Effect of Computer Keyboard Slope and Height on Wrist Extension Angle

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The goal of this study was to determine the systematic effect that varying the slope angle of a computer keyboard along with varying keyboard height (relative to elbow height) have on wrist extension angle while typing. Thirty participants typed on a keyboard whose slope was adjusted to +15°, +7.5°, 0°, –7.5°, and –15°. The height of the keyboard was set up such that participants' wrists were at the same height as their elbows, above their elbows, and four cm below their elbows. Results showed that as keyboard slope angle moved downward from +15° to –15°, mean wrist extension decreased approximately 13° (22° at +15° slope to 9° at –15° slope). Keyboard height had a similar effect with mean wrist extension decreasing from 21.8° when the keyboard was lower than elbow height, to 7.3° when the keyboard was higher than elbow height. Potential application of this research includes the downward sloping of computer keyboards, which could possibly be beneficial in the prevention of musculoskeletal disorders affecting the wrist.

INTRODUCTION

Most conventional computer keyboards have a built-in positive slope, which requires the user to extend the wrist approximately 20° while typing (Simoneau, Marklin, & Monroe, 1999). Raising the legs on the back of the keyboard will increase the positive slope angle and, concomitantly, further increase wrist extension. The positive slope of many conventional keyboards complies with the current voluntary U.S. guidelines for visual display terminal (VDT) workstation layout (ANSI/HFS 100, 1988), which states that keyboard slope should be between 0° and +25°. There are a number of positively sloped keyboards on the market, but commercially available keyboards and keyboard support surfaces that allow the user to slope the keyboard downward represent a small portion of the total market. The goal of negatively sloped keyboards is to decrease wrist extension so the wrist is held close to a neutral wrist posture, thereby theoretically lessening the probability of a work-related musculoskeletal disorder (WMSD) of the hand or wrist. WMSDs at the wrist include carpal tunnel syndrome and tenosynovitis.

Based on the literature, it appears that deviated wrist posture in the flexion/extension plane is implicated in the etiology of WMSDs of the wrist (Armstrong, 1986). Studies measuring carpal tunnel pressure have shown that carpal tunnel pressure decreases as the wrist moves toward a neutral posture in the flexion/extension plane (Rempel, Kier, Smutz, & Hargen, 1997; Weiss, Gordon, Bloom, So, & Rempel, 1995). Less pressure in the carpal tunnel is beneficial because the median nerve, which passes through the carpal tunnel, is under less compression and is less likely to show the symptoms of carpal tunnel syndrome. In theory if a typist were to type on a negatively sloped keyboard with a wrist extension angle closer to a neutral posture than the approximately 20° extension with a conventional keyboard, then the typist would be less susceptible to WMSDs.

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LITERATURE REVIEW

Research on how a negatively sloped keyboard affects wrist position – wrist extension in particular – has been sparse. In a study of 12 office workers, Hedge and Powers (1995) allowed their participants to make a downward adjustment to the slope angle of a platform that supported a conventional keyboard with an integrated palm rest. The mean self-selected slope angle of the keyboard platform was –12°, which resulted in a keyboard slope close to 0°. The wrist extension angle averaged 13° with the conventional keyboard supported on a horizontal platform, whereas the wrist angle averaged 1° *flexion* with the platform sloped negatively.

In another study, Hedge, McCrobie, Land, Morimoto, and Rodriguez (1995) investigated negatively sloped keyboards in a corporate office in Phoenix, Arizona. In the control group, 15 people typed on a conventional keyboard on a desktop or keyboard tray, and in the test group, 23 participants typed on a keyboard tilted downward on a desktop or keyboard tray (the keyboard used in this study had a preset tilt-down mechanism). Hedge et al. found that the wrist extension angle for the control group averaged 19.4°, whereas the wrist extension for the test group, who typed on the negatively sloped keyboards, was 10.7°. The exact slope angle of the keyboard was not reported by the authors.

In a third study of negatively sloped keyboards, Albin (1997) measured the wrist extension of users typing on a conventional keyboard supported by a platform sloped at three angles: horizontal, positive, and negative. Although Albin (1997) did not find a platform angle having a significant effect on wrist extension angle, he noted that a keyboard platform whose slope can be adjusted offered the user flexibility in accommodating individual preferences. Again, the slope angle of the keyboard was not reported by the author.

In summary, it appears from the literature that negatively sloped computer keyboards do reduce wrist extension. However, the slope angle of the keyboards tested and reported in the literature were adjusted by the individual, preset to only one angle, or not reported. Therefore, it is difficult to infer from these study results the systematic effect of the magnitude of keyboard slope on wrist extension angle. In addition, it is not clear from these previous studies if the height of the keyboard in relation to elbow height was well controlled.

Changes in wrist extension angle can also be accomplished by adjusting the height of the keyboard support surface, which modifies the height of the wrist relative to the elbow. The advent of office furniture with an adjustable keyboard support surface allows a user to position the keyboard height above, even with, or below the elbows. A search of the literature yielded no published research on the systematic effect of height of the keyboard relative to the elbow on wrist extension angle. Considering that keyboard slope and height can influence the extension angle of the wrist, the objective of this study was to determine how the magnitude of a computer keyboard's slope angle, both positive and negative, along with the computer keyboard height, affect wrist position in the flexion/extension and radial/ulnar planes. Results from this laboratory study can form the basis for a field study of computer users who type on sloped keyboards to ascertain whether sloping a keyboard negatively reduces wrist extension angle in actual work situations.

