EVALUATION OF THREE COMPUTER KEYBOARD DESIGNS

by

ALEKSANDRA ZECEVIC

Faculty of Kinesiology

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ABSTRACT

The purpose of this study was to evaluate the influence of computer keyboard design on hand position, typing productivity and keyboard preference. These variables were assessed on two alternative keyboard designs which were distinguished from the standard flat keyboard by their split, and from one another by the amount of lateral inclination of the right and left halves of the keyboard. The FIXED keyboard featured a split angle of 12° and a moderate lateral inclination angle of 10°. The user adjustable OPEN keyboard was used with a 15° split setting which resulted in a marked 42° of demiboard lateral inclination.

Sixteen typists, who completed 10 hours of training on both alternative keyboards, were videotaped by two camcorders while typing set texts on all three keyboards. Hand position was assessed using three dimensional video analysis. Typing productivity and keyboard preference were also investigated.

Forearm and wrist angles were significantly different ($p < 0.05$) among the three designs tested. Both alternative keyboards placed the forearm and wrist closer to neutral positions than did the standard keyboard. The OPEN keyboard, reduced pronation, but simultaneously increased radial deviation. The FIXED keyboard kept the forearm in moderate pronation and the wrist closer to neutral. More time was spent in neutral and moderate ranges of wrist motion when subjects typed on the FIXED compared with the other two designs. Typing productivity was reduced by 10% on the FIXED and 20% on the OPEN designs compared with the standard keyboard. No significant difference in preference was found between the standard and FIXED keyboards both of which were preferred over the OPEN keyboard.

The design that represented moderate changes to the standard keyboard (i.e., the FIXED design) preserved productivity, and was well accepted by users. The FIXED design may have a greater potential for reducing cumulative trauma disorders of the wrist because it facilitates healthy hand postures while typing.

Keywords: Computer keyboard, keyboard design, 3D video analysis, wrist movements, hand posture, CTD

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1 INTRODUCTION

"Today's keyboard is ideal for people with arms coming out of their chests, and fingers all the same length. But efforts to design a layout that suits ordinary people have failed - so far"

(Ian Litterick, 1981, p. 66)

1.1 The Problem

Both at work and at home, computers are being used extensively by increasing numbers of people. Without leaving the computer station, users can perform a variety of tasks including word processing, data analysis, electronic mailing, graphic design, accounting and reviewing reports. Horowitz (1992) estimated that nearly half of the American work force (45 million) used computers. In addition, Frank (1995) reported that in 1994 25% of Canadian households (2.6 million) had a computer, which was a substantial increase from 10% in 1986.

The explosion in computer use has led to increasing reports of work-related health concerns often referred to as cumulative trauma disorders (CTD)[1]. Since direct contact between the computer video display terminal (VDT) and the operator is established most often through a keyboard, attempts have been made to identify and reduce specific musculo-skeletal problems associated with its use (e.g., carpal tunnel syndrome, tendonitis, tendosynovitis, De Quervian's disease). An epidemic of CTD among computer operators was already experienced in Australia in the mid 1980s (Blair and Bear-Lehman, 1987; Green and Briggs, 1989; Johansson and Shahnavaz, 1995). The peak for keyboard related injuries occurred in 1985-86 (Low, 1990) and investigators

[1] Cumulative Trauma Disorders - CTD. Disorders caused, precipitated, or aggravated by repeated or sustained exertions of the body that develop gradually over periods of weeks, months or years. CTDs are also referred to as repetitive trauma disorders, repetitive strain injuries, overuse syndrome or work-related disorders (Armstrong, 1992).

found that females were affected more than males, and that the percentage of the day that had been spent doing keyboard work and the number of years of keyboard use were significantly associated with the development of CTD symptoms. It was also reported that the likelihood of injury rose rapidly after more than five hours of VDT work per day (Oxenburgh, Rowe and Douglas, 1985). Accurate information regarding the extent of occupational injuries caused by the use of VDTs is not available. The Canadian Centre for Occupational Health and Safety (1994) suggested that the lack of national occupational health and safety standards and the variety of coding systems for recording work-related injuries and illnesses, made it difficult to evaluate statistics on workplace CTD. Existing data suggested that an increase in office-based work had contributed to the raised incidence of CTD in the past ten years. Varied sources (Ashbury, 1995; Lewis, 1996; Valenta, 1994) supported the concept of an increase in costs, pain and suffering from CTD that will increasingly burden the Canadian health care system.

The use of a computer keyboard usually results in prolonged periods within constrained body positions (e.g., sitting), causing static muscle loads primarily on the neck, shoulders and back. These postures are often associated with reduced blood circulation that prevents the supply of nutrients and removal of by-products to and from working muscles, thereby causing rapid fatigue and pain (Bertolini and Drewczynski, 1990; Grandjean, Hünting and Pidermann, 1983; Hünting, Läubli and Grandjean, 1981). Ergonomic guidelines regarding computer station setup, that are established for the purpose of minimizing stress to the user's body, are limited and are often misunderstood by the user. The combination of the aforementioned factors can lead to discomfort, pain and chronic health problems.

Despite the ongoing controversy in recognizing direct causality between musculoskeletal problems and work with VDTs (Vender, Kasdan and Truppa, 1995), there have been an increasing number of studies that have indicated a connection between VDT use and the development of musculoskeletal problems. Several work-related risk factors that contribute to the development of CTD of the upper limb were identified and described (Armstrong, 1992). Some of them, like hand position, repetitiveness and forcefulness, are directly connected to the use of computer keyboard. It has been recognized that the flat layout of the standard QWERTY keyboard requires the user to make postural adaptations to conform to the keyboard (Barry, 1995; Grandjean et al., 1983). During typing, movements of the wrist (e.g., extension/flexion and radial/ulnar deviation) cause tendons to be displaced past, and compressed against, adjacent anatomic surfaces. Maintaining this position for long periods of time without sufficient physiological recovery of the arm muscles and soft tissues may result in injuries. Also, arm muscles are forced to keep forearms and hands stable to allow dynamic, high frequency and accurate repetitive movement of the fingers. The extremes in hand posture are physically stressful if maintained long enough, and therefore they may exacerbate the risk of developing CTD. Additional ergonomic variables, such as lower arm support, keyboard position (Bergqvist, Wolgast, Nelsson and Voss, 1995), and the type of keyboard (Green, Briggs and Wrigley, 1991) were also identified with increased risk of developing the injury. In the past several years new scientific evidence established relationships between wrist position while typing and change of the intracarpal tunnel pressure that may explain occurrence of nerve entrapments (Rempel, Bloom, Tal, Hargens and Gordon, 1992; Sommerich and Marras, 1994).

Numerous unsuccessful attempts have been made to change key arrangements as well as the physical appearance of the keyboard (Barry, 1995; David, 1986; Litterick, 1981). These changes might have improved posture of the hand and forearm and reduced unnecessary movements to reach the keys. So far, however, all changes appear to have been rejected by the users. Scientific and empirical evidence were not strong enough to justify the costs of retraining and obtaining new equipment. Recently, increased numbers of people experiencing CTDs due to VDT use might indicate a new era in redesign of a computer keyboard, as well as a changed attitude of the users towards accepting new keyboards. Although computer users are a diverse group with respect to age, body size, gender, training and knowledge, most use the same computer input device, namely the keyboard. Changes in keyboard design acceptable to users which could improve hand position and at the same time retain or improve productivity would have wide spread implications in reducing cumulative trauma disorders associated with typing.

1. 2 Purpose of the study

The purpose of this study was to evaluate the influence of the three keyboard designs on hand position, typing productivity and keyboard preference. The three keyboards evaluated were the standard flat design, the Microsoft Natural keyboard (FIXED) and FlexPro keyboard (OPEN). The FIXED keyboard was characterized by its split design with fixed split angle of 12° and moderate lateral inclination angle of 10°. The user adjustable OPEN design was set on the 15° split which resulted in approximately 42° of lateral inclination angle. The FIXED keyboard and a selected configuration on the OPEN keyboard represented two increasing levels in redesigned features compared to the traditional keyboard, with respect to the amount of lateral inclination of the keyboard halves. In addition, the Microsoft Natural was chosen for its wide distribution and sales as an ergonomic keyboard. To the author's knowledge, there is no market usage information available in the literature.

Hand posture was assessed based on four distinctive angles, namely forearm pronation, the wrist angle and its two planar components extension/flexion and radial/ulnar deviation, and time spent in designated ranges of wrist motion. Productivity was evaluated by calculating number of characters typed, number of errors made and total time required for the typing task. Preference, as a measure of keyboard acceptance was assessed on the basis of the scores awarded to each design on a 10 point visual digital scale. The assumption that neutral wrist angle (zero position for pronation, extension/flexion and radial/ulnar deviation) produced the least postural risk for developing cumulative trauma disorders was applied in the present study.

The scope of this study was limited to three keyboard designs, 16 healthy experienced typists and consideration of selected kinematic variables of the hand position while typing. The main limitations of the study were: 1. the focus on only wrist positions of the dominant hand; 2. limited typing time selected for the postural analysis; 3. a limit of ten hours of training time on the alternative keyboard designs prior to testing; 4. no control of sitting position during testing with respect to chair height or elbow angle.

1. 3 Operational Definitions

Direct Linear Transformation (DLT):

A technique adopted from analytical photogrammetry which allows the calculation of spatial coordinates from two or more sets of planar coordinates (Abdel-Aziz & Karara, 1971).

Extension/Flexion:

The angle between the forearm vector (lateral epicondyle of the humerus to the head of the ulna) and the projection of the hand vector (head of the ulna to the distal end of 5th metacarpal) onto the sagittal (xz) plane. Extension was considered positive and flexion - negative.

Forearm Pronation:

The angle between the horizontal plane and the vector defined by the head of ulna and the midway point between the styloid processes on the radius and ulna. The zero position for measuring pronation was with the palm upward facing medially. Pronation was considered positive.

Keyboard Slope or *Keyboard Tilt:*

Angling of the keyboard toward the user (forward) or away from user (backward).

Lateral Inclination Angle:

Upward rotation of the medial edge of the left and right halves of the alphanumeric part of the keyboard around an anterior/posterior axis.

Neutral or Zero Starting Wrist Position For Measuring Extension/Flexion and Radial/Ulnar Deviation:

The extended wrist in line with the forearm (American Academy of Orthopedic Surgeons, 1965).

Postural risk for developing cumulative trauma disorders of the wrist:

Risk was considered to increase with an increase in wrist angles from neutral and with extended time spent in the extreme angle ranges.

Radial/Ulnar Deviation:

The angle between the midforearm vector (midforearm to midway between the styloid processes on the ulna and radius) and the projection of the mid-hand vector (midway between the styloid processes on radius and ulna to the distal end of 3rd metacarpal) in the transversal (xy) plane. Radial deviation was considered positive and ulnar deviation - negative.

Split Keyboard Angle:

Outward rotation of the left and right halves of the alphanumeric part of the keyboard around a vertical axis.

Wrist angle:

The angle between the forearm and hand measured using markers placed on the lateral epicondyle of humerus, head of ulna and the distal end of the 5th metacarpal.

Wrist Leveler:

A hinged rail that raises the front of the Microsoft Natural keyboard allowing the user to maintain a straighter wrist position.

Wrist Extension/Flexion and Radial/Ulnar Deviation Ranges of Motion:

Extreme flexion	($< -20^\circ$)	Extreme ulnar dev.	($< -25^\circ$)
Moderate flexion	(-20° to -10°)	Moderate ulnar dev.	(-25° to -15°)
Neutral	(-10° to $+10^\circ$)	Neutral	(-15° to $+5^\circ$)
Moderate extension	($+10^\circ$ to $+20^\circ$)	Moderate radial dev.	($+5^\circ$ to $+15^\circ$)
Extreme extension	($> +20^\circ$)	Extreme radial dev.	($> +15^\circ$)

(Based on data provided in: American Academy of Orthopedic Surgeons, 1965; Rempel et al. 1992; Swanson, Hagert and de Groot Swanson, 1987).

2 LITERATURE REVIEW

The following review of the literature outlines: 1) the history of keyboard development, 2) the suggested risk factors, related to keyboard design, for the development of CTD and (3) the methodology and results of the available research regarding the efficiency of alternative keyboard designs.

2. 1 Historical Overview of Keyboard Designs

The variety of changes to the standard keyboard, that have arisen in the market recently, are a result of an evolution of the traditional design. This historical overview will examine briefly the issue of keyboard layout (key allocation), and changes that have led, in part, to alterations of the physical design of the traditional keyboard.

The first keyboard was designed by the inventor of the typewriter, C. L. Shole in 1868 and it included both the alphabet and the set of numbers from 0 to 9 (i.e., alphanumeric). The first layout of the keys on the keyboard is believed to be in the alphabetic order from left to right. Its advantage was that anyone speaking English would know the alphabet (Figure 1). This way it was believed to be easy for users to orient to the keyboard, and it required almost no training (Barry, 1995). Unfortunately the most serious defect of the early typewriters was the tendency of the type-bars to clash and jam when struck in rapid succession. To slow down the typist and to reduce type-bar clashes, Shole rearranged the key order. The **QWERTY** key arrangement thus evolved primarily as a chance solution to an engineering design problem in the construction of the early typewriters (David, 1986) and was later transferred to the computer keyboard.

The most prevalent alternative layout compared to QWERTY was the **Dvorak Simplified Keyboard** (Figure 2). It was patented in 1936 by A. Dvorak and W.L. Dealey. The Dvorak minimized the movements of the fingers (from 25.6 km per day on a standard to 1.6 km per day on the Dvorak keyboard), balanced the load over the fingers according to their relative strengths, and allowed alternate hand keying (Litterick, 1981; Noyes, 1983). The key arrangement was based on the fact that some letters in the English language occurred more often than others. Placing these letters under the strongest fingers

1 2 3 4 5 6 7 8 9 0
A B C D E F G H I J
K L M N O P Q R S T
U V W X Y Z

Note. Adapted from "Keyboards", by J. Barry, 1995, in K. Jacobs & C. M. Bettencourt (Eds.) Ergonomics for therapists, (p. 162), Boston: Butterworth - Heinemann.
Figure 1. The alphabetic keyboard layout.

7 5 3 1 9 0 2 4 6 8
P Y F G C R L
A O E U I D H T N S
Q J K X B M W V Z

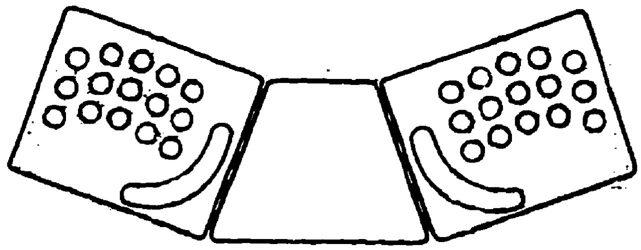
Note. Adapted from "Keyboards", by J. Barry, 1995, in K. Jacobs and C. M. Bettencourt (Eds.) Ergonomics for therapists, (p. 162), Boston: Butterworth - Heinemann.
Figure 2. The Dvorak keyboard layout.

and in the home row (i.e., the middle row) eliminated the extra movement caused by "hurdles" on QWERTY. Unfortunately the Dvorak keyboard was never accepted mainly due both to the necessity to retrain typists already using QWERTY, and to the capital investments in buying new typewriters (Barry, 1995).

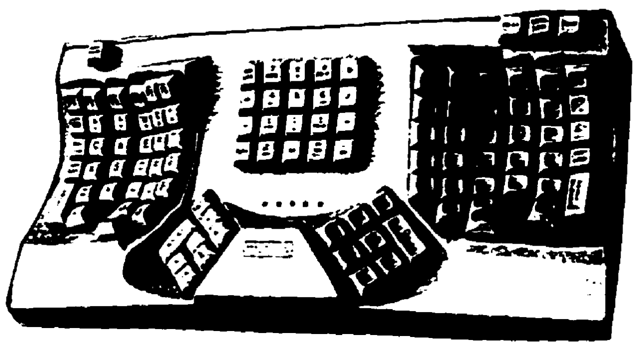
While some alternative keyboards addressed the key arrangement, others were directed to changes in design in order to improve the functional anatomical position of the hand. In 1926, **Klockenberg** first proposed a solution that was believed to be oriented towards postural improvements. The changes included: splitting the keyboard in two halves (i.e., one for each hand), angling them 15° from the center, and tilting them downward to reduce unnatural, uncomfortable and fatiguing postures. Those solutions apparently reduced wrist and shoulder deviations and lowered aches, pain, and fatigue. Klockenberg also suggested that the key rows should be arched to follow the natural arc of the fingers (Kroemer, 1972; Stelman and Henifin, 1983). In 1930s Rhein-Metal manufactured the first adjustable split keyboard (David, 1986) following Klockenberg's design, but it apparently was never adopted for use.

It took almost 5 decades for the first modern alternative keyboards to be manufactured. They each apply at least one of Klockenberg's solutions for postural improvement. The first was Kroemer's (1972) **K - keyboard** that was favored in terms of error rate and keystroke frequency (Figure 3). A test of marathon typing on the K-keyboard showed that subjects did not quit due to aches and pains, as was reported with the standard keyboard, but they quit due to the inability to concentrate (Noyes, 1983). Therefore, 20 years ago a design existed that 'may' have been better posturally than the flat layout but again it was not implemented. The reasons are unclear.

The first design to address both the biomechanics of the human hand and arm, and keying logic was the **Maltron Keyboard** developed by L. Malt in 1976 (Figure 4). It reduced the amount of hand movement upwards and sideways to strike the keys (David, 1986). The keyboard was split in the middle to reduce ulnar deviation, and it was laterally inclined 10° to reduce pronation. Keys were arranged so that they followed the natural arc of the human fingers (Barry, 1995; Litterick, 1981; Noyes, 1983). The key logic of the Maltron was based upon the results of analyzing frequencies of letters in the English



Note. Adapted from "QWERTYUIOP - dinosaur in a computer age", by I. Litterick, 1981, New Scientist, Jan, p. 67.
Figure 3. K-keyboard.



Note. Adapted from "Keyboards", by J. Barry, 1995, in K. Jacobs and C. M. Bettencourt (Eds.) Ergonomics for therapists, (p. 163), Boston: Butterworth - Heinemann.
Figure 4. Maltron keyboard .

language. It was found that the homerow covered 91% of the most common letters while the QWERTY homerow contained only 51% . The Maltron layout reduced successive use of the same finger 11 times and reduced hurdles 256 times (David, 1986). Despite these obvious improvements, no change of the key layout was found acceptable to users. The reasons appear to include the need for retraining.

Evidently, it has been clear for several decades that QWERTY is not the most optimal design for comfortable and efficient typing. Research has been conducted, and solutions offered, but so far none has been implemented. A likely reason for this is that standard keyboards are being produced and sold in large numbers and manufacturers may not have an economic interest in investing in new designs. Also, to justify the change, employers' costs to retrain the existing pool of users would have to be balanced against the advantages of the new design. However, the increase in incidence of CTDs among office workers has been obvious since the 1980s. Law suits that have followed, and the expenses caused by the loss of working hours and medical treatments, have initiated a new phase in the search for new keyboard designs.

2. 2 CTD Risk Factors Related to Computer Keyboard

The previous section showed how the standard keyboard arose as one that exhibited no evolution related to ergonomic principles. It is therefore no surprise that the design of this standard keyboard has been implicated as a causation factor in occupational work-related injuries (i.e., CTD). Several non-occupational and occupational risk factors for the development of the musculoskeletal disorders of the arm and hand have been found. Occupational factors include awkward postures, repetitiveness and forcefulness of movements, mechanical stress, low temperatures, wearing gloves and vibration (Armstrong, 1986; Armstrong, 1992; Armstrong, Fine, Goldstein, Lifshitz and Silverstein, 1987; Armstrong, Radwin, Hansen, Kennedy, 1986). Non-occupational factors include systemic diseases, pre-existing injuries, age, gender, recreational factors, wrist size, pregnancy and the use of oral contraceptives (Armstrong, 1983). Many of the occupational hazards of work environments can be reduced through modification of existing equipment and in this case the video display terminal.

Since the computer keyboard is the only part of the VDT in direct physical contact with the user, factors related to keyboard design are of particular importance. Five risk factors, based on the occupational factors listed earlier, were selected for this review as the most significant to both standard and alternative keyboard designs. They are: wrist position, keyboard height, wrist supports, repetition and force applied. Please note that both keyboard height and wrist support have an effect on wrist position

Position of the wrist. Armstrong (1986) stated that wrist posture was the most frequently cited occupational risk factor for the development of CTD. The conventional keyboard forces the hands to be placed much closer together than the elbows, resulting in internal rotation of the arms, and ulnar deviation of the wrists (Carter and Banister, 1994). To position the hands on the keyboard, one must also fully pronate the forearms (Rose, 1991) and abduct and flex the shoulders to bring the hands to a full horizontal position (Kroemer, 1972). Hedge and Powers (1995) further added that to fully lay over a flat keyboard, the hand must be not only be deviated towards the ulna but it must float in the air over the keys without resting upon them. During sustained typing, arm muscles tend towards fatigue and the forearms tend to rest on the work surface, which brings the hands into a wrist-extended posture. Armstrong and Chaffin (1979) investigated biomechanics of the carpal tunnel and influence that the wrist size, wrist position and hand position have on the forces inside the wrist. Findings suggested that when forceful exertion of finger flexor muscles was combined with wrist flexion or extension, the synovial membranes surrounding the extrinsic finger flexor tendons were compressed, further compressing the median nerve against intra-wrist structures. This additionally supported the arguments that exertions with certain hand and wrist positions can influence carpal tunnel syndrome.

In the past several years, research has established a relationship between the position of the wrist and changes in carpal tunnel pressure (CTP). Rempel et al. (1992) reported that CTP substantially increased when the hand was ulnarly deviated more than 20° or radially deviated more than 15°. The lowest CTP (6.3 mmHg) was found when the wrist was in 5° ulnar deviation, 3.5° flexion and 45° of metacarpophalangeal flexion. Keir, Bach, Engstrom and Rempel (1996) also suggested a curvilinear relationship between wrist extension and flexion, and CTP. The importance of this information was highlighted by the findings of Hargens, Rominie, Sipe, Evans, Mubarak and Akeson (1979) that conducted animal testing and obtained complete blockage of nerve conduction at an intra-compartmental pressure as low as 50 mmHg.

Keyboard height. Grandjean, Hünting and Pidermann (1983) reported that higher keyboard positions were preferred by many users because they could therefore lean back at an angle of 97° to 121°. This adjustment was understandable due to the fatigue that develops during the working day and therefore causes the worker to want to lean back in their chair. Grandjean, Hünting and Nishiyama (1984) observed that the most preferred keyboard height for the operator was 71-87 cm above the floor, with this height having a direct relationship with the height of the chair. They considered keyboard height especially interesting due to its influence on the static loading of the hands, arms and shoulders. Keyboard height should also be adjustable during daily use, for the operator to accommodate to changing sitting positions and to obtain relief from static postures. The selection of adjustable chairs, tables and keyboard trays, which are readily available, allows easy adaptation of keyboard height to the anthropometry of the user, as well as additional adjustments if the height becomes uncomfortable.

Wrist support. When the hand and arms are placed in front of the upper body, they produce a substantial moment of force (due to weight) that has to be counterbalanced by muscles of the trunk. Wrist supports were designed with the intention of reducing musculoskeletal loads and thereby decreasing the risk of developing CTD of the upper extremity. However, the benefits of wrist support use are still unclear. Wrist supports have been associated with backward leaning and decreased inter-vertebral pressure, but have also been reported to create simultaneous increases in pressures of the forearm and wrist on the support (Nakaseko, Grandjean, Hünting and Gierer, 1985). Benedix and Jessen (1986) tested 12 secretaries who were suffering muscle pain. They demonstrated that the load on the trapezius was significantly greater with a wrist support than without. Horie, Hargens and Rempel (1993) suggested that the use of wrist supports increased carpal tunnel pressure by over 120% compared with typing without resting the wrists on the support. They did not find a difference in CTP with the wrists resting on the desk compared to wrists resting on the wrist support. The authors concluded that use of wrist supports does not decrease CTP, and therefore may not prevent carpal tunnel syndrome.

Repetition. Typing is an activity where the same joints and muscle groups of the fingers, hand and forearm, are involved in intensely repeated movements. According to Armstrong (1986), typing is by definition a typical repetitive activity. A typist, with an average speed of 60 words per minute, makes 5 - 6 keystrokes per second or 18000 keystrokes per hour. Keying rates can be as high as 50,000 - 200,000 keystrokes per day, depending on the number of hours spent typing. Keying repetition is a necessary function of the typing task. It is directly proportional to typing productivity, and therefore little can be done to reduce it as a risk factor, perhaps aside from reducing the number of errors.

Forcefulness. The force required to activate the keys of the keyboard is lower than hand force requirements in many other activities. However, when combined with repetitiveness and awkward positions, forcefulness can be an important factor. Dennerlein and Rempel (1994) found that although the activation force of the keyboard keys was approximately 0.6 N, keyboard users exerted an average of four times greater force than necessary (i.e., 2.4N). Armstrong, Foulke, Martin, Gerson and Rempel (1994), demonstrated that the key force exerted by a user is related to the design and stiffness of the key. These results indicated that keyboard reaction force can be used as an index of finger forces during keying tasks. However, it is not clear if force plays a major role in the causation of CTD in heavy VDT work.

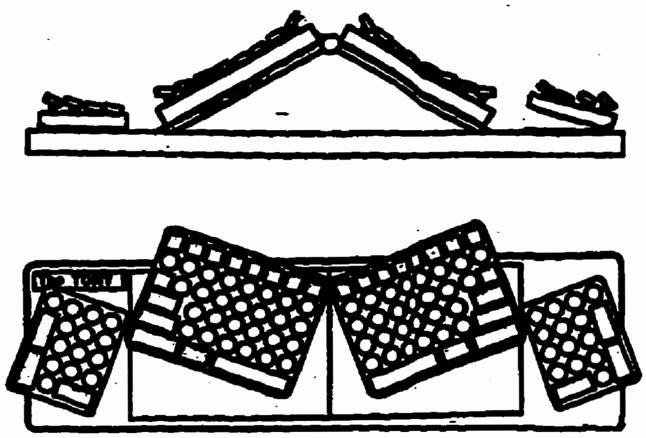
The present study focused on hand and forearm position during the use of different keyboard designs. Although the evaluated designs incorporated aspects related to wrist supports and the height of the homerow keys, factors related to the force exerted on the keys were not in the scope of this study.

2. 3 Research on Standard and Alternative Keyboards

Following unsuccessful attempts to change key logic due to the need for retraining, many investigators have focused on changing the shape of the keyboard in order to decrease the risk factors for the development of CTD. Today there are more than 13 commercially available alternative models (e.g., Apple Adjustable, BAT, Eraze-Eaze, FlexPro, Floating Arms, Lexmark, Microsoft Natural, MiniErgo, Mykey, Peace adjustable, TONY!, Vertical keyboard, Wave, etc.). Most of these are still in need of being recognized by the market.

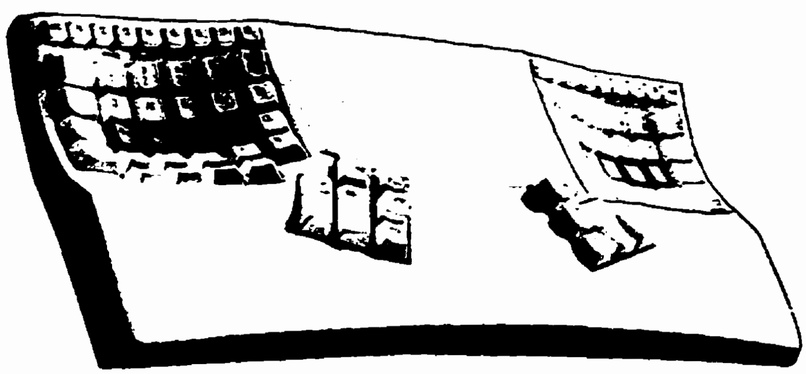
When investigating standard and alternative keyboard designs, most researchers realized the advantage of simultaneous observation of multiple measurements in recognizing if an alternative design reduced the risk of developing CTD while maintaining the productivity and preference of the user. Still, the significance and combination attributed to selected measurements differed among the authors. The following review is focused on selected research, related to the present study, that investigated the advantages and disadvantages of the standard and alternative keyboard designs. Ten studies will be presented in more detail with respect to the methodology used and the results that are applicable to the present study.

