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Finger motion, wrist motion and tendon travel as a function of keyboard angles

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Abstract

Objective. This study assessed the impact of keyboard angles (in terms of Pitch, Roll and Yaw) on tendon travel and wrist and finger joint kinematics for the flexor digitorum profundus and flexor digitorum superficialis.

Design. A repeated measures, laboratory study was conducted. Independent variables were three Pitch angles, three Roll angles, three Yaw angles, and three keyboard separation distances. Dependent variables were tendon travel, wrist deviation, wrist and finger joint kinematics, and Borg comfort rating.

Background. The increased usage of computers and the risk of cumulative trauma disorders have led to the development of alternate keyboards. This study is a biomechanical assessment of several keyboard designs.

Methods. Lightweight wrist and finger goniometers were used to measure motion of the wrist in three planes, and for three finger joints. Fifteen experienced typists (eight women, seven men) typed a standard text on 30 keyboard conditions. Regression equations were used to calculate tendon travel from joint positions.

Results. Tendon travel is sensitive to changes in Pitch, Roll and Yaw angles with ~13% difference between the minimal and maximal tendon travel. A flat keyboard produced more tendon travel than keyboards with greater Pitch and Roll angles.

Conclusions. There is a trade-off between wrist and finger positions; as the wrist extends more, the finger joints flex more to compensate. Keyboards imposed different trade-offs between the wrist and finger positions, affecting the overall tendon travel.

Relevance

Alternate keyboard designs can significantly affect tendon travel and may address reduced repetitiveness in typing by reducing the amount of tendon travel.

Keywords: Alternate keyboard; Carpal tunnel syndrome; Tendon travel; Wrist deviations; Musculoskeletal disorders; Flexor digitorum profundus; Flexor digitorum superficialis

1. Introduction

The explosive growth of personal computers remains unabated today. Dataquest [1] has estimated that in 1998, 50% of all US households had at least one computer, up from only 27% in 1995. The increased computer usage has raised concerns of potentially debilitating musculoskeletal disorders (MSDs) arising from the repetitiveness and long duration of keyboard operations. Work-related musculoskeletal disorders (WRMSDs) continue to affect computer users. The incidence rate for repeated trauma in 1996 was 276,600 cases, as reported by the Bureau of Labor Statistics [2].

Highly repetitive movements, high force requirements, and awkward sustained postures are well-recognized risk factors for WRMSDs such as carpal tunnel syndrome, tendinitis, and deQuervain's syndrome [3–8]. Furthermore, the highly repetitive nature of typing at a computer keyboard is also widely recognized; skilled typists can easily exceed 500 keystrokes per minute, for a rate of 30,000 keystrokes per hour of continuous typing. Although only a force of 0.47 N is required to activate a single key, studies have shown that the actual strike force ranges from 3.33 to 1.84 N [9]. The cumulative force has been estimated to be in the range of 3.7–14.4 kN*s/day [10]. The synergistic effect of multiple risk

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factors of force and repetition is more important than either risk factor alone [4].

The flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) muscles of the forearm are two major finger flexor muscles and are the only muscles involved in flexion of all four fingers [11]. Tendons of both the FDS and FDP pass through the carpal canal and are contained within a common sheath in the canal. Movement of the flexor tendons within the common sheath has been used as an indicator of biomechanical stress by several researchers. Moore et al. [12] used tendon excursion as one of the measurands for a repetitive and forceful task using a hand tool. Wells et al. [13] compared the amount of tendon travel for industrial workers and data entry clerks. Sommerich et al. [10] quantified the biomechanics of typing for 25 experienced computer users in three different occupational groups. The average tendon travel, normalized to 1 h of continuous typing, ranged from 30 to 59 m/h for the three groups. Researchers postulate that friction develops as a result of the repetitive sliding of tendons within their sheaths during the performance of highly repetitive activities such as typing. This friction may contribute to disorders of the tendons, their sheaths, or adjacent nerves [12,14], Goldstein et al. [15] demonstrated a traction effect in the flexor tendons within the carpal canal, and tendon blood flow has been shown to decrease as tendon tension increases [16].

Reports of operator discomfort and upper extremity MSDs [17,18] have been associated with computer workstation use. In response, manufacturers of keyboards are producing alternate keyboard designs such as those that split the keyboard, sometimes rotating the keyboard halves laterally as well as separating them horizontally. These changes stem from earlier research studies [19–21] which provided guidance on the design of split keyboards to reduce awkward positions of the wrists and forearms.

Early research looked at various keyboard-half rotations, but was limited in the biomechanical measures observed. Studies were generally limited to rough measurements of joint positions [22,23], muscle activity required to maintain static postures of the upper extremity [21,24], and subjective evaluations [20,25]. One biomechanically oriented study quantified continuous joint position, muscle activity, carpal tunnel pressure, and finger flexor tendon travel [26] but was limited to only one split keyboard condition. Thus, there is a lack of biomechanically based studies of the effect of keyboard modifications.

