be submitted to Human Factors and Ergonomics journal in Spring, 1997.

The Effect of Alternative Computer Keyboard Designs on Wrist and Forearm Posture. Will be submitted to Human Factors and Ergonomics journal in Spring, 1997.

Variance of Wrist and Forearm Posture From Typing on Computer Keyboards. Will be submitted to Scandinavian Journal of Work, Environment, and Health in Summer, 1997.

Wrist and Forearm Posture of the Right and Left Upper Extremities from Typing. Will be submitted to Scandinavian Journal of Work, Environment, and Health in Summer, 1997.

Ratios of Reduction in Ulnar Deviation and Forearm Pronation Due to Adjustments in Slant and Tilt Angles of Computer Keyboards. Will be submitted to Scandinavian Journal of Work, Environment, and Health in Summer, 1997.

In addition, the authors plan to publish an article in a magazine written specifically for the lay audience.

Should You Buy an Alternative Computer Keyboard? Will be submitted to Ergonomics in Design magazine in Autumn, 1997.

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APPENDIX 1: SUBJECT CONSENT FORM

Marquette University Agreement of Consent for Research Subjects

Title of Investigation: "An Ergonomic Study of Alternative Keyboard Designs"

Investigators: Dr. Richard Marklin
Dr. Guy Simoneau, P.T.

Date: November 1, 1994 - October 31, 1996

Purpose of the study: The purpose of this study is to determine if keyboard designs have a beneficial effect on the motion patterns of the upper extremities (arms).

Methods: Twenty subjects who have been diagnosed by their physician as having carpal tunnel syndrome (pain in the wrist and hand) and 20 subjects without carpal tunnel syndrome will voluntarily participate in this study. Each subject will be asked to make two visits to the Industrial Ergonomics Laboratory at Marquette University. The initial visit to the laboratory will last approximately two hours. The subject will fill out a brief health questionnaire, standard measurements of height and weight will be taken, the chair and desk used for typing will be adjusted to the proper settings for the subject, and finally the subject will take part in a familiarization session with the keyboards and typing tasks.

The second testing session will take place within three days of the initial visit and will last approximately three hours. During this session, the subject will be asked to type for a period of 20 minutes on 5 occasions. Each subject will use four different keyboards and one keyboard will be used twice. The subject will be asked to type in his/her customary manner at a typing speed of at least 50 words per minute. Prior to the typing tasks, small instruments and reflective markers to measure movement of the arms during typing will be attached to both arms using medical adhesive tape. A video camera will be used to film the subject as he/she is typing. The camera is designed to pick up the reflected light from the round markers attached to the subject's skin. In addition, data will be collected from the movement sensors attached to the arms of the subject.

Potential risks: There are no significant risks to the subjects engaged in the study. There is only a rare chance of skin irritation from the tape that attaches the small instruments and round reflective markers to the skin. This risk is minimized by asking each subject if he/she is allergic to tape and by using surgical quality, hypoallergenic 3M tape. The small instruments attached to the fingers and wrists present no risk of musculoskeletal injury since they do not load the joints in any manner. Also, since all electrical components are isolated in the instruments and are not in contact with the body, there is no risk of electrical shock. Finally, all subjects with carpal tunnel syndrome will need to be referred by their physician to participate in the study, with their physician judging that their participation in the study will not place them at risk for further injury.

The subjects participating in the study are free to ask any questions they may have at any time before or during the study.

When I sign this statement, I am giving my informed consent to the following basic considerations:

- The investigation and my part in the investigation have been defined and explained to me by a member of the research team, and I understand this explanation.
- The procedures of this investigation and a description of any risks and discomforts have been provided to me and have been discussed in detail with me.
- I have been given an opportunity to ask whatever questions I may have had, and all such questions and inquiries have been answered to my satisfaction.
- I understand that I am free to deny any answers to specific items or questions in interviews or medical history questionnaires.
- I understand that any data or answers to questions will remain confidential with regard to my identity.
- No written or verbal agreement has been offered which includes any exculpatory language that clears Marquette University alleged fault or guilt. I have not waived or released the University or its representatives from liability for negligence, if any, which may arise in the conduct of the research project.

