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Effects of negatively sloped keyboard wedges on risk factors for upper extremity work-related musculoskeletal disorders and user performance

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Several changes to computer peripherals have been developed to reduce exposure to identified risk factors for musculoskeletal injury, notably in keyboard designs. Negative keyboard angles and their resulting effects on objective physiological measures, subjective measures and performance have been studied, although few angles have been investigated despite the benefits associated with their use. The objective of this study was to quantify the effects of negative keyboard angles on forearm muscle activity, wrist posture, key strike force, perceived discomfort and performance and to identify a negative keyboard angle or range of keyboard angles that minimizes exposure to risk factors for hand/wrist injuries. Ten experienced typists (four males and six females) participated in a laboratory study to compare keyboard angles ranging from 0° to −30°, at 10° increments, and a keyboard with a 7° slope, using a wedge designed for use with standard QWERTY keyboards. Repeatability of exposures was examined by requiring participants to complete two test sessions 1 week apart. Dependent variable data were collected during 10 min basic data entry tasks. Wrist posture data favoured negative keyboard angles of 0° (horizontal) or greater, compared to a positive keyboard angle of 7°, especially for the flexion/extension direction. In general, the percentage of wrist movements within a neutral zone and the percentages of wrist movements within ±5° and ±10° increased as keyboard angle became more negative. Electromyography results were mixed, with some variables supporting negative keyboard angles whilst other results favoured the standard keyboard configuration. Net typing speed supported the −10° keyboard angle, whilst other negative typing angles were comparable, if not better than, with the standard keyboard. Therefore, angles ranging from 0° to −30° in general provide significant reductions in exposure to deviated wrist postures and muscle activity and comparable performance.

Keywords: Keyboard; Key strike force; Data entry; WMSD

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1. Introduction

Research in the area of computer workstation design, most notably keyboard design and placement, has been driven by the growing number of work-related musculoskeletal disorders (WMSDs), such as carpal tunnel syndrome (CTS), associated with their use. Keyboard design research has focused on wrist posture, wrist and forearm support methods and the effects on the neck and shoulder musculature during keying. Negatively sloped keyboards may reduce exposure to risk factors for WMSDs, thereby reducing risk.

Stack (1987) reported in an Australian field study that a negatively sloped keyboard design has been a major improvement in addressing CTS problems in the Tasmanian public service. Research has been conducted by Hedge and associates (Hedge 1994, Hedge and Powers 1995, Hedge *et al.* 1995, 1999, Hedge and Morimoto 2001) using a keyboard tray that achieves a negative slope. It was found that wrist extension was reduced, less discomfort during keying was reported and more typing movements were made with the wrist in a neutral zone compared to the conventional keyboard configuration. Gilad and Harel (2000) also found that a negatively sloped keyboard was subjectively evaluated as more comfortable compared to the standard keyboard configuration, Tony™ and split designs.

The effects of negative keyboard angles on the risk of hand/wrist WMSDs are theoretically beneficial with regard to aetiology. For example, carpal tunnel pressure has been implicated as a causal factor for CTS. Rempel *et al.* (1997) found that carpal tunnel pressure levels approached 30 mmHg when passively extending the wrist 30°. The implication for typing tasks is significant given that average wrist extension angles during typing have been reported to be between 13° and 33° (Sommerich and Marras 1994, Hedge and Powers 1995, Honan *et al.* 1995, 1996).

Additionally, specifications for key activation forces of most keyboards fall between 0.2 N and 0.9 N (Rose 1991), although measured key strike forces have been reported to exceed this value by 2.5 to 4.6 times (Armstrong *et al.* 1994, Feuerstein *et al.* 1994, Martin *et al.* 1994). Further, the weight of a relaxed finger resting on a key ranges from 0.3 N to 1.2 N, often outweighing the key activation force (Rose 1991), and thereby introducting static muscle exertions to hold the fingers over the keyboard. Few studies were found that quantified muscle activity levels during negative keyboard angle use. Gilad and Harel (2000) found the mean electromyographic (EMG) activity measured for selected forearm muscles to be 28–58% less for a negatively sloped keyboard system than for the Tony™ and split keyboard designs, although the negative angle(s) studied were not specified. Studies of performance effects, the main concern of employers, have resulted in inconsistent findings. Increases in typing proficiency and typing quality have been cited in two studies (Hedge *et al.* 1995, Gilad and Harel 2000), whilst others have found no differences in mean typing speed, accuracy, errors or cumulative typing time (Hedge and Powers 1995, Simoneau and Marklin 2001).

These studies provide compelling evidence to support research regarding negatively sloped keyboard systems for reducing musculoskeletal stresses. However, few negative angle keyboards and their resulting effects on objective physiological measures (such as muscle activity, wrist posture, etc.), psychological measures (such as perceived discomfort) and performance have been studied. The objective of this study was to quantify the effects of various negative keyboard angles on forearm muscle activity, wrist posture, key strike force, perceived discomfort and performance to identify a negative keyboard angle or range of keyboard angles that minimizes exposure to risk factors for hand and wrist WMSDs. A laboratory study was conducted to compare keyboard slopes at 7° and ranging from 0° to −30°, at 10° increments, using an experimental wedge designed for use with current QWERTY keyboards. It was hypothesized that keyboard angle would affect muscle activity, wrist posture within a neutral zone, key strike forces and reported discomfort; whilst performance would remain constant.

