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The effects of split keyboard geometry on upper body postures

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Split, gabled keyboard designs can prevent or improve upper extremity pain among computer users; the mechanism appears to involve the reduction of awkward wrist and forearm postures. This study evaluated the effects of changes in opening angle, slope and height (independent variables) of a gabled (14°) keyboard on typing performance and upper extremity postures. Twenty-four experienced touch typists typed on seven keyboard conditions while typing speed and right and left wrist extension, ulnar deviation, forearm pronation and elbow position were measured using a motion tracking system. The lower keyboard height led to a lower elbow height (i.e. less shoulder elevation) and less wrist ulnar deviation and forearm pronation. Keyboard slope and opening angle had mixed effects on wrist extension and ulnar deviation, forearm pronation and elbow height and separation. The findings suggest that in order to optimise wrist, forearm and upper arm postures on a split, gabled keyboard, the keyboard should be set to the lowest height of the two heights tested. Keyboard slopes in the mid-range of those tested, 0° to $-4°$, provided the least wrist extension, forearm pronation and the lowest elbow height. A keyboard opening angle in the mid-range of those tested, 15°, may provide the best balance between reducing ulnar deviation while not increasing forearm pronation or elbow separation. These findings may be useful in the design of computer workstations and split keyboards. The geometry of a split keyboard can influence wrist and forearm postures. The findings of this study are relevant to the positioning and adjustment of split keyboards. The findings will also be useful for engineers who design split keyboards.

Keywords: keyboard design; input device design; upper extremity posture

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1. Introduction

Computer users can experience elevated rates of upper body musculoskeletal problems when they use computers for many hours per week (Gerr *et al.* 2006). These musculoskeletal problems have been associated with a number of postural effects, such as elevated keyboard height, wrist ulnar deviation and sustained head rotation (Sauter *et al.* 1991, Bergqvist *et al.* 1995, Gerr *et al.* 2006). A systematic review of intervention studies among computer users concluded that the use of an alternative mouse or a forearm support can prevent musculoskeletal disorders (Brewer *et al.* 2006). These interventions reduce awkward wrist and forearm postures or decrease forearm or shoulder muscle loads. Two randomised controlled intervention studies have also demonstrated that the use of a split keyboard can reduce or prevent hand and arm pain and musculoskeletal disorders among computer users (Tittiranonda *et al.* 1999, Moore and Swanson 2003).

The positive health effects of the split keyboards are likely due to the more neutral wrist and forearm postures associated with their use compared to the postures required during typing on a conventional keyboard (Kroemer 1972, Marklin and Simoneau 2004). These keyboards are split into two halves, one for each hand, and include an opening angle to reduce ulnar deviation, a raised centre (gable angle) to reduce pronation and a near flat front-to-back surface angle (slope) to reduce wrist extension (Marklin *et al.* 1999). The underlying health basis for the split design may be from the neutral wrist and forearm postures, which reduce forearm muscle loads and pressures in the carpal tunnel (Marek *et al.* 1992, Marklin and Simoneau 2004, Rempel *et al.* 2008).

While a number of studies have compared wrist and forearm postures during typing on a split geometry keyboard to a conventional keyboard (Smith *et al.* 1998, Marklin *et al.* 1999, Tittiranonda *et al.* 1999, Zecevic *et al.* 2000, Rempel *et al.* 2007), few studies have evaluated the effects of changes in geometry within a split keyboard design (Nakaseko *et al.* 1985, Honan *et al.* 1995). The purpose of this study was to determine the effects of changes in the opening angle, slope and height of a split, gabled keyboard on typing performance, usability and wrist and forearm postures. The question was: if one starts with one split, gabled

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keyboard design (i.e. gable (14°), slope (−8°), opening (12°) and height (4 cm above elbow)), would increasing the opening angle or increasing the slope or increasing the height of the keyboard lead to more or less neutral distal upper extremity postures?

2. Methods

This was a laboratory study in which 24 subjects performed a touch typing task on seven keyboard test conditions while the finger, wrist, forearm and elbow postures of both upper extremities were measured. The independent variables were keyboard slope, opening angle and height. The dependent variables were subjective ratings and rankings, typing speed and right and left postures (i.e. wrist extension, wrist ulnar deviation, forearm pronation, elbow posture). The study was approved by the Institutional Review Board at the University.