The aim of this study was to quantify the effect of various combinations of keyboard angles (in Pitch, Roll and Yaw) on biomechanical stressors, as measured by tendon travel, wrist deviations and joint kinematics during a standardized typing task. This study will provide information on whether different keyboard angles can reduce the degree of biomechanical stress, and if so, by what magnitude.

2. Methods

2.1. Approach

The approach of this study was to conduct a laboratory experiment in which wrist and finger motions were measured during a standardized typing task. Thirty combinations of keyboard Pitch, Roll and Yaw angles and separation distances of the keyboard halves were tested in random order. Tendon travel and kinematic variables were calculated to determine the effect of the keyboard modifications on biomechanical stressors.

2.2. Study participants

Fifteen volunteers participated in this experiment: eight women and seven men. They ranged in age from 19 to 50 yr, with a mean age of 31.5 yr. All were touch typists capable of typing at least 40 words per min (wpm) with a maximum error rate of 5%, and had no history of upper extremity disorders. Most had used a computer keyboard on a regular basis although none were employed in jobs primarily involving data entry work. They were informed of the purpose of the experiment and signed a consent form prior to testing. The experimental protocol had been reviewed and approved by the University's Human Subjects Committee.

2.3. Experimental design

The experimental design was a repeated measures design. The independent variables were Pitch angle (0°, 12.5°, 25°); Roll angle (0°, 15°, 30°), Yaw angle (0°, 15°, 30°) and Separation Distance (0, 9.2, 18.4 cm). Table 1 presents the different angles for the 30 test conditions. Changes in Pitch affect motion in the flexion/extension plane, changes in Roll affect pronation/supination, and changes in Yaw affect radial/ulnar motion. The separation distances were not crossed with the Pitch, Roll and Yaw angles since this would have created too many test conditions. Most of the test conditions used the 9.2-cm separation; this was chosen based on the minimal distance needed to test the 30° Yaw condition. The 0 cm separation was used in conjunction with a 7° Pitch (Condition 30) to represent the standard keyboard. Inclusion of a larger separation distance (18.4 cm) tested the effect of increased distance alone, without modifying Pitch, Roll and Yaw.

Dependent variables were tendon travel of the *profundus* and *superficialis* tendons, wrist deviations in the three planes of movement, and subjective comfort rating.

Table 1
Test conditions: keyboard configuration

Keyboard condition	Separation distance (cm)	Pitch (°)	Roll (°)	Yaw (°)
1	0	0	0	0
2	18.4	0	0	0
3	9.2	0	0	0
4	9.2	0	15	0
5	9.2	0	30	0
6	9.2	0	0	15
7	9.2	0	0	30
8	9.2	0	15	15
9	9.2	0	15	30
10	9.2	0	30	15
11	9.2	0	30	30
12	9.2	12.5	0	0
13	9.2	12.5	15	0
14	9.2	12.5	30	0
15	9.2	12.5	0	15
16	9.2	12.5	0	30
17	9.2	12.5	15	15
18	9.2	12.5	15	30
19	9.2	12.5	30	15
20	9.2	12.5	30	30
21	9.2	25	0	0
22	9.2	25	15	0
23	9.2	25	30	0
24	9.2	25	0	15
25	9.2	25	0	30
26	9.2	25	15	15
27	9.2	25	15	30
28	9.2	25	30	15
29	9.2	25	30	30
30	0	7	0	0

2.4. Apparatus

Lightweight and flexible wrist monitors were used to measure motion of the subject's right and left wrists. These monitors were developed in the Biodynamics Laboratory at Ohio State University [27]. They consist of two thin metal strips connected with a rotary potentiometer which measured the angle between the two metal segments; the output represented angle as voltage. One monitor was placed on the dorsal side of the wrist with the potentiometer centered on the wrist to measure movement in the radial/ulnar plane. The second monitor, on the lateral side of the wrist, measured movement in the flexion/extension plane. Pronation/supination motion was measured by a monitor attached to the distal and proximal ends of the forearm. The potentiometer measured rotation of the distal end of the forearm with respect to the stationary proximal end. The monitors were calibrated by positioning the wrists at several known angles and recording the voltages for these angles. Each of the six wrist monitors was calibrated separately. Six channels (three from each wrist) were connected to a 12 bit analogue-to-digital (A/D) converter board, which was connected in turn to a computer for data collection. A commercial data collection software was used (Global Lab Data Acquisition, Data Translation, Marlboro, MA, USA).