2. Methodology

2.1. *Experimental design*

A laboratory study was conducted to test for the effects of keyboard angle, day, order and gender on wrist postures, forearm muscle activity, key strike force, self-reporting of discomfort and typing performance using a within participants design. Order of exposure to keyboard angle was balanced using a Latin square.

2.2. *Dependent variables*

2.2.1. Electrogoniometric measurements. A bi-axial electrogoniometer (SG65, Biometrics, Gwent, UK) was used to measure wrist flexion/extension (FE) and radial-ulnar (RU) deviation. Goniometers were attached whilst the hand and forearm were in a neutral position (arm resting at the participant's side, elbow flexed 90°, wrist straight, and hand pronated to minimize crosstalk (Buchholz and Wellman 1997)) using the manufacturer's guidelines. Calibration of the goniometers occurred before data collection. Positive angles denoted wrist extension and ulnar deviation, whilst negative angles denoted wrist flexion and radial deviation.

All goniometric data were analysed using DataLOG™ Software (Biometrics). Data collected during the typing task were software filtered and smoothed. Data unassociated with the typing task (i.e. reaching to turn the page, floating hands over the keys for an extended period of time without typing, etc.) were removed from the analysis by using an IDENT switch to mark the times of such instances. These markers were easily noted in the program during data analysis, and time lengths were extracted from the signal.

Mean FE and RU deviation angles were calculated for the entire 10-min testing period, minus the first and last 10 s of the experimental condition. Additionally, the percentage of movements spent within a neutral zone (< 15° extension, < 30° flexion, < 15° radial or ulnar deviation) and within ± 5° and ± 10° were calculated and compared across conditions.

2.2.2. Electromyography measurements. EMG measurements of the flexor carpi ulnaris (FCU) and extensor carpi ulnaris (ECU) muscles of both arms were obtained using 10 mm, circular Ag/AgCl pregelled bipolar disposable electrodes. Standard preparatory measures and electrode locations were implemented (Soderberg 1992, Perotto 1994). Interelectrode distance was set to 2.5 cm. EMG signals were hardware amplified, band-pass filtered (10 – 500 Hz), root mean square (RMS) converted (with 110 ms time constant), and A/D converted. The time constant was set such that the signal did not exceed 2 – 3 volts. Input impedance was measured using a standard voltmeter to ensure impedance was within acceptable levels (0 – 10 volts).

After stabilization (15 min), resting EMG and maximum voluntary exertions (MVEs) were obtained. Resting EMG measurements were recorded at 256 Hz for 10 s with the participant's hands in his/her lap or resting on a table. Three 5 s MVEs were collected for each muscle in both forearms independently while seated, with a 1-min rest period between each trial. Three types of MVE tests were performed, as a study by Juul-Kristensen *et al.* (2002) showed that handgrip tests underestimate MVE by an average of 34%. The three tests were: (1) handgrip strength test (overall forearm muscle activation test); (2) wrist FE tests (individual forearm muscle activation tests); and (3) hand-twisting test. Handgrip strength was assessed using a dynamometer (Jamar Adjustable Dynamometer, Asimow Engineering Co., Los Angeles, CA). The wrist FE MVE tests were performed using a stationary handle connected to an adjustable chain while positioned in a typing posture. MVE for the FCU was obtained by requiring participants to perform a wrist flexion exertion, and for the ECU was obtained during a wrist extension exertion. In the hand-twisting test, participants were asked to twist a rod held in both hands while seated. This test was performed twice, alternating the direction of twisting for each hand. MVE tests were randomized across participants for the first test session and the same sequence was used in the second test session. The peak RMS EMG signal was identified for each trial using LabView Software (Barr *et al.* 2001), and the maximum value across all tests was used as the MVE for that muscle for normalization of task EMG.

Participants performed a 5-min practice task, during which the EMG signal was monitored for abnormalities. Task RMS EMG was sampled at 256 Hz using a National Instruments A/D bit card and LabView software, which smoothed (10 Hz low pass filter) and stored data. These smoothed data were used to estimate normalized force levels. Time segements identified in the electrogoniometric data as extraneous were also removed from the EMG dataset. Means were calculated for the entire 10-min testing period minus the first and last 10 s of the experimental condition. Processed data were expressed in terms of percentage MVE and compared across conditions.

2.2.3. Key strike force measurements. Two 22.2 N (5 lbf) Model LBS Series load buttons (Interface, Scottsdale, AZ, USA) were used to measure key strike forces. The load button was small and cylindrical, 3.05 mm in height and 9.65 mm in diameter, with an accuracy of $\pm 0.25\%$. A Dell QuietKey^{TM} keyboard was engineered to allow the load buttons to monitor one key each without damaging the integrity of the keyboard's performance (figure 1). Participants were unaware which keys were being investigated. Load buttons were housed underneath the 'E' and 'N' keys inside foam and between the metal plate and the circuit board. The foam kept the load button in place under the correct key and also allowed for a consistent and normal feel to the user for all the keys.