2.1. *Subjects*

Subject inclusion criteria were the ability to touch type 40 words per min on a split keyboard (Microsoft Natural Elite or similar) and at least 3 d of experience using a split keyboard. Subjects were excluded if they reported current head, neck, back or arm injuries or difficulty performing a typing task for an entire day. Subjects were recruited with flyers placed on the university campus, at a local temporary employment agency and in the community.

The mean age of the subjects was 30.0 (SD ± 11.2) years. There were 12 males (50%) and 12 females (50%). Most participants (n = 17) were from the university staff, students or the general public; seven were from a temporary hiring agency. Most participants (79%) had greater than 1 week experience typing on a split keyboard and most (88%) were right handed. The mean subject height and weight (without shoes) were 170.5 (±11.8) cm and 72.1 (±19.5) kg; right arm length (elbow to end of middle finger) was 42.6 (±3.6) cm; right hand length (palm side, distal wrist crease to end of middle finger) was 18.4 (±1.3) cm and right middle finger length (dorsal side from metacarpophalangeal joint to tip of finger) was 10.2 (±0.75) cm.

Figure 1. Experimental setup, subjects type during experiment while forearm and wrist postures are recorded by camera banks in the corners of the room.

2.2. *Keyboard test conditions*

A split adjustable keyboard (model GTU-0077; KeyOvation, Austin, TX, USA) was used for all keyboard test conditions. The keyboard was modified by increasing the maximum possible opening angle and by adding a wrist support to each half of the keyboard (Figure 1). The wrist support dimensions were 19.5 cm × 8 cm × 3.5 cm. Seven keyboard configurations were selected to assess the effects of three keyboard factors (independent variables): opening angle (three levels); slope (four levels); and height (two levels) (see Table 1, levels within each factor are bold). For all keyboard configurations, the gable angle was 14°. This angle was selected because in a prior study of existing keyboards it appeared that this gable angle was associated with distal upper extremity postures closest to neutral (Rempel *et al.* 2007). Gable angle was measured in the coronal plane on each half of the keyboard. The slope was set by controlling the angle between the work surface and the front-to-back surface of the keycaps in the sagittal plane. Then the opening angles were achieved by rotating each side of the keyboard in the plane of the keycaps until each half deviated from the closed position the number of degrees required (Smutz *et al.* 1994).

2.3. *Practice session*

On the day of the study, subjects warmed up by typing on a split keyboard (model SKR-4200U; KeyOvation) in configurations A and E (Table 1) for 20 min per configuration. Subjects were instructed to avoid resting their wrists on the wrist rest or work surface while typing; this is a common instruction to typists in order to prevent contact stress at the wrist. A typing program (Typing Workshop Deluxe; Valusoft Inc., Waconia, MN, USA) presented text on the screen, which was typed by subjects. The program also calculated net typing speed during the practice and test sessions. Subjects were eliminated from the study if they were unable to type at least 40 words/min in a 10 min test on the configuration A keyboard during the practice session.

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Table 1. Angles and heights of seven keyboard configurations tested. Mean typing speed in words per min and wrist, forearm and elbow postures (SD).