EXPERIMENTAL METHOD

Participants

A total of 30 healthy women volunteered to participate in the study. All participants were asymptomatic of WMSDs affecting the upper extremities, typed at least 40 words per minute (wpm), and worked in jobs requiring typing at least 3 hr/workday. The demographic and anthropometric data for the three groups of 10 participants are presented in Table 1. No significant differences among the groups were noted for any of the variables reported in Table 1, $F(2, 27) = 0.36$ to 1.72, $p = .20$ to .70.

Experimental Design

We used a three-way mixed design. The within-subjects independent variables were keyboard slope (five levels: +15°, +7.5°, 0°, –7.5°, and –15°) and hand (right and left). The between-subjects independent variable was

TABLE 1: Mean Demographic and Anthropometric Data of Participants

	Keyboard Heights		
	Wrists Above Elbows N = 10	Wrists Even with Elbows N = 10	Wrists Below Elbows N = 10
Height (m)	1.64 (0.04)	1.65 (0.08)	1.61 (0.04)
Weight (kg)	67.7 (13.7)	76.3 (18.6)	62.7 (17.2)
Shoulder width (cm)	37.7 (1.74)	37.1 (3.14)	36.0 (2.46)
Elbow to wrist length (cm) Left forearm	24.7 (0.95)	24.1 (1.62)	24.3 (1.29)
Elbow to wrist length (cm) Right forearm	24.7 (0.91)	24.2 (1.60)	24.3 (1.32)
Range of motion (°) Wrist extension – Left	79.8 (4.37)	84.3 (6.15)	82.9 (8.2)
Range of motion (°) Wrist flexion – Left	85.3 (6.29)	85.5 (8.30)	87.6 (5.42)
Range of motion (°) Wrist extension – Right	81.9 (4.75)	82.6 (3.17)	80.3 (6.31)
Range of motion (°) Wrist flexion – Right	87.4 (6.93)	85.4 (7.68)	88.7 (6.60)

Note: Standard deviations appear in parentheses.

height of wrist relative to elbow (three levels: even, 5 cm above, and 4 cm below). All 30 participants were tested while typing on five keyboard slopes (+15°, +7.5°, 0°, –7.5°, and –15°). Of the 30 participants, 10 had their wrists at the same height as their elbows during testing, 10 had their wrists 4 cm below their elbows, and 10 had their wrists 5 cm above their elbows. The dependent variables were (a) mean, minimum, and maximum wrist ulnar deviation (right and left); (b) mean, minimum, and maximum wrist extension angle (right and left); (c) mean, minimum, and maximum elbow flexion angle (right and left); and (d) typing speed (wpm) and typing accuracy.

Apparatus

As shown in Figure 1, a fixture for an IBM-compatible, conventional QWERTY keyboard was built so the keyboard could be sloped at precise, predetermined positive and negative angles. The key tops were parallel to the top surface of the keyboard (not stepped as in stadium seating). Adjustable-length stilts made of threaded bolts adjusted the keyboard's slope angle to five settings: +15°, +7.5°, 0°, –7.5°, and –15°. A stop was added to the fixture to keep the keyboard from sliding. The keyboard did not have a built-in wrist rest, but a separate wrist rest constructed of high-density rubber was connected to the fixture. The top of the wrist rest, which was level with the front edge of the keyboard, remained horizontal for all keyboard slope conditions.

Wrist position was measured with monitors designed and developed at the Biodynamics Laboratory at the Ohio State University (Marras & Schoenmarklin, 1993). These monitors, which were accurate to within 1.5° and repeatable to within 1.5°, collected on-line position data of the right and left wrists' radial/ulnar and flexion/extension angles. A goniometer was attached to each elbow to monitor elbow angle. Position data from all goniometric devices mounted on the wrists and elbows were sampled at 300 Hz, fed into a 12-bit analog-to-digital converter, and stored on a PC.

Experimental Protocol

Upon arrival at the laboratory, each participant signed an approved human consent form. A brief medical survey was completed by the participant, and basic anthropometric dimensions and range of motion of the wrists were recorded by the experimenter. Goniometric monitors were attached to the right and left wrists and elbows and then calibrated. The participant then sat on a height-adjustable chair next to a VDT workstation. The setup of the VDT workstation complied with voluntary U.S. guidelines (ANSI/HFS 100, 1988).

The height of the keyboard was then aligned so the wrists were even with, 5 cm above, or 4 cm below the elbow (depending on the participant's keyboard height assignment). The bony landmarks palpated at the wrists and elbows were the midpoint of the lateral aspect of the ulnar styloid process and the most prominent region of the lateral epicondyle, respectively. The wrist was below the elbow by only 4 cm and not 5 cm because of early contact between the underside of the keyboard shelf and the superior aspect of the thighs on some participants. In order to maintain constant wrist height during typing sessions, participants were instructed to type so their wrists were either in contact or slightly above the wrist rest.