LabView was used to calculate peak values of each individual key strike force and overall peak value for each key. Data from the load buttons were collected continuously

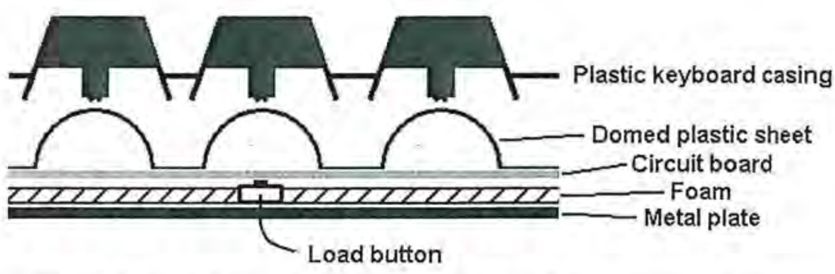

Figure 1. Load button location inside keyboard (cross sectional view).

for the 10-min experiment. Baseline noise and key strike threshold were determined by using various key striking patterns sampled at 1024 Hz, 512 Hz and 256 Hz to determine an appropriate sampling frequency. Analysis of the results indicated that a sampling frequency of 512 Hz was necessary to accurately estimate key strike forces (for details, see Woods 2002), contrary to previous studies using 250 Hz (Gerard *et al.* 1996, 2002a,b).

2.2.4. Performance. SkillCheck typing test software (SkillCheck, Inc., Burlington, MA, USA) was used to administer a pre-test task, practice tasks and typing tasks for all experimental conditions. The program provided text passages for participants to recreate and was limited to the computer screen. Performance measures calculated by the software (i.e. test duration, gross typing speed, number of errors, errors per minute, net typing speed, missing words, extra words, joined words, split words and misspelled words) were automatically recorded for each condition.

2.2.5. Self-reported postural discomfort questionnaire. A postural discomfort questionnaire was completed after each experimental condition. The Corlett postural discomfort scale was used to assess a participant's subjective feelings of discomfort following exposure to each keyboard angle (Corlett and Bishop 1976). Participants indicated on a 7-point scale (ranging from 0 = extremely comfortable to 7 = extremely uncomfortable) the amount of discomfort they experienced for the forearm, wrist, palm and fingers independently.

2.3. *Independent variable*

The independent variable was keyboard angle. The natural positive sloping of the keyboard was estimated to be 7° between the keyboard support surface and the plane crossing the centre of the keys in the 'Q' row and 'Z' row. Keyboard wedges were used to position the keyboard (figure 2) at 0°, −10°, −20° and −30°; but the angle of 7° was presented naturally (i.e. with no wedge present). The keyboard wedge was a triangular prism spanning the entire width of a standard QWERTY keyboard. To prevent possible confounding effects of a perceived wrist rest, a fixed stop was used to prevent slipping while typing for all experimental conditions, thus minimizing the exposure of the top edge of the wedge.

Figure 2. Side view of experimental keyboard wedge (in this case giving a keyboard slope of 0°).

2.4. *Typing task description*

A 43.2 cm monitor and standard QWERTY keyboard were placed on a Generation IV fully adjustable bi-level table (SIS Human Factor Technologies, Londonderry, UK) for the typing task. Text passages used for testing were extracted from a technical communication text. Different text passages were used for practice and test sessions to minimize learning. All passages were equivalent in word length and reading level. Passages were designed to last the duration of each experiment. No passage was ever completed prior to the end of a test session. No numeric keypad and mouse activity was required for the task.

2.5. *Participants*

Participants included ten (four male and six female) experienced typists (with a mean age of 22.1 years) who spent at least 20 h at a standard keyboard each week. Nine of the ten participants were right-handed. Participants used the ten-digit touch-typing method and typed a minimum of 45 words per minute. They were screened for current hand/wrist WMSDs using the Nordic Questionnaire (Kuorinka *et al.* 1987). Participants also needed to have negative findings on Phalen's and/or Tinel's tests (Phalen 1966, Kuschner *et al.* 1992) and report no symptomology (pain, numbness or tingling) in the median nerve distribution of the hand (thumb, index, middle and ring fingers, and palm) (Rempel *et al.* 1998). Participants exhibiting any signs of WMSDs, severe hand/wrist injury or arthritis, or who used anti-inflammatory medication, were excluded.

2.6. *Procedure*

Potential participants received a verbal and written description of the project, its objectives and the procedures used, and completed informed consent documents prior to any data collection. Participants were screened and inclusion was determined; this was followed by the scheduling of two test sessions at a later date. The two test sessions were completed at the same time of day on the same day of the week, 1 week apart, to assess repeatability.

On testing days, data collection equipment was attached and calibrated and preliminary measures collected (e.g. resting EMG, MVE, etc.). The workstation was adjusted to the typing posture used by Hedge *et al.* (1999); the workstation parameters (keyboard height and chair height) were recorded and reproduced for the second test session. The appropriate keyboard wedge was placed under the keyboard and a 5-min practice-typing task ensued, followed by a 5-min rest period and the 10-min typing task and a second 5-min rest period. During this second rest period, goniometer data were downloaded, the next keyboard wedge was set up and the postural discomfort questionnaire was administered. This procedure was repeated for each experimental condition until all five had been completed. Protocols for the second test session were identical to the first. Participants followed the same balanced Latin square design for both test sessions.

2.7. *Statistical data analysis*

Descriptive statistics (i.e. means, medians, standard deviations, frequency counts, etc.) were calculated for each dependent variable where appropriate. The Shapiro-Wilk's normality test was performed on all continuous variables to ensure that assumptions pertaining to normality were met for subsequent analyses. Repeated measures ANOVA was used to assess the effects of order, keyboard angle, gender, day and the keyboard angle by gender interaction. Tukey's honestly significant difference was used for post-hoc analysis for significant findings. Findings were considered significant at $p < 0.05$.