	Keyboard configurations									
	A	B	C	D	E	F	G			
Opening angle (°)	**12°**	**15°**	**18°**	12°	12°	12°	12°	Opening *p*-value[II]	Slope *p* value[III]	Height *p*-value[IV]
Slope (°)	**−8°**	−8°	−8°	**−4°**	**0°**	**+8°**	−8°			
Height (cm)[V]	**4**	4	4	4	4	4	**8**			
Typing speed (wpm)	60.5 (9.3)	56.9 (12.3)	59.2 (11.4)	60.3 (14.6)	59.6 (11.2)	60.2 (11.3)	59.5 (11.4)	$p = 0.08$	$p = 0.96$	$p = 0.55$
Right wrist extension(°)	8.3 (9.5)^{a}	8.0 (9.4)^{b}	6.5 (9.7)^{a,b}	7.8 (9.9)^{1}	8.2 (10.8)	14.4 (20.4)^{1}	9.0 (8.6)	$p = 0.003$	$p = 0.03$	$p = 0.45$
Left wrist extension(°)	9.9 (22.8)	9.5 (23.36)	8.8 (22.5)	9.7 (22.7)	10.4 (22.9)	16.0 (29.9)	10.0 (22.4)	$p = 0.12$	$p = 0.24$	$p = 0.62$
Right ulnar deviation(°)	3.6 (17.2)^{a,b,§}	2.7 (17.1)^{a,c}	0.7 (16.6)^{b,c}	2.5 (18)	0.7 (17.5)	7.1 (30)	6.5 (17)§	$p < 0.0001$	$p = 0..79$	$p = 0.003$
Left ulnar deviation(°)	10.7 (23.7)^{d,e,§§}	8.3 (24)^{d}	7.4 (23.1)^{e}	8.3 (23.4)	7.5 (23.7)	12.8 (34.5)	13.6 (23.2)§§	$p = 0.0002$	$p = 0.84$	$p < 0.001$
Right pronation(°)	58.3 (11.4)^{a,1,§}	59.2 (11.1)	59.6 (11.4)^{a}	58.5 (11.4)^{2}	59.1 (11.3)^{3}	61.5 (11.7)^{1,2,3}	60.0 (10.8)§	$p = 0.0008$	$p < 0.0001$	$p = 0.0009$
Left pronation(°)	58.9 (9.4)^{d,§§}	59.2 (9.4)^{e}	60.0 (9.8)^{d,e}	58.5 (9.1)^{4}	58.7 (9.7)^{5}	60.3 (9.5)^{4,5}	61.3 (9.4)§§	$p = 0.002$	$p = 0.002$	$p < 0.0001$
Right finger flexion(°)[I]	9.3 (22.7)	9.9 (22.9)	9.2 (22.2)	9.4 (22.3)	10.2 (22.3)	11.6 (23.4)	9.5 (22.2)	$p = 0.19$	$p = 0.98$	$p = 0.67$
Left finger flexion(°)[I]	4.2 (9.6)^{d}	5.3 (10.0)^{d}	4.3 (10.5)	4.6 (10.4)	4.6 (9.8)	9.8 (23.5)	4.0 (9.6)	$p = 0.02$	$p = 0.81$	$p = 0.34$
Elbow separation(cm)[I]	55.8 (6.1)^{a}	56.9 (5.8)^{b}	59.1 (5.4)^{a,b}	55.2 (6.1)	54.9 (6.5)	54.5 (7.5)	57.0 (6.4)	$p < 0.0001$	$p = 0.43$	$p = 0.10$
Right elbow height(cm)[>]	68.3 (6.1)^{1,2,§}	68.3 (5.8)	68.9 (5.4)	67.7 (6.1)	66.8 (6.5)^{1}	66.6 (7.5)^{2}	70.4 (6.4)§	$p = 0.10$	$p = 0.0003$	$p = 0.0001$
Left elbow height(cm)[I]	68.9 (3.7)§§	68.7 (3.6)	69.1 (3.7)	68.4 (3.9)	67.9 (3.7)	69.3 (3.6)	70.5 (4.2)§§	$p = 0.40$	$p = 0.72$	$p = 0.0005$

[I] n = 20.

[II] repeated measures ANOVA comparing opening angle effects only (keyboard configurations A,B, and C).

[III] repeated measures ANOVA comparing slope effects only (keyboard configurations A,D,E, and F).

[IV] repeated measures ANOVA comparing height effects only (keyboard configurations A and G).

[V] Height from the elbow to the tops of the D or K keys.

Note: Analysis is stratified by factor (opening, slope, height). Within a row, values within a factor that are significantly different (Tukey test) are noted by a common superscript (opening right side (^{a,b,c}), opening left side (^{d,e,f}), slope right side (^{1,2,3}), slope left side (^{4,5,6}), height right side (§), height left side (§§)). (n = 24 unless otherwise noted.)