The presentation order of the five keyboard slopes was randomized for all participants to avoid learning and order effects. The keyboard was adjusted to the first slope, and the participant practiced typing at that slope level for 5 min. The participant typed using the Typing Tutor 6.0 program (Kriya Systems, Inc., Sterling, VA) and typed 7th-grade social sciences text (for an example, refer to Simoneau et al., 1999). Following a 2-min rest after 5 min of practice, the participant typed for 8 min with the keyboard set to the first slope. She then rested for 5 min while the keyboard was adjusted to the next slope. The participant practiced typing for 5 min, rested for 2 min, and then typed for another 8 min. This procedure was repeated until she typed on the keyboard at all five slope angles.

Typing Performance Data

The Typing Tutor 6.0 software recorded the typing performance of each participant's 8-min typing sessions. The performance measures were typing speed (wpm), accuracy percentage, total characters typed, and total number of errors left in the document.

Kinematic Data

Five samples of kinematic data of 30-s duration were collected at 2-min intervals throughout each of the 8-min typing sessions. Mean angular positions for each participant for radial/ulnar and flexion/extension planes of movement were calculated as the average position in the plane of interest during the 150 s (5 samples × 30 s) of data collected for each keyboard slope. Maximum and minimum angular positions were calculated as the averages of the maxima and minima angular positions, respectively, from all of the respective 30-s sampling periods. Prior to analysis, raw data were filtered with a fourth-order, zero phase shift, 7-Hz Butterworth low-pass filter.

Statistical Analysis

The conditioned wrist and elbow data from all participants were pooled for statistical analysis.

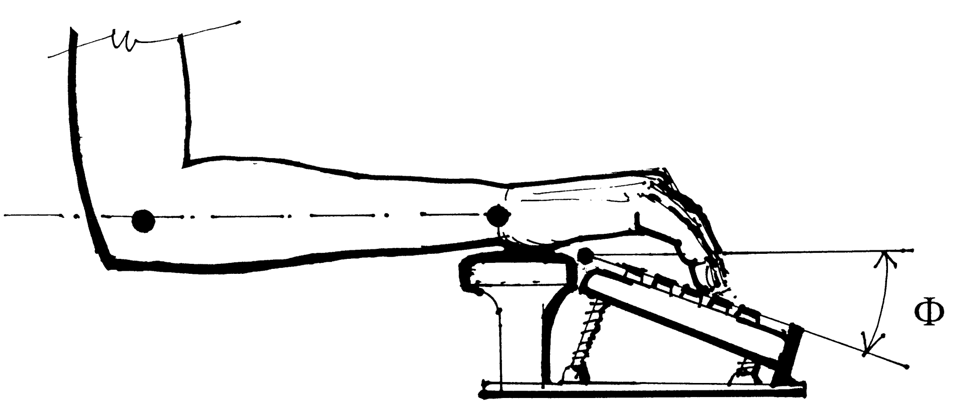

Figure 1. Design of the keyboard test fixture with a negatively sloped keyboard.

A three-way analysis of variance (ANOVA) was performed to determine whether there were significant differences in the kinematic dependent variables among the five slope conditions and three wrist heights and between the two hands. A two-way ANOVA was performed for typing performance data from the Slope × Wrist Height interaction. In addition, interactions were analyzed for all dependent variables.

RESULTS

Typing Performance

There was no significant difference in mean typing speed among the five slope conditions, $F(4, 104) = 1.64$, $p = .17$, which ranged from 54.7 to 56.9 wpm. Similarly, there was no significant difference in mean typing accuracy among the five slopes; accuracy ranged from 99.2% to 99.4%, $F(4, 104) = 1.26$, $p = .29$. Despite the fact that the participants in each keyboard height group were different, the mean typing speeds across wrist heights were not significantly different, $F(2, 26) = 0.25$, $p = .78$. The mean typing speeds for the keyboard even with, lower than, and above the elbow were 53.7, 56.4, and 58.2 wpm, respectively.

Elbow Angle

The mean angles of the left and right elbows for the three keyboard heights varied from 93.2° for the wrist 5 cm above the elbow to 78.2° for the wrist 4 cm below the elbow, as shown in Figure 2. Within each keyboard height condition, the mean elbow angle varied at most only 3° across the five keyboard slope conditions, which was statistically significant but not of practical importance, $F(4, 96) = 5.9$, $p = .0003$.