Linear correlations (Pearson's or Spearman's Rho) were also used to assess the repeatability of each dependent variable. Critical values for correlation coefficients were used to determine significance and were calculated based on sample size. All variables except MVE variables had samples of $N = 50$, thus critical values were $r_P^{CV} = 0.288$ (Fisher 1973) for Pearson's correlations for normal data and $r_S^{CV} = 0.279$ (Zar 1972) for Spearman's Rho correlations for non-normal data. MVE variables had samples of $N = 10$ and data were normally distributed; thus the critical value was $r_P^{CV\text{-MVC}} = 0.632$ (Fisher 1973). Strong correlations were defined as $r_{Pearson}^{\mathrm{MVC}} > 0.632$ and weak correlations as $r_{Pearson}^{\mathrm{MVC}} < 0.632$ for MVE variables. Strong correlations for remaining parametric and non-parametric variables were defined as values above or equal to 0.6, moderate correlations were defined as values from 0.279 to 0.599 and values below 0.279 were considered weak correlations. Corresponding p-values were used to indicate the strength of these correlations.

The postural discomfort questionnaire data consisted of ratings for various body parts. Repeated measures ANOVA was conducted on body parts to determine significance among the ratings and to assess if body parts could be grouped into logical body systems, starting with the most distal body part (i.e. the fingers) and moving upward. The part-grouping process continued until: (1) ratings showed significance between body parts; (2) ratings showed significance by keyboard angle; (3) body groups or parts showed significance by side; or (4) ratings showed significance by day. After final part groupings were identified, ratings were normalized using sum score divided by maximum sum score. Normalizing was necessary since summed body group ratings were likely to be greater than summed ratings of original body parts for the ten participants. Repeated measures ANOVA was performed on these normalized values to test for the effects of keyboard angle and gender.

3. Results

Descriptive statistics for the dependent variables are presented in table 1. In general, most dependent variable data could be pooled across days and no order effects were found.

3.1. *Repeatability*

Linear correlations were computed to assess repeatability across testing days (table 2). Apart from MVE variables, Pearson's correlations were above 0.59, indicating a strong correlation between days. All MVE correlations were below 0.50. All nonparametric correlations had Spearman's Rho above 0.33 except for the left FCU EMG, which had a correlation coefficient of 0.07. These variables were the only variables that did not show repeatability from day 1 to day 2. Of the correlations, 13% were weak, 19% were moderate and 68% were strong.

3.2. *Electrogoniometric data*

The effect of keyboard angle was significant for all dependent variables, with the exception of right hand RU movements within 5° and within 10°. In general, the $-30°$

Table 1. Descriptive statistics for the dependent variables by keyboard angle, giving mean (standard deviation) values.

Dependent variable	Keyboard angle	Left arm	Right arm	Dependent variable	Keyboard angle	Left arm	Right arm
			Electrogoniometric data				
Mean FE (°)	7°	30.8 (6.8)	34.0 (6.2)	Mean RU (°)	7°	14.1 (7.1)	10.8 (8.2)
	0°	28.8 (6.9)	38.7 (6.3)		0°	14.7 (7.1)	12.2 (8.5)
	−10°	21.5 (7.2)	20.8 (5.3)		−10°	16.2 (6.8)	13.1 (9.1)
	−20°	10.8 (6.9)	11.3 (6.0)		−20°	19.3 (7.0)	14.7 (9.2)
	−30°	3.2 (7.2)	2.4 (6.2)		−30°	21.3 (6.8)	17.1 (9.5)
%FE in neutral zone	7°	3.0 (7.9)	0.7 (1.4)	%RU in neutral zone	7°	55.4 (44.8)	68.6 (38.5)
	0°	6.3 (13.1)	3.5 (5.1)		0°	48.3 (42.1)	62.9 (39.8)
	−10°	25.3 (30.0)	22.1 (18.6)		−10°	45.8 (39.4)	54.5 (44.3)
	−20°	70.3 (28.9)	70.0 (29.2)		−20°	30.8 (36.0)	45.3 (43.4)
	−30°	91.2 (13.2)	94.4 (10.4)		−30°	19.2 (29.6)	37.5 (43.9)
% FE < 10°	7°	0.4 (1.3)	0.07 (0.2)	% RU < 10°	7°	33.5 (36.3)	50.3 (42.6)
	0°	1.2 (20.4)	0.6 (1.4)		0°	27.3 (32.6)	43.0 (43.1)
	−10°	11.0 (20.4)	5.4 (6.1)		−10°	18.0 (23.4)	35.8 (41.7)
	−20°	45.4 (32.1)	45.0 (33.6)		−20°	11.2 (19.9)	31.4 (41.9)
	−30°	71.1 (23.6)	77.0 (17.6)		−30°	4.8 (15.0)	28.2 (41.3)
% FE < 5°	7°	0.01 (0.0)	0.02 (0.1)	%RU < 5°	7°	10.9 (17.1)	22.8 (33.7)
	0°	0.1 (0.2)	0.1 (0.4)		0°	8.6 (15.1)	17.8 (29.5)
	−10°	3.0 (8.4)	1.0 (1.4)		−10°	4.8 (12.1)	17.8 (32.4)
	−20°	21.4 (25.1)	20.4 (21.9)		−20°	2.6 (8.4)	17.4 (34.3)
	−30°	40.5 (23.51)	44.0 (20.9)		−30°	1.6 (6.7)	15.4 (32.3)
			EMG data				
FCU (% maximum)	7°	10.91 (3.9)	4.96 (2.8)	ECU (% maximum)	7°	12.98 (4.2)	6.12 (2.4)
	0°	10.75 (3.5)	4.86 (2.7)		0°	11.25 (4.4)	5.83 (2.2)
	−10°	10.78 (3.3)	5.47 (3.2)		−10°	11.39 (4.1)	6.03 (2.5)
	−20°	10.11 (3.1)	5.30 (3.0)		−20°	11.09 (4.3)	6.28 (2.7)
	−30°	9.97 (3.6)	5.28 (3.0)		−30°	11.25 (4.2)	6.62 (2.8)