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2.4. Workstation set-up

The chair arm supports were removed, the back support was locked to an inclination angle of 105° and the chair seat pan height was adjusted so that the subject's feet were flat on the floor and the thighs were approximately horizontal. Subjects were instructed to rest back against the back support during typing. The monitor was positioned so that the centre of the monitor was 15° below the horizon from the eyes and approximately 60 cm from the eyes. For each test condition, the keyboard was placed in a standardised location on the work surface so that the D and K keys (home row) were 19.0 cm from the front edge of the support surface. The keyboard support surface height was adjusted so that the D and K keys were either 4 or 8 cm above elbow height (floor to bottom of elbow) depending on the test condition. It was not possible to consistently achieve lower keyboard heights than the 3 cm above elbow height in order to maintain clearance between the top of the thighs and the bottom of the work surface. The keyboard height (top of work surface to top of D or K key) ranged from 8 to 10 cm and the work surface thickness was 3 cm. The chair position was moved forward or backward so that the upper arms were in 10° of forward flexion while typing.

2.5. Marker placement, data collection and posture calculations

Subjects wore short-sleeve shirts to expose their arms. To record the right and left elbow, forearm, wrist, finger postures, eight lightweight plastic plates were mounted to the dorsum of each hand, forearm, middle proximal phalanx and the lateral epicondyle using double-sided tape (Figure 1). The plates were 44 × 40 × 5 mm (15 g), 76 × 40 × 5 mm (22 g), 31 × 15 mm and 16 × 16 mm, respectively. Infrared emitting diodes (IREDs) were mounted on each plate: three IREDs on the hand plate; three IREDs on the forearm plate; two IREDs on the middle proximal phalanx plate; one IRED on the lateral epicondyle plate.

The three-space coordinates of each IRED marker were recorded continuously at 10 Hz using 2 Optotrak 3020 sensor banks (Northern Digital, Ontario, Canada). The sampling rate is adequate to calculate the mean posture for a keyboard configuration (3000 samples). A reference posture of 0° wrist flexion, 0° wrist deviation and 45° forearm pronation was collected by having the subject place their palms onto a trapezoidal block located on the table in place of the keyboard. Data for this reference posture were recorded for 10 s and used for subsequent posture calculations.

The methods for calculating wrist posture and forearm pronation were similar to a previous study (Rempel *et al.* 2007) and involved the identification of two perpendicular planes that passed through the centre of the wrist and the elbow and projected the hand marker plate on to the planes to calculate ulnar deviation and wrist extension.

2.6. Testing protocol

Keyboard configuration order was randomised for each subject using a random number generator. The subject typed text from a passage displayed on the screen (the text passages were extracted from short stories by contemporary authors that included all the letters of the alphabet, numbers and punctuation). Approximately 2 min into the typing task, unannounced to the subject, posture data were recorded for 5 min with the motion tracking system. After 10 min of typing, the typing test was stopped and the subject's net typing speed was recorded. Net typing speed was the gross typing speed minus errors. Subjects completed a usability questionnaire for the keyboard condition and after a 3-min pause, the next keyboard condition was tested. The usability questionnaire (modified from ISO 9241) assessed seven characteristics of the keyboard including activation force of the keys, keying rhythm, fatigue of the upper extremities and posture.

After testing on all seven keyboard configurations, subjects rank ordered the keyboard conditions by categories (ease of use, accuracy, speed, comfort, overall) from 'best' (1) to 'least favourable' (7). The subjects were also asked to select their first choice among the keyboard configurations.

2.7. Statistical analysis

Differences in postures were evaluated using repeated measures ANOVA. A separate model was run for each factor (i.e. slope, opening angle, height); due to the study design, interactions could not be explored. Significant findings were subsequently evaluated with the post-hoc Tukey test for multiple comparisons (SAS Institute, Cary, NC, USA). As a repeated measures study, the statistical comparison is within each subject and is between the average posture during one keyboard condition and the average posture during another condition. Differences in subjective ranking of keyboards were evaluated using Friedman's two-way ANOVA by ranks.