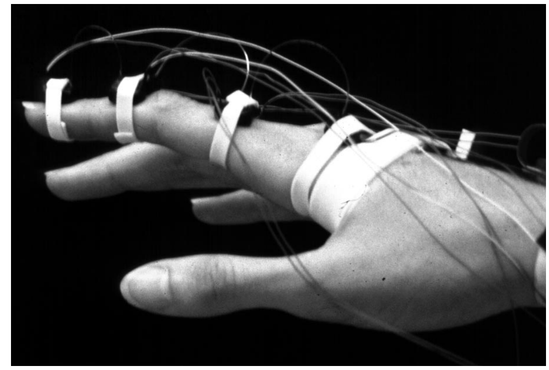

Fig. 1. Opto-electric finger monitors, for the MP, PIP and DIP joints.

Finger joint angles were collected using a small, lightweight opto-electric finger monitor which was also developed in the Biodynamics Laboratory [28]. The monitor was based on the principles of fiber optics and comprised an infrared LED emitter and receiver connected by an optical fiber. The emitter and receiver units were placed on either side of the finger joint of interest, with the optical fiber arching over the joint, as shown in Fig. 1. Changes in joint angle altered the curvature of the fiber which, in turn, affected the amount of light transmitted across the fiber. The greater the curvature of the fiber, lesser light was transmitted from the emitter to the receiver unit. Three finger monitors were used, one for each of the following joints of the left index finger: metacarpophalangeal joint (MP), proximal interphalangeal joint (PIP), and distal interphalangeal joint (DIP). Calibration involved placing each joint in a series of angles, ranging from 0° to 80° (with the exception of the DIP joint which was calibrated only to 70° due to the difficulty in bending this joint to 80°), and recording the voltage readings at each angle. The three finger monitors were calibrated separately in this manner. The three finger channels were connected to the same A/D board as the wrist monitors. The sampling frequency for the wrist and finger monitors was 300 Hz. The position data of the wrist and finger joints were subsequently processed to derive the velocity and acceleration values using Laplace transforms [29].

An adjustable keyboard (Comfort Keyboard System, Health Care Keyboard Company, Wauwatosa, WI, USA), shown in Fig. 2, was used for all test conditions. This keyboard is unique in having almost infinitely adjustable angles in three planes; it was also possible to separate the keyboard halves by as much as 25 cm.

2.5. Test paragraph

A standard text paragraph with no numerical or symbolic characters was provided to the subjects via a

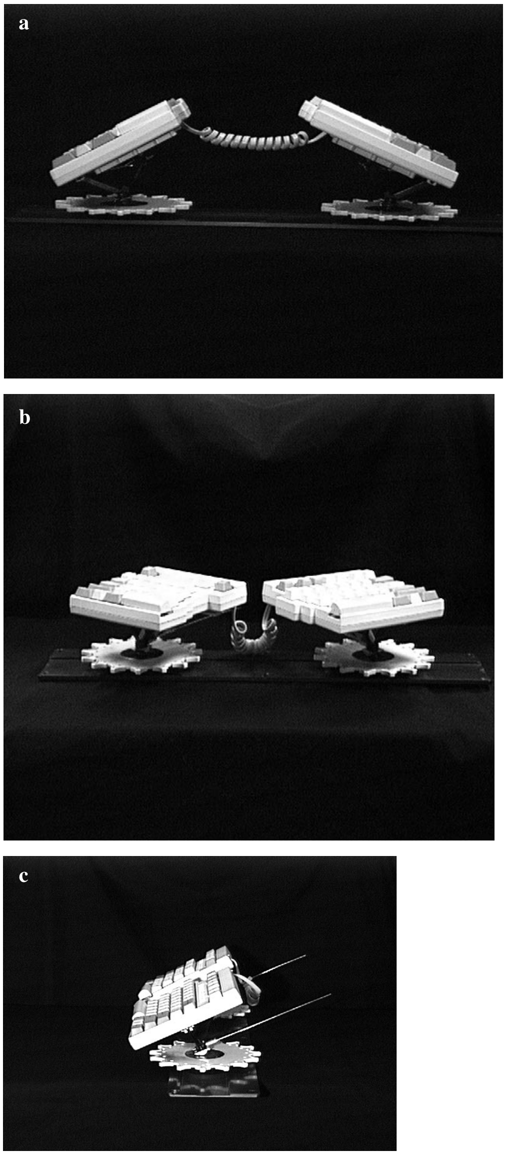

Fig. 2. Test keyboard, in various configurations.

commercially available typing program (Typing Tutor V, Kriya Systems, Sterling, VA, USA). The paragraph contained 111 words (496 characters) and was considered sufficiently long to allow quantification of the typing task. The maximum data collection window was 3 min which was sufficient for almost all subjects. Subjects were instructed not to correct their errors while typing, since error correction would have added extraneous keystrokes. After each trial, typing speed and accuracy data were presented by the software, and any trial where the error rate exceeded 5% was repeated.