Key strike force (N)			Performance data				
Keyboard angle	Key 'N'	Key 'E'	Net typing speed (wpm)	Number of errors	Missing words	Misspelled words	Extra/ Joined/ Split words
7°	1.0 (0.2)	1.1 (0.2)	56.4 (8.7)	16.4 (10.5)	1.7 (0.9)	14.1 (9.8)	1.2 (1.6)
0°	1.0 (0.2)	1.1 (0.2)	55.1 (9.2)	15.8 (11.7)	0.7 (1.0)	13.8 (9.6)	1.7 (1.9)
−10°	1.0 (0.2)	1.1 (0.2)	57.8 (8.3)	18.3 (11.8)	0.8 (1.0)	15.9 (10.5)	1.4 (2.0)
−20°	1.0 (0.2)	1.1 (0.3)	56.6 (7.3)	15.0 (9.3)	1.1 (1.3)	13.2 (8.1)	0.7 (0.9)
−30°	1.0 (0.2)	1.1 (0.2)	53.9 (7.4)	16.8 (9.9)	0.7 (1.0)	15.0 (9.6)	0.6 (1.0)

			Discomfort rating			
Keyboard angle	Right hand	Right wrist	Right forearm	Left hand	Left wrist	Left forearm
7°	0.2 (0.2)	0.2 (0.3)	0.2 (0.3)	0.2 (0.2)	0.3 (0.2)	0.2 (0.2)
0°	0.2 (0.2)	0.3 (0.2)	0.3 (0.3)	0.2 (0.2)	0.3 (0.2)	0.3 (0.3)
−10°	0.2 (0.2)	0.3 (0.2)	0.3 (0.3)	0.2 (0.2)	0.3 (0.2)	0.3 (0.3)
−20°	0.2 (0.2)	0.2 (0.2)	0.3 (0.3)	0.2 (0.2)	0.3 (0.3)	0.3 (0.3)
−30°	0.3 (0.2)	0.3 (0.2)	0.3 (0.3)	0.2 (0.2)	0.3 (0.2)	0.3 (0.3)

FE = wrist flexion (−)/extension (+); RU = wrist radial (−)/ulnar (+) deviation; FCU = flexor carpi ulnaris electromyography (EMG); ECU = extensor carpi ulnaris EMG.

Table 2. Linear correlations between the dependent variables across testing days.

Parametric correlations: Pearson's		
Variable	Correlation (R)	p-value
Normalized EMG right–FCU$^{\tau}$	0.59	0.00
Mean RU–left$^{\tau}$	0.63	0.00
Mean FE–right$^{\psi}$	0.93	0.00
Net typing speed$^{\psi}$	0.90	0.00
MVE right–FCU$^{\lambda}$	0.20	0.58
MVE right–ECU$^{\tau}$	0.44	0.20
MVE left–FCU$^{\tau}$	0.28	0.43
MVE left–ECU$^{\tau}$	0.49	0.15

Nonparametric correlations: Spearman's Rho		
Variable	Spearman's Rho	Probability > |Rho|
Normalized EMG right–ECU$^{\tau}$	0.58	0.00
Normalized EMG left–FCU$^{\lambda}$	0.07	0.64
Normalized EMG left–ECU$^{\tau}$	0.43	0.00
Mean of key strike force peaks–'E' key$^{\psi}$	0.93	0.00
Mean of key strike force peaks–'N' key$^{\psi}$	0.89	0.00
%FE in neutral zone–left$^{\psi}$	0.87	0.00
%RU in neutral zone–left$^{\tau}$	0.56	0.00
Mean FE–left$^{\psi}$	0.87	0.00
Mean RU–right $^{\psi}$	0.64	0.00
%FE in neutral zone–right$^{\psi}$	0.93	0.00
%RU in neutral zone–right$^{\psi}$	0.72	0.00
%FE $< 5°$–left$^{\psi}$	0.85	0.00
%RU $< 5°$–left$^{\psi}$	0.63	0.00
%FE $< 5°$–right$^{\psi}$	0.90	0.00
%RU $< 5°$–right$^{\tau}$	0.48	0.00
%FE $< 10°$–left$^{\psi}$	0.88	0.00
%RU $< 10°$–left$^{\psi}$	0.64	0.00
%FE $< 10°$–right$^{\psi}$	0.91	0.00
%RU $< 10°$–right$^{\psi}$	0.73	0.00
Final ranking$^{\psi}$	0.83	0.00
No. of errors$^{\psi}$	0.64	0.00
Missing words$^{\tau}$	0.44	0.00
Extra/Joined/Split words$^{\tau}$	0.33	0.02
Misspelled words$^{\psi}$	0.66	0.00
Normalized left hand discomfort rating$^{\psi}$ (TIMs, RPs, Palm)	0.85	0.00
Normalized left wrist discomfort rating$^{\tau}$	0.59	0.00
Normalized left forearm discomfort rating$^{\psi}$	0.80	0.00
Normalized right hand discomfort rating$^{\psi}$ (TIMs, RPs, Palm)	0.79	0.00
Normalized right wrist discomfort rating$^{\psi}$	0.84	0.00
Normalized right forearm discomfort rating$^{\psi}$	0.84	0.00
Self-rating$^{\psi}$	0.72	0.00