3. Results

Mean typing speeds were not significantly different between levels within each of the three factors tested (Table 1). Based on repeated measures ANOVA,

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there were significant differences in mean right wrist extension, right and left wrist deviation, left finger flexion, elbow separation, right and left forearm pronation between levels for each of the three keyboard factors tested (i.e. slope, opening angle, height) (Table 1 and Figure 2). Post-hoc pair-wise comparisons revealed that for right wrist extension, the only significant differences were between two pairs of keyboard opening angles (A:C, B:C) and one keyboard slope comparison (D:F). For left wrist extension, there were no differences between keyboard conditions. For right wrist deviation, all pairwise comparisons were significantly different between keyboard opening angles (A:B, A:C, B:C) and between keyboard heights (A:G). For left wrist deviation, the significant differences were between two opening angle comparisons (A:B, A:C) and height (A:G). For left finger flexion, the only significant difference was between one opening angle comparison (A:B). For elbow separation, the significant differences were between two pairs of opening angles (A:C, B:C). For right forearm pronation, the only significant differences were between one opening angle comparison (A:C) and between three pairs of slopes (A:F, D:F, E:F) and between the heights (A:G). For left forearm pronation, the only significant differences were between two pairs of opening angles (A:C, B:C) and between two pairs of slopes (D:F, E:F) and between the heights (A:G).

Subjective ratings of keyboards are presented in Table 2; lower scores are better ratings. Based on the Friedman test, which evaluated across all seven keyboard configurations, there were no significant differences in any of the ratings. When asked to choose the most preferred keyboard, the most popular choice was the ‘F’ keyboard configuration, followed by the ‘G’ keyboard configuration, while the least preferred was the ‘B’ keyboard configuration.

4. Discussion

Wrist and forearm postures during keyboard use may be influenced by many factors, including anthropometry, typing style, task, chair, workstation set-up and keyboard design. This study found no differences in typing speed or error rates across the keyboard geometries tested. However, the study found that, for a split, gabled keyboard design, when all other factors were held constant, the keyboard opening