2.6. Procedure

Subjects were shown the test equipment including the adjustable keyboard and monitors and received an explanation of the study objective and their role; they then signed a consent form. Anthropometric measurements were taken for each subject at the beginning of the test period according to NASA 1024 [30]; these measurements included standing and sitting height, weight, age, handedness, shoulder breadth, upper and lower arm length, length of hand and finger segments, joint thickness and grip strength. A height-adjustable workstation supported the keyboard, computer and monitor. The seat pan and backrest of the chair used in the experiment were also adjustable in height. The arms of the chair had been removed to avoid interfering with the subject's arms during typing. The chair and workstation were adjusted such that the subject was seated with the feet resting comfortably on the floor, the knees, elbows, and torso-trunk angle were approximately 90° and the computer monitor placed at approximately eye-level.

After the workstation adjustment, wrist monitors were attached to left and right wrists. Next, the finger monitors were attached to the left index finger on the MP, PIP and DIP joints, then all wrist and finger monitors were calibrated. Wrist monitor calibrations were performed twice: before and after the experiment, while the finger monitors were calibrated 4–6 times: before and after the experiment and several times during the experiment. The additional calibrations were needed for the finger monitors because of their sensitivity to very small displacements on the finger joints. In contrast, the wrist monitors, being both larger in size and affixed to the forearm, were not as sensitive to small changes in position.

Subjects were given a chance to acclimate to typing on the adjustable keyboard with the wrist and finger monitors attached. After the acclimation period (ranging from 5 to 15 min, depending on the subject's comfort level), testing began. Each subject was tested under all 30 conditions, with the order of conditions randomized. Videotape cameras positioned laterally and posteriorly recorded gross body postures, including head/neck angles and shoulder abduction. After completion of each condition, subjects also provided a comfort rating using the Borg 10-point scale. Collection of wrist and finger monitor data was controlled by the experimenter; data collection started after the subject began typing, and ended just before the subject finished the paragraph. This was done to eliminate non-typing motion artifacts associated with beginning or ending a typing task, such as sudden or abrupt movements of the hands towards or away from the keyboard.

After completion of a test condition, the keyboard halves were changed to the angles and separation distance for the next condition, and the process repeated. The keyboard changes usually took several minutes to achieve the correct level of precision in angles, and since the subject was inactive during this period, it also served as a rest break for the subject. This eliminated the issue of fatigue from repetitive typing during the test session.

2.7. Tendon travel calculation

Tendon travel was calculated as a function of the keyboard design, standardized to unit time. Earlier research has shown how joint motion can be translated into tendon travel. It has been demonstrated that the tendon excursion for the *extensor digitorum communis* tendon can be predicted from the motion of the PIP and MP joints of the finger [31]. Similarly, Armstrong and Chaffin [32] have shown that the displacement of the FDP and FDS could be obtained once the data were normalized for joint tendon thickness. Their regression equations were used to calculate tendon travel for the FDP and FDS.

2.8. Analyses

Using the calibration data, separate regression equations were generated for each subject. This permitted the angular voltages from the wrist and finger monitors to be converted to degrees, using the unique calibration values for that subject. Mean wrist angles, velocity, and acceleration values were calculated for the wrist in all three planes of motion, as well as for each finger joint. Tendon travel was calculated for the two tendons, for each subject, for each test condition and summary statistics derived.

Wrist deviation (WD) was another measure which incorporates wrist position in the three planes of movement: radial/ulnar, flexion/extension, and pronation/supination. It is a linear combination of the percent deviation of position in each of the three planes and provides another way of assessing the biomechanical stressors, one which focuses solely on the wrist. Statistical analysis was conducted using SAS (SAS Institute, Cary, NC) for analysis-of-variance (ANOVA) tests for significant differences between means for the 30 test conditions and the main effects of Pitch, Roll, and Yaw angles on tendon travel and wrist deviations. Paired *t*-tests were performed to test specific conditions against each other. All variables were normalized to the completion of the typing task, not the time to complete the test.

3. Results

3.1. Tendon travel

Large individual differences were seen in the amount of cumulative tendon travel (CTT) as shown in Fig. 3. There was more tendon travel for the FDS than the FDP in all keyboard conditions. This may reflect the fact that the FDS flexes the middle phalanges while the FDP flexes the distal phalanges [33]. However the two tendons are very closely correlated with a Pearson correlation coefficient of 0.99 across all keyboard conditions.

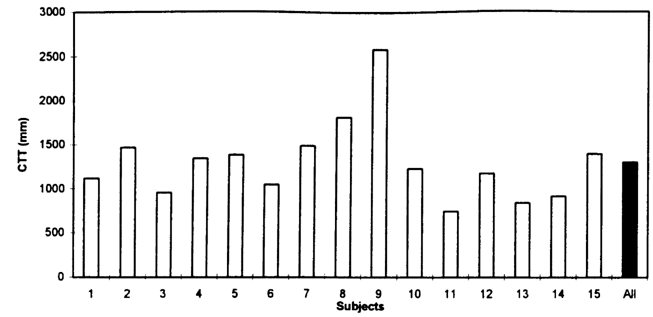

Fig. 3. Average cumulative tendon travel (*superficialis*), by subject.