Radial/Ulnar Wrist Angle

The mean ulnar angle of the wrists varied significantly across the keyboard slopes, $F(4, 108) = 24.2$, $p < .00001$, but as shown in Table 2 and Figure 3, the differences among the mean ulnar angles were 4.3° or less (13.2°–15.9° for the left wrist and 10.4°–14.7° for the right wrist, for

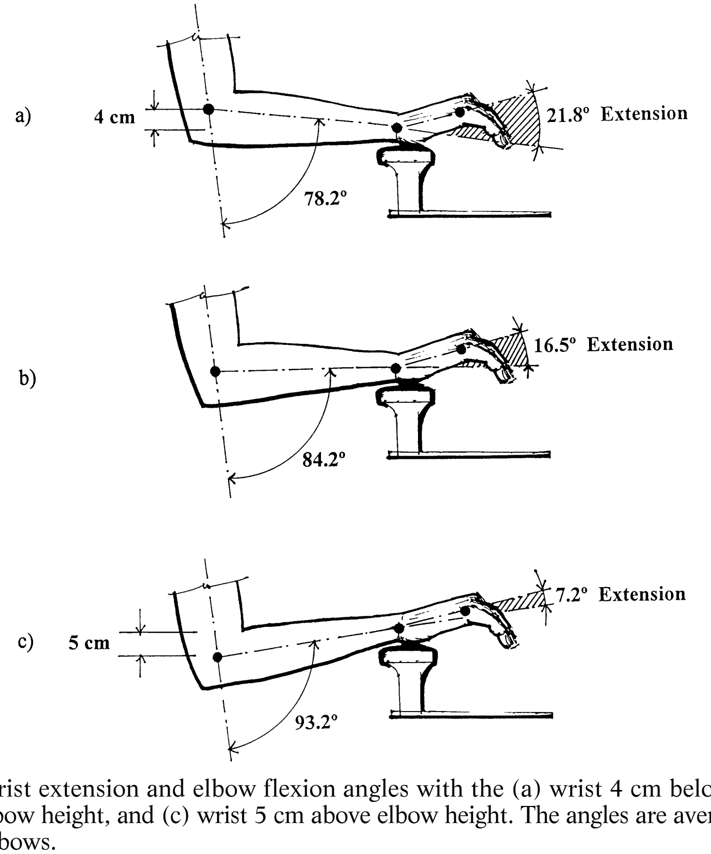

Figure 2. Mean wrist extension and elbow flexion angles with the (a) wrist 4 cm below elbow height, (b) wrist even with elbow height, and (c) wrist 5 cm above elbow height. The angles are averages of both left and right wrists and elbows.

TABLE 2: Mean Ulnar Deviations (in degrees) of the Left and Right Wrists as a Function of Keyboard Height, Keyboard Slope, and Hand

	Keyboard Heights					
	Wrists Above Elbows		Wrists Even with Elbows		Wrists Below Elbows	
	Left $N = 10$	Right $N = 10$	Left $N = 10$	Right $N = 10$	Left $N = 10$	Right $N = 10$
+15° Slope	13.7 (2.4)	12.0 (4.3)	16.1 (2.6)	13.3 (3.8)	9.8 (3.5)	5.9 (3.6)
+7.5° Slope	14.5 (2.4)	14.0 (4.1)	16.5 (2.7)	13.8 (4.5)	10.8 (3.5)	7.4 (3.8)
0° Slope	16.5 (2.5)	14.6 (3.9)	16.3 (2.8)	14.2 (4.5)	11.5 (3.5)	9.2 (4.3)
–7.5° Slope	15.8 (2.4)	16.4 (4.1)	17.2 (2.6)	15.7 (4.8)	12.9 (3.5)	11.5 (4.3)
–15° Slope	16.8 (2.5)	17.2 (4.0)	18.0 (2.8)	15.2 (4.5)	12.8 (3.3)	11.6 (4.4)

Note: Standard deviations appear in parentheses.

+15° to –15° keyboard slope, respectively). Tukey post hoc analysis revealed that mean ulnar deviation for the two positive slopes were significantly less than ulnar deviation from the two negative slopes. There was no main effect for keyboard height on mean ulnar deviation, $F(2, 27) = 2.2$, $p = .13$, and there was no significant Keyboard Height × Slope interaction, $F(8, 108) = 1.5$, $p = .16$. In addition, there was no significant main effect for hand, $F(1, 27) = 2.2$, $p = .15$.

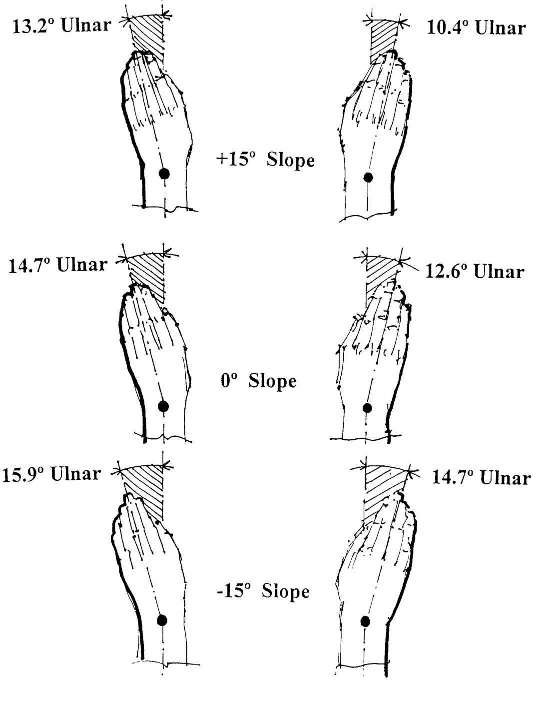

Figure 3. Mean ulnar deviations of the left and right wrists from typing on +15°, 0°, and –15° sloped keyboards.