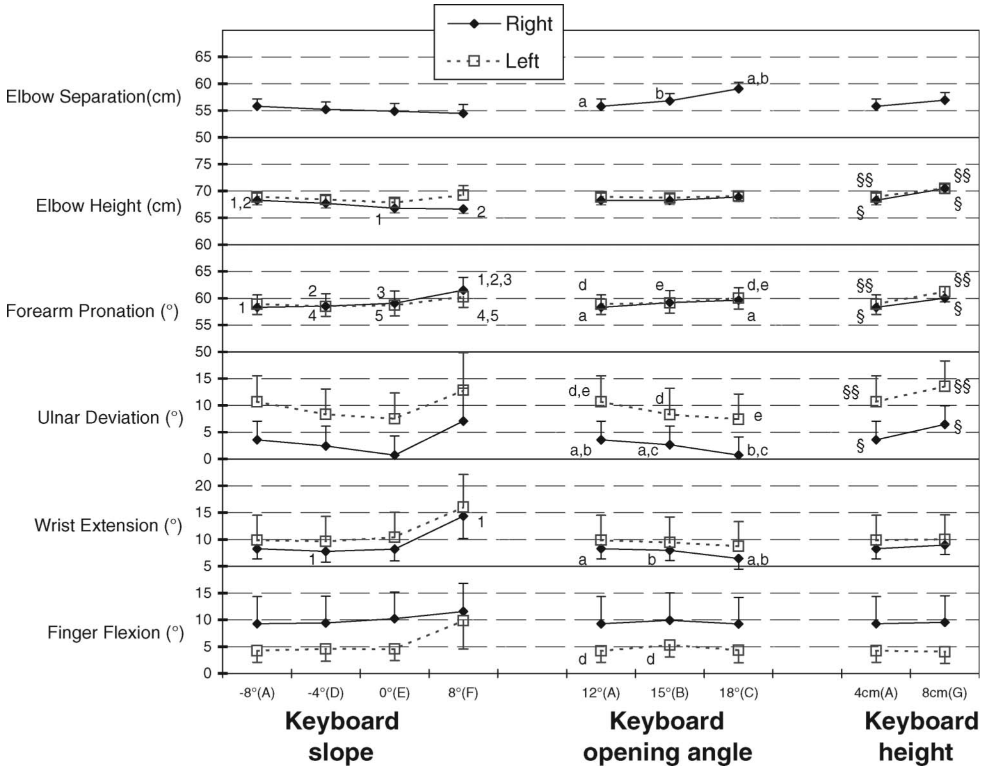

Figure 2. Mean finger, wrist and forearm postures and distances (±SEM) grouped by three keyboard factors: slope; opening angle; and height (n = 24). The chart is structured so that lower values are more neutral postures. Significant differences are noted by a common superscript (opening right side (^{a,b,c}), opening left side (^{d,e,f}), slope right side (^{1,2,3}), slope left side (^{4,5,6}), height right side (§), height left side (§§).

Table 2. Subjective rank order rating of keyboard configurations by ease of use, accuracy, speed, comfort and overall characteristics (n = 16).

	Keyboard configurations							
	A	B	C	D	E	F	G	*p*-value[a]
Ease of use	3.9 (1.9)	4.8 (1.6)	4.1 (1.6)	4.2 (2.2)	4.2 (2)	3.3 (2)	3.5 (2.1)	$p > 0.25$
Accuracy	3.9 (1.8)	5.1 (1.7)	3.8 (2)	3.6 (2.1)	4.1 (1.7)	3.4 (2.1)	4.1 (2.1)	$p > 0.25$
Speed	3.9 (2)	4.9 (1.7)	3.8 (1.6)	4.4 (2.1)	3.8 (1.9)	3.6 (2.1)	3.6 (2.2)	$p > 0.50$
Comfort	4.4 (2.2)	4.5 (1.3)	4.1 (1.8)	4.1 (1.9)	4.2 (2)	3.2 (2.1)	3.5 (2.1)	$p > 0.50$
Overall	4.2 (1.9)	4.9 (1.6)	3.9 (1.8)	4.3 (2)	4.2 (2.2)	3.1 (2)	3.5 (1.9)	$p > 0.25$
Preference (%)	8.7	4.4	17.4	8.7	8.7	30.4	21.7	$p > 0.20$[b]

[a] Friedman's test.

[b] Chi-square goodness of fit test (n = 23).

Note: Ratings are from 1 (best) to 7 (worst). Participants were also asked which keyboard they would prefer.

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angle, slope and height all had significant effects on wrist, forearm and elbow postures.

Keyboard opening angle (12°, 15° and 18°) had a greater effect on the right wrist than the left wrist; a greater opening angle was associated with less ulnar deviation and less wrist extension. However, the larger opening angle led to an increase in forearm pronation and an increase in elbow separation. This indicates that participants likely compensated for the wider opening angles not only by decreasing wrist ulnar deviation but also by increasing shoulder abduction. In a study of keyboards without a gable, a 0° vs. 12° degree opening angle led to a 9.2° to 11.5° reduction in ulnar deviation in the right and left hand, respectively (Marklin and Simoneau 2001). The Marklin study did not report wrist extension or forearm pronation.

Prior studies of the effect of a negative slope keyboard on posture have been limited to conventional keyboard designs (Hedge and Powers 1995, Simoneau *et al.* 2003, Woods and Babski-Reeves 2005). Some of these studies lowered the height of the keyboard at the same time as the negative slope was introduced, making it difficult to interpret whether the positive effects on wrist posture were due to height changes or slope changes. In the present study of a split, gabled keyboard, keyboard slope (−8°, −4°, 0°, and +8° (configurations A, D, E and F)), at a fixed keyboard height, had effects on right wrist extension, right elbow height and both right and left forearm pronation. Surprisingly, the only effect on wrist extension was that the 8° slope keyboard was associated with the greatest right wrist extension; there was no effect of the other keyboard slopes on wrist extension. The 8° slope was also associated with greater forearm pronation. The most negative slope evaluated (−8°; keyboard slopes away from user) was associated with an increase in right elbow height (i.e. shoulder elevation) but no change in elbow separation. A prior keyboard study altered the slope of a fixed split keyboard with a gable of 14° and an opening angle of 12° (Rempel *et al.* 2007). Changing the slope from 0° to −7° led to a 5° increase in ulnar deviation compared to 3° observed in this study, an 8° reduction in wrist extension compared to no change in this study and a 2° reduction in pronation compared to a 1° reduction observed in this study. Both studies used palm supports and the key heights were controlled. A possible explanation for the difference of the effect of slope on wrist extension is that the prior study used a keyboard with a curvature in the rows of keys, and the keyboard was higher in the −7° slope position than in the 0° position.