- In the event of physical injury resulting from biomedical and behavioral research procedures, medical treatment in an amount not to exceed $500 is available for such physical injury, but no monetary compensation is available for wages lost because of physical injury. Further information can be obtained by contacting the Director of Research Support, Marquette University (414-224-7200).

If I have questions at any time during this study, I should contact Dr. Richard Marklin (Marquette University, 414-288-3622) or Dr. Guy Simoneau (Marquette University, 414-288-3380).

I FURTHER UNDERSTAND THAT I AM FREE TO WITHDRAW MY CONSENT AND TERMINATE MY PARTICIPATION AT ANY TIME.

I, the person signing below, understand the above explanations. On this basis, I consent to participate voluntarily in the research study entitled "An Ergonomic Study of Alternative Keyboard Designs."

______________________________ Date: ____________________
(signature of subject giving consent)

______________________________ Location: ____________________
(signature of investigator)

Witnessed by: ______________________________

APPENDIX 2: DATA COLLECTION FORMS

EVALUATION FORM

DATE ______________ DATE OF BIRTH: ___/___/___

FEMALE MALE

DOMINANT HAND: Left / Right

OCCUPATION: ______________________________

Past Medical history:

Fracture wrist/hand [ ]

Arthritis [ ]

Numbness in Fingers [ ]

Pain In wrist/hand [ ]

Weakness [ ]

Other: ______________________________

____

SENSATION:

Semmes Weinstein Monofilaments

RIGHT	b	g	p	LEFT	b	g	p
Index	[]	[]	[]	Index	[]	[]	[]
Thumb	[]	[]	[]	Thumb	[]	[]	[]
Fifth	[]	[]	[]	Fifth	[]	[]	[]

RANGE OF MOTION

ROM	Right	Left
Extension		
Flexion		
Radial Deviation		
Ulnar Deviation		
CMC ABD	+ / -	+ / -
Fingertips to palm crease	+ / -	+ / -
Thumb to index (pulp to pulp)	+ / -	+ / -
Thumb to little (pulp to pulp)	+ / -	+ / -

STRENGTH

	Right	Left
Grip (2nd rung)	kg.	kg.
Pinch:		
Palmar (pulp to pulp)	kg.	kg.
Lateral (key)	kg.	kg.
3 Jaw Chuck	kg.	kg.

SPECIAL TESTS

	Right	Left
Phalen's sign:	+ / -	+ / -
Tinel's sign:	+ / -	- / -

ANTHROPOMETRY

Subject # _____

1. Shoulder to shoulder width		_______	cm.
2. Elbow to elbow width		_______	cm.
3. Elbow to tip of finger	left	_______	cm.
	right	_______	cm.
4. Elbow to wrist	left	_______	cm.
	right	_______	cm.
5. Middle finger length left		_______	cm.
	right	_______	cm.
6. Hand breadth metacarpal	left	_______	cm.
	right	_______	cm.
7. Height		_______	in.
		_______	cm.
8. Weight		_______	lbs.
		_______	kg.

Keyboard Survey

Name: ______________________ Employer: ______________________

Occupation: ______________________ Years in Typing Profession: ________

1. Keyboard used:

[ ] Lexmark [ ] Kinesis [ ] Floating Arms
[ ] Ergologic/Flexpro [ ] Microsoft

2. Hours spent practicing on this keyboard: _____ hours

3. Using the new keyboard, how long did it take to reach the same level of typing speed and accuracy you have with a standard flat keyboard? ____ hours

4. If you feel you did *not* reach the same level of typing speed and accuracy, how do you rate your speed and accuracy on the new keyboard as compared to the standard flat keyboard? Choose one percentage from each column.

Speed	Accuracy
[ ] 70%	[ ] 70%
[ ] 75%	[ ] 75%
[ ] 80%	[ ] 80%
[ ] 85%	[ ] 85%
[ ] 90%	[ ] 90%
[ ] 95%	[ ] 95%

5. Did you have any discomfort or pain from using the keyboard?

[ ] Yes
[ ] No

If you answered 'yes', where did you have this pain or discomfort? Check off each box that applies.