Wrist Extension Angle

As the keyboard slope angle was sloped downward 30° from +15° to –15°, wrist extension decreased approximately 13°, as indicated in Table 3 and Figure 4, $F(4, 108) = 140$, $p < .00001$. Mean wrist extension for both wrists decreased monotonically from 21.7° at 15° positive slope to 8.8° in the 15° negative slope condition. Tukey post hoc analysis showed that mean wrist extension angles for all five slope conditions were significantly different from each other. As shown in Figure 2, mean wrist extension positions for the three wrist heights also varied significantly, $F(2, 27) = 11.2$, $p = .0003$, ranging from 21.8° when typing with the wrists 4 cm below the elbows to 7.2° when the wrists were 5 cm above the elbows. There was no significant interaction between wrist height and keyboard slope, $F(8, 108) = 0.83$, $p = .58$, and no significant main effect for hand, $F(1, 27) = 0.15$, $p = .70$. The values reported in Figure 2 are the averages from both wrists.

Statistical analyses of maximum and minimum wrist extension were similar to mean extension angles when keyboard height was adjusted below and above the elbow. Keyboard height had a significant main effect on both maximum extension angle, $F(2, 27) = 9.3$, $p = .0008$, and minimum extension angle $F(2, 27) = 10.3$, $p = .0004$. As indicated in Table 4,

TABLE 3: Mean Wrist Extension Angles (in degrees) of the Left and Right Wrists as a Function of Keyboard Height, Keyboard Slope, and Hand

	Keyboard Heights					
	Wrists Above Elbows		Wrists Even with Elbows		Wrists Below Elbows	
	Left $N = 10$	Right $N = 10$	Left $N = 10$	Right $N = 10$	Left $N = 10$	Right $N = 10$
+15° Slope	15.4 (2.8)	12.4 (3.3)	22.5 (2.9)	23.8 (2.7)	29.0 (2.3)	27.1 (3.1)
+7.5° Slope	10.7 (2.9)	8.4 (3.6)	18.5 (3.0)	20.0 (3.0)	24.9 (2.5)	23.7 (3.0)
0° Slope	7.9 (2.6)	6.6 (3.4)	16.3 (3.2)	18.4 (2.8)	22.2 (2.6)	21.4 (3.4)
–7.5° Slope	4.5 (2.8)	2.9 (3.6)	12.7 (2.9)	14.7 (3.4)	19.8 (3.2)	18.0 (3.7)
–15° Slope	1.9 (2.4)	1.0 (3.7)	7.8 (2.9)	9.9 (3.5)	17.0 (3.0)	15.2 (4.0)

Note: Standard deviations appear in parentheses.

average maximum wrist extension decreased from approximately 30° when the keyboard was lower than the elbow to approximately 15° when the keyboard was higher than the elbow. The minimum wrist extension angles decreased from approximately 15° to near neutral position when the keyboard was raised from below the elbow to above the elbow, as shown in Table 5.

Similar to the independent variable, wrist height, keyboard slope significantly affected maximum extension angle, $F(4, 108) = 106$, $p < .00001$, and minimum extension angle, $F(4, 108) = 141$, $p < .00001$. Values in Table 4 reveal that the average maximum wrist extension was greatest (approximately 30°) at +15° keyboard slope and decreased monotonically to approximately 17° for the –15° keyboard slope. Except for the +7.5° and 0° slopes, post hoc analysis showed that maximum wrist extension positions were significantly different across the keyboard slopes. Minimum wrist extension data followed the same trend as maximum wrist extension data, as shown in Table 5.

DISCUSSION

Typing Performance

The narrow ranges of mean typing speeds (54–58 wpm) and accuracy (over 99%) indicate that participants quickly adapted to new keyboard slope angles and keyboard height, even with only 5 min of practice. The typing performance findings from this study are similar to those of Hedge et al. (1995), who found that a negatively sloped platform for a keyboard did not impair typing performance.

Elbow Position

The narrow range of elbow angles across the five slope conditions within each keyboard height condition indicates that the relative heights of the wrists and elbows were tightly controlled throughout the five keyboard slope conditions, resulting in the intended alignment of the forearms. For a given keyboard height,

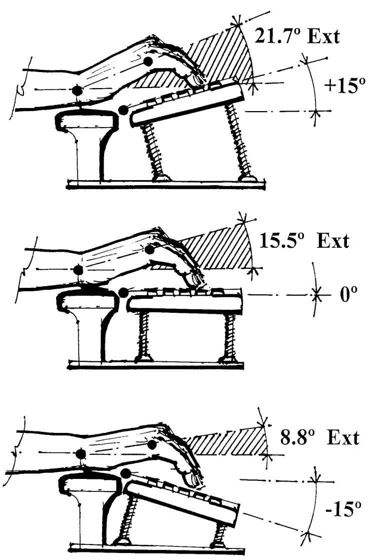

Figure 4. Mean wrist extension angles of both wrists from typing on +15°, 0°, and –15° sloped keyboards.