FE = wrist flexion (−)/extension (+); RU = wrist radial (−)/ulnar (+) deviation; FCU = flexor carpi ulnaris electromyography (EMG); ECU = extensor carpi ulnaris EMG; MVE = maximum voluntary exertion; TIM = thumb, index, middle fingers; RP = ring and pinky fingers.
λ = weak correlation (r_S, $r_P \leqslant 0.28$; $r_P{}^{MVC} < 0.63$)
τ = moderate correlation ($0.28 < r_P, r_S < 0.63$)
ψ = strong correlation (r_S, r_P, $r_P{}^{MVC} \geqslant 0.63$)

keyboard angle showed the lowest mean FE deviations and the greatest percentage of FE movements in a neutral zone, within 5° and within 10° (figure 3). For the majority of of these variables, the −30° keyboard angle differed from all other keyboards and there was no difference between the 0° and 7° keyboard angles. The 7° keyboard angle was found to produce the lowest mean RU deviations and the greatest percentage of RU movements within a neutral zone, within 5° and within 10° (figure 4). In most cases the 7° and 0° keyboard angles were not significantly different from each other but did differ significantly from the other keyboard angles.

The keyboard angle by gender interaction was significant only for mean left hand FE deviations. Mean values decreased as keyboard angle decreased, but gender differences were noted at the −30° keyboard angle, where males (7.7°) had higher mean FE values than females (0.3°).

3.3. *Electromyography data*

Few keyboard angle effects were found for EMG data. Left FCU and right ECU muscle activity differed significantly with keyboard angle (figure 5). The 7° keyboard angle required significantly less left FCU activity (3.6%) than any other keyboard angle. In general, each of the three negative keyboard angles required significantly less right ECU activity (11.4–11.6%) than the 0° (12.4%) or the 7° (13.4%) keyboard angle, although no significant differences were found among the negative angles.

Right FCU muscle activity differed significantly with gender, with females (7.3% maximum) having higher muscle activity levels than males (4.5% maximum).

3.4. *Key strike force data*

Mean key strike force was significantly greater for the 'N' key than for the 'E' key (1.07 N vs. 1.02 N). No other differences in key strike force were found.

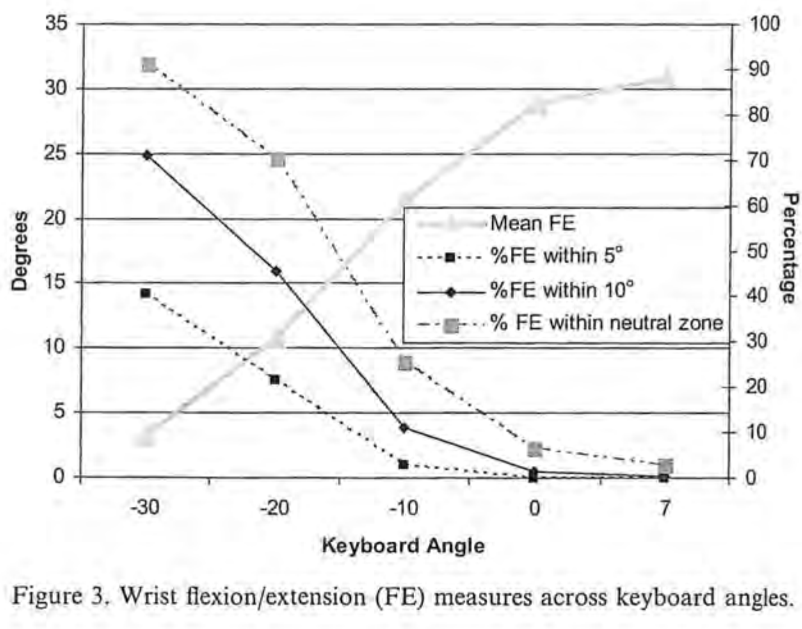

Figure 3. Wrist flexion/extension (FE) measures across keyboard angles.

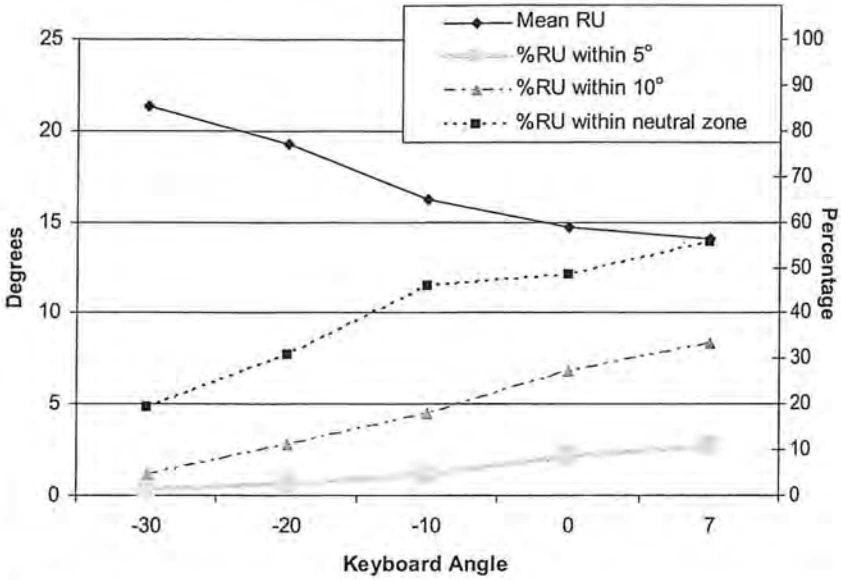

Figure 4. Wrist radial/ulnar deviation (RU) measures across keyboard angles.