Smutz, Serina and Rempel (1994) focused on methodology. They developed a method for determining the effectiveness of an adjustable keyboard design based on simultaneously measuring fingertip impact force, wrist position, productivity, comfort and ease of use. The study of Rempel, Honan, Serina and Tal (1994) combined the testing of different work-surface heights, hand angles and keyboard preference. Serina, Tal and Rempel (1994) focused on the measuring of the wrist, forearm and shoulder angles. Zipp, Heider, Halpern and Rohmert (1983) measured EMG activity of arm muscles, similar to Thompson, Thomas, Cone, Daponte and Markison (1990) (Figure 5). and Smith and Cronin (1993), who additionally analyzed hand angle data from video recordings of the upper body, calculated productivity and assessed preference. Gerard, Jones, Smith, Thomas, and Wang (1994) analyzed forearm EMG and learning rates on the Kinesis alternative keyboard (Figure 6). Dennerlein and Rempel (1994) simultaneously investigated fingertip impact forces and motion of the index finger during typing. Cakir (1995) used a series of questionnaires to assess general comfort, stress/strain caused by work, postural comfort and keyboard design. Chen, Burastero, Tittiranonda, Hollerbach, Shih and Denhoy (1994) simultaneously measured wrist posture, performance and subjective preference.



Note. Adapted from "Analysis of the TONY! variable geometry VDT keyboard", by D. A. Thompson, J. Cone, A. Daponte, and R. Markison, 1994, Proceedings of the Human Factor Society 34th Annual Meeting. Copyright 1983, 1984, 1985, 1987 by Anthony Neal Hodges.

Figure 5. The TONY! adjustable keyboard design.



Note. Adapted from "Keyboards", by J. Barry, 1995, in K. Jacobs and C. M. Bettencourt (Eds.) Ergonomics for therapists, (p. 164), Boston: Butterworth - Heinemann.

Figure 6. Kinesis keyboard.

Finally, the study of Simoneau, Marklin, Monroe and Zabors (1996) investigated wrist and forearm position angles. The major focus of the following section of this review will be on the methodology used in these studies.

2. 3. 1 Methodology

One of the problems in investigating new keyboard designs is the lack of a clearly established methodology. A wide variety of approaches and methodology used were used to investigate a variety of alternative keyboards.

Keyboards. The increased number of marketed alternative keyboard designs has been reflected in the research. While some researchers studied only the standard design (Serina et al., 1994), others (Smutz et al., 1994) focused on a prototype keyboard that was split in the middle, and had an adjustable distance between the halves (0 - 20 cm), an opening angle that reduced radial/ulnar deviation (0-90°), a lateral inclination angle that reduced pronation and an adjustable slope (-60 to +60°). Some authors chose one alternative and the standard keyboard for comparison purposes. The Kinesis keyboard (Smith and Cronin, 1993; Gerard et al., 1994), the Microsoft Natural keyboard (Rempel et al., 1994) and the TONY! adjustable keyboard (Thompson et al., 1990) were evaluated this way. Some adjustable keyboards, like the Apple Adjustable, allowed a normal flat configuration which was similar to the standard shape. Sommerich and Marras (1994) used this advantage to test the Apple Adjustable keyboard both in standard and split arrangements. In the study of Cakir (1995) the alternative keyboard featured a split adjustable angle between the halves of the alphanumeric part that ranged from 0-30°. Some recent studies simultaneously tested the standard and several alternative keyboards, like the Apple Adjustable, the Kinesis and the Comfort (Chen et al., 1994). Simoneau et al. (1996) did not report the names of the alternative keyboards tested but rather gave their descriptions: a fixed angle keyboard, an adjustable-angle split keyboard and a vertically inclined keyboard (Figure 7). In all studies the order of testing different keyboards was randomized.

Note. Adapted from "Wrist and forearm position during a typing task using various keyboard models", by G. Simoneau, R. Marklin, J. Monroe and J. Zabors, 1996, 20th Annual meeting of the American Society of biomechanics, Conference proceedings, Georgia Tech, Atlanta.

Figure 7. Three keyboard designs used in the study of Simoneau et al. (1996).

In the mid 80s Starr, Shute and Thompson (1985) attempted to correlate postural data, with subjective judgments of physical discomfort. They used one instant photograph for each of 100 subjects to measure eight postural parameters, one of which was hand position. Since that time the methodology of collecting data for hand angles has remarkably improved. Most recent studies have applied methods of data collection that allowed continuous measurement of wrist position and provided an accumulated average of wrist position and the range of wrist motions.

Video. Smith and Cronin (1993) superimposed images from two video cameras, to record upper body postures. The cameras were positioned perpendicular to the planes of extension/flexion and radial/ulnar deviation hand motion. The authors indicated that postural data were calculated from the video images with a goniometer by measuring deviation of hand and forearm angles from neutral postures. However, it is unclear how this process was executed and how the authors accounted for the influence of forearm pronation. In some studies (Gerard et al., 1994) video recordings were used only as an additional source for qualitative analysis of the amount of hand movement on each keyboard design tested.

With improvements in transformation methods for close range three dimensional cinematography, e.g., direct linear transformation (Abdel-Aziz and Karara, 1971; Shapiro, 1978), three dimensional analysis of human joints including wrist and fingers (Buford and Thompson, 1987; Small, Bryant and Pichora, 1992; Woltring, 1994) and wrist kinematics (Brumbaugh, Crowninshield, Blair and Andrews, 1982; Youm and Yoon, 1979), several new sophisticated motion analysis systems were available to investigators. Chen et al. (1994) used 3D motion analysis system (MacReflex) in investigating hand movements while typing. Two infrared cameras and two processors were incorporated in the system that delivered 3D xyz coordinates of infrared marker positions attached to the forearm and hand relative to a reference coordinate frame. The data collection rate was 25 Hz and an angle model of the wrist joint was used to obtain joint wrist angles approximating extension/flexion, radial/ulnar deviation and rotation. The authors did not report the accuracy of the system. Dennerlein and Rempel (1994) used a two camera 3-D Selspot motion analysis system with four infra-red markers mounted on the left index finger. Finger position data were collected at the frequency of 500 Hz. Synchronization with simultaneously measured finger force was triggered by the subject. Angles of the phalanges from the horizontal plane were calculated from Cartesian coordinates of the markers.

Goniometry. In spite of these dramatic improvements in possibilities for video analysis the most often used method for measuring wrist position during typing was goniometry. Smutz et al. (1994) and Rempel et al. (1994) used electro-goniometers to measure wrist extension/flexion, radial/ulnar deviation and forearm pronation on both upper extremities with a sampling frequency of 200 Hz. Serina et al. (1994) added shoulder abduction to the previous measurements. Simoneau et al. (1996) used electromechanical goniometers, to simultaneously monitor above mentioned wrist and forearm angles on both hands, but they did not report sampling frequency.

The use of goniometers in examining typing motion required attachment of the measurement equipment to the subject hands and forearms, and wiring to the data recording units. It was questionable how realistic hand movements of the subject were, while typing, considering the extra weight of the equipment and the restrictions imposed by wires. It was also questionable how accurate the measurements were due to possible skin movement under the goniometers.

Another three methods, also used in investigating keyboard designs, were EMG, finger impact forces and measurement of CTP. As these methods are not in the scope of present study they will not be discussed in detail. **Surface electromyography** has often been used to measure forearm muscle activity while typing (Gerard et al. 1994; Thompson et al., 1990). The most commonly tested muscles were: flexor carpi ulnaris, extensor carpi ulnaris, flexor digitorum sublimis and extensor digitorum communis. These muscles were tested both due to their significance in executing hand movements since they are often mentioned in cases of CTD, and their position in the forearm that allowed the use of surface electrodes. However, the studies interested in investigating muscle activity during prolonged static loading also tested trapezius and biceps (Zipp et al. 1983), while studies interested in abduction of the elbow and pronation included the testing of deltoid and pronator teres (Smith and Cronin, 1993).

The **force** exerted by fingers to activate keyboard keys was investigated using strain gauge load cells placed between the keycap and key-switch (Dennerlein and Rempel, 1994; Smutz et al. 1994). The sampling frequency was usually very high, i.e., 1000 to 2000 Hz. To quantify finger force, the measurements usually included maximum force, average force, duration of the keystroke and area under the force curve.

The study of Sommerich and Marras (1994) described a method of measuring changes in **CTP** when typing on two different keyboard configurations. They used fiberoptic pressure transducer inserted into the carpal tunnel to measure carpal tunnel pressure.

2. 3. 1. 1 Methodological Considerations

In the process of developing appropriate methodology for the present study many recommendations and experiences of other authors were applied. The following is a short overview of several methodological aspects that characterized standard and alternative keyboard research.

Subjects. In general, participants in studies about alternative keyboard designs were women, with the occasional participation of a few men. Most commonly subjects were clerical workers with lengthy typing experience on the standard keyboard, with a minimum typing productivity of 45 word per minute and no wrist injuries. However, some authors had different approaches. Serina et al. (1994), recruited 25 subjects, with broad demographic characteristics, from a temporary employment agency. The number of subjects in the studies included two (Sommerich and Marras, 1994), four subjects (Dennerlein and Rempel, 1994), five (Smutz et al., 1994), six subjects (Gerard et al., 1994), eight subjects (Thompson, 1990), 11 subjects (Chen et al., 1994), 25 subjects (Smith and Cronin, 1993) to 26 (Cakir, 1995). Simoneau et al. (1996) divided 30 subjects into three groups of 10 that were randomly assigned to one of the alternative keyboards. Each subject was tested on the standard and one alternative keyboards. The largest number of subjects (i.e., 50) was reported in the study of Rempel et al. (1994).

Hand. The selection of the hand to be tested was not explicitly described in most reports. It was obvious that the methodology chosen and the equipment used were in some cases the limiting factors for testing both hands. Only the right hand was tested in the studies of Smith and Cronin (1993) and Gerard et al. (1994), only the left wrist in the study of Sommerich and Marras (1994), while Rempel et al. (1994), Simoneau et al. (1996), Serina et al. (1994) and Smutz et al. (1994) tested both hands.

Testing setup. All studies that quantitatively investigated hand posture, while subjects typed on standard and alternative keyboard designs, required complicated equipment setup and for that reason they were conducted in laboratory settings. An adjustable table and adjustable chair were usually provided. However, in most of the studies the upright postures of subjects were controlled while typing to minimize wrist extension/flexion. This meant that the elbow was kept on the level of the middle row of the keyboard, or parallel to the floor, or the elbow angle was maintained at approximately 90° (Chen et al. 1994; Serina et al., 1994; Smith and Cronin, 1993; Smutz et al., 1994; Sommerich and Marras, 1994). This elbow control was not acceptable for the present study due to the forced upright sitting posture that it imposed upon subjects. It is possible to maintain this posture for a relatively short period of testing, but it is unrealistic in real working conditions, especially after a long working day. The interest of this study was to find out what the wrist posture was when subjects assumed the postures they considered comfortable.

Length of testing. There was a substantial difference between studies in total testing time as well as the time allotted to data collection. One group of the investigators used testing sessions ranging from 6 to 16 minutes (Rempel et al., 1994; Simoneau et al., 1996; Smutz et al., 1994; Thompson et al., 1990). The other group introduced extensive testing time between 20 minutes and two hours (Chen et al., 1994; Gerard et al., 1994; Smith and Cronin, 1993). The motion data collection was usually limited on 3 to 10 samples in 15 sec. to 5 min. increments. In this study, on average, two minutes of typing were used to evaluate typing productivity while 20 seconds of right hand typing of the exactly same text were used in analysis of the postural data.

Testing text varied between investigators and mainly was chosen to serve the purpose of the particular study. Several studies used different versions of Typing Tutor software packages that was used in the training of typists. The software automatically administered typing tests and computed typing speed (wpm) and percentage errors. In

Typing Tutor the text appeared on the screen and the subject retyped it (Chen et al., 1994; Gerard et al., 1994; Serina et al. 1994; Simoneau et al., 1996). Other authors used a variety of alphabetic texts (a text in which each sentence contained all letters of the alphabet) or random letters that subjects read from the document holder (Smutz et al., 1994; Smith and Cronin, 1993). Dennerlein and Rempel (1994) used a special testing text with a high frequency of the letter "f", because this key on the keyboard was equipped with a load cell for measuring impact force. For some studies (Rempel et al. 1994) it was unclear what kind of testing text was used. The reason that Typing Tutor was not used in the present study was the fact that in most working conditions, the typing stimulants do not come from the screen but rather from written material or the imagination of the user. Therefore a printed copy of selected text was provided to the subjects using a text holder.

Training. Finally, this review of methodology would not be complete without reference to the concerns, that were expressed by some authors, that comparing a well known and long used device, like a standard keyboard, to a new and unknown product, like an alternative keyboard, may not be fair. Still there is no clear agreement among the authors about necessity or appropriate length of training time needed for fair evaluation. Simoneau et al.(1996) reported 20 hours of training prior to testing on three alternative keyboards. Ferrel, Knight and Koeneman (1992) reported that 10 hours of training on the DataHand keyboard permitted the subjects to approximate their usual typing speed, while Smith and Cronin (1993) indicated that seven hours of training on a Kinesis keyboard was sufficient to reach a keying performance almost the same as a subject's pre-test level on the traditional keyboard. Gerard et al. (1994) suggested that training time on the Kinesis keyboard was relatively short, without specifying the exact length. Contrary to this, Cakir (1995) rationalized that only if benefits of a new keyboard design were obvious after a short time, would it have a chance of being accepted by the users. This was the reason Cakir did not introduce a training period, but used rather long warm-up periods prior to testing. Nevertheless, in the conclusion of his report Cakir indicated that some prolonged period of familiarization on the alternative keyboard is needed. Similar to Cakir, another group of studies did not provide any training on the alternative keyboard designs prior to testing but did provide a short warm-up of 3-10 minutes on each configuration (Chen et al., 1994; Rempel et al., 1994) or a learning period (of 14-15 minutes) until subjects reached a constant productivity (Serina et al., 1994; Smutz et al., 1994).

2. 3. 2 Wrist Posture

The design of the **traditional computer keyboard** has been a research topic since the early days of computers. Most of the recommendations of the research from 1980s, included such ideas as: the keyboard surface should be close to the table top, or that the keyboard should be movable, have already been implemented in the design of today's computer keyboard (Hünting, Läubli and Grandjean, 1981). More recent studies about the wrist and arm angles during typing with a standard keyboard, such as study conducted by Serina et al. (1994), in general suggested that subjects type with their wrists ulnarly deviated and extended, their forearms pronated and their shoulders abducted. Median values for right hand extension, ulnar deviation and pronation angles obtained in this study are summarized in Table 1. The authors also observed that joint angles varied widely between subjects while they typed on a standard keyboard, but that the typing posture did not vary substantially during 15-20 minutes of typing.

In the past several years the standard keyboard served for comparison purposes in studies that focused on analyzing **split keyboard designs** with moderate fixed split and inclination angles. The first such keyboard was the Kinesis, and the most recently marketed was the Microsoft Natural. The Kinesis keyboard was designed with the goal to reduce physiological stress and increase productivity, while minimizing adaptation requirements (Kinesis Corporation, 1991). To reduce operator retraining time it utilized a QWERTY layout. The distance between the halves reduced the angle of ulnar deviation of the wrist to near zero for the majority of users. The keypads sloped downward from the inside to outside edge, and were concave to better fit the natural shape of the operator's hands. The keys formed straight columns and slightly curved rows. Kinesis also featured a built in forearm - wrist support, and separate thumb-operated keypads to redistribute the workload from the weak little fingers to the stronger thumbs.

Table 1
Summary of previously reported wrist and forearm angles while typing on different keyboard designs

Source	Keyboard	Extension (deg)	Ulnar deviation (deg)	Radial deviation (deg)	Pronation (deg)
Smith & Cronin	Kinesis	12	-9		
(1993)					
n = 25	Standard	20	-12 to -25		
Chen et al. (1994)	Standard	21.8	-14.7		
n = 11	Apple Adjustable	16.9	-15.0		
	Kinesis	11.7	-4.5		
	Comfort	18.4	-13.5		
Rempel et al. (1994)	Standard	20	-15		72
n = 50	Microsoft Natural	14	-6		69
Serina et al.(1994)	Standard	15.3	-18.4		82.7
n = 25					
Simoneau et al. (1996)	Standard	17.6	-8.6		60.9
n = 10 per keyboard	Fixed split angle	15.1		0.3	55.8
n = 30 for standard	Adjustable split angle	15.3	-2.9		62.7
	Vertically inclined	12.5		5.1	39.8

Note. Signs for ulnar deviation were adjusted to correspond to definition of the angles in the current study For Rempel et al. and Serina et al. only the results for right hand are presented.

In 1993 Smith and Cronin ergonomically tested the Kinesis keyboard to determine if it reduced muscle load and improved typing posture while maintaining comparative performance and user preference to a traditional keyboard. EMG results revealed significantly lower muscle activity of the extensor carpi ulnaris (ulnar deviation), the extensor communis digitorum (extension of the digits) and the pronator teres (forearm pronation) when using the Kinesis keyboard compared to traditional keyboard. The posture analysis also showed substantially lower ulnar deviation and wrist extension using this keyboard. The evaluation concluded that subjects adopted more natural hand postures when keying with the Kinesis keyboard.

Another study, by Gerard et al. (1994), measured initial learning rates and EMG activity while using the Kinesis keyboard compared to the muscle activity recorded while typing on the standard keyboard. EMG data suggested that the Kinesis keyboard required less typing force than the standard keyboard thereby confirming the findings of the Smith and Cronin (1993). Detailed analysis of the data also suggested that the modified Kinesis design did not reduce the muscular activity required to hold the wrist in place while typing, but did reduce muscular activity required to move the fingers. Videotaped qualitative analyses revealed that the hands were moved much less while typing on the Kinesis keyboard.

The same year Rempel et al. (1994) conducted a study to evaluate the effects of the Microsoft Natural split fixed angle keyboard design, and working surface height on wrist and forearm posture. The results for the wrist joint angles of the right hand, presented in Table 1, show the mean values of wrist extension, ulnar deviation and pronation to be closer to neutral on the Microsoft keyboard compared to the standard keyboard. The authors also found that the increase in working surface height changed wrist extension to close to neutral.

Another direction of research focused on **adjustable keyboard designs** that offered the possibility of setting the split and lateral inclination angles to suit the personal preference of the user. These keyboard designs allowed step-by-step transition from a standard configuration to more radical setups. In the middle of the 60s and early 70s, Kroemer (1972) conducted a series of experiments to investigate the effects of keyboard orientation on typing performance. He designed the K- keyboard based on suggestions by Klockenberg. It had straight columns and curved rows and was split into halves for the right and left hands. The halves were attached to a trapezoid shaped centerpiece and could be kept horizontal or tilted laterally at 30, 45, 60 or 90^{o} angles. Kroemer focused on exploring whether or not different postures of the hand-wrist-forearm system produced muscular strain that affected the performance of keyboard operators. He found that there were more complaints about discomfort in the arms and wrists after work at the standard keyboard, but aches and pains in the shoulder were reported more frequently for the K - keyboard. These studies demonstrated that the lateral declination of the keyboard does not drastically change stroke or error frequency. Kroemers experiments also indicated that finding the design solutions for one postural problem does not eliminate possible increase of the complaints in other parts of the body.

The study of Zipp et al. (1983) tried to ascertain the optimal setup for an adjustable keyboard design. They used EMG to investigate myoelectric activities of the muscles involved in typing on the standard and the split and laterally inclined keyboards. The optimal muscle activity for pronation of the forearm and ulnar deviation of the wrist were reported. When the keyboard was inclined laterally and split horizontally, myoelectric activity decreased markedly. The optimal ranges, when electrical activity remained low, were 0-60^{o} pronation and 0-15^{o} ulnar deviation. The authors recommended the use of a split keyboard with split angle of 10-20^{o} and a lateral inclination angle of 10-20^{o}, to eliminate high static muscular work while preserving visual control of the keys.

Thompson et al. (1990) used a variable geometry keyboard called "TONY!" to evaluate the optimal configuration of a split QWERTY-type keyboard. The evaluation was based on muscle activity, measured by EMG, and subjective opinions. The TONY! keyboard allowed continuously variable split and lateral inclination angles from 0-90^{o}. Results showed lower muscle activity when the wrist was in a neutral position and minimal activity when the forearm also approached a neutral position. On average, subjects preferred the feel/touch of the TONY! due to less effort required, fewer aches and pains, more comfort and ease of use compared to the standard keyboard design. The opening angle of 18° and lateral angle of 30-60° emerged as ergonomically optimal when compared with the standard keyboard position. One of the advantages of the TONY! keyboard was variable geometry which allowed the subject to adjust angles to suit personal preferences or to modify these angles during the workday to relieve muscle tension.

The study of Cakir (1995) suggested that an adjustable keyboard may improve postural comfort and reduce fatigue if accepted by users. This author found that the period of familiarization with the fixed split angle keyboard is much longer than with the adjustable angle keyboard. For skilled typists it was difficult to change keyboards and learn new motor patterns. Cakir suggested that an adjustable alternative keyboard design might have more success with users because it allowed step-by-step adjustability.

The only study examining carpal tunnel pressure while typing on closed-standard and split configurations of the Apple Adjustable keyboard was conducted by Sommerich and Marras (1994). This study was important considering the previously outlined relationship between extreme wrist angles and an increase in CTP with its negative influence on nerve conduction. The study demonstrated that the split keyboard configurations substantially reduced ulnar deviation (7-8°) which resulted in a four to five fold reduction in mean CTP. The CTP data showed an apparent subject-specific nature of CTP that the authors suspected could provide some insight into the question of why one typist developed CTD symptoms and another did not. The authors also suggested that due to strong individual nature of CTP, that not every user would experience significant benefits in the use of an alternative keyboard.

In the past two years a number of studies have been conducted which simultaneously investigated several **alternative keyboard designs**. This has provided new measurements and allowed comparisons between various alternative and standard designs. Chen et al. (1994) performed qualitative evaluation of traditional, Apple Adjustable, Kinesis and Comfort keyboards. The evaluation was based on quantitative analysis of wrist posture and typing performance and on subjective analysis of preference. For wrist extension/flexion angles the means were significantly different (p value not reported) between each pair, except for the Apple Adjustable and Comfort keyboards.

Significantly lower ulnar deviation was observed only for the Kinesis keyboard. The median values for all wrist angles were included in Table 1. The authors suggested that properly designed alternative keyboards may improve wrist posture while typing, but that did not guarantee acceptance of the keyboard by the users.

In another study, Simoneau et al. (1996) used three commercially available alternative keyboards to determine the effectiveness of the fundamental keyboard design in placing the forearm and wrist in a more neutral position. The results (Table 1) showed that all three alternative keyboards placed at least one component of wrist and forearm posture in a more neutral position than the conventional keyboard. The split keyboards significantly reduced ulnar deviation ($p < 0.02$), while laterally inclined keyboard significantly reduced forearm pronation ($p < 0.01$). Only small changes were noted in the wrist extension angle with the alternative keyboards, but the authors did not report if the elbow height was controlled during the testing.

2. 3. 3 Productivity

The majority of studies investigating new alternative keyboard designs reported a need to examine productivity in conjunction with other factors. Smutz et al. (1994) considered productivity to be a good measure of how well the subjects had adapted to each configuration. Different ways of calculating typing productivity were reported. Studies that used Typing Tutor software were automatically provided with data regarding typing speed, in words per minute (wpm), and typing accuracy, in percentage of characters typed correctly, by the program (Gerard et al., 1994; Chen et al., 1994). Other studies used different formulas. Smutz et al. (1994) measured productivity using the formula that included all characters typed in a given time period and was corrected for errors. Smith and Cronin (1993) evaluated keying performance on the bases of the number of text entry words per minute, the number of random entry keystrokes per session and the number of errors per session.

Generally, productivity was not substantially reduced on the alternative keyboard designs that were similar to the standard, but it was much lower on the designs that were radically different from the standard configuration. For example, Sommerich and Marras

(1994) found that the split configuration of the Apple Adjustable keyboard did not reduce 60-63 wpm speed of typing for tested subjects. Chen et el. (1994) found that typing speed was similar for the Standard, Apple Adjustable and Comfort keyboards and much lower on the Kinesis keyboard. Smith and Cronin (1993) also found a significant decrease in typing performance on the Kinesis keyboard compared to the traditional ($p < 0.05$). Gerard et al. (1994) found that the average speed on the standard design was 73 wpm with an average accuracy 98%. On the Kinesis keyboard, subjects reached 72% of the average speed on the standard and 97 % accuracy on the standard keyboard. Cakir (1995) found that a split angle of 15^{o} reduced throughput to 95% of that on the standard keyboard, while a split angle of 30^{o} reduced throughput to less than 80% on the standard keyboard. A decrease in productivity could be expected due to years of standard keyboard use compared to just several hours of training time on the alternative design. Preservation of productivity, at levels close to productivity on a standard keyboard, on a design that reduces postural constraints would be the optimal solution for employers as well as users.

2. 3. 4 Preference

Kroemer, in the early 1970s, as well as Cakir, in 1995, realized the importance of subjective measurements and their strong influence on the acceptance of an alternative keyboard design. There are many differences in defining preference as well as in the methods of collecting data about subject's preference of different keyboard designs. Two major approaches in assessing the preference of an alternative keyboard design were rating scales and different types of questionnaires. Most authors did not provide information about the origin or validity of the instrument used to assess preference.

Smutz et al. (1994) used Borg rating scale and a questionnaire to evaluate ease of learning and use, comfort, location of any discomfort, and to compare alternative adjustable split designs to the standard keyboard. They found that the scale (0 - 10) was familiar, understandable and attractive for users. Chen et al. (1994) used questionnaires to assess comfort and usability for each of four keyboard designs tested. The authors did not specify if the questionnaire was adopted or custom-designed for the study. Smith and

Cronin (1993) also used a questionnaire to rate subjects' impressions of key force, key design, palm rest, comfort, fatigue, keying smoothness and appearance of each keyboard. Thompson et al. (1990) reported subjects' preference of the TONY! keyboard with respect to feel/touch, less effort required, fewer aches and pains and more comfort and ease of use but did not clearly specify the scale that was used to collect opinions. Cakir (1995) used questionnaires to test general comfort, stress/strain, postural comfort and design of keyboard design.

The results of preference assessment also differ among studies. Kroemer (1972) suggested that the angled position of the K-keyboard was preferred by subjects. Cakir (1995) suggested that user-adjustable designs have better prospects of being accepted than fixed designs due to the possibility of step-by-step adaptation. The appearance and potentiality of the adjustable keyboard tested by Cakir were favorably rated compared to the standard keyboard, while functionality and familiarity ratings were better for the standard. Smith and Cronin (1993) reported higher ratings for comfort and usability for the Kinesis keyboard, but lower ratings for performance compared to the traditional keyboard. Rempel et al. (1994) indicated that subjects preferred the standard keyboard over the Microsoft Natural. Chen et al. (1994) reported that subjects gave all three alternative keyboards equal or better ratings for comfort and usability compared to the standard keyboard. The variety in interpretation of preference, and in methods of collecting the subjective opinions makes it difficult to summarize the findings. It seems than when comfort and postural improvements were of primary concern in assessing preference, the alternative keyboards were rated better. On the contrary when productivity was strongly addressed, the standard keyboard was rated as more preferred.

2. 4 Summary

The related literature is conclusive in providing evidence for postural benefits of the split and laterally inclined angles of alternative keyboards. Some fixed angles alternative keyboard designs are not radically different from the traditional flat design. Other designs offer the possibility for greater adjustments in keyboard angles. Both concepts intend to provide wrist angles closer to neutral. However, although the flat traditional QWERTY keyboard layout might be considered a dinosaur in the computer age, it may be too well known by too many to allow any major change, as productivity and preference findings suggested.

In the early 1990s, for the first time alternative keyboard designs were used outside laboratory settings and were made available for retail use. The variety of designs available imposes a dilemma for potential users who must decide which design is best and worth the investment. This study is intended to contribute to the existing pool of knowledge regarding alternative keyboards.

3 METHODOLOGY

Sixteen subjects participated in the current study that investigated the influence of three computer keyboard designs on hand position, typing productivity and keyboard preference. This chapter focuses on procedures and operations used for collection and analysis of these data.