TABLE 4: Average and Standard Deviation of the Maximum Wrist Extension Angles (in Degrees) of the Left and Right Wrists as a Function of Keyboard Height, Keyboard Slope, and Hand

	Keyboard Heights					
	Wrists Above Elbows		Wrists Even with Elbows		Wrists Below Elbows	
	Left *N* = 10	Right *N* = 10	Left *N* = 10	Right *N* = 10	Left *N* = 10	Right *N* = 10
+15° Slope	22.9 (8.4)	23.0 (9.0)	29.8 (6.7)	31.6 (8.1)	34.6 (7.4)	36.1 (6.5)
+7.5° Slope	18.9 (10.3)	19.7 (8.7)	26.2 (7.3)	28.4 (7.6)	31.2 (7.4)	33.2 (7.8)
0° Slope	15.6 (12.1)	17.2 (9.6)	26.1 (8.0)	27.0 (7.8)	28.9 (9.0)	31.5 (6.9)
–7.5° Slope	12.2 (10.6)	13.5 (9.6)	20.5 (6.9)	24.4 (7.0)	27.2 (6.1)	28.7 (7.9)
–15° Slope	10.4 (10.4)	12.3 (10.2)	15.5 (7.7)	20.0 (8.0)	24.0 (8.6)	27.0 (8.1)

Note: Standard deviations appear in parentheses.

the mean elbow angle for both the right and left elbows did not vary more than 3° across all keyboard slopes. Based on the forearm lengths of the participants tested, a 3° change in elbow angle translates into a height change of approximately 1.3 cm at the wrist. The importance of maintaining tight control of elbow angle across the five keyboard slopes is that a change in elbow angle (representing a change in wrist height) can affect the wrist extension angle. An increase in elbow angle, either by lowering the elbow or raising the wrist, would change the orientation of the forearm and result in less wrist extension during typing. Conversely, raising the elbow or lowering the wrist would result in an increase in wrist extension.

Wrist Ulnar Deviation

The mean ulnar deviation angles measured in this study for the +7.5° slope, which were 13.9° for the left wrist and 11.7° for the right wrist, are similar to ulnar deviation angles measured on 90 participants typing on a conventional keyboard in a previous study (Simoneau et al., 1999). A +7.5° keyboard slope is similar to the built-in slopes of many commercially available computer keyboards. Also consistent with our earlier work is the observation that the left wrist was slightly more ulnarly deviated than the right wrist (14.6° vs. 12.6° ulnar deviation for 0° keyboard slope, as shown in Figure 3), although this difference was not significant in the present study. The reasons for

TABLE 5: Average and Standard Deviation of the Minimum Wrist Extension Angles (in degrees) of the Left and Right Wrists as a Function of Keyboard Height, Keyboard Slope, and Hand

	Keyboard Heights					
	Wrists Above Elbows		Wrists Even with Elbows		Wrists Below Elbows	
	Left *N* = 10	Right *N* = 10	Left *N* = 10	Right *N* = 10	Left *N* = 10	Right *N* = 10
+15° Slope	8.4 (8.4)	2.5 (8.0)	15.6 (6.7)	15.3 (7.8)	22.4 (8.7)	17.8 (8.9)
+7.5° Slope	2.9 (8.8)	–1.3 (7.4)	11.5 (6.8)	11.1 (8.6)	18.1 (7.6)	15.0 (9.6)
0° Slope	1.3 (10.4)	–3.4 (8.2)	9.17 (7.0)	9.3 (9.7)	15.2 (10.7)	11.1 (9.2)
–7.5° Slope	–1.9 (9.1)	–7.5 (9.0)	6.0 (7.7)	5.6 (9.0)	12.0 (6.4)	6.6 (8.0)
–15° Slope	–3.4 (9.1)	–9.7 (9.3)	0.9 (8.9)	0.1 (8.7)	9.5 (9.6)	3.2 (8.2)

Note: Negative degrees represent wrist flexion. Standard deviations appear in parentheses.

the apparent unequal ulnar deviations between the wrists are unknown, although it may be a result of the left hand typing more special function keys, such as CAPS, LOCK, and TAB. A comprehensive discussion of the differences in ulnar deviation between the left and right wrists during typing can be found in Simoneau et al. (1999).

As shown in Table 1 and Figure 3, mean ulnar deviation increased significantly when the keyboard was sloped from +15° to –15° (2.7° and 4.3° for the left and right wrists, respectively). This increase in ulnar deviation may be because of a change in forearm pronation. Typically, typists pronate their forearms approximately 65° when they type on a conventional keyboard (Simoneau et al., 1999), which means the wrists are not parallel to the keyboard surface. Typists may pronate their forearms less than 90° to reduce ulnar deviation. Marklin, Simoneau, and Monroe (1999) found that participants typing on tilted (also called *tented* or *vertically inclined*) keyboards reduced forearm pronation by 20° to 25° compared with a conventional keyboard and concomitantly reduced ulnar deviation by 12° to 14° in the left and right wrists, respectively. Sloping the keyboard downward may increase forearm pronation and thereby increase ulnar deviation at the wrist. Because forearm pronation was not measured in this study, it is not possible to determine if our suggestion is true – that participants increased forearm pronation as the keyboard was sloped downward.