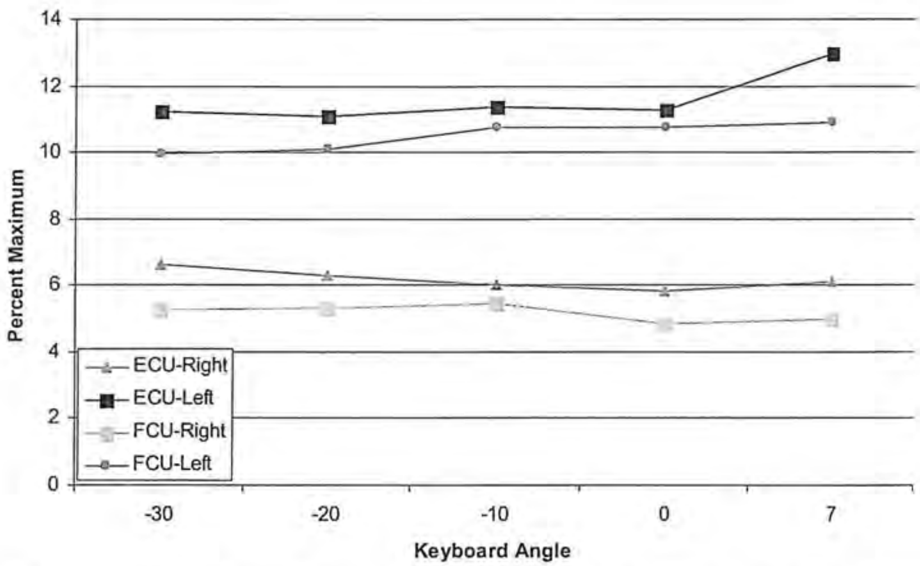

Figure 5. Mean electromyographic muscle activity levels across keyboard angles. ECU = extensor carpi ulnaris; FCU = flexor carpi ulnaris.

3.5. *Performance data*

Analyses showed that net typing speed increased across the two test sessions (55.2 wpm vs. 56.7 wpm) and errors, missing words and misspelled words decreased across test sessions (with an average of ~1.5% decrease). The −10°, 7° and −20° keyboard angles resulted in the highest net typing speeds (57.3 wpm, 56.1 wpm and 55.1 wpm respectively).

These keyboard angles differed significantly from the 0° and −30° keyboard angles. Males tended to have higher numbers of missing words than females (1.3 words vs. 0.3 words), and females performed significantly better than males on the 7° keyboard angle.

3.6. *Postural discomfort ratings*

Normalized discomfort values for the left hand, left forearm, right hand and right forearm showed significant difference by day of test (table 3). It is interesting to note that, for each body part, discomfort rating decreased from day 1 to day 2. Discomfort ratings for the left wrist and right wrist showed significant difference with gender. Males reported more discomfort for both the left and right wrists (overall average of 0.41 for males vs. overall average of 0.17 for females). Males reported more discomfort than females across keyboard angles for the left and right hand and right wrist. The difference between male and female ratings decreased as the keyboard angle became more negative.

4. Discussion

The objective of this study was to identify a negative keyboard angle or range of keyboard angles that minimized exposure to risk factors for hand/wrist WMSDs. In general, the hypotheses that were supported were: (1) wrist posture was within a neutral zone for a greater percentage of the time with regard to FE deviations but not to RU deviations; (2) performance remained constant when keyboard angle was varied; and (3) increased discomfort was reported for the −30° keyboard angle.

4.1. *Wrist posture*

The maximum negative slopes studied (−20° and −30°) greatly exceeded the slopes studied by Hedge and Powers (1995) (−12°) and Simoneau and Marklin (2001) (−15°), although the results were similar. Mean wrist extension angles in all three studies were between 1–3° for the most negatively sloped angles studied. Further, Hedge *et al.* (1999) found that 67% of typing movements (both FE and RU deviations) made whilst using negative keyboard angles were within a neutral zone. However, the present study found mean that the percentages of FE typing movements for both hands exceeded 70% and 90% within the same neutral zone for −20° and −30° keyboard angles respectively. Although there appear to be clear postural benefits associated with using negatively sloped keyboards, it is possible that previous studies underestimated the potential wrist posture benefits, and discrepancies in the values obtained may have been manifested

Table 3. Discomfort ratings for body part groupings that differed significantly by day of test Values are mean (standard deviation) of ratings.

Body part grouping	Day 1 Normalized values	Day 2 Normalized values
Left hand	0.23 (0.20)	0.19 (0.17)
Left forearm	0.32 (0.27)	0.24 (0.22)
Right hand	0.23 (0.19)	0.18 (0.18)
Right forearm	0.30 (0.28)	0.24 (0.25)

because of the use, or lack thereof, of a wrist rest. Nevertheless, wrist extension is clearly reduced when the keyboard is placed at a negative slope. Similar results were not as apparent for RU deviations, with the standard keyboard configuration resulting in lower RU deviations than with negatively sloped keyboards.