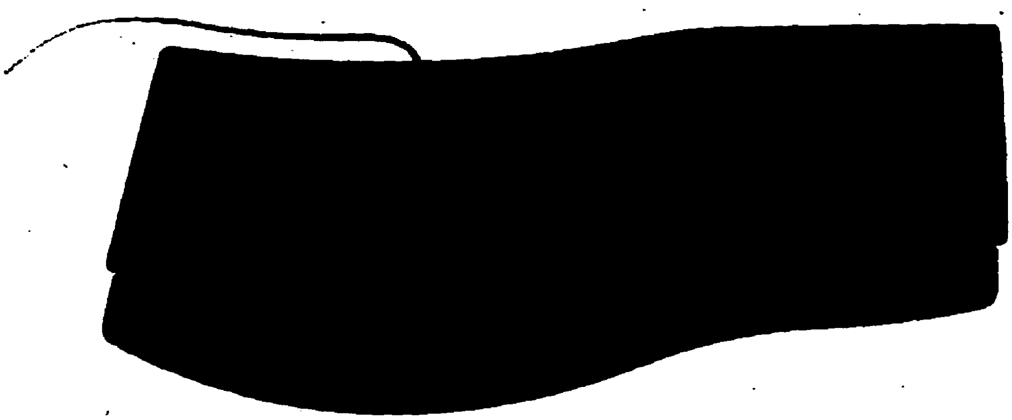
3. 1 Keyboards

A standard keyboard and two alternative computer keyboard designs represented by the Microsoft Natural and the FlexPro were included in the study (Figure 8). The alternative designs were chosen because their design characteristics clearly distinguished them from the standard flat keyboard. The two halves of the Microsoft Natural keyboard were fixed at an split angle of 12° and a lateral inclination angle of 10°. A built-in wrist leveler eliminated forward keyboard tilt. The FlexPro had a user adjustable keyboard angle that both elevated and rotated demiboards in two symmetrical arcs. In the study, this angle was fixed at 15° to reduce variability among subjects and produce a marked lateral inclination angle of approximately 42°. The standard keyboard does not feature either split or lateral inclination angle. To identify the alternative designs focusing on the unique feature which differentiated them, the Microsoft Natural keyboard was designated FIXED whereas the FlexPro was designated OPEN.

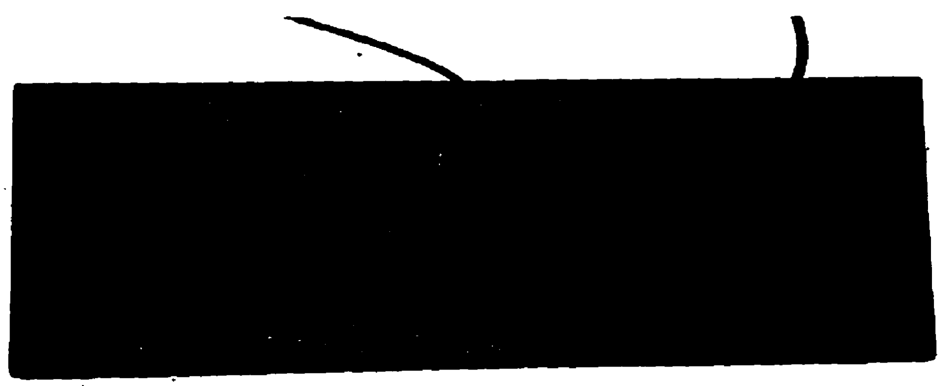
3. 2 Subjects

To be considered for participation in the study, subjects had to be healthy without diagnosis of cumulative trauma disorders in the past year. They also had to have been in the same job for at least 6 months and had to be currently using a computer keyboard more than 4 hours a day. Before beginning the study, each participant was given a letter of information about the nature and requirements of the research, and each signed a consent form approved by the Review Board for Health Sciences Research Involving Human Subjects, the University of Western Ontario (London, Ontario, Canada) (Appendix A).

FlexPro (OPEN) keyboard



Microsoft Natural (FIXED) keyboard



Standard (STAN.) keyboard

Figure 8. Keyboard designs used in the present study.

Although 27 volunteers consented to participate and began the training, only 16 (14 women and 2 men) completed all the requirements of the experimental design. All 16 were right hand dominant and on average each worked on a computer for 5.3 (+/- 2.3) hours a day. Most used the computer for correspondence, creating reports and copy typing, while a few utilized it for graphics and numeric input. With the exception of one subject who had experience typing on a Microsoft keyboard, none had used either a FIXED or an OPEN keyboard design prior to participation in this study (Table 2).

All subjects undertook 10 hours of training on a FlexPro (OPEN) and 10 hours of training on a Microsoft (FIXED) keyboard, over a period of two to three weeks, in their normal setting under typical working conditions. The order of training on each keyboard varied from subject to subject depending on keyboard availability. Subjects were encouraged to examine all possible adjustments offered by the alternative keyboard designs, but were told that they would be tested at the 15° user adjustable angle on the OPEN, and that the wrist leveler on the FIXED keyboard would be in the up position.

Table 2

Descriptive characteristics of the subjects

	Age (yrs)	Height (m)	Mass (kg)	Typing experience (yrs)	At present job (yrs)
Mean (SD)	33 (13)	1.66 (0.09)	67.7 (13.5)	15 (10)	5 (2)

Note. Total n = 16, female = 14, male = 2.

3. 3 Video Data Collection Set-up

Two Panasonic VHS camcorders (model PV-330 and model AG-190) were used to obtain independent views of hand position. The camcorders, mounted on Samson QuickSet tripods (models 4-73010-7 and 7204) which were positioned on tables, were approximately 2.2 m above the floor and 3.2 m apart (Figure 9). Camcorder - subject distances ranged from 5.3 and 5.6 m. The shutters on the camcorders were set on 1/1000s,

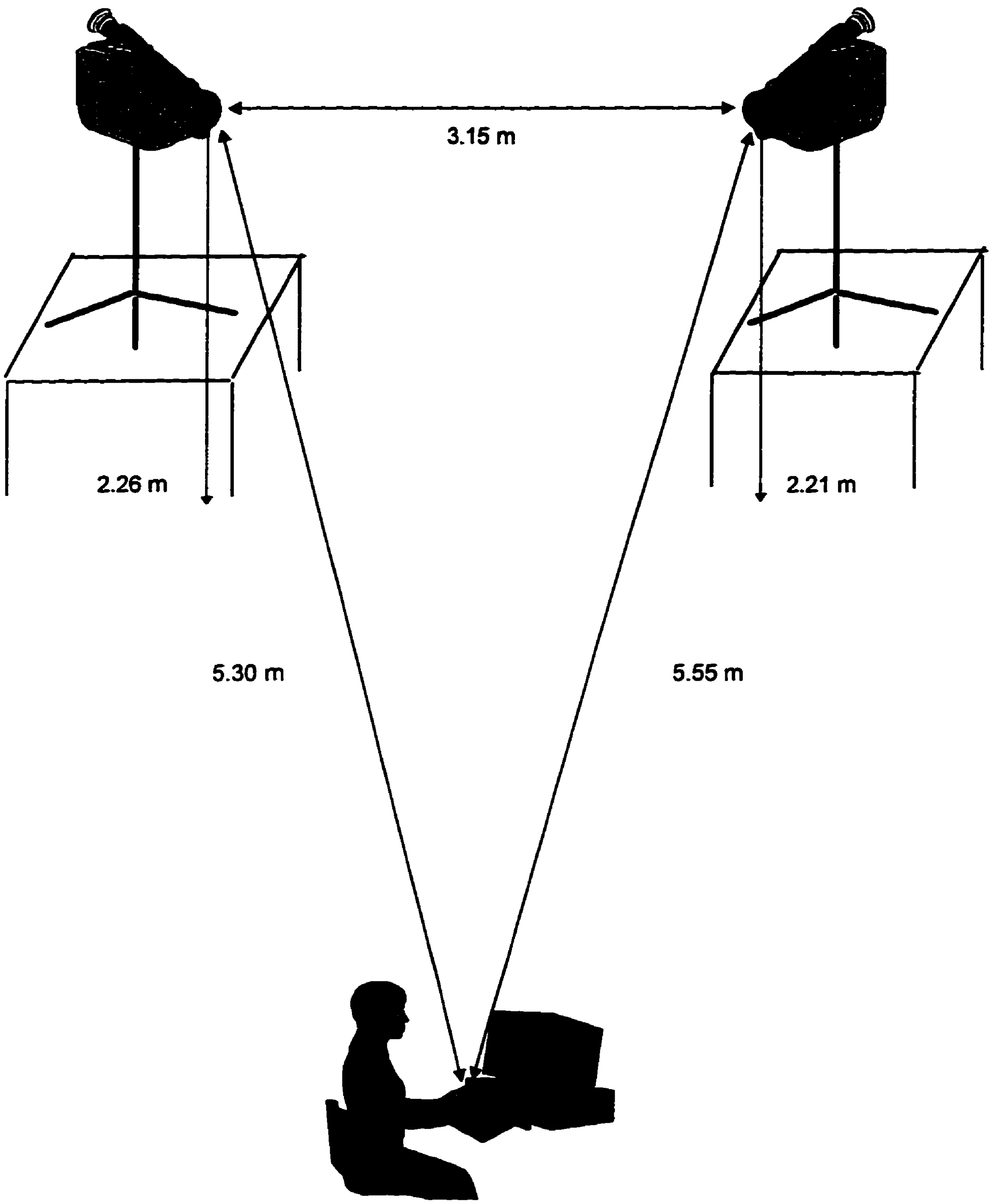


Figure 9. Video data collection setup.

and the focus was set manually. A photo light (Colortran model Quartz-King Dual 1000, No 116-021) served as an additional external light source. To ensure time synchronization, the output from both camcorders was fed into a Sony Special Effects Digital Generator (model XV-D1000) to produce a split screen image which was recorded on a Sony VCR (model SLV-57SUC). Date and time were superimposed on the upper image using a Panasonic Time-Date Generator (model WJ-810). A single video monitor was used to control camera coverage of the testing area. The field of view of each camera was limited to the forearm, hand and keyboard.

A specially constructed frame of non - uniform shape, to fully cover the space occupied by the motion to be analyzed, was used to calibrate the test area. The three dimensional coordinates of each control point on the frame had been previously determined using the DEA SWIFT Coordinate Measuring Machine (CMM) which had an accuracy of 1/100 mm (Kofman, 1996) (Table 3 and Figure 10). The calibration frame was placed on the typing desk and aligned with a fixed marker that ensured consistent positioning of the frame and the keyboards. The frame was videotaped prior to and following the test sessions for each subject. Figure 11 shows a split screen image of the calibration object recorded on videotape.

3. 4 Testing Protocol

Data were collected in the biomechanics laboratory of the Faculty of Kinesiology at the University of Western Ontario between March and November 1996. The session for each subject lasted between 30 and 60 minutes. Only the investigator and the subject were present during the testing.

The session began with a short discussion about the subject's experience of training on the alternative keyboards. The testing equipment and procedures were then explained and the subject was encouraged to ask questions and make comments. The video equipment was set up so that the subject could see the video images recorded in real time.

Table 3
Calibration frame control point coordinates in millimeters

POINT[2]	X	Y	Z
1	22.75	-97.46	160.44
2	136.29	-93.52	157.26
3 (*, #)	245.98	-95.28	160.17
4 (*)	353.6	-95.06	160.01
5	26.26	-38.16	82.78
6 (*)	137.29	-34.53	78.40
7 (*)	246.24	-37.16	83.01
8 (*)	352.73	-35.27	82.46
9	25.30	21.75	-0.46
10	134.68	22.52	-2.43
11	244.82	23.91	-.09
12	354.93	23.80	1.70
13 (#)	27.22	76.83	83.37
14 (*, #)	135.12	75.35	81.58
15 (*)	245.45	79.06	84.35
16 (*)	355.43	83.96	81.62
17	25.80	136.21	162.30
18	138.38	140.63	159.89
19 (*, #)	239.09	138.19	160.36
20 (*)	349.28	136.60	159.93
21 (#)	22.02	199.26	83.27
22 (*)	134.54	200.64	79.88
23 (*)	240.97	200.35	80.49
24 (*)	352.79	199.50	82.87
25	23.38	253.11	-3.15
26	134.16	254.64	-5.50
27	242.78	254.73	-5.26
28	352.85	255.54	-3.08
29	25.99	309.09	80.04
30 (*, #)	131.32	313.48	80.32
31 (*)	240.42	313.34	77.23
32 (*)	346.98	313.66	81.91
33	28.68	371.47	156.47
34	132.80	364.05	155.90
35 (#)	240.65	366.05	152.33
36 (*, #)	346.09	371.03	158.41
37	352.46	79.29	-88.10
38 (*)	354.12	22.52	-87.97
39 (*)	357.51	-33.45	-87.34
40 (*)	356.51	-90.77	-90.27
41 (*)	300.07	-93.37	-89.00
42 (*, #)	246.09	-91.70	-89.33
43 (#)	190.00	-91.20	-90.30
44	136.37	-93.36	-93.73
45	80.49	-95.09	-90.50
46	28.49	-92.97	-89.26
47	-27.64	-90.80	-87.93
48	-30.98	-36.14	-87.69
49	-27.98	19.03	-88.10
50	-32.54	78.43	-86.65

Note. Gray area indicates points under the frame

[2] The points on the frame used for calibration more than five times are labeled (*). The points used to verify digitizing accuracy of calibration frame more than once are labeled (#).

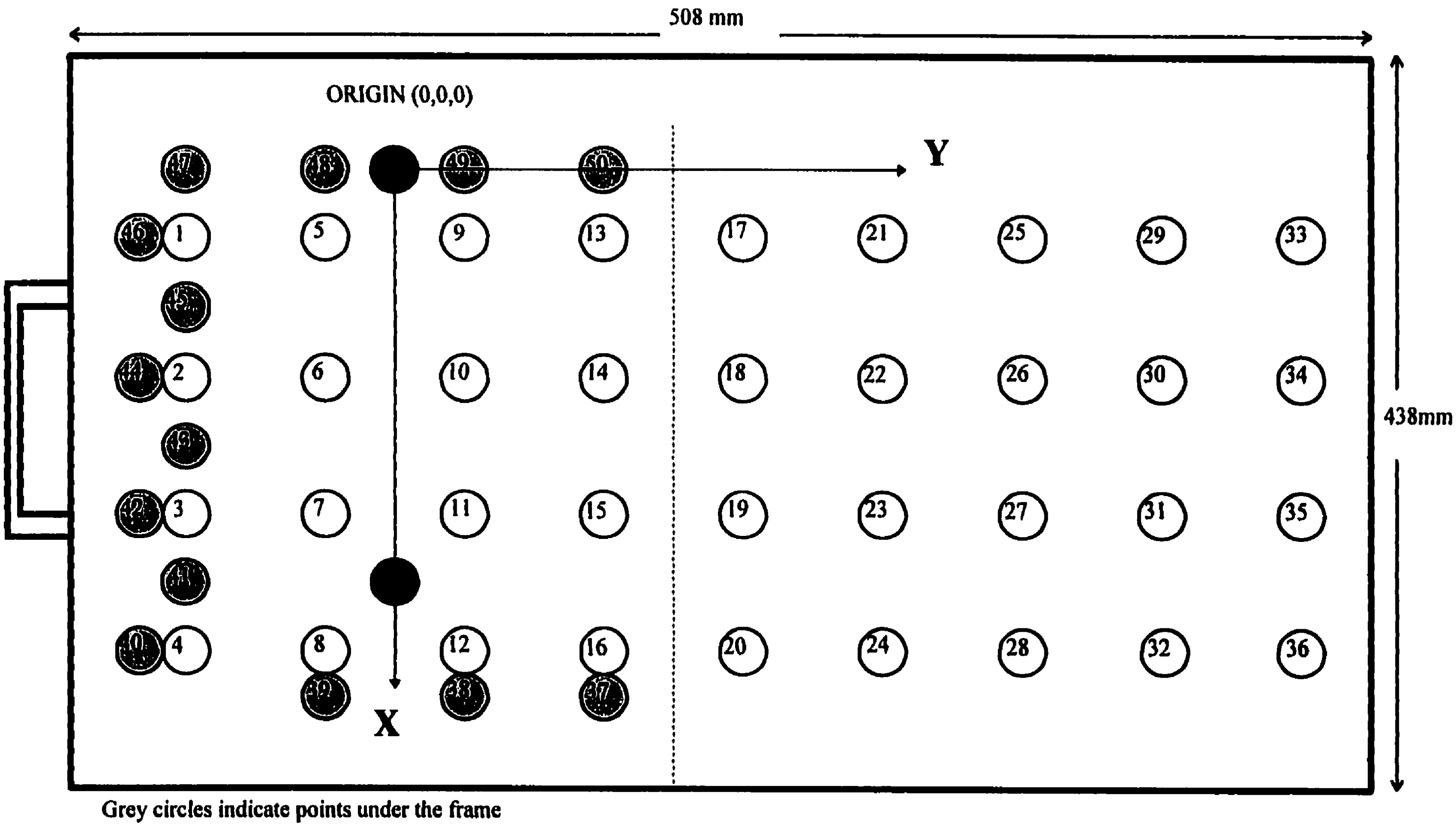


Figure 10. Calibration frame.

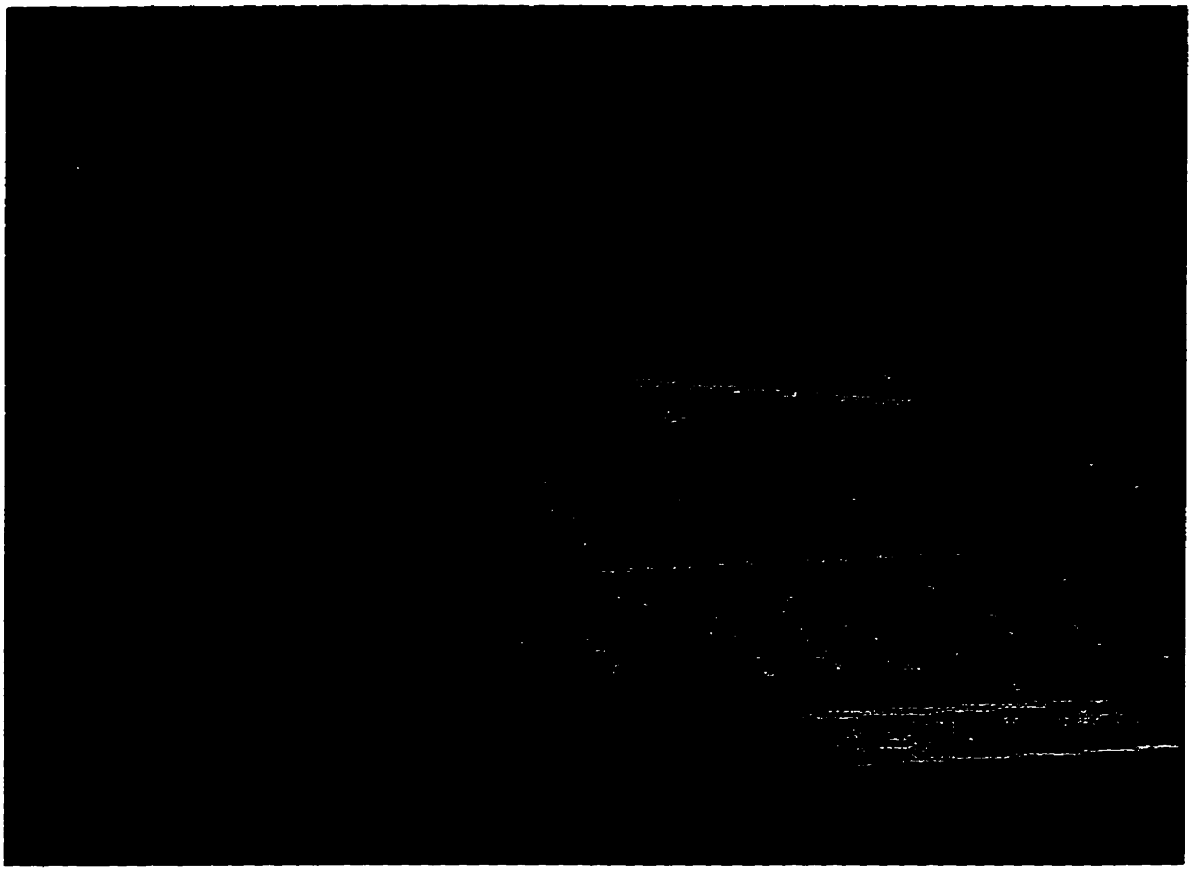


Figure 11. Split screen image of the calibration frame.

Circular markers 7 mm in diameter were positioned on the subject's right hand and forearm (Table 4). Six markers simulated the position of goniometer arms for wrist angle data collection described by Champney, Crist, Cushman, Lucas and Rogers (1983) and the seventh was added on the distal end of the third proximal phalange. The markers were constructed using white retro-reflective tape (3M Scotchlite reflective sheeting) attached to a black background (self-adhesive tape, 7847 matte black acrylic) to increase contrast (Figure 12). An anthropometer was used to locate the middle of the wrist (pt. 5) and to measure the middle of the forearm length and width (pt. 4). It was recognized that the position of the capitate bone more accurately represents the pivot point for radial/ulnar deviation. Reduced visibility of the marker disallowed the use of this point.

Once the markers were attached, subjects completed a questionnaire relating to keyboard preference (Figure 13). Preference was assessed using a ten point numerical rating scale ranging from "worst" (0) to "best" (10) for each keyboard design. The rating scale is considered the best method for categorizing judgment (Rosenthal and Rosnow, 1991). Based on their experience from the training sessions, subjects were asked to circle the number that best described their preference for each of the three keyboards. They were also asked to give comments to support their assessment.

Subjects then warmed up by typing a text resembling the one to be used in the actual test. This gave subjects an opportunity to get used to the experimental setup. They were also encouraged to adjust the chair, computer monitor and text holder, and generally to make themselves as comfortable as possible. A foot rest was provided upon request. The subjects were asked to type at their usual speed and to avoid correcting mistakes. When the subjects indicated that they were ready, the testing began.

The testing text was a combination of sentences extracted from Farmer, Graham and Jenkins (1985). It consisted of sentences that included all letters of the alphabet, words containing letters difficult to reach and words typed only by the right hand. The only difference between the testing texts for the three keyboards was in the sentence sequence and in the addition of one sentence that was different in each text. The role of the latter was to reduce recognition expected as a result of learning due to repetition. The

Table 4

Positions of the markers

Point	Designation	Location
1	ELBOW	lateral epicondyle of humerus
2	WRIST	head of ulna
3	5 MCP	5th metacarpal - distal end
4	MIDFOREARM	middle of forearm length and width
5	MIDWRIST	middle distance between radial and ulnar styloid
6	3 MCP	3rd metacarpal - distal end
7	3 PIP	3rd proximal phalange - distal end

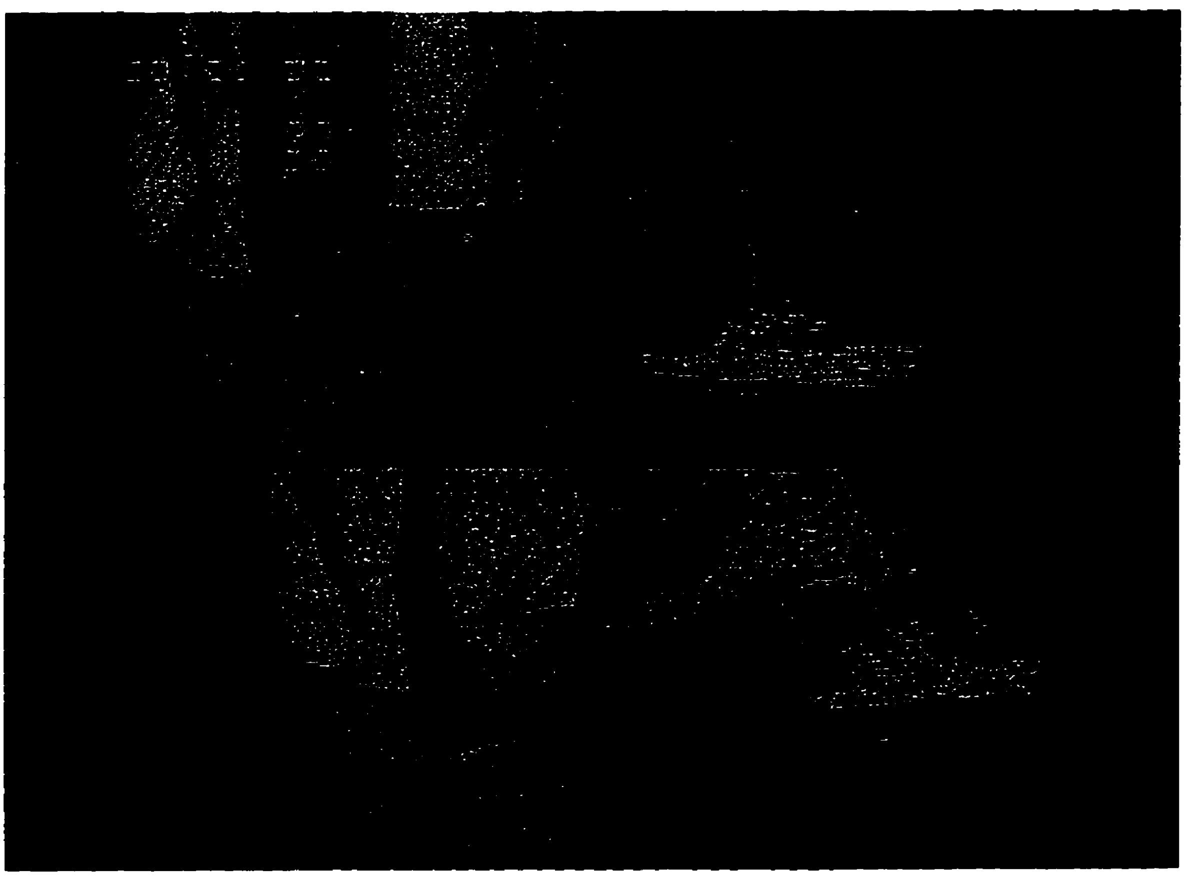


Figure 12. Split screen image of markers attached to anatomical reference points.

NAME CODE: ____________________

PREFERENCE

Flex-Pro (angle 15^0)

Please rate this keyboard in terms of preference. Circle the number you think best describes this keyboard.

0 1 2 3 4 5 6 7 8 9 10

Worst Satisfactory Best

Please write comments to support your rating:

Microsoft keyboard

Please rate this keyboard in terms of preference. Circle the number you think best describes this keyboard.

0 1 2 3 4 5 6 7 8 9 10

Worst Satisfactory Best

Please write comments to support your rating:

Standard Keyboard

Please rate this keyboard in terms of preference. Circle the number you think best describes this keyboard.

0 1 2 3 4 5 6 7 8 9 10

Worst Satisfactory Best

Please write comments to support your rating:

Figure 13. Preference questionnaire.

right handed section, which was the only section to be used in the video analysis of hand position was always located in the same place within the text (Appendix B).

Upon completion of typing on one keyboard, the next keyboard was connected to the computer. Visibility of the points in both testing views was verified while the subject typed several sentences to get accustomed to the new keyboard. Subjects were asked to make any necessary adjustments in chair height and/or position. The same procedure was followed for the third keyboard. Keyboard order was varied among subjects to reduce the possibility of systematic error due to expected improvement of the performance on the last compared to the first keyboard tested.

3. 5 Video Data Reduction

The Ariel Performance Analysis System (APAS) was employed to calibrate the testing area, grab video sequences, digitize data points, transform planar coordinates into spatial coordinates using the direct linear transformation (DLT) method, filter calculated data and print output files.

The first step in video data reduction involved calibration of the testing space using the known positions of between 13 and 23 control points on the calibration frame. Visibility was the factor determining the actual number of points used. To assess the adequacy of the calibration the spatial coordinates of between three to eight points on the frame, not previously used in the calibration, were computed for each session and compared with their known values.

The second step consisted of grabbing a video sequence of the subject's typing performance on each of the three keyboards. Due to the complexity and labor-intensive nature of the video data reduction, frame grabbing was limited to the second line of the right hand typing section. Pressing the ENTER key at the beginning and end of the line indicated the start and end of the selected sequence. Black and white video images were captured with a sampling frequency of 20 fields per second and stored in the computer memory. Since a fast typist cannot type more than 5-6 characters per second, this sampling frequency was considered adequate and was confirmed by a pilot study in which data loss associated with various sampling frequencies was examined. On average, the sequence lasted 20 s or 400 video frames per trial.

Third, the APAS was used to digitize the seven designated anatomical landmarks in order to obtain their two dimensional coordinates. A cursor on the monitor was positioned over each point in succession. The point was then selected and its planar coordinates stored in the computer memory. Since the markers were retro-reflective they were digitized automatically whenever possible. Verification of the correct location of the automatic cursor positioning was always visually controlled on the computer monitor and adjusted or acknowledged manually.