[ ] Shoulder [ ] Elbow [ ] Forearm
[ ] Wrist [ ] Hand [ ] Finger

6. Compared to the standard flat keyboard, did you find that the new keyboard was: (choose one)

[ ] much harder to use than the standard.
[ ] harder to use than the standard.
[ ] about the same as the standard.
[ ] easier to use than the standard
[ ] much easier to use than the standard

7. Compared to the standard flat keyboard, did you find that the new keyboard was: (choose one)

[ ] much less comfortable than the standard.
[ ] less comfortable than the standard.
[ ] about the same comfort as the standard.
[ ] more comfortable than the standard
[ ] much more comfortable than the standard

8. Business Address: ______________________________________

9. Comments: ______________________________________

____

____

APPENDIX 3: SAMPLE TEXT

Sample of *alphabetic* typing task:

The giant panda has a white round face, black eye patches, and black ears. It has a black collar, a white body, a short white tail,and black feet. Its thick fur, measuring two or more inches in places, keeps it warm in winter. The panda's black and white coat gives it color camouflage. In its shady forest homeland the panda is almost invisible to the hunter at a distance of thirty yards. Pandas are about five or six feet in length. They can weigh 165 to 300 pounds.

Sample of *alphanumeric* typing task:

15 assemblies are put on accelerated test without replacement. If the first 4 failures occurred at 16.5, 19.2, 20.8 and 37.3 hours find a 90% confidence interval. Test the null hypothesis that the failure rate is 0.004 failure per hour using the 0.01 level of significance. 7 welded pieces were subjected to specified frequencies and their ties to failure were 211, 350, 384, 510, 539, 620, and 715 thousand cycles.

APPENDIX 4: ANTHROPOMETRIC MEASUREMENTS

Appendix A4-1. Descriptive statistics for anthropometric measures on all subjects (n=90).*

Variables	Mean ± S.D.	Minimum	Maximum
Height (m.)	1.64 ± 0.07	1.47	1.93
Height (in.)	64.43 ± 2.75	57.75	76.00
Weight (kg)	69.41 ± 16.68	38.56	127.01
Weight (lb)	153.03 ± 36.78	85.00	280.00
Shoulder to Shoulder Width	38.41 ± 2.20	33.50	45.20
Elbow to Elbow Width	42.40 ± 6.54	30.60	57.20
Right Side Distances			
Elbow to Finger Tip	42.76 ± 2.10	36.30	49.80
Elbow to Wrist	25.79 ± 1.41	22.60	30.50
Digit #3 Length	7.31 ± 0.47	6.10	8.60
Hand Breadth	7.52 ± 0.44	6.60	9.00
Left Side Distances			
Elbow to Finger Tip	42.54 ± 2.18	36.50	49.10
Elbow to Wrist	25.76 ± 1.41	22.40	30.40
Digit #3 Length	7.33 ± 0.48	6.00	8.30
Hand Breadth	7.47 ± 0.45	6.30	9.10

*All measurements are given in cm., unless noted

Appendix A4-2. Descriptive statistics for anthropometric measures by alternative keyboard used (n=30). Statistics are the mean and standard deviation.

Variables	Vertically-Inclined	Split-Adjustable	Split-Fixed
Height (m.)	1.6 ± 0.1	1.6 ± 0.1	1.6 ± 0.1
Height (in.)	64.4 ± 2.0	64.2 ± 3.5	64.6 ± 2.5
Weight (kg)	67.1 ± 17.2	72.5 ± 18.0	68.6 ± 14.1
Weight (lb)	147.9 ± 38.0	159.9 ± 39.7	151.2 ± 31.0
Shoulder to Shoulder Width	38.4 ± 2.0	38.5 ± 2.7	38.4 ± 1.8
Elbow to Elbow Width	41.6 ± 6.5	43.3 ± 7.2	42.3 ± 5.7
Right Side Distances			
Elbow to Finger Tip	42.8 ± 1.6	42.5 ± 2.6	43.0 ± 1.9
Elbow to Wrist	25.7 ± 1.0	25.6 ± 1.7	26.0 ± 1.4
Digit #3 Length	7.3 ± 0.5	7.3 ± 0.5	7.3 ± 0.4
Hand Breadth	7.5 ± 0.3	7.6 ± 0.5	7.5 ± 0.5
Left Side Distances			
Elbow to Finger Tip	42.6 ± 1.8	42.3 ± 2.7	42.7 ± 2.0
Elbow to Wrist	25.7 ± 1.1	25.7 ± 1.7	25.9 ± 1.4
Digit #3 Length	7.3 ± 0.5	7.3 ± 0.5	7.3 ± 0.4
Hand Breadth	7.4 ± 0.4	7.5 ± 0.5	7.5 ± 0.5

*All measurements are given in cm., unless noted

Appendix A4-3. Range of motion and strength of all subjects (n=90).