Paired *t*-tests of tendon travel for both tendons were conducted, testing the standard keyboard (Condition 30) against the other keyboards. For both tendons, Conditions 5, 21, and 23 were significantly different from the standard keyboards. For FDP, three additional conditions were significant: Conditions 10, 13, and 17 at $\alpha = 0.05$. Generally when Pitch was 0°, more extreme Roll produced lower tendon travel. However, with increasing Pitch, the same effect was achieved with moderate amounts of Roll. Only the 15° Yaw reduced tendon travel.

A Tukey test for pairwise comparisons of TTFDS was conducted between the keyboard conditions with 9.2 cm separation distance (Conditions 3–29). Condition 3 was significantly different when compared to other keyboard conditions with more extreme positions of Pitch, such as Conditions 21, 22, and 27. This indicates that greater Pitch angles produced more tendon travel, especially when combined with increasing Roll angles. Condition 3 also produced more tendon travel than Conditions 22 and 26, indicating the effect of increased Pitch alone with Roll held constant at 15°.

A comparison of the amount of joint movement for the subjects with the least and most tendon travel revealed some interesting differences. The subject with the most tendon travel had much more flexion in the MP joint than the subject with the least tendon travel. The opposite was observed for the DIP joint. Fig. 4 shows the joint-by-joint comparison, averaged across all keyboard conditions, for these two subjects.

To determine whether some of these individual differences in tendon travel were due to differences in hand sizes, a correlation was performed between tendon travel and hand anthropometry. Six hand dimensions were found to be statistically correlated with tendon travel: the length of the hand, finger, metacarpal, MP, PIP and DIP. The strongest correlations were found for the metacarpal, MP and PIP lengths, with the MP length accounting for almost 50% of the variance.

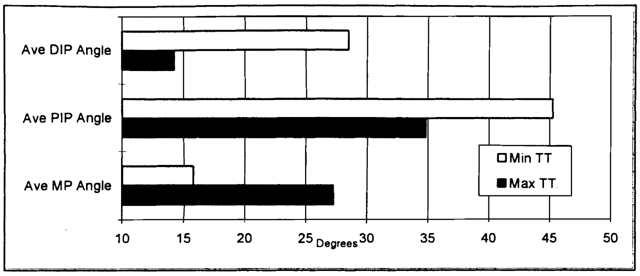

Fig. 4. Comparison of average finger joint angles, for subjects with maximum and minimum tendon travel.

3.2. Wrist deviation

Additional analyses were conducted to assess the impact of the keyboard angles on wrist angles alone. A unitary measure, WD, was constructed as a linear combination of the percent deviation of position in each of the three planes. The data were analyzed in terms of the main effects for Pitch, Roll and Yaw and the two-way interactions on WD shown in Figs. 5–7 for left and right hands. Most angle levels were significantly different from each other at $\alpha = 0.05$, as indicated by the asterisks in the figures. As would be expected, increasing Pitch increased the amount of wrist extension, which was also reflected as an increase in WD. On the other hand, increasing Roll moved the forearm from a fully pronated position to a more neutral one, midway between full pronation and full supination. This caused a decrease in the WD. Increased Yaw showed conflicting results between the right and left hands, with the left hand showing a slight decrease in WD, while the right hand showed an increase. However, only the results for the right hand were statistically significant, at Yaw 0° and Yaw 30°.

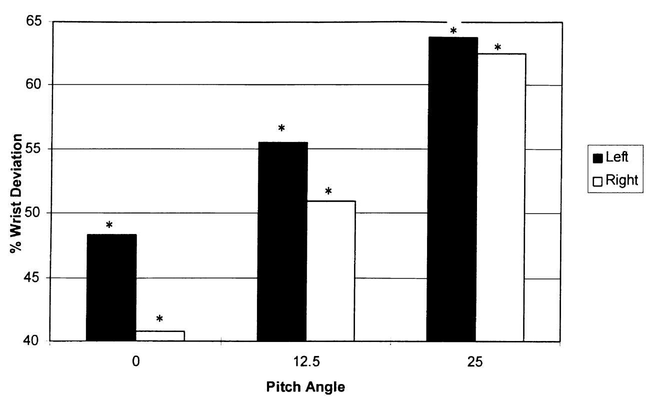

Fig. 5. Wrist deviations as a function of Pitch angle. *significant at alpha = 0.05.