Finally the two sets of planar coordinates for each point were transformed into spatial coordinates (X,Y,Z) using the DLT algorithm. The calculated position data were then filtered using a cubic spline with a smoothing factor of 1 mm to reduce small random digitizing errors. Files containing smoothed spatial coordinates of the points were subsequently transferred to other computer programs for further processing.

3. 6 Video Data Analysis

Two QuickBASIC application programs (Appendix C) were written by the investigator to compute pronation of the forearm, wrist angle, wrist extension/flexion angle and radial/ulnar deviation angle from the three dimensional coordinates of the points on the forearm and hand for each video frame. In the program TRANSFO.BAS the coordinates of the wrist (pt. 2) were subtracted from the coordinates of the seven anatomical coordinates to establish a translated axis system (X,Y,Z) for the forearm and hand with the origin (0,0,0) at the wrist (Figure 14). The dot product was used to calculate pronation of the forearm as the angle between the vector directed from the wrist (Pt. 2) to the midwrist (pt. 5) and a vector directed from the wrist to a point on the horizontal (XY) plane directly below the midwrist.

The translated coordinate system (X,Y,Z) with origin at the wrist was then rotated to orient the x axis with the forearm, the xy plane with wrist radial and ulnar deviation and the xz plane with wrist flexion and extension (Figure 15). This process, following the procedures outlined by Andrews (1993), included the following steps:

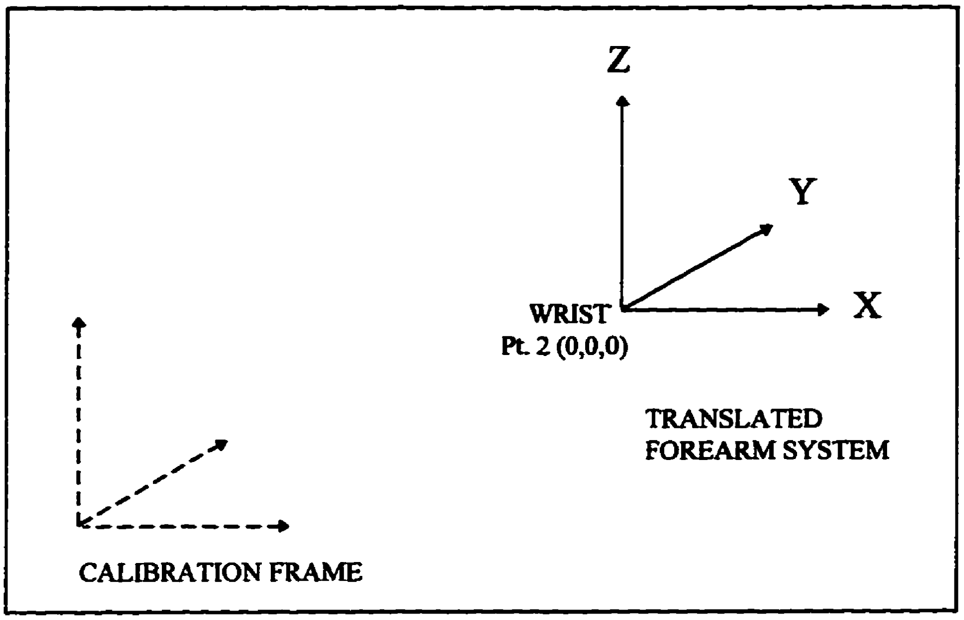


Figure 14. Translation of the anatomical reference points to a system (X,Y,Z) with origin at the wrist. The systems are oriented with respect to the position of the calibration frame on the typing table.

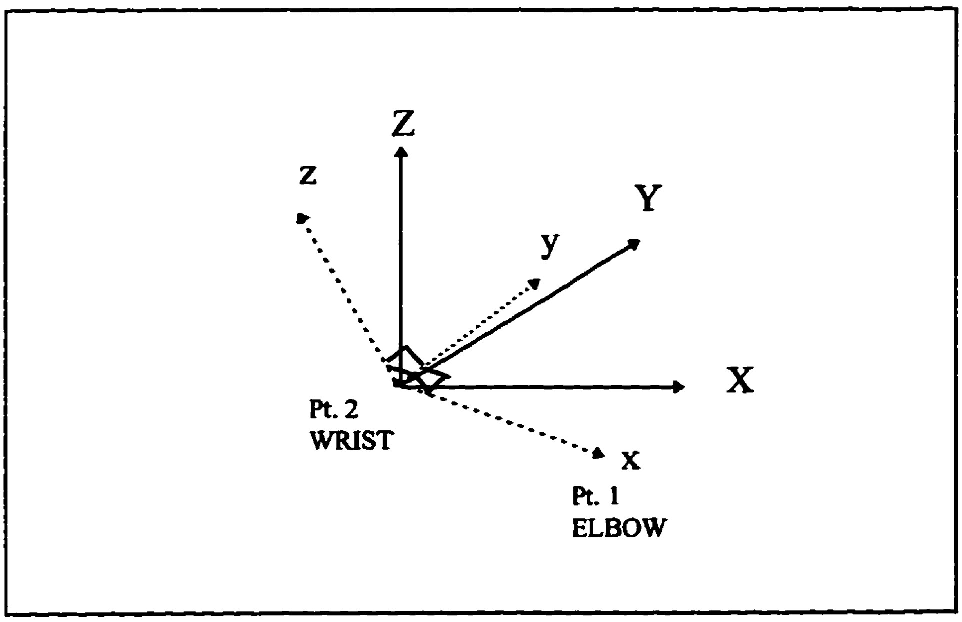


Figure 15. Final position of translated and rotated coordinate system of the forearm and hand (x,y,z), with wrist extension/flexion occurring in the xz plane and radial/ulnar deviation in the xy plane.

1. In each video frame instantaneous orientation of the rotated (x,y,z) coordinate system with origin at the wrist was determined using three noncollinear points namely the elbow (pt. 1), wrist (pt. 2) and midwrist (pt. 5) which defined the xy plane (Figure 16).
2. To locate the z axis, vector **V1** directed from the wrist to the elbow along the positive x axis was crossed into vector **V2** directed from the midwrist to the wrist. Since **V1** and **V2** were intersecting vectors, their cross product **V3** was perpendicular to the xy plane and represented the direction of the z axis (Figure 17).
3. To locate the y axis, vector **V3** was crossed into vector **V1** (Figure 18).
4. To transform the known translated coordinates of the anatomical landmarks obtained from digitizing into the new x,y,z, system aligned with the forearm, it was necessary to establish a 3x3 matrix of scalar orientation parameters. Unit vectors **I**, **J**, **K** were associated with the translated X,Y,Z frame and unit vectors **i**, **j**, **k** with the rotated x,y,z frame. The orientation of each unit vector in the rotated frame was specified in terms of three direction angles, one with respect to each of the **I**, **J**, **K** unit vectors in the original translated system (Figure 19). The nine associated direction cosines were the scalar orientation parameters which described the x,y,z axis system in terms of the X,Y,Z translated reference frame.

$$[C] = [\mathbf{i}\ \mathbf{j}\ \mathbf{k}] = \begin{bmatrix} c\alpha_x & c\alpha_y & c\alpha_z \\ c\beta_x & c\beta_y & c\beta_z \\ c\gamma_x & c\gamma_y & c\gamma_z \end{bmatrix}$$

5. The mapping of coordinates in the rotated x,y,z, system (**r**) into coordinates in the translated X,Y,Z (**R**)

$$\mathbf{R} = [C]\ \mathbf{r}$$

was premultiplied by $[C]^T$.

$$\mathbf{R}\,[C]^T = [C]^T\,[C]\ \mathbf{r}$$

This operation inverted the process expressing coordinates in the x,y,z system in terms of those in the X,Y,Z reference frame.

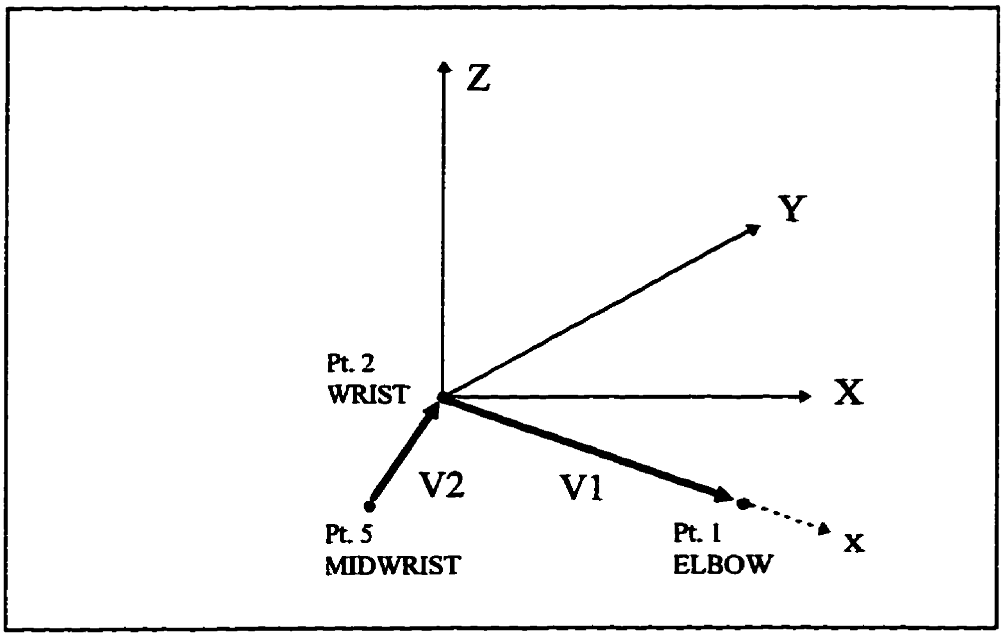


Figure 16. Three non-collinear points (Pt. 1, Pt. 2 and Pt. 5) define the xy plane in which radial and ulnar deviation of the wrist take place.

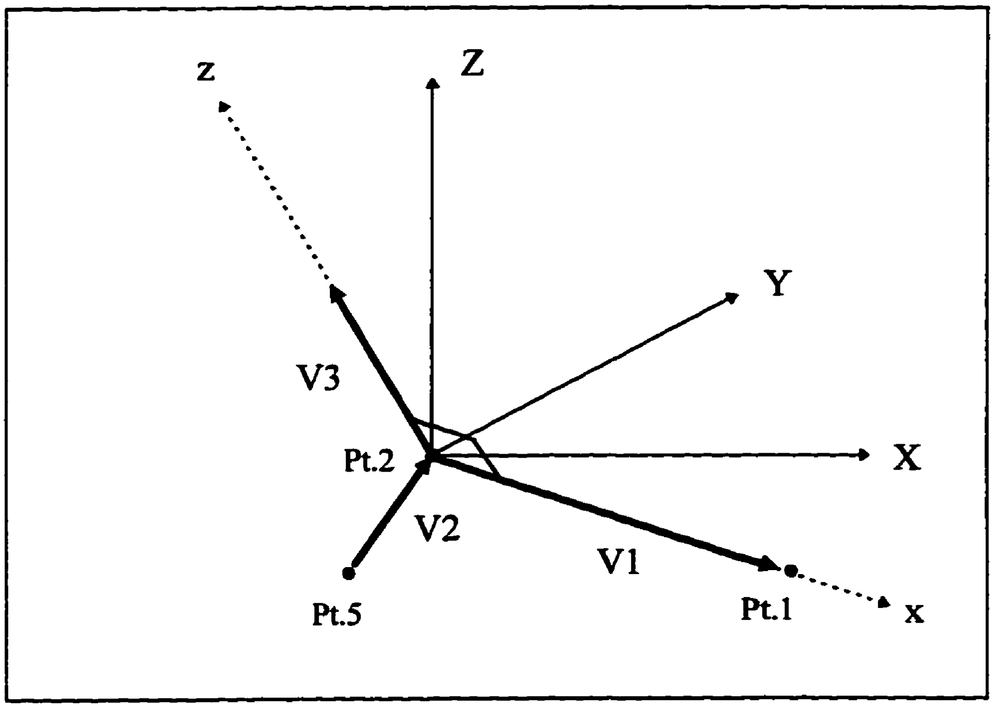


Figure 17. The cross product of **V1** and **V2** results in perpendicular **V3** aligned with the z axis. Wrist flexion and extension take place in the xz plane.

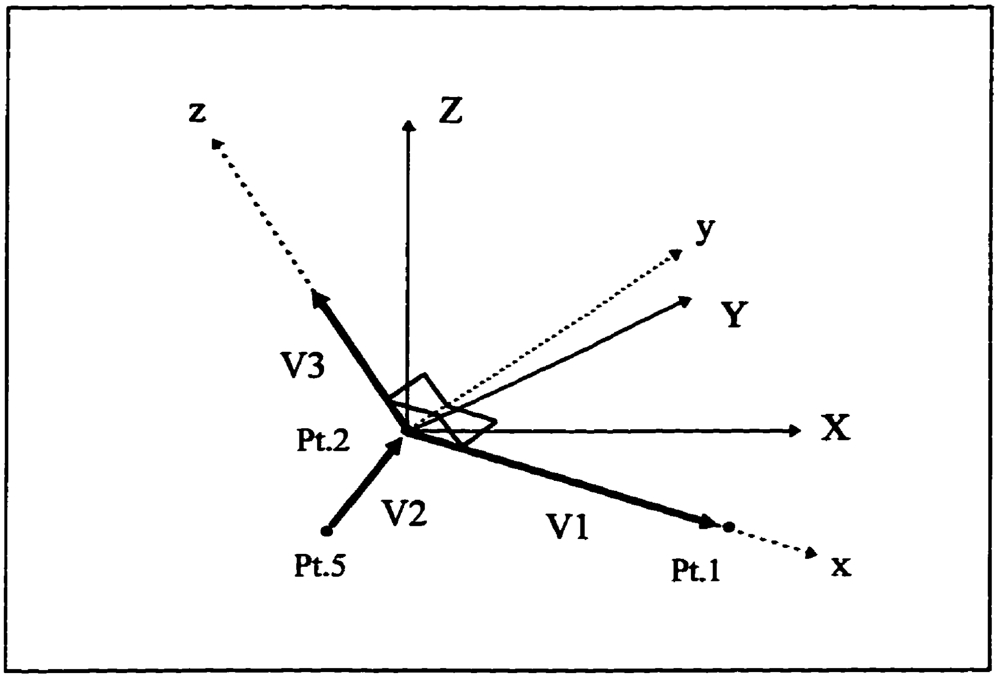


Figure 18. The cross product of V3 and V1 results in perpendicular axis y.

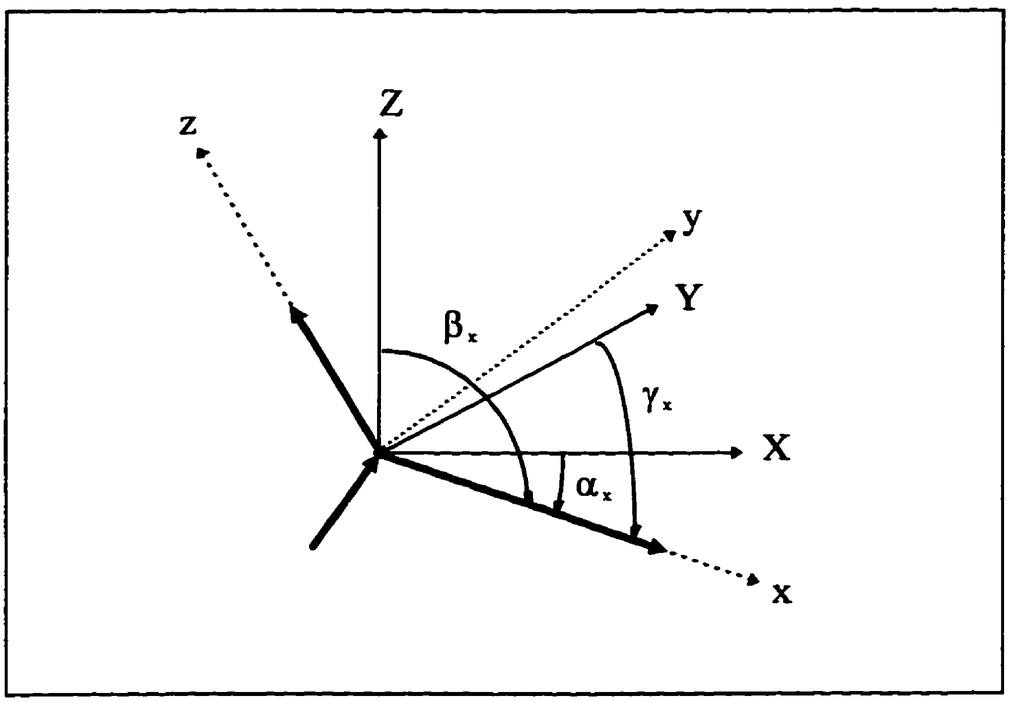


Figure 19. The orientation of the x axis of the x,y,z coordinate system is specified in terms of its three direction cosines (α_x, β_x, γ_x). A similar relationship exists for the other two axes.

Since [C] is orthogonal $[C]^T [C] = 1$ and therefore

$$\mathbf{r} = \mathbf{R}\,[C]^T$$

The transformated coordinates of anatomical points for each video frame were stored in an output file for processing in ANGLES.BAS program.

The ANGLES.BAS computed wrist angle, wrist extension/flexion and wrist radial/ulnar deviation angles for each video frame. Wrist angle was calculated using the dot product of the vector directed from the wrist (pt. 2) to the elbow (pt. 1) and the vector from the wrist to the 5 mcp (pt. 3). Extension/flexion which occurred in the xz plane was determined by dotting the wrist to elbow vector into the projection of the wrist to 5 mcp vector on the xz plane. Wrist radial/ulnar deviation which occurred in the xy plane was determinated by dotting the midwrist to midforearm vector into the projection of midwrist to 3 mcp vector on the xy plane.

To verify the accuracy of angle computations, a series of experiments with known angles and segment lengths on rigid models was conducted. Also, wrist angle computed from ANGLES.BAS was compared with wrist angle calculated by the APAS.

Time spent in five different ranges of wrist motion was also computed in the ANGLES.BAS program. Based on data provided in the literature (American Academy of Orthopedic Surgeons, 1965; Rempel et al. 1992; Swanson et al., 1987), the extension/flexion angle and the radial/ulnar deviation angle were classified into five designated angle ranges (i.e., neutral, moderate[2] and extreme [2] for each joint direction) as presented in the Tables 6 and 7, and Figures 20 and 21. The discrepancies in angle from neutral, are due to the differences in the anatomical joint ranges on either side. Temporal information was obtained from the number of video frames spent in each of these ranges.

Table 5

Designated wrist angle ranges for extension/flexion

Range		Degrees
Extreme flexion	EXTFL	$< -20^{o}$
Moderate flexion	MODFL	-20^{o} to -10^{o}
Neutral	NEUT	-10^{o} to $+10^{o}$
Moderate extension	MODEX	$+10^{o}$ to $+20^{o}$
Extreme extension	EXTEX	$> +20^{o}$

Table 6

Designated wrist angle ranges for radial/ulnar deviation

Range		Degrees
Extreme ulnar deviation	EXTUL	$< -25^{o}$
Moderate ulnar deviation	MODUL	-25^{o} to -15^{o}
Neutral	NEUT	-15^{o} to $+5^{o}$
Moderate radial deviation	MODRA	$+5^{o}$ to $+15^{o}$
Extreme radial deviation	EXTRA	$> +15^{o}$

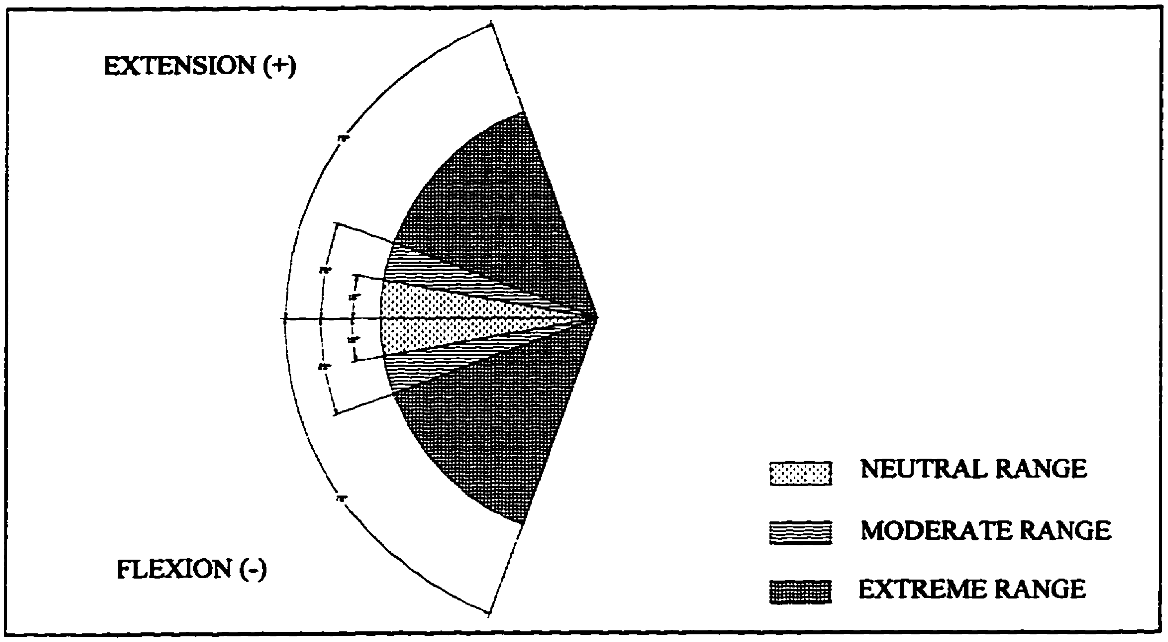


Figure 20. Classification of extension/flexion angle ranges.

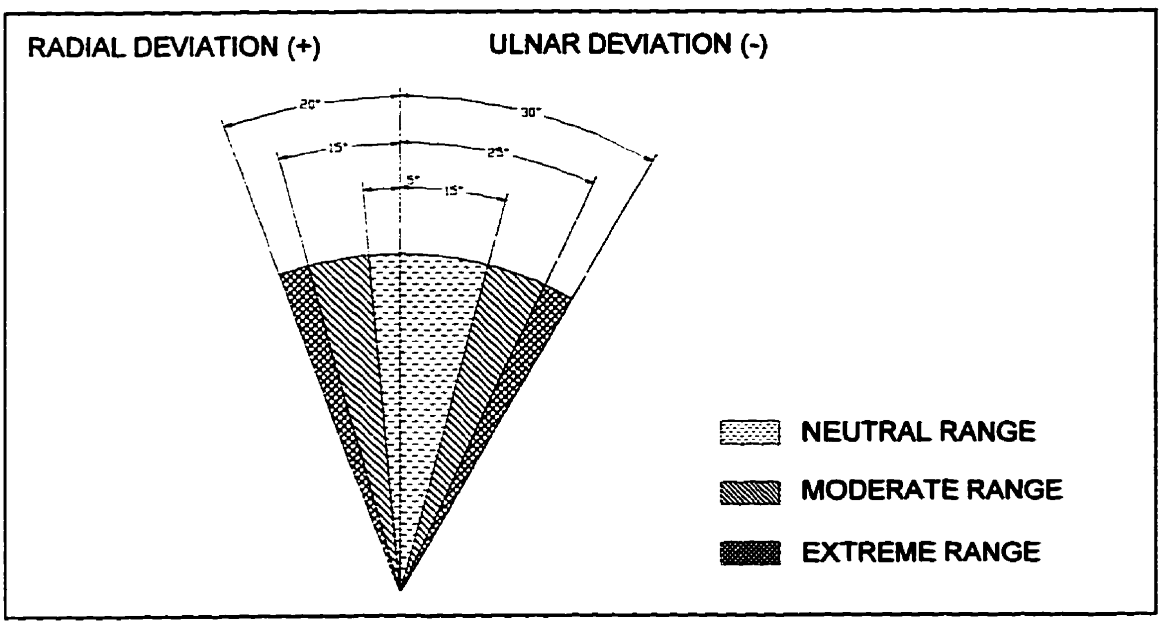


Figure 21. Classification of radial/ulnar deviation angle ranges.

3. 7 Assessment of Typing Productivity

Typing productivity is commonly defined as the number of correctly typed characters in a known time. In the current study, productivity was calculated from printouts of the entire text the subject typed during testing with time information being obtained from the videotaped record. The subject's productivity was calculated for each keyboard configuration using the following equation adopted from Smutz et al. (1994) :

$$P = ((C - 2E) / 5) * (60 / T)$$

where: P = productivity in words per minute
C = number of characters typed (5 characters/word)
E = number of errors made in characters
T = time duration in seconds

The number of characters typed included all characters and blank spaces in the text. It differed slightly across keyboards (535 for the OPEN, 565 for the FIXED and 544 for the standard) because one sentence was different in each testing text. All characters that were typed incorrectly (wrong place, missing word, no blank space, etc.) were considered errors. Visual control for the start and the end of the typing was obtained by following the use of the ENTER key on the video recording.

3. 8 Statistical Analysis

Pearson Product moment correlation coefficients were calculated to assess the test - retest reliability of digitizing using SigmaStat 1.0 (Jandel Scientific Software, San Rafael, California) statistical software.

In the ANGLES.BAS computer program the means and standard deviations for each hand position angle were calculated for all video frames in a trial. The mean angles served as a basis for comparing subjects and for establishing group means to compare hand position angles across the three keyboards.

Four One Way Repeated Measures of analysis of Variance tests (ANOVA) were performed to compare the three keyboards on the following: forearm pronation, wrist angle, extension/flexion angle and radial/ulnar deviation angle. ANOVA was also used to compare typing productivity and keyboard preference on the three keyboards. If the F ratio was significant the Student-Newman-Keuls method was used to make post hoc pairwise comparisons.

Pearson product moment correlation coefficients were calculated to describe the relationships between three keyboards within the same angle, and to describe relationships between typing productivity and keyboard preference (SigmaStat 1.0). The correlations were interpreted as follows (Weber and Limb, 1970):

$.90 < r < 1.00$	very high
$.70 < r < .89$	high
$.40 < r < .69$	modest
$.20 < r < .39$	low
$0 < r < .19$	slight

A two way ANOVA with repeated measures on both factors (three keyboards x five designated angle ranges) was used to compare the percent of time spent in different angle ranges for extension/flexion and radial/ulnar deviation.

The level of significance adopted for rejecting the Null Hypothesis was $p < 0.05$ for all statistical tests.

4 RESULTS AND DISCUSSION

In this chapter, after a consideration of measurement accuracy, the results are presented and discussed in terms of hand position, typing productivity and keyboard preference. Group data for a maximum of 16 and minimum of 13 subjects (please see the results and discussion of missing data) typing a test text on OPEN (FlexPro), FIXED (Microsoft Natural) and standard designs are presented and discussed, followed by a brief overview of significant individual cases. At the end of the chapter the findings are summarized.

4. 1 Measurement Accuracy

The accuracy of the calibration frame digitizing was assessed for each trial. Table 7 shows the average difference between the known coordinates of three to eight independent control points and the coordinates obtained by digitizing these points and processing them through the DLT. If the values of the independent control points differed more than 2 mm for Y and Z, or more than 6 mm for X, the calibration frame was redigitized until these tolerances were achieved. The greater discrepancy in the X coordinate was accepted because X represented the dimension that was out of the major plane of both camera views. Other investigators (e.g., Albert and Miller, 1996; Kofman, 1996; Shapiro, 1987) have also reported greater discrepancies in one of the three directions.

Table 7

Average difference between actual and calculated coordinates for independent control positions on the calibration frame [a]

	X (mm)	% of entire field of view	Y (mm)	% of entire field of view	Z (mm)	% of entire field of view
Mean	1.641	0.21	0.603	0.08	0.649	0.08
SD	(1.613)		(0.678)		(0.701)	

[a] Note. n = 37 control points over seven sessions.

Digitizing accuracy of the forearm and hand markers was assessed by test-retest reliability on a single trial. Results showed a very high correlation between coordinate pairs (Table 8). The correlation was below 0.95 in only three cases and these were related to the X coordinate. As mentioned previously, the X coordinate was not in the major plane of two camera views, so lower correlation and reduced accuracy might be expected.