Variables	Mean ± S.D.	Minimum	Maximum
Right Side			
Wrist Extension (deg) *	62.58 ± 8.74	35.00	86.00
Wrist Flexion (deg)	66.71 ± 7.81	42.00	90.00
Wrist Radial Deviation (deg)	23.01 ± 5.93	5.00	38.00
Wrist Ulnar Deviation (deg)	35.43 ± 5.64	16.00	48.00
Grip Strength (kg)	27.78 ± 6.17	14.00	42.00
Palmar Pinch (kg)	3.15 ± 0.84	1.25	5.25
Lateral Pinch (kg)	6.58 ± 1.55	2.00	10.00
3-Jaw Chuck Pinch (kg)	5.18 ± 1.39	1.50	8.75
Left Side			
Wrist Extension (deg) *	64.28 ± 7.97	40.00	86.00
Wrist Flexion (deg)	65.21 ± 7.61	42.00	86.00
Wrist Radial Deviation (deg)	24.50 ± 6.58	14.00	50.00
Wrist Ulnar Deviation (deg) **	35.79 ± 6.16	20.00	52.00
Grip Strength (kg)	25.88 ± 5.99	10.00	43.00
Palmar Pinch (kg)	2.74 ± 0.84	1.25	4.75
Lateral Pinch (kg)	6.29 ± 1.38	2.00	10.25
3-Jaw Chuck Pinch (kg)	4.77 ± 1.34	2.25	8.25

* Variable found to have a significantly greater ($p < 0.05$) mean value in the split fixed keyboard compared to both the split adjustable and inclined keyboards using the Duncan's Multiple Range test.

** Variable found to have a significantly greater ($p < 0.05$) mean value in the split fixed keyboard compared to the split adjustable keyboard using the Duncan's Multiple Range test.

Appendix A4-4. Range of motion and strength for subjects by keyboard (n=30). Statistics are the mean and standard deviation.

Variables	Vertically-Inclined	Split-Adjustable	Split-Fixed
Right Side			
Wrist Extension (deg)	60.7 ± 10.3	61.0 ± 6.9	66.0 ± 7.5
Wrist Flexion (deg)	67.6 ± 8.4	66.0 ± 7.1	66.5 ± 7.8
Wrist Radial Deviation (deg)	21.6 ± 5.0	23.2 ± 5.7	24.2 ± 6.7
Wrist Ulnar Deviation (deg)	35.1 ± 5.0	35.1 ± 5.5	36.1 ± 6.2
Grip Strength (kg)	27.2 ± 6.1	28.4 ± 6.2	27.8 ± 6.1
Palmar Pinch (kg)	3.0 ± 0.8	3.4 ± 0.9	3.1 ± 0.8
Lateral Pinch (kg)	6.6 ± 1.4	6.9 ± 1.3	6.2 ± 1.8
3-Jaw Chuck Pinch (kg)	5.0 ± 1.4	5.5 ± 1.4	5.0 ± 1.3
Left Side			
Wrist Extension (deg)	62.6 ± 8.1	61.8 ± 5.2	68.4 ± 8.4
Wrist Flexion (deg)	65.0 ± 7.9	64.2 ± 7.1	66.4 ± 7.6
Wrist Radial Deviation (deg)	23.2 ± 7.8	24.9 ± 5.5	25.4 ± 6.0
Wrist Ulnar Deviation (deg)	35.6 ± 6.5	33.8 ± 4.5	37.9 ± 6.5
Grip Strength (kg)	25.2 ± 5.5	27.5 ± 6.0	25.0 ± 6.1
Palmar Pinch (kg)	2.6 ± 0.7	3.0 ± 0.9	2.6 ± 0.8
Lateral Pinch (kg)	6.4 ± 1.2	6.3 ± 1.4	6.1 ± 1.5
3-Jaw Chuck Pinch (kg)	4.5 ± 1.2	5.2 ± 1.3	4.6 ± 1.3