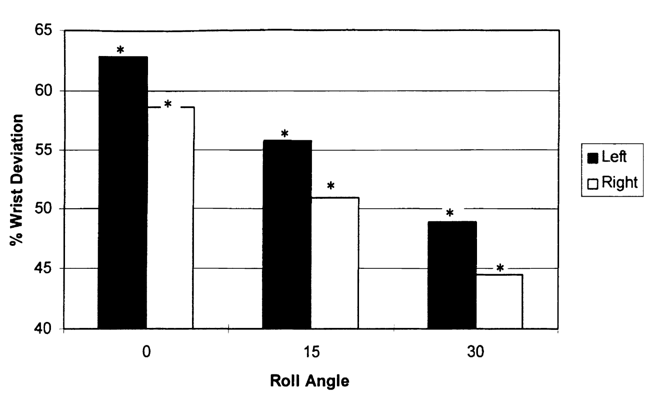

Fig. 6. Wrist deviations as a function of Roll angle. *significant at alpha = 0.05.

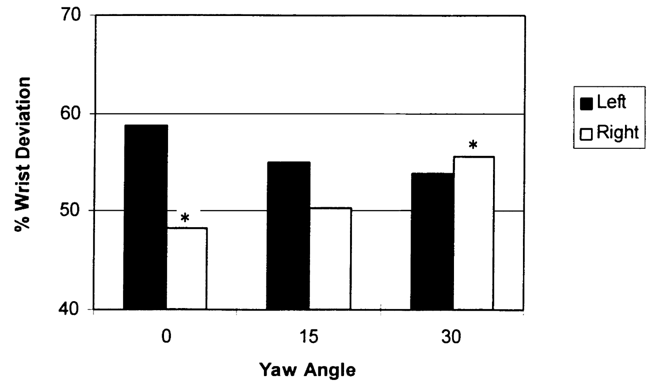

Fig. 7. Wrist deviations as a function of Yaw angle. *significant at alpha = 0.05.

3.3. Wrist and finger joint kinematics

Analysis of variance was performed for the various kinematic variables for wrist joints in the three planes of motion, in addition to finger joints. Table 2 shows the *P*-values for the analyses, corrected (Bonferroni) for multiple comparisons. It can be seen that the main effect of *Pitch* is significant for most wrist kinematic variables. Increasing Pitch produced greater radial deviation, wrist extension and more pronation. Of the finger joints, only the MP joint is affected by Pitch which decreased slightly as Pitch increased; the PIP and DIP joints were not significantly affected by changes in Pitch.

The main effect of *Roll* is also significant for most of the wrist kinematic variables. Larger Roll produced greater radial deviation, but less wrist extension and less pronation. With the finger joints, however, it was more significant for the PIP joint than the MP or DIP joints. Both PIP and DIP joints showed greater flexion as Roll increased, although the effect was more pronounced for the PIP joint.

A similar pattern is seen in the main effect of *Yaw*. Increasing Yaw produced greater radial deviation in the right hand. Recall that the majority of the test conditions separated the keyboard halves by 9.2 cm. Thus, at the Yaw 0°, the wrist was closer to the neutral position than would occur with no separation distance between keyboard halves. With greater Yaw, the wrist moved

Table 2
P-values for main effects of Pitch, Roll and Yaw and two-way interactions for angle, velocity and acceleration, for wrist and finger joints (shaded cells are significant at $\alpha = 0.05$)

Variable	Pitch	Roll	Yaw	Pitch × Roll	Pitch × Yaw	Roll × Yaw
RU-Right-Angle	0.0001	0.0001	0.0001	0.002	0.0008	0.0001
RU-Left-Angle	0.0001	0.0001	0.0001	0.0001	0.0033	0.0033
RU-Right-Velocity	0.0001	0.0001	0.0001	0.6252	0.0094	0.0669
RU-Left-Velocity	0.0001	0.0001	0.0001	0.1356	0.0001	0.0045
RU-Right-Acceleration	0.0001	0.0001	0.0002	0.6959	0.017	0.0429
RU-Left-Acceleration	0.0001	0.0001	0.0001	0.1677	0.0001	0.0033
FE-Right-Angle	0.0001	0.0083	0.0001	0.0002	0.3889	0.0001
FE-Left-Angle	0.0001	0.0001	0.0001	0.0036	0.0004	0.0001
FE-Right-Velocity	0.008	0.1319	0.5199	0.3824	0.7038	0.3926
FE-Left-Velocity	0.0047	0.0281	0.0008	0.2917	0.0001	0.4587
FE-RightAcceleration	0.031	0.1918	0.6564	0.321	0.658	0.4273
FE-Left-Acceleration	0.0081	0.0931	0.0012	0.2236	0.0001	0.3794
PS-Right-Angle	0.0001	0.0001	0.0001	0.0706	0.0357	0.0004
PS-Left-Angle	0.0006	0.0001	0.0001	0.2152	0.8463	0.068
PS-Right-Velocity	0.0003	0.0034	0.1956	0.6811	0.6061	0.7885
PS-Left-Velocity	0.0222	0.2616	0.9192	0.781	0.2743	0.43
PS-Right-Acceleration	0.0003	0.0036	0.3219	0.7726	0.6168	0.6374
PS-Left-Acceleration	0.0684	0.251	0.7807	0.7185	0.2258	0.5584
MP-Angle	0.0002	0.9635	0.0024	0.4198	0.2993	0.0008
MP-Velocity	0.001	0.2434	0.252	0.7625	0.0019	0.0711
MP-Accleration	0.0002	0.0171	0.0194	0.4465	0.0003	0.086
PIP-Angle	0.6236	0.0001	0.0001	0.3244	0.002	0.5978
PIP-Velocity	0.2613	0.0062	0.3862	0.5586	0.0033	0.5466
PIP-Acceleration	0.1588	0.0009	0.0118	0.8781	0.0025	0.4914
DIPAngle	0.6944	0.0027	0.0001	0.5241	0.2384	0.0979
DIP-Velocity	0.7064	0.0525	0.003	0.6618	0.3292	0.1933
DIP-Accleration	0.4145	0.0693	0.0093	0.8602	0.3258	0.0673
Wrist Deviation-Right	0.0001	0.0001	0.0044	0.6882	0.0001	0.254
Wrist Deviation-Left	0.0001	0.0001	0.3131	0.6559	0.0021	0.2261
TTSUP	0.1022	0.3134	0.3432	0.3372	0.6286	0.1111
TTPRO	0.0818	0.2543	0.4182	0.2326	0.6415	0.053