Table 8
Test-retest reliability coefficients for anatomical point coordinates based on one trial on a standard keyboard [a]

Points	X	Y	Z
1	0.979	1.000	0.987
2	0.871	0.989	0.968
3	0.950	1.000	0.981
4	0.980	1.000	0.991
5	0.981	1.000	0.993
6	0.876	0.980	0.953
7	0.841	0.985	0.979

[a] Note. n = 310 video frames

Test-retest reliability coefficients were also calculated for a trial in which the midwrist point (pt. 5) was not visible in the video record. It therefore had to be estimated in every frame during digitizing. The results for the point showed very high and high correlation in the Y (0.94) and the Z (0.84) directions but only a modest correlation in the X direction (0.59). The latter was considered unacceptable (Table 9). Consequently two trials in which the midwrist point was not visible were eliminated from the analyses of radial/ulnar deviation and forearm pronation angles. The trials were retained for the calculation of wrist angle and wrist flexion/extension angle since pt. 5 was not involved in these calculations.

Validity of the computed anatomical angles, calculated through custom software which translated and rotated the coordinate system, was examined first by analyzing data obtained from four rigid body models with known angles, and by using drawings in three planes on millimeter paper. The calculated angles were within three degrees of their measured values. This difference was accepted because of the difficulty in obtaining

Table 9
Test-retest reliability coefficients for anatomical point coordinates based on one trial on a SPLIT keyboard when midwrist point (pt. 5) was not visible [a]

Points	X	Y	Z
1	0.930	1.000	0.980
2	0.968	1.000	0.987
3	0.983	1.000	0.989
4	0.843	0.990	0.955
5	0.594	0.940	0.838
6	0.968	0.990	0.981
7	0.903	0.986	0.972

[a] Note. n = 355 video frames

precise angle measurements on the physical models. Second, wrist angles calculated by the APAS from the original digitized point coordinates were compared with the same angles calculated from the translated and rotated coordinates. The values were identical. Third, elbow coordinates in the translated and rotated system were verified to be x = segment length, y = 0, z = 0. Finally, logical checks were made between the calculated angles and the videotaped records of the trials.

These procedures verified that the digitizing and subsequent computations produced accurate estimates of the anatomical angles related to hand position.

4. 2 Hand Position

Hand position on the three keyboards was assessed in the terms of average pronation of the forearm and wrist angle with the latter being further decomposed into extension/flexion and radial/ulnar deviation contributions (Table 10). Individual angle values for each subject were represented by the average for that angle over all video frames analyzed for a particular trial. The number of video frames included in these calculations ranged from 299 to 631.

4. 2. 1 Pronation

Zero pronation was defined by the forearm on the table surface with the hand vertically oriented palm inward. Ninety degrees of pronation occurred when the palm touched the table surface. The number of subjects included in the analysis of forearm

Table 10

Means and standard deviations for forearm and wrist angles for all subjects on the three keyboard designs

Subject	Pronation [+] (deg)			Extension [+] / Flexion [-] (deg)			Radial[+] / Ulnar[-] deviation (deg)		
	OPEN	FIXED	STAN.	OPEN	FIXED	STAN.	OPEN	FIXED	STAN.
AS	38.2	56.4	61.5	26.7	17.2	27.7	11.4	7.8	8.4
	(2.8)	(5.4)	(5.6)	(2.8)	(2.7)	(3.0)	(2.5)	(4.9)	(7.3)
CW	28.5	45.1	51.9	11.3	7.9	20.1	2.0	-3.4	-4.6
	(3.0)	(5.3)	(4.8)	(4.3)	(4.3)	(5.3)	(4.1)	(6.3)	(7.2)
CZ	43.1	57.1	62.0	13.5	-9.6	5.4	-	-	-
	(2.4)	(3.0)	(3.4)	(4.9)	(4.5)	(5.1)	-	-	-
DB	19.9	46.2	51.2	18.5	12.1	20.8	14.7	-0.8	0.1
	(1.9)	(3.8)	(4.0)	(3.1)	(3.0)	(3.3)	(3.4)	(4.8)	(4.7)
JR	35.8	55.1	51.8	2.3	-6.6	12.1	-7.6	-15.9	-15.3
	(4.1)	(3.8)	(6.7)	(4.6)	(3.8)	(4.1)	(3.9)	(3.4)	(6.4)
KH	47.0	-	-	0.8	0.8	-7.9	-9.0	-	-
	(3.0)	-	-	(4.4)	(8.7)	(7.5)	(8.0)	-	-
KP	20.4	47.5	54.0	19.9	9.1	24.9	15.7	5.6	7.2
	(3.8)	(4.6)	(7.6)	(3.3)	(2.3)	(2.1)	(3.5)	(5.3)	(5.0)
LH	33.6	46.6	51.2	-1.9	-0.1	13.1	2.3	1.9	0.1
	(2.1)	(4.8)	(5.8)	(3.0)	(3.2)	(3.6)	(1.8)	(4.2)	(8.4)
MG	48.3	61.0	72.4	-7.6	-4.0	7.5	3.7	-1.3	-10.4
	(2.7)	(7.3)	(8.0)	(2.7)	(3.3)	(3.0)	(1.5)	(4.0)	(7.4)
ML	38.6	60.1	65.8	-3.4	-11.7	1.3	-4.8	-9.3	-14.2
	(2.6)	(2.2)	(2.6)	(3.1)	(3.4)	(4.4)	(2.3)	(4.6)	(2.4)
PW	28.0	53.7	53.1	5.9	-2.4	11.2	1.6	-13.0	-20.1
	(3.3)	(3.4)	(8.9)	(3.6)	(3.5)	(5.0)	(2.2)	(3.2)	(6.0)
SL	23.2	42.3	45.2	10.8	8.7	24.3	5.8	3.0	2.8
	(3.0)	(3.8)	(6.0)	(4.0)	(4.0)	(4.7)	(3.4)	(2.8)	(5.5)
TG	24.5	51.7	56.1	7.9	-1.4	11.1	11.6	-0.6	-8.5
	(4.4)	(3.6)	(3.1)	(5.0)	(4.4)	(5.0)	(5.0)	(5.5)	(6.7)
VM	35.0	55.3	66.1	5.4	-3.0	6.0	6.5	-3.0	-13.3
	(3.3)	(3.0)	(4.4)	(2.8)	(6.7)	(3.1)	(3.0)	(8.1)	(8.8)
VP	31.1	49.1	54.0	12.0	2.8	13.3	5.3	-3.7	-14.3
	(2.2)	(2.0)	(2.0)	(3.6)	(3.1)	(3.2)	(3.0)	(6.5)	(3.7)
WM	42.0	-	-	-12.2	-15.0	-8.6	-6.1	-	-
	(1.9)	-	-	(4.1)	(3.1)	(4.8)	(2.6)	-	-

Note. Dashes indicate missing data

pronation was reduced from 16 to 14 because of inadequate visibility of the midwrist marker (Pt. 5) in the video records of the subjects KH and WM for the FIXED and standard keyboards.

The mean pronation angles associated with each of the three keyboards were significantly different (Appendix D, Tables 20 and 21) from one another. Forearm pronation was less when using the OPEN design (33.6°) than the FIXED (51.9°). The greatest pronation occurred when typing on the standard keyboard (56.9°) (Table 11). All subjects showed less pronation when typing on the OPEN than the FIXED keyboard. With the exception of JR and PW, all subjects also showed a modest decrease in pronation from the STAN to the FIXED designs (Figure 22).

Table 11

Means and standard deviations for average forearm and wrist angles on the three keyboard designs

AVERAGE ANGLE	N	OPEN	FIXED	STAN.
Pronation	14	33.6 (9.04)	51.9 (5.87)	56.9 (7.52)
Wrist angle	16	166.3 (6.55)	166.2 (5.11)	159.0 (4.61)
Extension (+) / flexion (-)	16	6.9 (10.4)	0.3 (8.95)	11.4 (10.77)
Radial (+) / ulnar (-) deviation	13	3.5 (7.87)	-2.5 (6.88)	-6.3 (9.28)

Note. All pairwise comparisons for a given angle were significantly different ($p < 0.05$)with the exception of the difference in wrist angle between OPEN and FIXED designs.

Average values of forearm pronation in the current study were similar to the results of Simoneau et al. (1996) who reported 60.9° on a standard, 55.8° on a fixed split angle (FIXED design) and significantly ($p < 0.01$) reduced pronation of 39.8° on a laterally inclined keyboard (similar to the OPEN design). Rempel et al. (1994) however reported 72° on a standard keyboard and 69° on a Microsoft Natural (FIXED design) showing a similar trend to that found in the current study despite a substantial difference

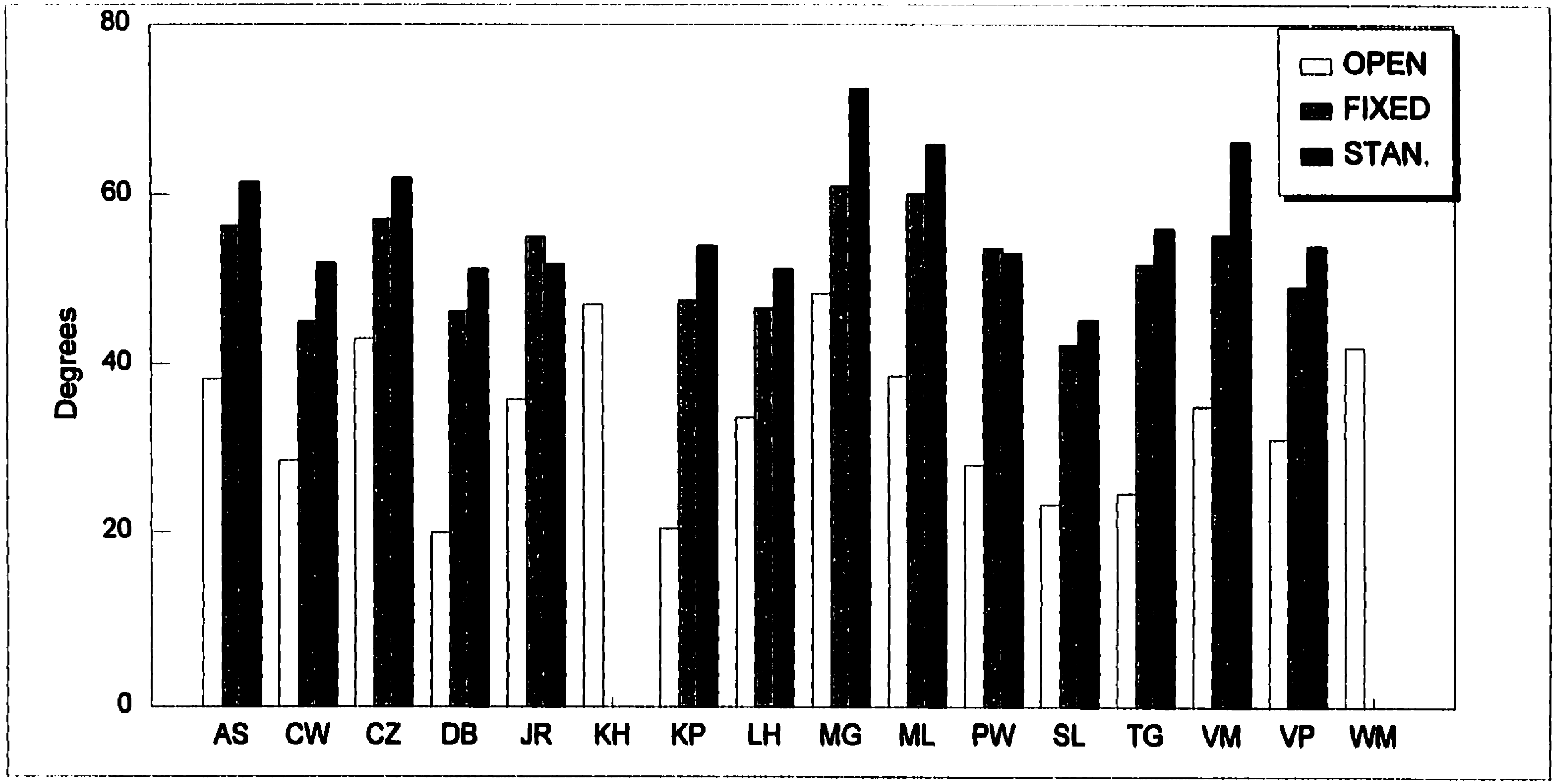


Figure 22. Average pronation angles for all subjects on the three keyboard designs.

in absolute values. The pronation of 82.7° on the standard keyboard reported by Serina et al. (1994) was much higher than in any other study.

The marked lateral inclination angle of the keys on the demiboards of the OPEN keyboard design (42°) prevented extreme pronation. This physically prevented the typist from pronating the forearm as much as on the other two keyboards. The FIXED keyboard featured a moderate 10° of lateral inclination that also reduced forearm pronation but to a lesser degree. By comparison, the flat layout of the standard keyboard kept the hands in extensive pronation.

4. 2. 2 Wrist angle

Average wrist angle, calculated from the spatial coordinates of the elbow, wrist and 5th metacarpal was similar for the OPEN (166.3°) and the FIXED (166.2°) keyboards but significantly (Appendix D, Tables 22 and 23) lower for the standard keyboard (159.0°). The larger average wrist angles noted when typing on both alternative keyboards may indicate a slight improvement in hand position towards a more neutral position compared to the lower average values on the standard keyboard (Figure 23).

To the investigator's knowledge wrist angle has not been reported previously in the literature. Most often wrist position was reported in terms of extension/flexion and radial/ulnar deviation which actually represent the decomposition of wrist angle into two independent planes of motion.

4. 2. 3 Extension - Flexion

Results indicated that on average subjects kept their wrists in slight extension while typing on two of the three keyboard designs. The mean value for wrist extension associated with the standard keyboard (11.4°) was significantly larger than average wrist extension on the OPEN (6.9°) which in turn was significantly larger than the average angle on the FIXED (0.3°) (Appendix D, Tables 24 and 25). The latter signified a nearly neutral wrist position in terms of extension/flexion (Table 11).

Examination of individual cases (Table 10) indicated that 14 subjects typed with the wrist extended on the standard keyboard, 12 on the OPEN and only 9 on the FIXED

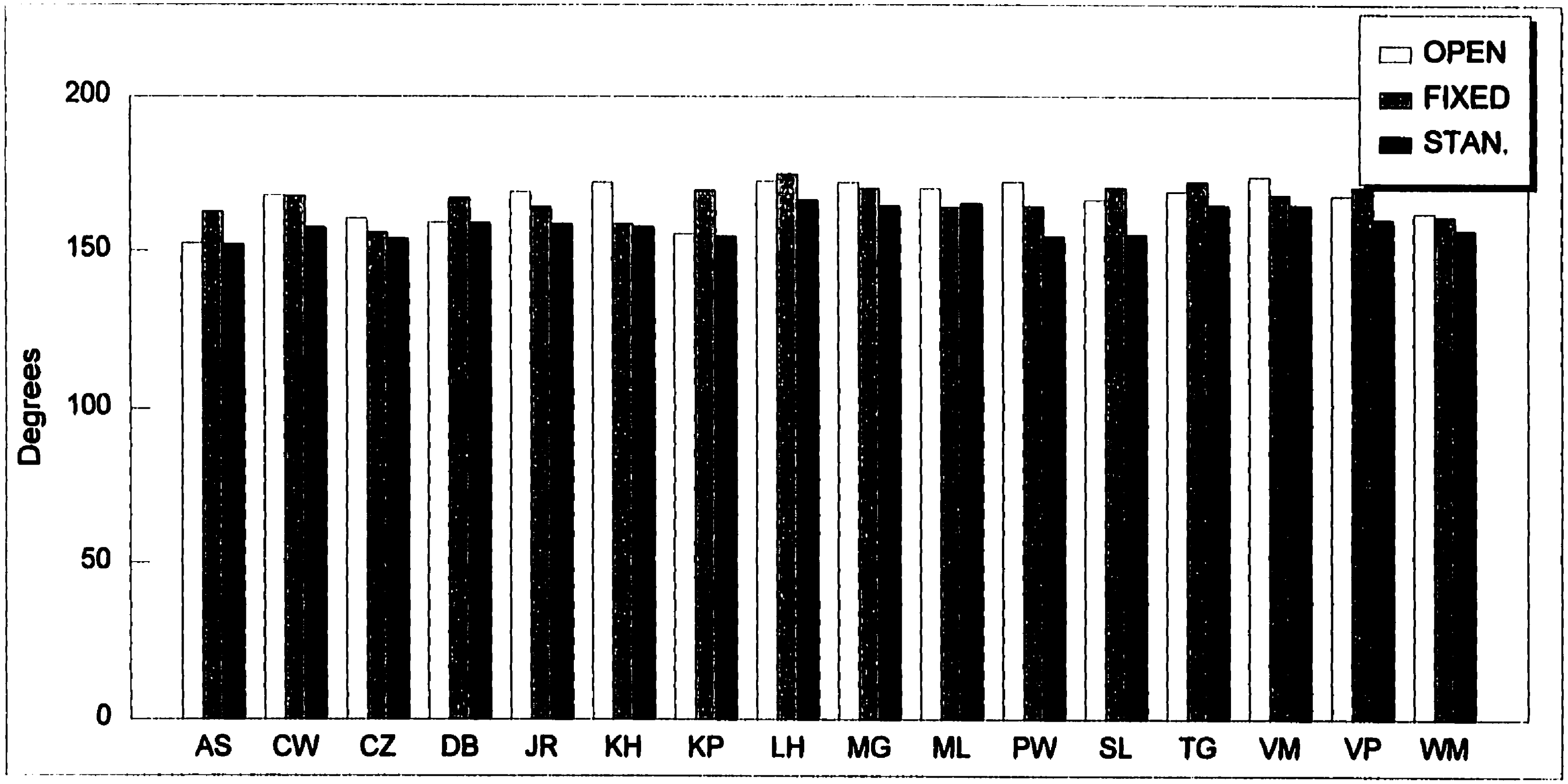


Figure 23. Average wrist angles for all subjects on the three keyboard designs.

design, indicating a trend toward reduced extension of the wrist on the alternative designs. Subjects who kept their wrists extremely extended (AS, CW, DB, KP, SL) or flexed (WM) on the standard keyboard, in spite of lower values, exhibited a tendency to retain similar hand positions on the two alternative keyboards (Figure 24). This might have reflected a strongly developed individual typing style that was transferred across keyboard designs.

Mean values for wrist extension while typing on the standard keyboard obtained in the current study were somewhat lower than the 11.7° to 21.8° range reported previously (Chen et al., 1994; Rempel et al., 1994; Serina et al., 1994; Simoneau et al., 1996; Smith and Cronin, 1993). The most probable reason for the discrepancy is methodological. In the studies cited, subjects were required to sit in an erect position, which resulted in an elbow angle of approximately 90°. In the current study, an attempt was made to simulate actual typing conditions in the workplace. Therefore, no controls were placed on the subject's posture or arm position. A qualitative analysis of the videotapes showed that 10 subjects kept the elbow flexed less than, three greater than and three close to 90°. The overall group tendency for greater elbow flexion may help to explain the lower mean values for wrist extension found in the current study.

Keyboard configuration also appeared to influence wrist extension. The flat standard design was less than 20 mm higher than the table surface on the side nearest the typist. The far side was elevated about 10° to improve key visibility. When typing on a standard keyboard, the fingers have to be moderately flexed to establish effective contact with the keys. Consequently, the wrist must be extended to allow enough operating space to accommodate finger flexion.

Reduced wrist extension while using the FIXED keyboard could be explained by the test setup and use of the wrist leveler in an up position. The wrist leveler raised the middle of the front edge of the keyboard approximately 35 mm. The large palm support area between the user and the keys presented a physical barrier that did not allow subjects to extend the wrists but rather forced the hand to float over, or to rest [the palm], on the support. Review of the video tapes showed that most subjects at least occasionally rested their palms on the support. With the wrist leveler in the up position the keyboard was

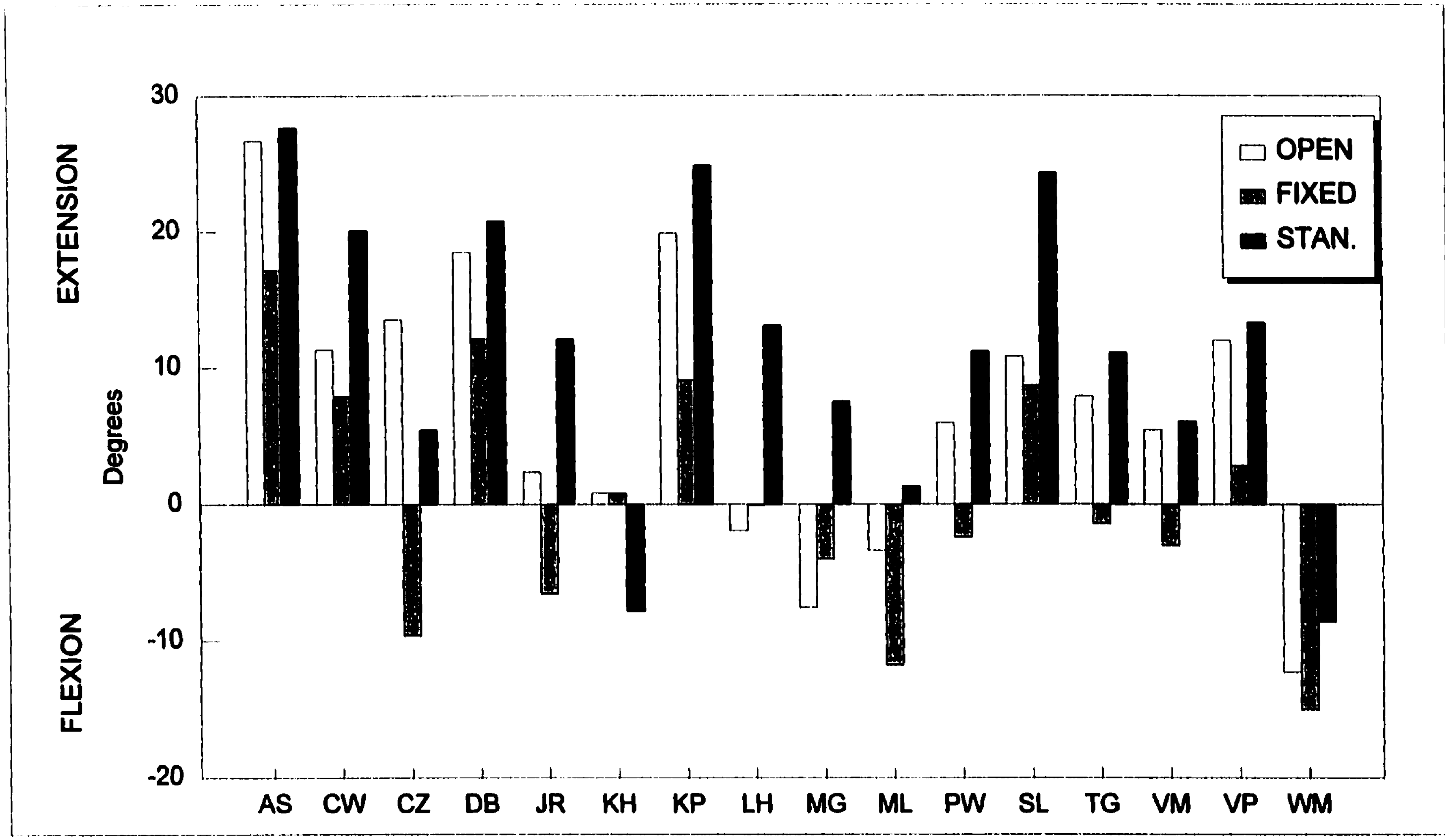


Figure 24. Average extension/flexion angles for all subjects on the three keyboard designs.

higher than and almost parallel to the table surface. All this contributed to reducing extension of the wrist while typing on the FIXED keyboard.

Average wrist extension when typing on the OPEN keyboard was less than on the standard keyboard but higher than on the FIXED. The demiboards on the OPEN design were rotated 15° in the horizontal plane. Consequently reduction in the wrist extension angle was due to a change in the orientation of the hand. The front side of the demiboard did not have a barrier similar to the palm rest on the FIXED that would stop wrist from extending. This might explain why some subjects retained extreme extension while typing on the OPEN design.

Both alternative keyboard designs positioned the hand in more neutral extension/flexion than did the standard keyboard. The FIXED keyboard placed the hand in the most neutral position, almost completely eliminating wrist extension.

4. 2. 4 Radial - Ulnar Deviation

The number of subjects included in the analysis of radial/ulnar deviation was 13 for the FIXED and the standard, and 15 for the OPEN keyboards. Due to reasons outlined previously, data from subjects KH and WM were not included. In addition the midforearm marker (pt. 4) was not positioned correctly on subject CZ. During the measurements CZ kept her forearm fully pronated (palm down) on the table surface. This flattened the soft tissues and actually increased forearm width compared to its width when unsupported. As point 4 was used to calculate radial/ulnar deviation the values for CZ were not considered sufficiently accurate to be included in this phase of the analysis.

Mean values for the radial/ulnar deviation angle indicated that subjects kept their hands ulnarly deviated while typing on the standard (-6.3°) and the FIXED (-2.5°) keyboards and radially deviated while typing on the OPEN (3.5°) (Table 11). All differences between keyboards were statistically significant (Appendix D, Tables 26 and 27). The FIXED significantly reduced ulnar deviation while the OPEN significantly increased radial deviation. Taking into consideration the smaller range of wrist motion towards the radius (20°) than towards the ulna (30°) (American Association of Orthopedic Surgeons, 1965), the FIXED keyboard could be considered the best of the three keyboards tested in keeping the wrist closest to the neutral position with respect to radial/ulnar deviation.

Individual cases for radial/ulnar deviation (Table 10) showed similar hand positioning on the FIXED and the standard keyboards with the angle on the FIXED being closer to neutral. On the FIXED and the standard keyboards four subjects kept the wrist in radial deviation and nine in ulnar deviation. By contrast, on the OPEN keyboard, eleven kept the wrist in radial, and four in ulnar deviation. Most subjects exhibited high values at one extreme or the other. As a result the average appeared to be in the neutral range for all keyboards (Figure 25). Three subjects (AS, KP and SL) had their hands in extreme radial deviation on all three keyboards. Comparison with the flexion/extension angle data for the same three subjects revealed that they also kept their wrists extremely extended. This might suggest a relationship between extreme wrist extension and extreme radial deviation. Unfortunately the number of cases was not sufficiently large to draw a firm conclusion.

The fact that the highest mean value for ulnar deviation was associated with the standard keyboard was expected due to previous findings (Serina et al., 1994) that typists tended to keep their hands much closer together than their elbows and that they covered the typing area by deviating the wrist toward the ulna. The FIXED design featured a split angle of 12° that forced hand rotation in the horizontal plane placing the wrist in a more neutral position. This was confirmed by the results. The marked lateral inclination angle on the OPEN keyboard substantially changed the orientation of the hand compared to the standard keyboard. The homerow orientation on the OPEN was switched from left-right to up-down thus increasing the height of the keys closer to the middle of the keyboard. Most subjects appeared to place the forearms parallel and close to the table surface requiring them to radially deviate their wrists in order to reach the higher keys.