4.2. *Electromyography*

Muscle activity findings were contradictory, showing benefits for negative keyboard angles when considering the right arm activity and the standard keyboard resulting in lower activity levels for the left arm. Increased loading on the left hand due to key layout may account for this finding; however, overall, this study showed more loading on the right hand. Possible explanations include a dominantly right-handed population, higher key strike forces for the right hand and static loading (potentially leading to localized muscle fatigue). Fatigue was not specifically measured in this study, although it may be useful to look at this variable in future studies.

4.3. *Key strike force*

Key strike force was not affected by keyboard angle, although differences were found between the 'E' and 'N' keys, with higher values obtained for the 'N' key. These results could be attributed to the largely right-handed population, but are more likely due to the location of the key. The right index finger is forced to curl a greater percentage of its range as documented by Rose (1991). Negative keyboard angles tended to yield lower mean key strike force values than the standard keyboard for the 'N' key, although this finding was not statistically significant. Interestingly, 'E' key strike forces increased almost linearly with keyboard angle except for a decrease at the $-30°$ keyboard angle. These results may be due to the greater extension required for the left hand to strike the 'E' key, since it was then above home row, and the possible subsequent lifting of the hand and arm to reach it, which could have contributed increased momentum to strike the key.

4.4. *Performance measures in comparison with discomfort*

Most performance measures remained constant across keyboard angles, but they did differ significantly by day of test. Participants may have felt more comfortable after completing the first trial and their familiarity with the text passages may have unavoidably led to better performance, even with 1 week in between experiments. On the other hand, this may indicate that typing with negative keyboard angles is easily learned. In general, typing at negatively sloped keyboard angles yielded better or comparable results to the standard keyboard, particularly regarding error measures. Contrarily, Gilad and Harel (2000), Simoneau and Marklin (2001) and Hedge and Powers (1995) found no significant differences with regard to typing quality measures (i.e. mean typing accuracy, mean errors, cumulative typing time) for the negative keyboard angles they studied.

Contradictions in the results existed between objective measures (favouring the negative keyboard angles) and subjective measures (favouring the standard). However, discomfort decreased from the first to second test session, which may lead to general support for the objective findings. The findings in this study did not support the results found by Hedge (1994) that a majority of workers reported less discomfort when using negatively sloped keyboards. Participants in the present study, however, were not professional typists, as they were in the Hedge (1994) study. This fact may have resulted in increases for discomfort in the present study because typing was not a full-time task for the participants, and they may not have adapted to the rigorousness of the typing tasks.

4.5. *Repeatability of results*

No previous studies were found that addressed repeatability of data entry exposure variables (although studies have been performed on repeatability of EMG measures). For the most part, variables correlated extremely well by day of test, indicating that exposure levels are fairly constant. Repeatability was hard to achieve for certain EMG measures, potentially related to MVE. While steps were taken to ensure electrodes were located in the same place across test sessions, marks were in some cases difficult and impossible to identify. Skin flaking or washing of these areas may have resulted in the loss of marks. However, the shaved areas of the arm were readily apparent and provided for similar electrode placement. Aside from MVE, only the left hand mean FCU muscle EMG value did not correlate by day of test, and this muscle was the more difficult of the two to locate for electrode placement.

4.6. *Limitations*

There were several limitations in this study. The wedges were one possible source of error. The extreme angle of $-30°$ resulted in the work surface top coming in contact with a single participant's legs due to her anthropometry. This implies that people with small stature may not be able to use negatively sloped keyboards at extreme angles. Lack of a wrist rest may have also affected typing posture. It was hypothesized that a wrist rest would interfere with the natural movement of the hands whilst typing, and potential hazards with its use were forewarned by Simoneau and Marklin (2001). Hence, a wrist rest was not used in this study (as in other studies). Removal of the wrist rest may have contributed to a dynamic, more animated typing posture. However, wrist rests are not intended to be used continuously during typing, but rather during rest periods. Therefore, the study design should be representative of normal typing postures. Placement of the load button inside the keyboard may have been a limitation. Ideally, to measure a key strike force most accurately, a load button should be placed in direct contact with the finger. The load buttons were placed underneath a circuit board, a plastic-domed sheet and the plastic keycap. Each of these components possibly experienced deformations during key strike forces or absorbed part of the key strike.

Difference in the number of male and female participants may have resulted in gender differences that may not exist with equal gender populations. However, studies by Powers and Hedge (1992), Hedge (1994), Hedge and Powers (1995), Hedge *et al.* (1995, 1999), Gerard *et al.* (1996, 2002a,b) Gilad and Harel (2000), Hedge and Morimoto (2001) and Simoneau and Marklin (2001) studied all female or primarily female participants. These studies either made no mention of gender differences or were unable to identify gender differences. This study provided interesting gender differences unlike previous literature.

5. Conclusions

This study sought to identify a negative keyboard angle, or range of angles, that minimized exposure to risk factors for hand and wrist WMSDs. Relevant objective and subjective measures revealed contradictory findings. It was evident from these results that a single optimal keyboard angle could not be identified. Personal preference might decide which angle is best, based on subjective measures. However, this study concludes that a typing angle within the keyboard angle range of 0° to −30° provides objective postural benefits and reduced muscle activity in some cases, with improved or equivalent typing performance when compared to the standard keyboard. Future studies should include other types of keyboards (such as split keyboards or other alternative designs) to determine the benefits of negative slopes in conjunction with other risk factor-reducing properties of these keyboards.

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