into more radial deviation. The changes in the left wrist were not as pronounced, and may reflect a different arm/hand position, perhaps attributable to the greater amount of instrumentation on the left hand (the three finger monitors were placed on the left index finger).

Interaction effects are more significant for Pitch × Yaw and less significant for Roll × Yaw, whereas Pitch × Roll are significant for only a few wrist variables, mainly having to do with radial/ulnar and flexion/extension angles.

The kinematic variables of velocity and acceleration are of particular importance from the perspective of understanding the extent of the biomechanical stressors that arise from typing tasks. Velocity and acceleration in the radial/ulnar plane are affected by all three main effects of Pitch, Roll and Yaw. Generally, velocity and acceleration decreased with greater Pitch, Roll and Yaw angles. In contrast, for pronation/supination, Pitch is the most significant variable, primarily showing a decrease in velocity with increasing Pitch, while Roll, Yaw and the interaction terms have little impact. Flexion/extension variables showed even less of an impact of the main effects and moderate interactions.

3.4. Borg comfort rating

The Borg comfort ratings showed that increasing Pitch from 0° to 25° increased the perception of discomfort only slightly, but changing Yaw from 0° to 30° more than doubled the discomfort rating (higher Borg ratings indicated greater discomfort). Increasing Roll had almost no effect on the Borg ratings.

4. Discussion

Tendon travel, a measure of biomechanical stress, has been shown to be sensitive to changes in the keyboard parameters: specifically, in changes to the Pitch, Roll, and Yaw angles of the keyboard. Tendon travel was chosen as a dependent measure because of its possible role in the development of WRMSDs such as carpal tunnel syndrome or tendinitis. Quantifying the amount of movement of the tendons provides one way to compare the efficacy of various design modifications in reducing the risk of injuries.

The difference between the conditions which produced the minimum and maximum tendon travel amounted to almost 13%. The CTT, as derived from the 3-min test, can be extrapolated to the equivalent amount of tendon travel for more realistic time intervals. For instance, the greatest tendon travel for the FDP, 1327.4 mm in Condition 3, is equal to 26.5 m of tendon travel for 1 h of uninterrupted typing. Contrast this to the amount of tendon travel in Condition 22, which produced the least amount of tendon travel; 1 h of uninterrupted typing would produce 23.5 m of tendon travel. Assuming that in a typical 8-h workday, if a computer operator spends 6 h in uninterrupted typing (the rest of the time is assumed to be for non-typing tasks), the equivalent CTT would be 159 m for the highest tendon travel condition, and 141 m for the lowest. Sommerich et al. [27] hypothesized that 50 m of tendon travel per shift constituted a low risk benchmark and 150 m per shift constituted a high risk benchmark. While their values should be used with caution as they considered only the wrist's contribution to tendon travel, they serve as a rough approximation to high and low risk jobs. Hence, the difference of 18 m between the greatest and least amount of tendon travel over a projected workday can mean the difference between a job which exceeds the high risk benchmark and one that does not.

The conditions which minimized tendon travel (Conditions 22 and 27) had the greatest Pitch and moderate Roll. On the other hand, Condition 3 (Pitch 0°, Roll 0°, Yaw 0°) produced significantly more tendon travel than those conditions with greater Pitch and Roll. The contribution of Yaw was unclear; it may work in combination with Roll and Pitch to affect tendon travel. Pitch increased wrist extension, while Roll decreased pronation and moved the forearm closer to the neutral position between supination and pronation. As the wrist became more extended, the fingers may have flexed or 'curled' more to compensate. The combination of these may reduce the amount of motion in the flexor tendons during typing. There appears to be a *trade-off between the wrist and finger positions*, such that as one increases or decreases the amount of flexion or extension, the other joints must compensate in order for the fingers to reach the desired keys.