The results obtained for radial/ulnar deviation in the current study were similar to the findings of Simoneau et al. (1996) who reported ulnar deviation of -9° for a standard keyboard, significantly ($p < 0.02$) reduced radial deviation of 0.3° for a keyboard similar to the FIXED and radial deviation of 5° for a keyboard similar to the OPEN. The mean values reported in other studies were higher. Rempel et al. (1994) reported -15° for

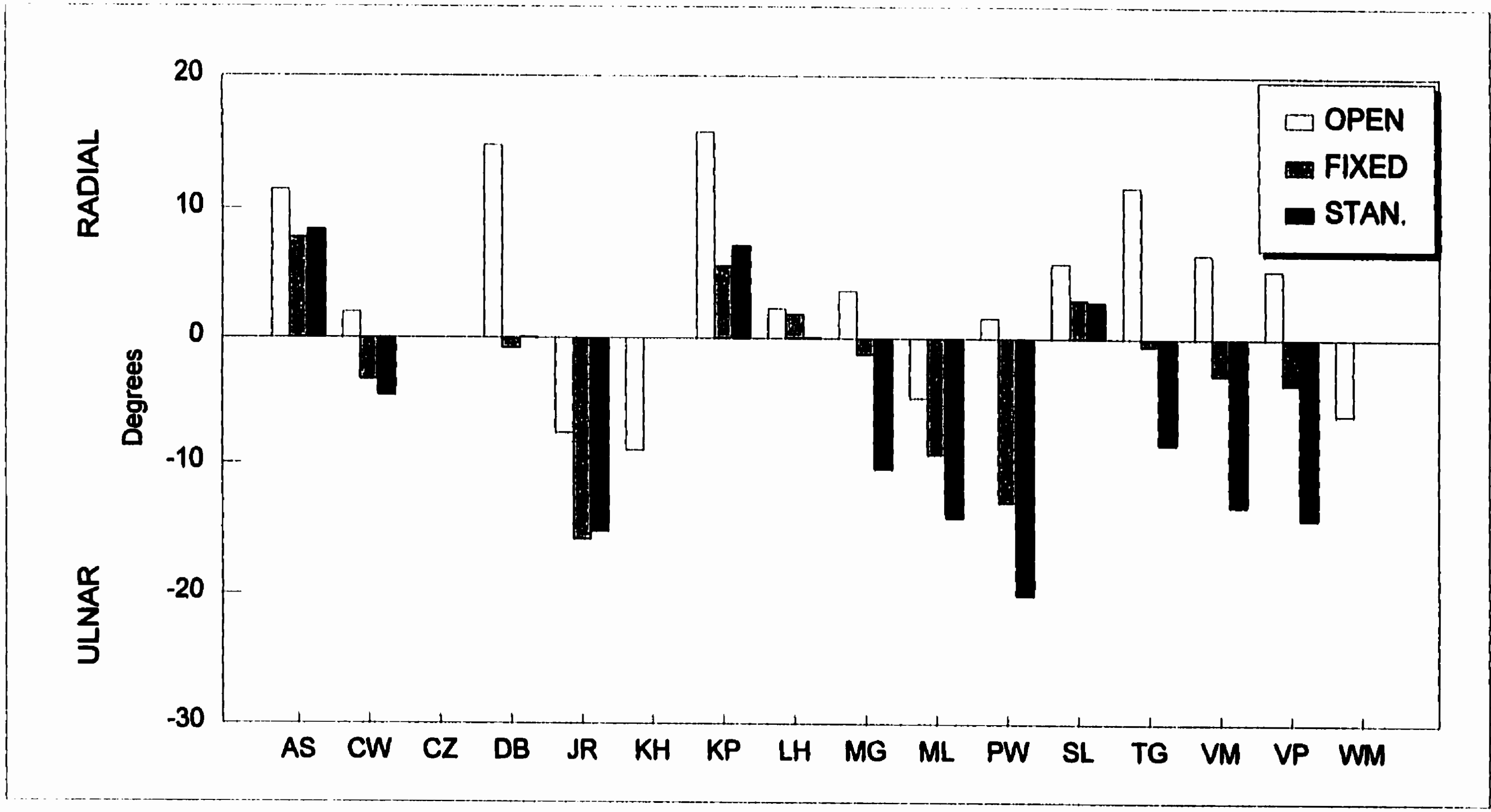


Figure 25. Average radial/ulnar deviation angles for all subjects on the three keyboard designs.

standard and -6° for Microsoft Natural (FIXED) keyboard which still indicated substantial reduction in ulnar deviation on the alternative design. Chen et al. (1994) reported ulnar deviation of -14.7° on the standard, -15° on the Apple Adjustable, -4.5° on the Kinesis and -13.5 on the Comfort keyboard. Of the four keyboards they tested the only one showing significantly reduced ulnar deviation was the Kinesis, which was similar to the FIXED design. The same pattern of reduced ulnar deviation on the alternative design is confirmed by the findings of Smith and Cronin (1993) who reported between -12° and -25° on the standard and -9° for Kinesis keyboards. The value of -18.4° ulnar deviation on the standard keyboard reported by Serina et al. (1994) is somewhat higher than in other studies. The lower mean values obtained in this study, compared to the cited studies, could be partially attributed to the difference in methodology.

An overview of the results for all planar components of the wrist angle indicated the possibility that wrist angle might serve as an initial indicator of hand position on an alternative keyboard design. It appeared that values of pronation, extension/flexion and radial/ulnar deviation closer to neutral (zero) resulted in an increased value of the wrist angle, bringing it closer to 180°. However, it would require numerous variable keyboard designs and a substantially larger pool of participants to clarify the role of this angle in the evaluation of a new keyboard design.

4. 2. 5 Angle Correlation Between Keyboard Designs

Pearson moment correlation coefficients between the three keyboards were calculated for each of the anatomical angles (Table 12). To estimate the predictive utility of the correlation coefficients the coefficient of determination (r^2 x 100) was also calculated (Weber and Limb, 1970).

The correlations for pronation angle between three keyboards varied from modest to high (0.62 - 0.78) and were higher between the standard keyboard and both alternative designs than between two alternative designs. The correlations for the wrist angle varied from low to modest (0.27 - 0.67) and none could be considered highly predictive. The correlations for extension/flexion (0.73 - 0.82) as well as for radial/ulnar deviation (0.80 -

0.88) were high. Observed correlations for radial/ulnar deviation could predict up to 77% of the variation in another keyboard.

Table 12
Coefficients of correlation and determination between three keyboard designs for forearm and wrist angles

Angle	Design	FIXED			STAN.		
		r	r^2x100	p	r	r^2x100	p
Pronation	OPEN	0.62	38%	0.011	0.78	61%	< 0.001
n = 14	FIXED	--			0.75	56%	< 0.001
Wrist	OPEN	0.27	7%	0.310	0.67	45%	0.004
n = 16	FIXED	--			0.54	29%	0.028
Extension / flexion	OPEN	0.80	64%	< 0.001	0.73	53%	< 0.001
n = 16	FIXED	--			0.82	67%	< 0.001
Radial / ulnar deviation	OPEN	0.86	74%	< 0.001	0.80	64%	< 0.001
n = 15 OPEN	FIXED	--			0.88	77%	< 0.001
n = 13 FIXED & STAN.							

The high correlations between keyboards for extension/flexion and radial/ulnar deviation provided support for observations of individual typing style. It appeared that the way a subject positioned the hand on the standard keyboard was transferred to the two alternative designs. It is possible, however, that ten hours of training were not sufficient to develop a specific style on the new designs. As Cakir (1995) mentioned, skilled typists have been trained to hold the arms and hands in very specific positions and they have been doing it for years. They have developed motor patterns that are difficult to change.

4. 2. 6 Time Spent in Designated Ranges of Motion

There are indications that the more time spent in an awkward posture, the greater the risk of developing musculoskeletal injury. Previous research suggested the importance of analyzing the temporal component of hand posture while typing on the computer keyboard (Armstrong, 1992; James, Harburn and Kramer, 1996; Karlqvist, Hagberg and Selin, 1994). To obtain this kind of information, five angle ranges for extension/flexion and radial/ulnar deviation were determined based on data from the literature, as outlined in Tables 5 and 6 and Figures 20 and 21 in the previous chapter. The number of video frames that the wrist was kept in each of the designated ranges was then determined and expressed as a percentage of total time.

The time spent in various extension/flexion angle ranges indicated that when subjects typed on the FIXED keyboard design the hand was predominantly in a neutral position. When typing on the OPEN and the standard keyboards, subjects tended to keep the wrist in moderate or extreme extension (Figure 26). Thus typing on the traditional keyboard design not only required placing the wrist in extension but also involved longer periods of time spent in that position thereby increasing the risk of developing musculoskeletal injury. On the OPEN design, risk for injury was somewhat reduced while on the FIXED design risk, as defined by time spent in the extreme angle ranges, it was almost eliminated. The statistically significant differences for the time spent in five ranges of extension/flexion were found only between the FIXED and the standard, and the OPEN and the standard pairs of keyboards for the neutral range, and between the FIXED and the standard pair of keyboards in the extreme extension angle (Appendix D, Tables 32 and 33). This indicated that, compared to the two alternative designs, the wrist tended to be in greater extension for a longer periods of time while typing on the standard keyboard.

An analysis of individual cases (Table 13) on the standard keyboard showed that three subjects typed with their wrists in extreme extension for almost the entire time, while another seven subjects typed with their wrists in moderate or extreme extension for most of the time. On the OPEN keyboard, moderate and extreme extension were noticeable for seven subjects. AS and DB were the only two subjects who kept their hand in moderate extension on the FIXED keyboard. On the contrary, subject WM kept her wrist in moderate flexion most of the time on the OPEN and the FIXED keyboards. AS exhibited the greatest extension and the longest time spent in extreme extension on all three keyboards possibly due to inappropriate chair height.

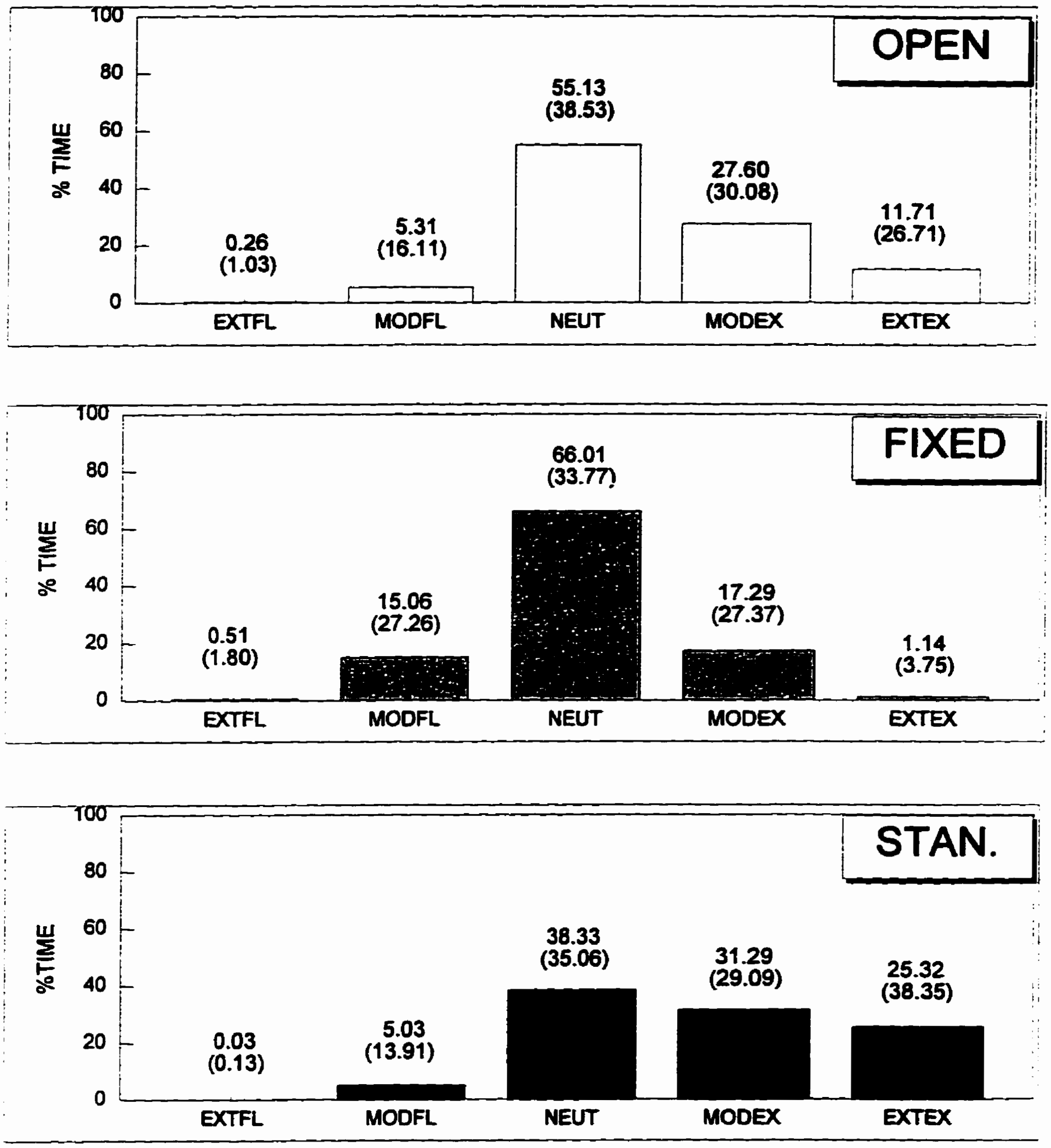


Figure 26. Group means for percentage of time spent in designated extension/flexion ranges. Standard deviations are indicated in parentheses.

Table 13

Percentage of time spent in designated extension/flexion ranges for all subjects on the three keyboard designs

Subject	Extreme Flexion (< -20°)			Moderate Flexion (-20° to -10°)			Neutral (-10° to +10°)			Moderate Extension (+10° to +20°)			Extreme Extension (>+20°)		
	OPEN	FIXED	STAN.	OPEN	FIXED	STAN.	OPEN	FIXED	STAN.	OPEN	FIXED	STAN.	OPEN	FIXED	STAN.
AS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	84.9	0.5	98.7	15.1	99.5
CW	0.0	0.0	0.0	0.0	0.0	0.0	40.0	66.5	4.6	58.7	33.5	39.3	1.3	0.0	56.1
CZ	0.0	1.0	0.0	0.0	45.7	0.0	22.2	53.3	83.0	70.8	0.0	16.0	7.0	0.0	1.0
DB	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27.9	0.0	70.0	71.0	41.8	30.0	1.1	58.2
JR	0.0	0.0	0.0	1.0	18.5	0.0	95.2	81.5	28.3	3.8	0.0	70.0	0.0	0.0	1.7
KH	0.0	0.0	0.0	0.3	9.1	46.0	97.7	72.8	48.5	2.0	17.1	4.5	0.0	1.0	1.0
KP	0.0	0.0	0.0	0.0	0.0	0.0	0.4	69.0	0.0	52.3	30.0	2.0	47.3	1.0	98.0
LH	0.0	0.0	0.0	0.5	0.0	0.0	99.5	100.0	21.9	0.0	0.0	76.6	0.0	0.0	1.5
MG	0.0	0.0	0.0	18.3	5.7	0.0	81.7	94.3	80.0	0.0	0.0	20.0	0.0	0.0	0.0
ML	0.0	0.0	0.0	1.5	65.6	0.0	98.5	34.4	95.4	0.0	0.0	4.6	0.0	0.0	0.0
PW	0.0	0.0	0.0	0.0	1.9	0.0	86.1	98.1	41.4	13.9	0.0	54.1	0.0	0.0	4.5
SL	0.0	0.0	0.0	0.0	0.0	0.0	41.0	61.9	0.0	58.0	38.1	21.0	1.0	0.0	79.0
TG	0.0	0.0	0.0	0.0	1.5	0.0	63.0	98.0	40.6	36.0	0.5	58.0	1.0	0.0	1.4
VM	0.0	0.0	0.0	0.0	4.0	0.0	94.4	96.0	90.0	5.6	0.0	10.0	0.0	0.0	0.0
VP	0.0	0.0	0.0	0.0	0.0	0.0	29.8	98.5	14.6	69.0	1.5	82.2	1.2	0.0	3.2
WM	4.1	7.2	0.5	63.3	88.9	34.5	32.6	3.9	65.0	0.0	0.0	0.0	0.0	0.0	0.0

The results of analyses of time spent in extreme ranges of radial/ulnar deviation indicated that the FIXED design kept the hand in a neutral posture most of the time, the standard in neutral and moderate ranges of ulnar deviation, while the OPEN design substantially increased the time spent in radial deviation (Figure 27). This could indicate a possibility of an increased risk of developing musculoskeletal problems of the hand when using the OPEN design. Statistically significant differences for time spent in the five ranges of radial/ulnar deviation were found between FIXED and standard keyboards for the neutral range, and between OPEN and FIXED, and OPEN and standard keyboards for moderate radial deviation range (Appendix D, Tables 34 and 35). This indicated that, compared with the other two designs, when typing on the OPEN keyboard design the wrist tended to be more radially deviated for a longer period of time.

Analysis of individual cases (Table 14) revealed that on the OPEN keyboard, seven subjects spent almost all their typing time in moderate and extreme radial deviation. On the standard keyboard two subjects spent most of the time in moderate radial deviation, while another two spent most of the typing time in moderate ulnar deviation. Very few extremes were recorded with the FIXED deign. Just two subjects (AS and KP) spent more than the half of their typing time in radial deviation while subject JR spent more than half of the time in ulnar deviation.

The findings suggest that keyboard design may influence the amount of time spent in neutral, moderate or extreme wrist positions. The design that successfully reduced the time spent in extremes, could be considered the most appropriate for reducing the risk of developing cumulative trauma disorders. To the investigator's knowledge, information about time spent in designated angle ranges on different keyboard designs has not been reported previously in the literature.

4. 3 Typing Productivity

Productivity was calculated in words per minute (wpm) from the printouts of the texts a subject typed during testing sessions and from the temporal information obtained from video recordings. Unfortunately the data for the OPEN and the standard keyboards for subject TG were not properly saved and therefore could not be included in this portion

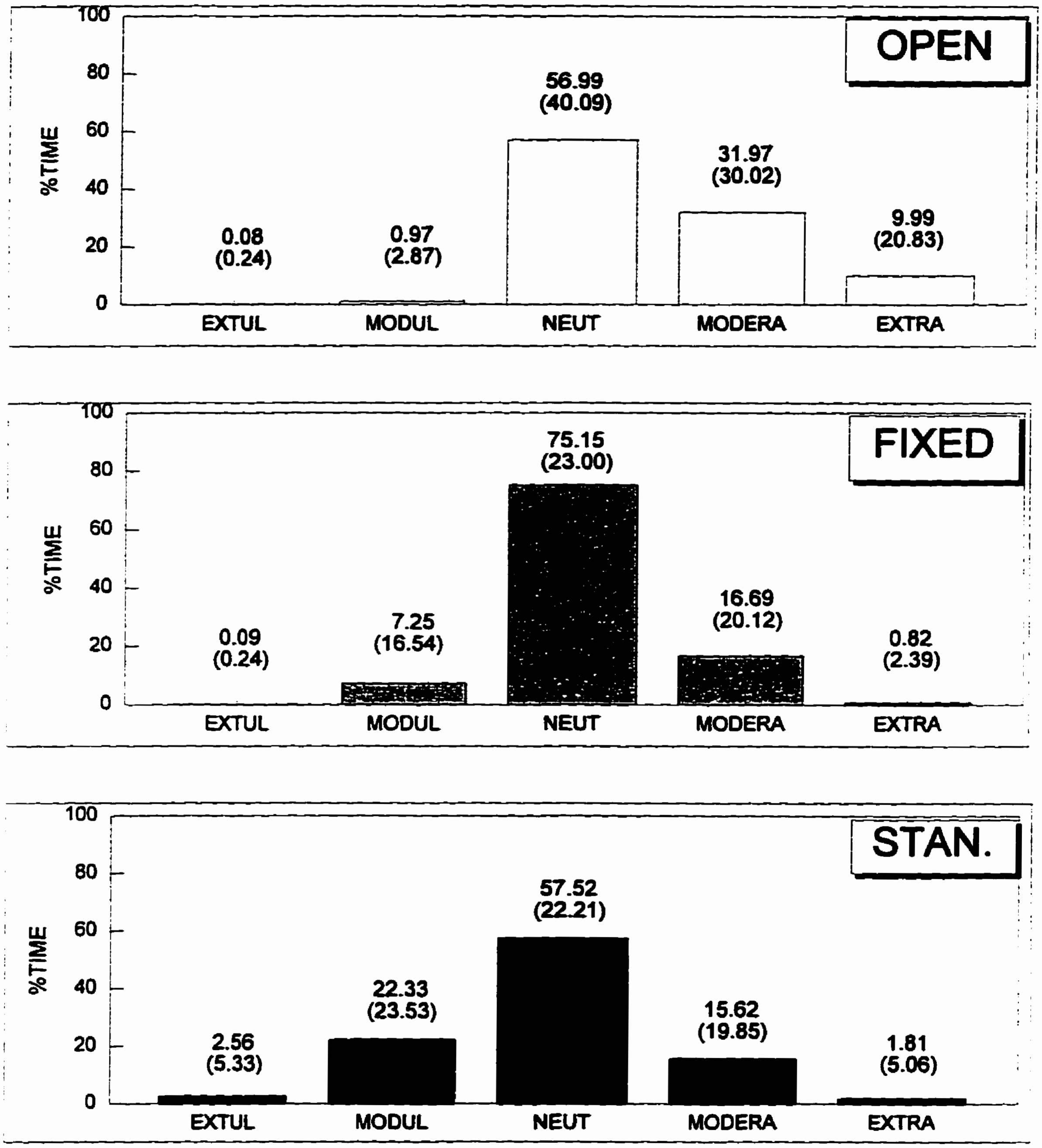


Figure 27. Group means for percentage of time spent in designated radial/ulnar deviation ranges. Standard deviations are indicated in parentheses.

Table 14

Percentage of time spent in designated radial/ulnar deviation ranges for all subjects on the three keyboard designs

Subject	Extreme Ulnar Deviation (< -25°)			Moderate Ulnar Deviation (-25° to -15°)			Neutral (-15° to +15°)			Moderate Radial Deviation (+5° to +15°)			Extreme Radial Deviation (>+15°)		
	OPEN	FIXED	STAN.	OPEN	FIXED	STAN.	OPEN	FIXED	STAN.	OPEN	FIXED	STAN.	OPEN	FIXED	STAN.
AS	0.0	0.0	0.0	0.0	0.0	0.6	2.0	30.2	36.2	90.8	61.3	45.4	7.2	8.5	17.8
CW	0.0	0.0	0.0	0.4	1.5	2.6	86.2	93.3	83.9	13.4	5.2	13.5	0.0	0.0	0.0
CZ	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DB	0.0	0.0	0.0	0.0	0.0	0.6	0.0	97.4	93.3	48.0	2.6	6.1	52	0.0	0.0
JR	0.9	0.8	6.3	2.8	58.2	44.6	96.3	41.0	49.1	0.0	0.0	0.0	0.0	0.0	0.0
KH	0.0	-	-	11.0	-	-	73.3	-	-	16.7	-	-	0.0	-	-
KP	0.0	0.0	0.0	0.0	0.8	0.5	1.0	45.7	35.1	34.4	51.3	58.7	64.6	2.2	5.7
LH	0.0	0.0	0.0	0.0	0.5	6.1	89.4	84.3	59.7	10.6	15.2	34.2	0.0	0.0	0.0
MG	0.0	0.0	0.0	0.0	0.0	23.2	84.9	99.5	72.5	15.1	0.5	1.3	0.0	0.0	0.0
ML	0.0	0.0	0.0	0.0	4.2	53.9	100.0	94.5	46.1	0.0	1.3	0.0	0.0	0.0	0.0
PW	0.0	0.4	19.0	0.0	23.1	62.8	96.1	76.5	18.2	3.9	0.0	0.0	0.0	0.0	0.0
SL	0.0	0.0	0.0	0.0	0.0	1.9	42.0	97.0	68.0	58.0	21.0	30.1	0.0	0.0	0.0
TG	0.0	0.0	1.0	0.0	0.4	9.0	8.3	88.1	85.5	66.3	11.5	4.5	25.4	0.0	0.0
VM	0.0	0.0	4.0	0.0	5.0	37.3	29.3	63.0	48.0	70.0	32.0	8.7	0.7	0.0	0.0
VP	0.0	0.0	0.0	0.0	0.5	47.2	47.6	84.5	52.2	52.4	15.0	0.6	0.0	0.0	0.0
WM	0.3	-	-	0.3	-	-	99.4	-	-	0.0	-	-	0.0	-	-

Note. Dashes indicate missing data

of the analysis. The results of the only subject (DB) who had previous experience on a FIXED keyboard were not eliminated from the study because she was consistent with group performance.

The difference in average productivity between each of three keyboards was statistically significant (Appendix D, Tables 28 and 29). It was highest on the standard keyboard (56.1 wpm), lower for FIXED (50.1 wpm) and lowest for OPEN (45.1 wpm) (Table 15). On the OPEN keyboard subjects thus reached 80%, and on the FIXED 89.3%, of their productivity versus the standard keyboard. Individual subject productivity across all keyboards tested varied between 27 and 74.5 wpm, with an average of 50 wpm for the group. The results for individuals indicated that subjects JR, KP, SL and VP were more productive on the FIXED design than on the standard keyboard (Figure 28). Only two subjects, AS and DB, were more productive on the OPEN than on the FIXED keyboard.

Many studies have detected a reduction in productivity on a keyboard design that was radically different from the traditional. Chen et al. (1994) indicated that subjects had an average typing speed of approximately 40-46 wpm for Comfort, Apple Adjustable and standard keyboard designs, and only 23 to 31 wpm for the Kinesis keyboard. Gerard et al. (1994) found that after two hours of typing on a Kinesis keyboard, the average typing speed did not reach more than 72% of speed compared with the standard keyboard. Smith and Cronin (1993) also found significantly higher text entry and letter throughput ($p < 0.05$) on the traditional versus the Kinesis keyboard. Cakir (1995) found a decrease in text throughput as the split angle between the halves of an adjustable keyboard was increased. When the angle was set at 15°, the throughput was 95% of the throughput on the conventional keyboard. When the split angle was set on 30°, throughput was less than 80%. The same author indicated that a reduction in performance of 20% decreased the probability of users' acceptance of any new type of equipment in a working conditions. Productivity would also be of primary importance for management. An alternative design that preserves high productivity and does not require a long training period, would have a better chance of acceptance.

Not unexpectedly, the results of the current study indicated that typists were most productive when using the standard keyboard. However, given the fact that they had only

Table 15

Typing productivity for all subjects on the three keyboard designs

Subject	OPEN (wpm)	FIXED (wpm)	STAN. (wpm)
AS	39.4	36.3	47.3
CW	45.5	57.8	69.4
CZ	46.0	50.0	59.7
DB	59.2	56.2	74.5
JR	34.9	38.5	38.2
KH	38.4	45.9	60.8
KP	32.1	41.6	38.5
LH	53.1	54.0	55.1
MG	27.0	38.5	46.4
ML	52.3	58.8	60.6
PW	57.5	58.1	69.1
SL	43.4	46.9	43.6
TG	--	45.7	--
VM	58.9	62.0	67.8
VP	36.6	45.9	45.2
WM	52.8	65.0	65.2
Mean	45.1	50.1	56.1
(SD)	(10.25)	(8.99)	(12.06)

Note. Dashes indicate missing data

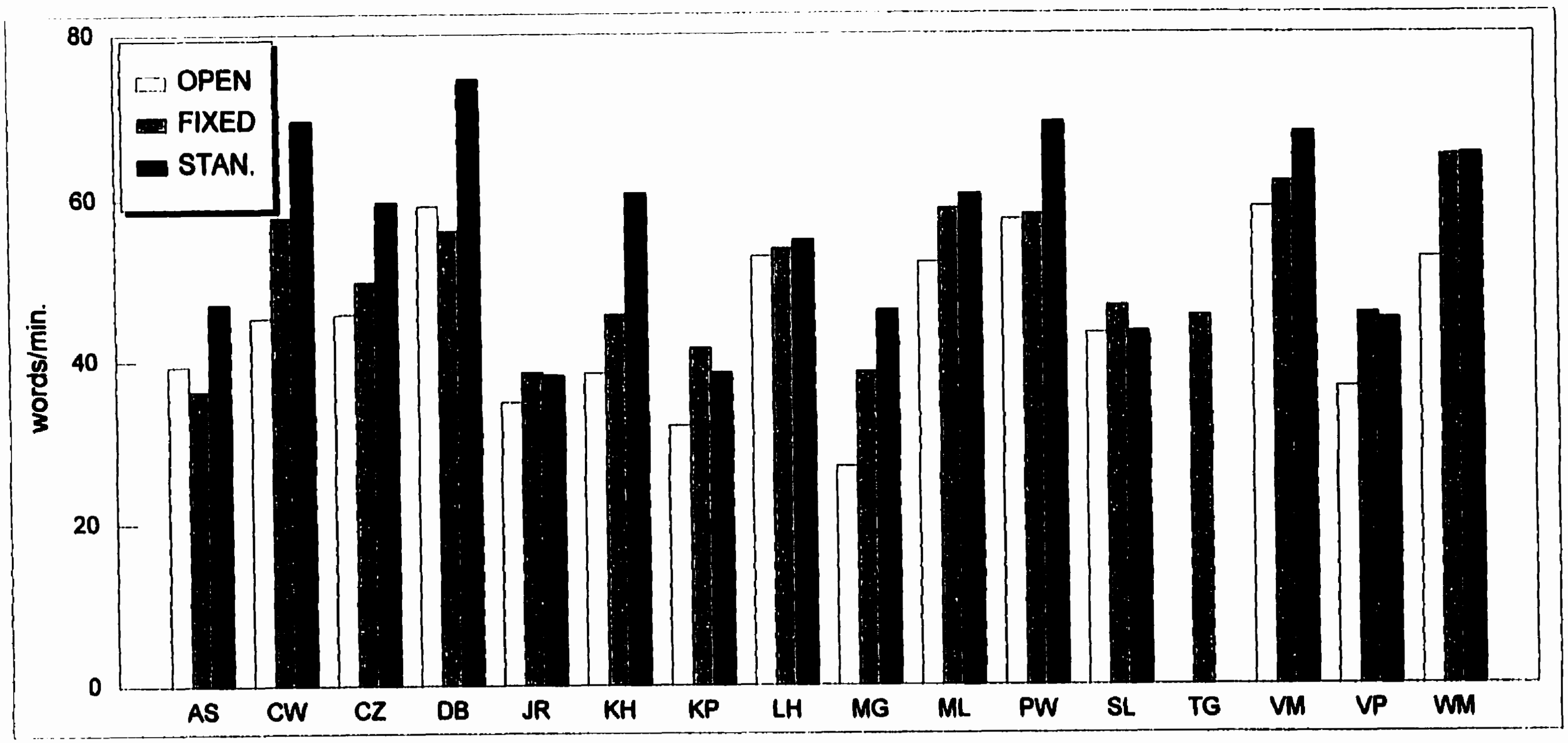


Figure 28. Productivity for all subjects on the three keyboard designs.