The height of the keyboard (DK keys set 4 and 8 cm above elbow height (configurations A and G)) had effects on wrist deviation, forearm pronation and elbow height, but no effects on wrist extension or elbow separation. The lower height was associated with less ulnar deviation, less pronation and lower elbow height. The effects of keyboard height on elbow height are consistent with and may explain the observation by Bergqvist *et al.* (1995) that a keyboard height of 5 to 10 cm above elbow height was associated with neck/shoulder pain compared to lower keyboard heights. It is interesting to note that keyboard height had almost as much or more influence on pronation and wrist deviation as the changes in keyboard opening angle or slope. The study findings support a recommendation for the lower keyboard height in order to reduce wrist ulnar deviation and forearm pronation and lower elbow height. Since a gabled, split keyboard is higher than a conventional keyboard, keyboard designers should consider ways to minimise the height of a split keyboard.

The changes in joint postures associated with different keyboard designs may alter the risk for musculoskeletal problems. The change in wrist extension, ulnar deviation and forearm supination toward a more neutral posture can change the position and loads of the extrinsic finger and wrist muscles and can change pressure in the carpal tunnel (Marek *et al.* 1992, Rempel *et al.* 2007). These changes can reduce risk of tendon, nerve and muscle injury (Marek *et al.* 1992, Rempel *et al.* 1999). The reduction in elbow elevation or elbow separation (i.e. shoulder abduction) may be accompanied by a reduction in shoulder and neck muscle loads and, therefore, may help prevent neck and shoulder pain. Although some of the significant changes in postures between keyboard conditions are relatively small, if the task is performed for many hours per day, these small differences may be beneficial.

A limitation of the study was that the subject's exposure to each keyboard condition was brief; therefore, the subjective ratings of keyboards should be interpreted with caution. It is also known from previous keyboard studies that subject preference is not generally correlated with more neutral upper body postures (Honan *et al.* 1995). Therefore, subjective preferences after short-term exposures may not be the best guide for hand tool selection. Studies of longer duration (i.e. greater than 1 month) can determine whether the postural improvements with the split keyboard design seen in this short-term study have health merit (Tittiranonda *et al.* 1999, Brewer *et al.* 2006). Another limitation is that only one type of keyboarding task, a simple text entry task, was tested. Typing tasks that include more non-alpha keys, which are arranged at the sides of the keyboard, may produce different findings. Finally, this was not a full factorial study design and therefore it was not possible to evaluate interaction effects between keyboard slope, opening angle and height. It would be useful to examine these interactions in future studies.

Overall, the study suggests that in order to optimise wrist, forearm and shoulder postures, on a split, gabled keyboard, the keyboard should be set to the lower height level (4 cm above elbow height) in order to reduce ulnar deviation and the elbow height (i.e. reduce shoulder elevation). The effects of keyboard slope on wrist extension, forearm pronation and elbow height were mixed. On the plus side, the 8° slope led to a lower elbow height. On the minus side, it tended to more wrist extension and forearm pronation. The $-8°$ slope led to the reverse effects. Slopes in the mid-range of those tested, $-4°$ to 0°, provided the least wrist extension, forearm pronation and lowest elbow height. The effects of keyboard opening angle were also mixed. The 18° opening angle led to the least ulnar deviation and wrist extension, but also produced the most elbow separation (i.e. shoulder abduction) and forearm pronation. The mid-range opening angle, 15°, may provide the best balance between reducing ulnar deviation while not causing greater elbow separation or forearm pronation. The study findings should provide some guidance to computer users, keyboard designers and those human factors engineers who are responsible for computer workstation design.

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