In theory, the increase in ulnar deviation from sloping the keyboard negatively may mitigate the health benefit of decreased wrist extension from negatively sloped keyboards. As the wrist deviates from a neutral posture, the net reaction forces from the carpal bones pressing on the tendons and on their sheaths passing through the wrist increase (Armstrong & Chaffin, 1978a, 1978b; Schoenmarklin & Marras, 1990). Greater net reaction forces against the tendons and their sheaths would theoretically increase the risk of tendinitis or tenosynovitis.

Similarly, carpal tunnel pressure increases as the wrist is moved in the range of 10°–20° ulnar deviation (Kier, Wells, & Ranney, 1997). Regarding ulnar deviation, it is not known whether the biomechanical effects of increased net reaction forces on tendons or carpal tunnel pressure on the median nerve are significant enough to increase the risk of WMSDs from typing on negatively sloped keyboards (as compared with positively sloped keyboards).

Wrist Extension from Keyboard Slope

As depicted in Figure 4, results from this study show that when the keyboard was sloped from +15° to –15° (a 30° change in slope), mean wrist extension decreased approximately 13° from 21.7° to 8.8°. In other words, mean wrist extension decreased approximately 1° for every 2° of change in downward slope angle. Even though the wrist was in an extended position across all five slope conditions and did not reach a neutral position, the lower extension angles at the negative keyboard slopes are theoretically beneficial with respect to etiology of WMSDs affecting the wrist. Under no fingertip loading, Rempel et al. (1997) measured carpal tunnel pressure of 18.5 mm Hg at 15° wrist extension and found the pressure increasing to 27.7 mm Hg at 30° wrist extension. The carpal tunnel pressures increased to 41.1 and 53.5 mm Hg for 15° and 30° wrist extension angles, respectively, when the fingertips exerted a 6 *N* force, which is within the magnitude of typical fingertip forces from typing on a computer keyboard (Rempel, Serina, & Klinenberg, 1997; Sommerich, Marras, & Parianpour, 1996).

In the present study, sloping the keyboard negatively at –7.5° and –15° produced mean wrist extension angles less than 15° (except when the wrist was 4 cm below the elbow). According to Rempel et al. (1997), wrist extension angles close to the neutral position are potentially less injurious to the user than are extreme extension angles. With greater wrist extension angles, higher pressure in the carpal tunnel would exert more pressure against the median nerve and could contribute to the development of carpal tunnel syndrome.

In addition to carpal tunnel pressure studies demonstrating benefits of reduced wrist extension, wrist extension angles closer to a neutral position would theoretically decrease the probability of developing WMSDs. Armstrong and Chaffin (1978a, 1978b) modeled the tendons statically in the wrist with a free body diagram and showed that the reaction force exerted against the tendons from the carpal bones and flexor retinaculum, which prevent the tendons from bowstringing, increased as the wrist extended. Schoenmarklin and Marras (1990) applied dynamics to Armstrong and Chaffin's (1978a) model and showed that acceleration of the wrist in the flexion/extension plane increased the reaction forces on the tendons even more than in the static analysis.

Although the results from modeling of tendons are theoretical (and to our knowledge, there is no published literature on measurement of actual reaction forces on the tendons from the wrist structures), histological experimental studies on tendons passing through the carpal tunnel have shown degenerative changes in tendon structure. Armstrong, Castelli, Evans, and Diaz-Perez (1984) found hypertrophy and increased density in the synovial tissue of the tendons passing through the carpal tunnel. These authors suggested that biomechanical factors, such as repeated exertions with a flexed or extended wrist posture, could have partially caused degenerative changes in tendon tissue.

In an investigation of the viscoelastic properties of tendons and their sheaths, Goldstein, Armstrong, Chaffin, and Matthews (1984) found that flexion/extension wrist angle increased the strain difference among tendons, their sheaths, and bones and ligaments that form the anatomical pulley. When the wrist was extended approximately 10°, the strain in the flexor digitorum profundus tendons, which pass through the carpal tunnel and move the fingers, was approximately 10% to 15% lower on the side distal (hand side) to the flexor retinaculum than on the proximal side (forearm side). This difference in strain within a tendon creates shear traction forces, which are further magnified when the wrist angle is deviated to 65° flexion or extension (Goldstein et al., 1984). In summary, carpal tunnel pressure studies, histologic studies of tendons, and modeling of the wrist show experimental and theoretical benefits of reducing wrist extension while typing.

Wrist Extension from Computer Keyboard Height

To our knowledge, no systematic studies have been published on how inclination angle of the forearm affects wrist extension. Therefore, the following discussion is limited to results from the present study. This study showed that wrist extension angle can be reduced to an average of 7.2° by raising the wrist 5 cm above the elbow, or magnified to an average of 21.8° by lowering the wrist 4 cm below the elbow. Close inspection of the data in Table 2 reveals that mean wrist extension angles for all positive and negative slopes were not greater than 15.4° when the keyboard was elevated above the elbow, whereas mean wrist extensions for all keyboard slopes were greater than 15° when the wrist was lower than the elbow. With regard to biomechanics of the wrist, typing with the keyboard above elbow height is beneficial compared with placing the keyboard toward one's lap, because with the higher keyboard, wrist extension can be limited to 15° or less. Measurements of carpal tunnel pressure suggest that 15° or less of wrist extension likely is not deleterious with respect to the development of nerve disorders in the wrist (Rempel et al., 1997).