10 hours of practice on each of the alternative designs, a reduction of just 10% on the FIXED keyboard suggested that with additional experience, productivity on this keyboard might come close to, or perhaps even surpass, that on the standard keyboard. A decrease in productivity of 20% on the OPEN keyboard somewhat reduced its chances for user acceptance.

4. 4 Preference

Table 16 contains the scores subjects gave to all three tested keyboard designs on the 10-point numerical rating scale of preference. On average the standard keyboard scored 7.5, closely followed by the FIXED with a score of 7.1. The least preferred keyboard was the OPEN with a score of only 3.1. Preference for the FIXED and standard keyboards, over the OPEN keyboard was statistically significant, but there was no significant difference in preference between the FIXED and the standard designs (Appendix D, Tables 30 and 31). During data collection and discussions with participants in the study it was noted that users felt very strongly about the alternative designs, expressing both positive (accepting) and negative (rejecting) preferences. The ratings on the numerical rating scale were in many cases extreme, zero or ten.

Although the standard keyboard design received the highest average preference rating, half the subjects ranked one of the alternative designs better than the standard keyboard. The standard was rated as the most preferred by eight, the FIXED by six and the OPEN by only two subjects. The OPEN design was ranked last by 12 subjects compared with only four subjects giving the FIXED design this rating. The standard keyboard was not ranked last by any of the subjects indicating users' overall satisfaction with this keyboard design.

Preference for the standard keyboard was understandable, given the subjects' familiarity and extensive experience with it. A surprising finding was that there was no significant difference in subject preference between the standard and the FIXED keyboards. This high acceptance of the FIXED design may be explained by relatively conservative changes in keyboard features compared with the OPEN design. The FIXED keyboard improved wrist posture while preserving visibility of keys and design

Table 16

Subject preference for each keyboard design (scale 0 to 10)

Subjects	OPEN	FIXED	STAN.
AS	3	6	7
CW	0	7	10
CZ	0	6	9
DB	1	10	4
JR	0	10	7
KH	4	10	8
KP	7	4	5
LH	3	7.5	8
MG	2	8	5
ML	0	9	10
PW	6	3	8
SL	8	4	6
TG	3	7	10
VM	8	2	10
VP	3	10	8
WM	0	10	5
Mean	3.0	7.1	7.5
(SD)	(2.9)	(2.7)	(2.0)

similarity. Several comments of the subjects indicated that the size of the FIXED design might be a limiting factor in its acceptance by users with smaller hands, particularly women (Table 17).

The low preference of the OPEN keyboard can be attributed to a variety of factors. It was extremely unstable whenever a key was pressed. The wrist-rests were not steady, a factor which annoyed many subjects to the point that they requested the wrist-rests be removed during the testing sessions. The marked lateral inclination angle reduced the visibility of the keys. The orientation of the demiboards changed the way the keys were activated. Instead of a customary downward push, the force had to be exerted sidewise or inward. Some subjects could not accommodate to this change.

During the experiment one group of subjects moved to new offices and changed work loads. In the comment sheet, one subject from this group indicated that so many recent changes made it unlikely to accept a change of the keyboard at this time. This underlines the importance of a researcher being familiar with the overall working conditions of the participating subjects.

Results of keyboard preference in other studies were not similar. Rempel et al. (1994) reported that subjects preferred the standard keyboard over Microsoft Natural (FIXED) after a brief exposure to the new design. By contrast Chen et al. (1994) reported that, based on comfort and usability ratings, all three alternative keyboards tested were preferred to the standard flat keyboard.

Cakir (1995) indicated that the most important hindrance to the acceptance of ergonomically designed keyboards was the difficulty skilled typists had in learning new motor patterns. He suggested that adjustable keyboards should offer slow and continuous change that might increase the possibility of new design acceptance. The experience from this study was somewhat different. Most subjects expressed satisfaction with participating in the study because it gave them new insight into the options available and increased their awareness about the way they use a keyboard in everyday work. Within six months two participants persuaded their employers to purchase one of the alternative keyboards they tried in the experiment. One participant bought an ergonomic keyboard for her sons

Table 17

Subject's comments for preferring or disliking a keyboard design

Keyboard	Pro's	Con's
OPEN	Allows freedom of movement and a relaxed arm position; is comfortable while copy typing; has a natural feel.	Unable to type at usual speed; difficult to edit; demiboards are shaking, bouncing and springing-back; wrist rests are unstable and uncomfortable; difficult to find keys (e.g., backslash); function keys are in an awkward position; increased angle is frustrating; awkward hand position; difficult to find a good position for the fingers and wrists; a lot of strain is imposed on the body; pain in the hand while in contact with the wrist support.
FIXED	Able to type as well as on the standard; able to familiarize quickly; has good design, layout, rigidity, key shape and wrist rest; has attractive appearance; has comfortable wrist-support; easy to use; feels natural; reduces strain on the body; generally comfortable; allows comfortable position of upper body; allows longer periods of work without feeling discomfort.	Too big for small hands; stiff; too much space between keys; some keys have a different setup; too little difference compared with the standard design; feel occasional discomfort.
STAN.	Familiar; can achieve high accuracy and typing speed; easy to use; small hands can easily get to all keys; readily available on all workstations; the most comfortable.	Keeps hands too close together; too flat; the keys are too close together, limiting mobility; does not offer any wrist support; uncomfortable for the wrists; causes strain in forearms and wrists; long work periods on it are tiring.

at home even though she preferred the standard design. This indicated that some subjects became educated as to the benefits of some keyboards from their participation in the study.

The increase in errors during the period of familiarization also played a role in reducing acceptance of an alternative keyboard design (Cakir, 1995). In this study, a comparison of the number of errors for the three designs tested indicated a similar trend. The average number of typing errors was the highest (15.8) on the least preferred OPEN keyboard, lower (7.8) on the FIXED, and lowest (5.7) on the standard keyboard. Finally, correlations between typing productivity and keyboard preference were slight for all three keyboards (Table 18) indicating that productivity was not a good predictor of preference.

Table 18
Coefficients of correlation and determination for productivity and preference on the three keyboard designs

Keyboard		r	r^2x100	p
OPEN	n = 15	0.025	0%	0.929
FIXED	n = 16	- 0.086	1%	0.750
STAN.	n = 15	0.284	8%	0.306

4. 5 Summary of Results

Simultaneous observation of multiple alternative keyboards allowed them to be compared with one another and with the standard design. The following is a summary of the average group results for each of the variables tested in the current study. First, compared to the standard keyboard, the OPEN keyboard design on average reduced extreme forearm pronation by more than 23° while the FIXED design produced a moderate 5° reduction of forearm pronation. Second, both alternative keyboards also reduced wrist extension compared to the standard design. The average extension angle on the FIXED keyboard was close to zero reflecting substantial decrease compared to the OPEN and standard keyboards. Third, ulnar deviation of the wrist was highest on the standard, but was also noted on the FIXED design although in the latter case it was only half as large. On the OPEN design, an increase in radial deviation was most probably a result of the change in hand orientation while typing. As far as temporal variables were concerned, considerable typing time was spent in undesirable extension and ulnar deviation on the standard keyboard design, and in extension and radial deviation on the OPEN keyboard. On the FIXED design the wrist was positioned most of the time in more neutral or moderate ranges of extension/flexion and radial/ulnar deviation. Fourth, the results for two non-postural variables showed that typing productivity was best on the standard design, 10% reduced on the FIXED design and 20% reduced on the OPEN design. Finally, the subjects were not only more productive on the standard design, but this design was also rated highest on the preference scale. Surprisingly there was not significant difference in preference between the standard and the FIXED design. The OPEN design was poorly accepted by the subjects due to instability of the demiboards and reduced visibility of the keys. All factors taken into consideration, and recognizing the bias of the experimental design in favor of the standard keyboard, these results pointed to the superiority of the FIXED design.

5 SUMMARY AND CONCLUSIONS

The purpose of this study was to evaluate the influence of keyboard design on hand position, typing productivity and keyboard preference. These variables were assessed on two alternative designs, i.e., FlexPro (OPEN) and Microsoft Natural (FIXED), which were clearly distinguishable from the standard keyboard by their split, and from one another by the amount of lateral inclination of their left and right halves. The FIXED keyboard featured a split angle of 12° and a moderate lateral inclination angle of 10°. The user-adjustable OPEN keyboard was set on the 15° split which resulted in a marked 42° lateral inclination angle of the demiboards.

Sixteen right hand dominant typists, who completed 10 hours of training on both alternative keyboard designs prior to testing, participated in the study. Hand position was assessed using three dimensional video analysis. Reflective markers placed on designated anatomical landmarks of the right forearm and hand identified the points to be used in subsequent calculations of wrist orientation. Two camcorders recorded forearm and hand movements while the subject typed a designated text on each of the three keyboard designs. An Ariel Performance Analysis System (APAS) was employed to grab a designated video sequence involving only typing with the right hand. The APAS was also used to digitize the data points, transform their two sets of planar coordinates into spatial coordinates using the direct linear transformation algorithm, smooth the data and print output files. Approximately 400 frames were grabbed per trial at a rate of 20 Hz. Custom software was written to calculate average forearm pronation and wrist angles as well as wrist extension/flexion and radial/ulnar deviation components. Percent of time spent in designated angular ranges of motion was also calculated. Apart from postural measurements, typing productivity and keyboard preference were assessed for each keyboard design. Productivity was calculated in words per minute, taking into account the number of characters typed and the number of errors made in a known time. Keyboard preference was assessed using a 10 point numerical rating scale. Data obtained for hand position, typing productivity and preference for three keyboards were compared using one and two way repeated measures ANOVA and Pearson correlation coefficients.

The results indicated that, with the exception of wrist angle on the two alternative keyboards, forearm and hand postures while typing on the standard and two alternative keyboard designs were significantly different ($p < 0.05$) (Table 19). Both alternative designs placed the forearm and wrist closer to a neutral position than did the standard keyboard. More time was spent in neutral and moderate ranges of extension/flexion and radial/ulnar deviation when typing on the FIXED than on the OPEN or the standard keyboards. Comparison between the two alternative designs showed that the OPEN design, with demiboards inclined at 42°, was superior in reducing extensive pronation, whereas the FIXED, with only 10° of lateral inclination, had the advantage of keeping the forearm in moderate pronation while also keeping the wrist in the most neutral extension/flexion and radial/ulnar deviation. Compared to typing productivity when using standard keyboard, productivity was reduced approximately 10 % when typing on the FIXED design and 20% on the OPEN design. Although subjects generally expressed a strong preference for the standard keyboard no significant difference was noted between it and the FIXED design. Preference for the OPEN design, however, was significantly lower than for the FIXED or the standard.

Table 19
Summary of pairwise statistically significant differences ($p < 0.05$) between keyboards for all variables

Keyboards	Wrist Angle	Extension / Flexion Angle	Radial / Ulnar Deviation Angle	Pronation Angle	Productivity	Preference
OPEN-FIXED	NO	YES	YES	YES	YES	YES
OPEN-STAN.	YES	YES	YES	YES	YES	YES
FIXED-STAN.	YES	YES	YES	YES	YES	NO

Several limitations in the current study should be noted. First, the typing time involved in assessing performance on each keyboard was relatively short. Second, in an attempt to simulate the usual working conditions in the laboratory, no controls were placed on chair height or elbow angle. Third, only the wrist was observed. Potential influences of the more proximal joints of the arm were not monitored. It is possible that a relatively good position of the wrist was attained due to awkward angles of the elbow and shoulder joints. Fourth, only the dominant hand was observed, and differences between the dominant and non-dominant hand were not investigated. Additionally, the adjustability of the FlexPro keyboard was eliminated to introduce a common lateral inclination angle which was more extreme than the one on the FIXED design. Other adjustments of this keyboard by individual subjects may have resulted in better performances. Finally, several subjects exhibited similar hand positioning on all three keyboards tested. This could be an indication that ten hours of training was insufficient for subjects to develop a specific typing style on the two modified keyboard designs. Typing style, perfected through years of typing on the traditional keyboard, may have been transferred to the other two keyboard designs. For the same reasons, typing productivity and keyboard preference were also likely biased in favor of the standard keyboard.

Taking into consideration all elements of the evaluation (hand position, typing productivity and keyboard preference), and within the limitations of the study, the following conclusions for each keyboard design tested appear warranted. Because the standard keyboard placed and kept the hand in an awkward posture for a long period of typing time it is more likely to produce musculoskeletal injury. Although the OPEN keyboard design, with its demiboards set at a lateral inclination of 42°, reduced pronation of the forearm to the greatest extent, it also kept the wrist in substantial extension and radial deviation, thus reducing one postural risk factor and increasing the other. The FIXED keyboard, with its moderate design changes over the standard, was considered better than the other two because it was superior in placing and keeping the hand in a nearly neutral position, it was very well accepted, and subjects achieved almost 90% of their productivity on the standard keyboard. The FIXED design introduced several design innovations to the standard keyboard such as moderate split (12°) and lateral inclination (10°) angles, a large built-in wrist support and wrist leveler in the up position. Combined they produced observed improvements of wrist posture while typing. In general, it was concluded that a design that implements moderate changes to the standard keyboard layout, in terms of split and lateral inclination angles, has the potential to improve hand posture and thereby reduce the risk of developing cumulative trauma disorders of the wrist due to keyboard use.

This study provided new evidence concerning the effects that different keyboard designs have on the potential reduction in the risk of developing cumulative trauma disorders. Although these results suggest that some keyboard designs are a good solution for improving hand posture, individual typing technique should also be taken into account. Typing seems to be a very specific skill and improvements associated with some alternative designs do not necessarily apply to all typists.

Based on the results of this investigation of alternative keyboard designs several recommendations can be made. The typing surface on which the keyboard is placed should be adjustable vertically and should allow backward and forward tilt. Keyboards of different sizes should be available to accommodate different hand sizes. Keyboard angles should be adjustable but keyboard construction must be robust and stable. Individual preference of a new design should be respected and typists should not be forced to adopt designs against their will.

Further research into alternative computer keyboard designs could take several directions. It would be interesting to train several groups of novice typists on different designs and test their productivity. The groups could be observed longitudinally to obtain cumulative effects of different hand positions while typing and to record the occurrence of upper extremity musculo-skeletal problems. Finally, possible typing style transfer from one keyboard design to another deserves more attention. If typing style is highly automated, and therefore difficult to change, the question is should the existing pool of typists be of primary concern while planning keyboard designs, or should a posturally optimal keyboard design be introduced in training the new generation of typists?

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APPENDIX A:

Letter of information, consent form and Review Board Approval

The UNIVERSITY *of* WESTERN ONTARIO

Department of Occupational Therapy • Faculty of Applied Health Sciences

Revised: January 30, 1996

LETTER OF INFORMATION

"Study of Physical Work Behaviours, Psychosocial Factors and Quality of Life"

What is the purpose and what are the potential benefits of the study?
The study in which you are asked to participate is designed to evaluate the physical and psychosocial ways you perceive work-related stress, in order to try to understand the effects of work-related stress. In this regard, this study will evaluate the ergonomic difference(s) between three computer keyboards. This information may make a contribution to the understanding of work-related stress, which has physical and psychosocial stressors.

What are the procedures?
The testing procedure involves evaluating your work performance at work, or in the lab, using three different computer keyboards. You will need to practice on each of the two redesigned keyboards before actual testing takes place. You will also be asked about your attitudes and beliefs about certain components of your work with the keyboards. To evaluate your performance at work, you will be videotaped while working at your regular keyboard or at a redesigned keyboard (which we will provide you). We will also be using some physical assessments of your work station. You will also be asked to answer questions on several survey or interview forms. The practice sessions may cause your productivity to be lessened minimally. This effect has been approved and is understood by your supervisor(s). Permission for these practice sessions has been given by Lorraine Moore/Susan Garner/your supervisor ____________________.

How long will the testing take?
The videotaping will occur only during a few minutes of your work day or at your convenience. The videotaping camera, will be set up for assessing your movements after you have learned to use each redesigned keyboard and for a brief period of time while you are using your regular keyboard.

Are there any risks or discomforts associated with the tests?
There are no known physical or psychological risks associated with the above outlined procedures, which are commonly used in research and clinical settings.

Will your results be kept confidential?
The overall results of the study will be made available to you on request. Your individual results will be held in strict confidence and shared with you on request. No person other than the investigators will be given access to your records without your expressed permission. When the results are publically reported, individual records will be coded and recorded as group data.

Elborn College •London, Ontario •Canada •N6G 1H1 •Telephone: (519) 661-2175 • Fax: (519) 661-3894

What if you withdraw from the study?
Your participation is voluntary and you are entirely free to withdraw your consent to participate and discontinue the testing at any time and for any reason. You are also under no obligation to answer any survey or interview question that you may find objectionable or that may make you feel uncomfortable.

Who should you contact if you have questions?
Please feel free to contact Dr. Harburn (the study's Project Co-ordinator) at the address below, or by phone, to ask any questions you may have about the study.

Aleksandra Zecevic,
Masters level student,
Faculty of Kinesiology,
The University of Western Ontario,
London, Ontario.
(519) 679-2111 ext 8360

Dr. Karen L. Harburn, Project Co-ordinator,
Department of Occupational Therapy,
The University of Western Ontario,
London, Ontario.
(519) 679-2111 ext 8967

The UNIVERSITY of WESTERN ONTARIO

Department of Occupational Therapy • Faculty of Applied Health Sciences

CONSENT FORM FOR PARTICIPATION

Study of Physical Work Behaviours, Psychosocial Factors and Health

I____________________, have read the accompanying letter of information, have had the nature of the study explained to me, and I agree to participate. All questions have been answered to my satisfaction.

________________________ ____________________________________

Date Signature

Elborn College • London, Ontario • Canada • N6G 1H1 • Telephone: (519) 661-2175 • Fax: (519) 661-3894

The UNIVERSITY of WESTERN ONTARIO

Vice-Provost • Health Sciences • Health Sciences Centre

REVIEW BOARD FOR HEALTH SCIENCES RESEARCH INVOLVING HUMAN SUBJECTS

1995-96 CERTIFICATION OF APPROVAL OF HUMAN RESEARCH

ALL HEALTH SCIENCES RESEARCH INVOLVING HUMAN SUBJECTS AT THE UNIVERSITY OF WESTERN ONTARIO IS CARRIED OUT IN COMPLIANCE WITH THE MEDICAL RESEARCH COUNCIL OF CANADA "GUIDELINES ON RESEARCH INVOLVING HUMAN SUBJECT."

1995-96 REVIEW BOARD MEMBERSHIP

THE REVIEW BOARD HAS EXAMINED THE RESEARCH PROJECT ENTITLED:
"Physical work behaviours, psychosocial variables and quality of life."

REVIEW NO: E3981R

AS SUBMITTED BY: Dr. K. Harburn, Occupational Therapy, Elborn College

AND CONSIDERS IT TO BE ACCEPTABLE ON ETHICAL GROUNDS FOR RESEARCH INVOLVING HUMAN SUBJECTS UNDER CONDITIONS OF THE UNIVERSITY'S POLICY ON RESEARCH INVOLVING HUMAN SUBJECTS.

APPROVAL DATE: 01 February 1996 (change in study title)

AGENCY: MRC

TITLE:

Bessie Borwein, Chairman

c.c. Hospital Administration

APPENDIX B:

Testing text

Testing text for FlexPro keyboard

M F S W

Please type your code name and the letter marked on the top of this page (e.g., az12f)
ENTER

All existing joists of every size supplied by this company are of junk quality.

ENTER
ENTER

hop junk nip lump ply no hip lupin kin non hum mop jump junk hilly pony

ENTER

An experienced English speaker realizes that jargon is the very quintessence of bad form in writing. Like all business correspondence answers to complaints should be courteous, cheerful, tactful, clear complete, and brief.

ENTER
ENTER

you pull no milk mull up you pop nul punk bill only oil hunk mum moon pully

ENTER

Many analysts predict that nearly half of Japanese homes will have PSs by the year 2000.

Using mouse open "File"
Choose "Save as..."
Type your code name and the letter marked on the top of this page (e.g., az12f)
Press "OK"

Testing text for Microsoft Natural keyboard

M F S W

Please type your code name and the letter marked on the top of this page (e.g., az12m)
ENTER

An experienced English speaker realizes that jargon is the very quintessence of bad form in writing.

ENTER
ENTER

hop junk nip lump ply no hip lupin kin non hum mop jump junk hilly pony

ENTER

Like all business correspondence answers to complaints should be courteous, cheerful, tactful, clear complete, and brief. All existing joists of every size supplied by this company are of junk quality.

ENTER
ENTER

you pull no milk mull up you pop nul punk bill only oil hunk mum moon pully

ENTER

The Japanese launch of Windows 95 was delayed partly because of difficulties of adapting the program to the language.

Using mouse open "File"

Choose "Save as..."

Type your code name and the letter marked on the top of this page (e.g., az12m)

Press "OK"

Testing text for standard keyboard

M F S W

Please type your code name and the letter marked on the top of this page (e.g., az12s)

ENTER

The Windows 95 could be the catalyst that pushes many homes into the computer age.

ENTER

ENTER

hop junk nip lump ply no hip lupin kin non hum mop jump junk hilly pony

ENTER

All existing joists of every size supplied by this company are of junk quality. An experienced English speaker realizes that jargon is the very quintessence of bad form in writing.

ENTER

ENTER

you pull no milk mull up you pop nul punk bill only oil hunk mum moon pully

ENTER

Like all business correspondence answers to complaints should be courteous, cheerful, tactful, clear complete, and brief.

Using mouse open "File"

Choose "Save as..."

Type your code name and the letter marked on the top of this page (e.g., az12s)

Press "OK"

Warm-up text

M F S **W**

Please type your code name and the letter marked on the top of this page (e.g., az12w)

ENTER

After several years of under - performance compared with US market, some Canadian stocks are set to shine.

ENTER

ENTER

ok nip hunk juhu mho hum jolly phony plum limn mom ply loop mop non

ENTER

Raspberry juice, when mixed with lime juice and stirred with a swizzle stick, has quite a good flavor. In democracy, personal effort is significant.

ENTER

ENTER

best gaze test scarf gad water tug downtown holly hip pip plum phony joy jolly

ENTER

Investors in Canada stocks who've kept the faith during dismal year should be rewarded in 1996 - provided they are selective.

Using mouse open "File"

Choose "Save as..."

Type your code name and the letter marked on the top of this page (e.g., az12w)

Press "OK"

APPENDIX C:

Listings of custom software

```
'======================================================================
'
'
'            Program TRANSFO.BAS is developed by
'                 Aleksandra Zecevic
'                   Graduate student
'                 Faculty of Kinesiology
'               University of Western Ontario
'
'
'======================================================================

'Last revised Jan 2, 97.
'Program TRANSFO.BAS consists of: coordinate input, translation of the
'origin to the wrist, calculation of the pronation angle,
'rotation of the coordinate system (using direction cosines) to forearm,
'multiplication of the original coordinate values with direction cosines
'matrix, output of the new coordinate values in the file .COR that will be
'used in ANGLES.BAS, and the output of the pronation angle.
'Raw coordinates were obtained from Ariel's file .WKS. Velocity and
'acceleration were deleted in Lotus. The position data were saved as .TXT,
'file to be used in this program.
'To make arrays as big as possible, points had to be renamed to count
'for zero available in BASIC. Therefore pt 1 became pt 0, pt 2 became pt 1, etc.
'Calculations are based on Andrews, J.G. (1993). Segment and joint orientations
' in 3D space [Tutorial]. 17 th Annual Meeting of the ASB, The University
'of Iowa; Iowa City, October 1993.


CONT:
DEFINT I-L

DIM C(5, 545, 4)
DIM PAB(545), PABA(545), PBBA(545), PSVE(545), PTETHA(545)
DIM V1X(545), V1Y(545), V1Z(545), V1MAG(545)
DIM V2X(545), V2Y(545), V2Z(545), V2MAG(545)
DIM V3X(545), V3Y(545), V3Z(545), V3MAG(545)
DIM V4X(545), V4Y(545), V4Z(545), V4MAG(545)
DIM PX(545), PY(545), PZ(545)
DIM QX(545), QY(545), QZ(545)
DIM RX(545), RY(545), RZ(545)
DIM NC(5, 545, 4)

COLOR 15
CLS
FILES "D:\ALEXKB\*.TXT"
PRINT
INPUT " PLEASE WRITE NAME OF THE FILE YOU WOULD LIKE TO USE:", NAME$
PRINT
file$ = "D:\ALEXKB\" + NAME$ + ".TXT"


'Determining total number of frames for the file
OPEN file$ FOR INPUT AS #7
```

```
    NFR = 0
    DO WHILE NOT EOF(7)
        INPUT #7, DUM
        NFR = NFR + 1
    LOOP
CLOSE #7
NFR = NFR / 20   '20 values per frame (frame #, time + x,y,z * 6 points)
PRINT "Number of frames = ", NFR

'Coordinate input
COLOR 11
OPEN file$ FOR INPUT AS #7
FOR J = 1 TO NFR
    INPUT #7, C(0, J, 0), C(0, J, 1)  'J = frame # and time from the pt 1
    FOR I = 0 TO 5                    'I = points (elbow, wrist, mtc5, midfoarm, midwrist, mtc3)
        FOR K = 2 TO 4                'K = x,y,z
            INPUT #7, C(I, J, K)
        NEXT K
    NEXT I
NEXT J
CLOSE #7

'======================================================================

'Linear transformation
'The program translates origin of the coordinate system to the point #1 (wrist),
' which becomes the origin of forearm (anatomical) coordinate system.
FOR J = 1 TO NFR
    X0 = C(1, J, 2)                   'wrist coordinates
    Y0 = C(1, J, 3)
    Z0 = C(1, J, 4)
    FOR I = 0 TO 5
        C(I, J, 2) = C(I, J, 2) - X0
        C(I, J, 3) = C(I, J, 3) - Y0
        C(I, J, 4) = C(I, J, 4) - Z0
    NEXT I
NEXT J

'Control print for input values (optional)
'FOR I = 0 TO 5
'  FOR J = 1 TO NFR
'    FOR K = 0 TO 4
'        PRINT USING "#######.##"; C(I, J, K);
'    NEXT K
'    PRINT
'  NEXT J
'INPUT A$
'NEXT I

'======================================================================

'Calculating pronation angle using vector wrist-midwrist and vector
'wrist-y axis (x and y are the same as for midwrist, but z value is 0)
FOR J = 1 TO NFR
```

```
  PAB(J) = (C(4, J, 2) * C(4, J, 2)) + (C(4, J, 3) * C(4, J, 3)) + (C(4, J, 4) * 0)
  PABA(J) = SQR((C(4, J, 2) ^ 2) + (C(4, J, 3) ^ 2) + (C(4, J, 4) ^ 2))
  PBBA(J) = SQR((C(4, J, 2) ^ 2) + (C(4, J, 3) ^ 2) + 0)
  PSVE(J) = PAB(J) / (PABA(J) * PBBA(J))
  PTETHA(J) = (ATN((1 - (PSVE(J) ^ 2)) ^ .5 / PSVE(J))) * (180 / 3.141593)
  PTETHA(J) = 90 - PTETHA(J)           'vertical is zero, read angle from zero
  PRINT J; PTETHA(J)
NEXT J
INPUT A$
MAXP = PTETHA(1)
MINP = PTETHA(1)
    FOR J = 1 TO NFR
        IF PTETHA(J) > MAXP THEN MAXP = PTETHA(J)
        IF PTETHA(J) < MINP THEN MINP = PTETHA(J)
    NEXT J
SUMPTETHA = 0
KTR = 0
    FOR J = 1 TO NFR
        KTR = KTR + 1
        SUMPTETHA = SUMPTETHA + PTETHA(J)
    NEXT J
AVEPTETHA = SUMPTETHA / KTR
RANPTETHA = MAXP - MINP              'range of the angle

SUMSDPTETHA = 0                      'standard deviation
FOR J = 1 TO NFR
  SUMSDPTETHA = SUMSDPTETHA + (PTETHA(J) - AVEPTETHA) ^ 2
NEXT J
SDPTETHA = SQR(SUMSDPTETHA / (NFR - 1))


PRINT "   MINIMUM"; "   MAXIMUM"; "     RANGE"; "   AVERAGE"; "        SD"
PRINT USING "#########.#"; MINP; MAXP; RANPTETHA; AVEPTETHA; SDPTETHA
INPUT A$
INPUT A$

'=========================================================================
'Rotation
FOR J = 1 TO NFR
 CLS
 V1X(J) = C(0, J, 2) - C(1, J, 2)        'vector1 = wrist(1) to elbow (0)
 V1Y(J) = C(0, J, 3) - C(1, J, 3)        'unit vector (i)
 V1Z(J) = C(0, J, 4) - C(1, J, 4)
 V1MAG(J) = SQR((V1X(J)) ^ 2 + (V1Y(J)) ^ 2 + (V1Z(J)) ^ 2)

 V2X(J) = C(1, J, 2) - C(4, J, 2)        'vector2 = midwrist(1) to wrist (1)
 V2Y(J) = C(1, J, 3) - C(4, J, 3)        'makes lateral direction positive
 V2Z(J) = C(1, J, 4) - C(4, J, 4)
 V2MAG(J) = SQR((V2X(J)) ^ 2 + (V2Y(J)) ^ 2 + (V2Z(J)) ^ 2)

 V3X(J) = ((V1Y(J) * V2Z(J)) - (V1Z(J) * V2Y(J)))   'crossing v1 and v2 to
 V3Y(J) = -((V1X(J) * V2Z(J)) - (V1Z(J) * V2X(J)))  'get perpendicular unit
 V3Z(J) = ((V1X(J) * V2Y(J)) - (V1Y(J) * V2X(J)))   'vector (k)
 V3MAG(J) = SQR((V3X(J)) ^ 2 + (V3Y(J)) ^ 2 + (V3Z(J)) ^ 2)
```

```
  V4X(J) = ((V3Y(J) * V1Z(J)) - (V3Z(J) * V1Y(J)))   'cross product of v3 (k)
  V4Y(J) = -((V3X(J) * V1Z(J)) - (V3Z(J) * V1X(J)))  'and v1 (i) to get
  V4Z(J) = ((V3X(J) * V1Y(J)) - (V3Y(J) * V1X(J)))   'perpendicular unit vector (j)
  V4MAG(J) = SQR((V4X(J)) ^ 2 + (V4Y(J)) ^ 2 + (V4Z(J)) ^ 2)

'  PRINT USING "####"; J;
'  PRINT USING "#########.#"; V1MAG(J); V2MAG(J); V3MAG(J); V4MAG(J)
NEXT J

'              ==============================

  'To get the I,J,K scalar components of the unit vectors i,j,k (that correspond to
  'the positive x,y,z axes of forearm) each vector is devided with its
  'magnitude.
FOR J = 1 TO NFR
  PX(J) = V1X(J) / V1MAG(J)
  PY(J) = V1Y(J) / V1MAG(J)
  PZ(J) = V1Z(J) / V1MAG(J)

  RX(J) = V4X(J) / V4MAG(J)
  RY(J) = V4Y(J) / V4MAG(J)
  RZ(J) = V4Z(J) / V4MAG(J)

  QX(J) = V3X(J) / V3MAG(J)
  QY(J) = V3Y(J) / V3MAG(J)
  QZ(J) = V3Z(J) / V3MAG(J)
NEXT J
'              ==============================

'To obtain direction cosines one must find dot product of unit vectors and
'x,y and z of initial coordinates. The result will be rotational 3x3 matrix
'of direction cosines.
'In this case due to perpendicularity of the unit vectors, the direction
'cosines will be the same as the unit vectors.
'Multiplying the initial coordinates with the transposed matrix of direction
'cosines will give new set of coordinates for each point in the coordinate
'system of the forearm.

CLS
COLOR 14
KTR = 0
FOR I = 0 TO 5
  FOR J = 1 TO NFR
    KTR = KTR + 1
    NC(I, J, 2) = (C(I, J, 2) * PX(J)) + (C(I, J, 3) * PY(J)) + (C(I, J, 4) * PZ(J))
    NC(I, J, 3) = (C(I, J, 2) * RX(J)) + (C(I, J, 3) * RY(J)) + (C(I, J, 4) * RZ(J))
    NC(I, J, 4) = (C(I, J, 2) * QX(J)) + (C(I, J, 3) * QY(J)) + (C(I, J, 4) * QZ(J))
    NC(I, J, 0) = C(I, J, 0)
    NC(I, J, 1) = C(I, J, 1)
  NEXT J
NEXT I

'Printout of the values coming out of transformation (optional)
```

```
'FOR I = 0 TO 5
'  FOR J = 1 TO NFR
'     FOR K = 0 TO 4
'        PRINT USING "#####.###"; NC(I, J, K);
'     NEXT K
'     PRINT
'  NEXT J
'  INPUT A$
'NEXT I

'=====================================================================

'Output file for new set of coordinates
'The same organization of data as the .TXT coming from Lotus
OUTFILE$ = "D:\QB45\" + NAME$ + ".COR"
OPEN OUTFILE$ FOR OUTPUT AS #8
 FOR J = 1 TO NFR
     PRINT #8, USING "### "; C(0, J, 0);
     PRINT #8, USING "##.## "; C(0, J, 1);
     FOR I = 0 TO 5
        FOR K = 2 TO 4
           PRINT #8, USING " ####.#"; NC(I, J, K);
        NEXT K
     NEXT I
    PRINT #8,
 NEXT J
CLOSE #8


'Output file for values of pronation angle, same file name with
'letter P added at the beginning and with extension .TXT ready
'for statistical analysis (SigmaStat).
OUTFILE$ = "D:\QB45\P" + NAME$ + ".TXT"
OPEN OUTFILE$ FOR OUTPUT AS #11
PRINT #11, "PRONATION[deg]"
FOR J = 1 TO NFR
      PRINT #11, USING " #######.#"; PTETHA(J)
NEXT J
PRINT #11,
CLOSE #11

GOTO CONT
```

```
'=================================================================
'
'
'              Program ANGLES.BAS is developed by
'                   Aleksandra Zecevic
'                    Graduate student
'                  Faculty of Kinesiology
'                University of Western Ontario
'
'
'*****************************************************************************
'Last revised Jan 2, 1997.
'Program ANGLES.BAS is a part two of the calculation of the anatomical angles
'for the wrist. It uses transformed coordinates from the program TRANSFO.BAS
'This program calculates: spatial wrist angle (to check if values are the same
'as from APAS), ulnar/radial deviation angle and flexion/extension angle.
'Graphical presentation on the screen is included. Final product is
'the table  of min, max, ave, range and standard deviation for all angles.
'Two output programs will carry data to statistical software (SigmaStat) for
'further analysis

CONT:
DEFINT I-L

DIM NC(5, 545, 4)
DIM AB(545), ABA(545), BBA(545), SVE(545), TETHA2(545)
DIM FAB(545), FABA(545), FBBA(545), FSVE(545), FTETHA(545)
DIM UAB3(545), UABA3(545), UBBA3(545), USVE3(545), UTETHA3(545)
DIM GX(545), GY(545), HX(545), HY(545)


CLS
FILES "D:\QB45\*.COR"
INPUT " PLEASE INPUT NAME OF THE FILE YOU WOULD LIKE TO ANALYZE  ", NAME$
PRINT
FILE$ = "D:\QB45\" + NAME$ + ".COR"
OPEN FILE$ FOR INPUT AS #9
    NFR = 0
    DO WHILE NOT EOF(9)
        INPUT #9, DUM
        NFR = NFR + 1
    LOOP
CLOSE #9
NFR = NFR / 20
PRINT "NUMBER OF FRAMES   ", NFR
'INPUT A$


'Data input
COLOR 15
OPEN FILE$ FOR INPUT AS #9
FOR J = 1 TO NFR
    INPUT #9, NC(0, J, 0)
    INPUT #9, NC(0, J, 1)
```

```
     FOR I = 0 TO 5
          FOR K = 2 TO 4
               INPUT #9, NC(I, J, K)
          NEXT K
     NEXT I
NEXT J
CLOSE #9

'Control print of input values (optional)
'FOR I = 0 TO 5
'  FOR J = 1 TO NFR
'     FOR K = 0 TO 4
'          PRINT USING "######.##"; NC(I, J, K);
'     NEXT K
'     PRINT
'  NEXT J
'INPUT A$
'NEXT I

'*****************************************************************************

'Calculation of the spatial wrist angle between elbow and 5mcp to compare
'with output from APAS
FOR J = 1 TO NFR
  AB(J) = (NC(0, J, 2) * NC(2, J, 2)) + (NC(0, J, 3) * NC(2, J, 3)) + (NC(0, J, 4) * NC(2, J, 4))
  ABA(J) = SQR((NC(0, J, 2) ^ 2) + (NC(0, J, 3) ^ 2) + (NC(0, J, 4) ^ 2))
  BBA(J) = SQR((NC(2, J, 2) ^ 2) + (NC(2, J, 3) ^ 2) + (NC(2, J, 4) ^ 2))
  SVE(J) = AB(J) / (ABA(J) * BBA(J))
  TETHA2(J) = (ATN((1 - (SVE(J) ^ 2)) ^ .5 / SVE(J))) * (180 / 3.141593)
  IF TETHA2(J) < 0 THEN TETHA2(J) = TETHA2(J) + 180
'  PRINT TETHA2(J)
NEXT J
'INPUT A$

MAX = TETHA2(1)                         'detemining min, max and range
MIN = TETHA2(1)
     FOR J = 1 TO NFR
          IF TETHA2(J) > MAX THEN MAX = TETHA2(J)
          IF TETHA2(J) < MIN THEN MIN = TETHA2(J)
     NEXT J
SUMTETHA2 = 0
KTR = 0
     FOR J = 1 TO NFR
          KTR = KTR + 1
          SUMTETHA2 = SUMTETHA2 + TETHA2(J)
     NEXT J                             'calculation of average
AVETETHA2 = SUMTETHA2 / KTR
RANTETHA2 = MAX - MIN

SUMSDTETHA2 = 0
FOR J = 1 TO NFR                        'calc. of standard deviation
  SUMSDTETHA2 = SUMSDTETHA2 + (TETHA2(J) - AVETETHA2) ^ 2
NEXT J
SDTETHA2 = SQR(SUMSDTETHA2 / (NFR - 1))
```

```
'*****************************************************************************

'Determining ulnar-radial deviation angle using midforearm and midwrist vectors
FOR J = 1 TO NFR
   GX(J) = NC(3, J, 2) - NC(4, J, 2)
   GY(J) = NC(3, J, 3) - NC(4, J, 3)
   HX(J) = NC(5, J, 2) - NC(4, J, 2)
   HY(J) = NC(5, J, 3) - NC(4, J, 3)
   UAB3(J) = GX(J) * HX(J) + GY(J) * HY(J)
   UABA3(J) = SQR((GX(J) ^ 2) + (GY(J) ^ 2))
   UBBA3(J) = SQR((HX(J) ^ 2) + (HY(J) ^ 2))
   USVE3(J) = UAB3(J) / (UABA3(J) * UBBA3(J))
   UTETHA3(J) = (ATN((1 - (USVE3(J) ^ 2)) ^ .5 / USVE3(J))) * (180 / 3.141593)
   IF NC(5, J, 3) < NC(4, J, 3) THEN UTETHA3(J) = -UTETHA3(J)
'   PRINT UTETHA3(J)
'   INPUT a$
NEXT J
'INPUT A$

MAXU3 = UTETHA3(1)                         'detemining min, max and range
MINU3 = UTETHA3(1)
      FOR J = 1 TO NFR
            IF UTETHA3(J) > MAXU3 THEN MAXU3 = UTETHA3(J)
            IF UTETHA3(J) < MINU3 THEN MINU3 = UTETHA3(J)
      NEXT J
SUMUTETHA3 = 0
KTR = 0                                    'calculation of average
      FOR J = 1 TO NFR
            KTR = KTR + 1
            SUMUTETHA3 = SUMUTETHA3 + UTETHA3(J)
      NEXT J
AVEUTETHA3 = SUMUTETHA3 / KTR
RANUTETHA3 = MAXU3 - MINU3
                                           'calc. of standard deviation
SUMSDUTETHA3 = 0
FOR J = 1 TO NFR
   SUMSDUTETHA3 = SUMSDUTETHA3 + (UTETHA3(J) - AVEUTETHA3) ^ 2
NEXT J
SDUTETHA3 = SQR(SUMSDUTETHA3 / (NFR - 1))


'Calculation of time spent in 5 angle ranges for ulnar/radial deviation
U1 = 0
U2 = 0
U3 = 0
U4 = 0
U5 = 0
FOR J = 1 TO NFR
      IF UTETHA3(J) < -25 THEN U1 = U1 + 1
      IF UTETHA3(J) >= -25 AND UTETHA3(J) < -15 THEN U2 = U2 + 1
      IF UTETHA3(J) >= -15 AND UTETHA3(J) <= 5 THEN U3 = U3 + 1
      IF UTETHA3(J) <= 15 AND UTETHA3(J) > 5 THEN U4 = U4 + 1
      IF UTETHA3(J) > 15 THEN U5 = U5 + 1
```

```
NEXT J

SEC = NFR * .05                          'transfering frames into seconds
U1 = (U1 * .05)
U2 = (U2 * .05)
U3 = (U3 * .05)
U4 = (U4 * .05)
U5 = (U5 * .05)

'Screen printout of the values for each angle range
CLS
PRINT NAME$
PRINT "TOTAL TIME"; SEC
PRINT "    U1(<-25)  U2(-25,-15)  N3(-15,+5)  R4(+5,+15)  R5(>+15)"
PRINT USING "    #####.#"; U1; U2; U3; U4; U5

'****************************************************************************

'Determining Flexion-Extension angle between elbow and 5mcp
'PRINT "Flexion-extension = angle between elbow and 5mcp"
'PRINT "extension (+), flexion(-)"
FOR J = 1 TO NFR
  FAB(J) = (NC(0, J, 2) * NC(2, J, 2)) + (NC(0, J, 4) * NC(2, J, 4))
  FABA(J) = SQR((NC(0, J, 2) ^ 2) + (NC(0, J, 4) ^ 2))
  FBBA(J) = SQR((NC(2, J, 2) ^ 2) + (NC(2, J, 4) ^ 2))
  FSVE(J) = FAB(J) / (FABA(J) * FBBA(J))
  FTETHA(J) = (ATN((1 - (FSVE(J) ^ 2)) ^ .5 / FSVE(J))) * (180 / 3.141593)
  IF NC(2, J, 4) > NC(1, J, 4) THEN FTETHA(J) = -FTETHA(J)
'  PRINT FTETHA(J)
NEXT J
'INPUT A$

MAXF = FTETHA(1)                         'detemining min, max and range
MINF = FTETHA(1)
    FOR J = 1 TO NFR
        IF FTETHA(J) > MAXF THEN MAXF = FTETHA(J)
        IF FTETHA(J) < MINF THEN MINF = FTETHA(J)
    NEXT J
SUMFTETHA = 0
KTR = 0                                  'calculation of average
    FOR J = 1 TO NFR
        KTR = KTR + 1
        SUMFTETHA = SUMFTETHA + FTETHA(J)
    NEXT J
AVEFTETHA = SUMFTETHA / KTR
RANFTETHA = MAXF - MINF

SUMSDFTETHA = 0                          'calc. of standard deviation
FOR J = 1 TO NFR
  SUMSDFTETHA = SUMSDFTETHA + (FTETHA(J) - AVEFTETHA) ^ 2
NEXT J
SDFTETHA = SQR(SUMSDFTETHA / (NFR - 1))
```

```
'Calculaton of time spent in 5 angle ranges for flexion/extension
F1 = 0
F2 = 0
F3 = 0
F4 = 0
F5 = 0
FOR J = 1 TO NFR
     IF FTETHA(J) < -20 THEN F1 = F1 + 1
     IF FTETHA(J) >= -20 AND FTETHA(J) < -10 THEN F2 = F2 + 1
     IF FTETHA(J) >= -10 AND FTETHA(J) <= 10 THEN F3 = F3 + 1
     IF FTETHA(J) <= 20 AND FTETHA(J) > 10 THEN F4 = F4 + 1
     IF FTETHA(J) > 20 THEN F5 = F5 + 1
NEXT J

SEC = NFR * .05
F1 = (F1 * .05)
F2 = (F2 * .05)
F3 = (F3 * .05)
F4 = (F4 * .05)
F5 = (F5 * .05)

'Screen printout of the values for each angle range
PRINT NAME$
PRINT "TOTAL TIME"; SEC
PRINT "    F1(<-20)  F2(-20,-10)  F3(-10,+10)  F4(+10,+20)  F5(>+20)"
PRINT USING "    #####.#"; F1; F2; F3; F4; F5


'****************************************************************************

'Control screen print for all angles calculated  (optional)
'PRINT "          3D      U-RD3     FL-EX "
'FOR J = 1 TO NFR
'     PRINT USING "  #####.#"; J; TETHA2(J); UTETHA3(J); FTETHA(J)
'NEXT J
'INPUT A$

'Printing summary table for all angles
PRINT
PRINT
PRINT NAME$
PRINT "          3D      U-RD3    FL-EX"
PRINT "MINIMUM = "; USING "  ######.#"; MIN; MINU3; MINF
PRINT "MAXIMUM = "; USING "  ######.#"; MAX; MAXU3; MAXF
PRINT "RANGE   = "; USING "  ######.#"; RANTETHA2; RANUTETHA3; RANFTETHA
COLOR 14
PRINT "AVERAGE = "; USING "  ######.#"; AVETETHA2; AVEUTETHA3; AVEFTETHA
COLOR 15
PRINT "ST.DEV. = "; USING "  #####.##"; SDTETHA2; SDUTETHA3; SDFTETHA
INPUT A$


'****************************************************************************
```

```
'Graphic presentation of the hand in the forearm coordinate system
SCREEN 9
CLS
VIEW (0, 0)-(600, 30)
VIEW
WINDOW (-100, -100)-(400, 150)

CLS
FOR J = 1 TO NFR
    CLS
    LOCATE 1, 1: PRINT FILE$; J;
    PRINT "              Plane: X - Z"
    LOCATE 2, 1: PRINT "EXTENSION (+) / FLEXION (-) ANGLE =  ";
    PRINT USING "####.##"; FTETHA(J)
    LINE (NC(0, J, 2), NC(0, J, 4))-(NC(1, J, 2), NC(1, J, 4)), 14
    LINE -(NC(2, J, 2), NC(2, J, 4)), 14
    LINE (NC(3, J, 2), NC(3, J, 4))-(NC(4, J, 2), NC(4, J, 4)), 14
    LINE -(NC(5, J, 2), NC(5, J, 4)), 14
    LINE (NC(2, J, 2), NC(2, J, 4))-(NC(5, J, 2), NC(5, J, 4)), 14
    LINE (NC(1, J, 2), NC(1, J, 4))-(NC(4, J, 2), NC(4, J, 4)), 14
    CIRCLE (NC(2, J, 2), NC(2, J, 4)), 5, 13
    CIRCLE (NC(1, J, 2), NC(1, J, 4)), 4, 12
    CIRCLE (NC(1, J, 2), NC(1, J, 4)), 3, 12
    INPUT A$
NEXT J


FOR J = 1 TO NFR
    CLS
    LOCATE 1, 1: PRINT FILE$; J;
    PRINT "              Plane: X - Y  "
    LOCATE 2, 1: PRINT "RADIAL(+)/ULNAR(-) DEVIATION ANGLE = ";
    PRINT USING " ####.##"; UTETHA3(J)
    LINE (NC(0, J, 2), NC(0, J, 3))-(NC(1, J, 2), NC(1, J, 3))
    LINE -(NC(2, J, 2), NC(2, J, 3))
    LINE (NC(3, J, 2), NC(3, J, 3))-(NC(4, J, 2), NC(4, J, 3))
    LINE -(NC(5, J, 2), NC(5, J, 3))
    LINE (NC(2, J, 2), NC(2, J, 3))-(NC(5, J, 2), NC(5, J, 3))
    LINE (NC(1, J, 2), NC(1, J, 3))-(NC(4, J, 2), NC(4, J, 3))
    CIRCLE (NC(4, J, 2), NC(4, J, 3)), 5, 13
    CIRCLE (NC(1, J, 2), NC(1, J, 3)), 4, 12
    CIRCLE (NC(1, J, 2), NC(1, J, 3)), 3, 12

    INPUT A$
NEXT J

'*****************************************************************************

'Output files
'Printing angles into the file to be used for statistical analyis in SigmaStat
OUTFILE$ = "D:\QB45\A" + NAME$ + ".TXT"
OPEN OUTFILE$ FOR OUTPUT AS #10
PRINT #10, " NFR  TIME  3DANG  UL-/RA+  FL-/EX+ "
```

```
   FOR J = 1 TO NFR
      FOR K = 0 TO 1
         PRINT #10, USING "#####.##"; NC(0, J, K);
      NEXT K
      PRINT #10, USING "######.##"; TETHA2(J); UTETHA3(J); FTETHA(J)
   NEXT J
   PRINT #10,
CLOSE #10


'Output file for "time spent" data
OUTFILES$ = "D:\QB45\TS" + NAMES$ + ".TXT"
OPEN OUTFILES$ FOR OUTPUT AS #20
PRINT #20, " SUBJ  TIME  U1  U2  N3  R4  R5  F1  F2  F3  F4  F5"
PRINT #20, NAMES$;
PRINT #20, USING " ####.#"; SEC; F1; F2; F3; F4; F5; U1; U2; U3; U4; U5
PRINT #20,
CLOSE #20

GOTO CONT
```

APPENDIX D:

ANOVA tables

Table 20

One way ANOVA summary table for pronation angle

Source of variance	DF	SS	MS	F	p
Between keyboards	2	4852.1	2426.1	207.4	1.05E-016
Residual	26	304.2	11.7		

Table 21

Post hoc analysis, multiple comparison for pronation angle

Comparison	Diff. of Means	*p*	*q*	p < 0.05
OPEN - STAN.	24.86	3	27.20	Yes
OPEN - FIXED	4.94	2	5.40	Yes
FIXED - STAN.	19.93	2	21.80	Yes

Table 22

One way ANOVA summary table for wrist angle

Source of variance	DF	SS	MS	F	p
Between keyboards	2	557.3	278.7	17.5	9.38E-006
Residual	30	479.0	16.0		

Table 23

Post hoc analysis, multiple comparison for wrist angle

Comparison	Diff. of Means	*p*	*q*	p < 0.05
OPEN - STAN.	7.26	3	7.26	Yes
OPEN - FIXED	0.06	2	0.06	No
FIXED - STAN.	7.20	2	7.21	Yes

Table 24

One way ANOVA summary table for extension/flexion angle

Source of variance	DF	SS	MS	F	p
Between keyboards	2	995.7	497.9	23.9	6.26E-007
Residual	30	625.6	20.9		

Table 25

Post hoc analysis, multiple comparison for extension/flexion angle

Comparison	Diff. of Means	*p*	*q*	p < 0.05
OPEN - STAN.	11.09	3	9.72	Yes
OPEN - FIXED	4.53	2	3.96	Yes
FIXED - STAN.	6.57	2	5.75	Yes

Table 26

One way ANOVA summary table for radial/ulnar deviation angle

Source of variance	DF	SS	MS	F	p
Between keyboards	2	903.6	451.8	28.9	4.12E-007
Residual	24	375.7	15.7		

Table 27

Post hoc analysis, multiple comparison for radial/ulnar deviation angle

Comparison	Diff. of Means	*p*	*q*	p < 0.05
OPEN - STAN.	11.57	3	10.54	Yes
OPEN - FIXED	7.76	2	7.07	Yes
FIXED - STAN.	3.81	2	3.47	Yes

Table 28

One way ANOVA summary table for productivity

Source of variance	DF	SS	MS	F	p
Between keyboards	2	900.4	450.2	21.9	1.87E-006
Residual	28	575.3	20.5		

Table 29

Post hoc analysis, multiple comparison for productivity

Comparison	Diff. of Means	*p*	*q*	p < 0.05
OPEN - STAN.	10.95	3	9.36	Yes
OPEN - FIXED	5.23	2	4.47	Yes
FIXED - STAN.	5.73	2	4.89	Yes

Table 30

One way ANOVA summary table for preference

Source of variance	DF	SS	MS	F	p
Between keyboards	2	198.3	99.13	10.9	2.77E-004
Residual	30	272.9	9.10		

Table 31

Post hoc analysis, multiple comparison for preference

Comparison	Diff. of Means	*p*	*q*	p < 0.05
OPEN - STAN.	4.50	3	5.97	Yes
OPEN - FIXED	4.09	2	5.43	Yes
FIXED - STAN.	0.41	2	0.54	No

Table 32

Two way ANOVA summary table for time spent in designated ranges of extension/flexion angle

Source of variance	DF	SS	MS	F	p
Between keyboards	2	0.00	0.00*	15.48	< 0.0001
Designated angle ranges	4	81785.45	20446.36	15.08	< 0.0001
Keyboard x angle ranges	8	13653.73	1706.72	3.15	0.0028

* Error

Table 33

Summary table for [keyboard x designated angle ranges] interaction at each angle range for extension/flexion

	Comparison	Diff. of Means	*p*	*q*	p < 0.05
Extreme	FIXED - STAN.	0.48	3	0.09	No
Flexion	FIXED - OPEN	0.26	2	0.05	No
	OPEN - STAN.	0.23	2	0.04	No
Moderate	FIXED - STAN.	10.03	4	1.93	No
Flexion	FIXED - OPEN	9.75	3	1.88	No
	OPEN - STAN.	0.28	2	0.05	No
	FIXED - STAN.	27.68	3	5.32	Yes
Neutral	FIXED - OPEN	10.88	2	2.09	No
	OPEN - STAN.	16.80	2	3.23	Yes
Moderate	STAN. - FIXED	14.00	4	2.69	No
Extension	STAN. - OPEN	3.69	2	0.71	No
	OPEN - FIXED	10.31	3	1.98	No
Extreme	STAN. - FIXED	24.18	7	4.65	Yes
Extension	STAN. - OPEN	13.61	4	2.62	No
	OPEN - FIXED	10.57	4	2.03	No

Table 34

Two way ANOVA summary table for time spent in designated ranges of radial/ulnar deviation angle

Source of variance	DF	SS	MS	F	p
Between keyboards	2	359.1	179.6	2.18	0.1320
Designated angle ranges	4	95539.2	23884.8	33.26	< 0.0001
Keyboard x angle ranges	8	8152.4	1019.1	2.81	0.0072

Table 35

Summary table for [keyboard x designated angle ranges] interaction at each angle range for radial/ulnar deviation

	Comparison	Diff. of Means	*p*	*q*	p < 0.05
Extreme	STAN. - OPEN	2.14	6	0.47	No
Ulnar	STAN. - FIXED	2.14	5	0.47	No
Deviation	FIXED - OPEN	1.39E-017	2	3.07E-018	No
Moderate	STAN. - OPEN	18.39	8	4.06	No
Ulnar	STAN. - FIXED	13.07	5	2.89	No
Deviation	FIXED - OPEN	5.31	4	1.17	No
	FIXED - STAN.	15.28	3	3.38	Yes
Neutral	FIXED - OPEN	8.15	2	1.80	No
	OPEN - STAN.	7.13	2	1.58	No
Moderate	OPEN - STAN.	18.43	4	4.07	Yes
Radial	OPEN - FIXED	17.51	3	3.87	Yes
Deviation	FIXED - STAN.	0.92	2	0.20	No
Extreme	OPEN - FIXED	9.28	6	2.05	No
Radial	OPEN - STAN.	8.43	4	1.86	No
Deviation	STAN. - FIXED	0.85	3	0.19	No