Individual differences in typing, as seen in the variation in flexion by each finger joint shown in Fig. 4, may provide insight as to why some people suffer from cumulative trauma disorders while others, who have the same job duties, do not. This information can also be used to design different keyboards, as it is becoming obvious that one design does not fit all. For instance, people with longer finger segments (not necessarily long hands), especially in the MP segment, may curl their fingers in order to keep their fingers on the keys. This may cause greater movement of the flexor tendons during typing, resulting in higher amounts of tendon travel.

This study did not use wrist rests or arm supports, and so the hands were free to assume any position above the keyboard. If the wrist is 'anchored' to a wrist rest, the results may be different. In such a case, the amount of wrist extension and finger flexion may be changed which would consequently affect the amount of overall tendon travel.

Designers of alternative keyboards attempt to address the issue of wrist posture and to achieve the commonly cited recommendation to 'keep the wrists straight'. However, this recommendation fails to consider the trade-off between wrist and finger positions and how changes in one joint affect the others. Furthermore, what is not appreciated until now, is that the *design of the keyboard can also address the issue of the repetitiveness* in typing. Naturally, the number of keystrokes will be dictated by the task, but the repetitive wear and tear of typing, as measured by tendon travel, has been shown in this experiment to be affected by keyboard design. The difference of 13% between the minimum and maximum tendon travel is of occupational significance.

It is well accepted that the synergistic effect of two or more risk factors can be more damaging that the sum of them individually [4]. Thus, a keyboard design which can address both the wrist posture and the repetitiveness of keyboarding may have tremendous potential for mitigating the risk of WRMSDs. We suggest that the concept of tendon travel has great potential utility for the assessment of task risks, and the efficacy of equipment designs for reducing risks. Because tendon travel takes both wrist and finger motions into account, it can serve as a *unifying measure* by which to assess various keyboard designs.

A primary question of this study is whether different keyboard angles can reduce the degree of biomechanical stress, and if so, by what magnitude. An affirmative answer to this question would strengthen the rationale in redesigning keyboards, while a negative answer would call into question the logic of such an attempt. The results show that changing keyboard angles can reduce the amount of tendon travel: by imposing a moderate degree of wrist extension (increased Pitch), with a small degree of ulnar deviation (Yaw), combined with flexed fingers. Alternatively, the same results can be obtained with if greater radial deviation is induced (greater Yaw) with less pronation (increased Roll). These findings highlight the interactions between Pitch, Roll, and Yaw, and the trade-offs which can occur between wrist angles and finger flexion. Hence, it is not enough to simply recommend that the typist maintain a straight wrist, as this approach fails to consider the effect of wrist position on finger movements: the degree of finger flexion contributes to the overall tendon travel. The straight-wrist recommendation may be an oversimplication of the complex biomechanical interaction between wrist and finger joints. This oversimplification may account for the lack of conclusive evidence linking posture to carpal tunnel syndrome seen in the epidemiological review of workplace factors and MSDs conducted by NIOSH [8].

There are several limitations of this study that should be acknowledged. The maximal time duration for the typing task was 3 min. This was deliberately designed to be short, given the large number of conditions to be tested, but is not of sufficient duration to determine the effect of long-term use; the study was not intended to study the issues of fatigue associated with using the various keyboard configurations. The regression equations from Armstrong and Chaffin are sensitive only to motion in the flexion/extension plane; other three-dimensional effects, such as abduction/adduction of the index finger at the MP joint, are not evaluated here.

The keyboard used in this study, the Comfort Keyboard System, had a much greater depth than most keyboards. This depth prohibits users from resting their wrists on the desk surface or a standard wrist rest. Although extra-deep wrist rests were provided with the Comfort Keyboard System, they were not used in the current study. The absence of wrist rests and the height of the keyboard above the desk surface required constant static loading of the shoulder muscles in order to maintain the arms and wrists in the proper position for typing. However, since the objective of this study was not to assess static shoulder loading, this component of the typing task was considered irrelevant to the experiment. The dependent variable primarily affected by the static loading was Borg comfort rating which recorded the subject's perceived overall comfort level. In addition, since the typing period during each test condition generally lasted for only 1–2 min (rarely was the full 3-min allotment needed), this did not produce an excessive static burden on shoulder muscles.

5. Conclusions

The study presented the results of a biomechanically based study of different angles of Pitch, Roll, and Yaw as indicated by the amount of tendon travel which is a measurement of the amount of movement of the tendons within the carpal canal. It was found that different combinations of angles were able to reduce the amount of tendon travel, with almost 13% difference between the keyboard conditions which produced the greatest and least amount of tendon travel. It appears that tendon travel is affected by the interaction of wrist and finger positions, hence both should be taken into consideration in determining the appropriate keyboard design. The findings of this study point to a greater need to understand the biomechanical complexity of typing.

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