Although theoretically typing with the keyboard placed higher than the elbow may be beneficial to the wrist joint, several field and laboratory studies have shown that typing with an elevated keyboard causes pain and discomfort in neck, shoulder, and arm musculature. Life and Pheasant (1984) found that elevated keyboard height resulted in increased postural torque about the shoulder and increased shoulder discomfort. Erdelyi, Sihvonen, Helin, and Hanninen (1988) measured the EMG of the upper trapezius during typing and found that electromyograph (EMG) activity level decreased as the keyboard height was lowered. In a field study of several hundred VDT operators, reports of discomfort in the arms increased as the keyboard height was raised (Sauter, Schlieffer, & Knutson 1991). In a study of 150 employees working for a large metropolitan newspaper, Faucett and Rempel (1994) found that elevated keyboard height increased the reports of upper-extremity numbness of employees who had little control over their jobs. In another field study of 260 VDT workers (Bergqvist, Wolgast, Nilsson, & Voss, 1995), neck and shoulder discomfort increased 18% for every 1-cm increase in keyboard height.

Thus a preponderance of literature shows that the computer keyboard should not be raised above elbow height in order to minimize discomfort and muscular activity of the neck, shoulder, and upper extremities. A practical alternative to raising the keyboard above the elbows to minimize wrist extension is to place the keyboard level with the elbows and slope it downward 7.5° or 15°. This arrangement of keyboard height and slope should enable typists to maintain average wrist extension angles of 15° or less, which are within the natural alignment range of wrist extension.

Design of Slope Fixture

As shown in Figure 1, the keyboard tested in the present study did not have an integrated wrist rest, unlike the keyboard tested by Hedge and Powers (1995). They mounted a keyboard with an integrated wrist rest on a platform and then asked their participants to select a comfortable negative slope angle. Because the integrated wrist rest was on the same plane as the keyboard, the pivot point for measuring slope angle in Hedge and Powers' study was farther back than in the fixture for the present study (refer to Figure 1). The location of the pivot point is important because when the wrist rest is sloped downward, the hand tends to follow it and therefore would result in less wrist extension than if the wrist rest were horizontal. The difference between the integrated and separate wrist rests in Hedge and Powers' study and the present study may explain the approximately 10° difference of wrist extension measured at the lowest negative slope for the two studies.

Hedge and Powers measured an average of 1° flexion when the participants were typing on a wrist rest integrated with the keyboard, and results from the present study show an average of 9° wrist extension when the keyboard (but not the wrist rest) was sloped downward 15°. In addition, the differences in wrist extension results between Hedge and Powers' and this study could be the result of a difference in wrist height versus elbow height, which was not reported by Hedge and Powers. Future studies should take into account the relationship between the heights of the wrist rest and keyboard because both can affect wrist extension substantially in negative slope computer keyboard studies.

CONCLUSION

The goal of this study was to determine the systematic effect that varying the slope of a computer keyboard, along with the keyboard height (relative to elbow height), have on wrist extension angle while participants typed. The combination of keyboard height and slope that minimized wrist extension was a keyboard sloped 15° downward and elevated above elbow height. However, placing the keyboard higher than the elbows should be avoided because the literature has shown that this keyboard height increases discomfort of the neck, shoulder, and upper extremity. Results from this study have shown that if one were to place the keyboard so the elbow and wrist were at equal heights, and slope the keyboard downward (negatively) 7.5° or 15°, the wrist would be extended an average of 15° or less while typing.

With respect to carpal tunnel pressure and reaction forces against tendons and their sheaths, wrist extension angles of 15° or less are beneficial compared with wrist extension greater than 15° and would theoretically reduce the risk of WMSDs. Sloping the keyboard negatively, however, does increase ulnar deviation of both wrists as compared with positive slopes, and it may partially mitigate the beneficial effect of reduced wrist extension from typing on negatively sloped keyboards.

Because the participants in this study were 10-digit touch typists, our wrist extension findings may not apply to participants typing with four digits or fewer (hunt-and-peck method). Similarly, the wrist rest employed in this study was horizontal for all keyboard slopes; thus typists who use keyboards with integrated wrist rests may place their wrists at different extension angles than those found in this study. In order to address how typing style and design of wrist rests affect wrist extension angle, we are conducting a field study in large insurance companies of touch and nontouch (hunt-and-peck) typists who use keyboards sloped at various positive and negative angles.

ACKNOWLEDGMENTS

The authors express their gratitude to the Office Ergonomics Research Committee for sponsoring this project. In addition, thanks are due to Lois Harrison and David Cahaya for collecting and analyzing the data.

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Date received: October 8, 1999
Date accepted: July 21, 2000