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Kinematics of the fingers and hands during computer keyboard use

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Abstract

Background. Although there has been extensive research about the kinematics of the neck, arm, and wrist during computer keyboarding, there is almost no information concerning the kinematics of the fingers, thumbs, and hands. The purpose of this descriptive study was to establish normative values of the kinematics of the fingers and hands during computer keyboard use.

Methods. This study describes the angles, angular velocities, and angular accelerations of the metacarpophalangeal joints and proximal interphalangeal joints for the right and left hands of 20 computer keyboard users during a word-processing task. A new kinematic variable for computer keyboard use, hand/wrist displacement, is also defined and examined. Hand/wrist displacement refers to the translational movements of the hands in which the entire hand is repositioned to strike the keys. Kinematics of both hands of the keyboard users were captured using a three-dimensional motion capture system.

Findings. Metacarpophalangeal joint kinematics in flexion/extension and abduction/adduction are reported during typing. Proximal interphalangeal joint kinematics in flexion/extension are also reported. The means and standard deviations for finger postures, velocities and acceleration were generally not significantly different between the right and left hands, with the exception of the 1st digit (thumb). Hand/wrist displacement was significantly different between the right and left hands for side to side movements. Differences in kinematics among the fingers are discussed in view of their potential to be a risk factor for musculoskeletal disorders.

Interpretation. This study establishes baseline understanding of the kinematics of computer keyboard use. This information will be useful in future studies of potential risk factors associated with keyboard use.

Keywords: Typing; Musculoskeletal disorders of the upper extremities (MSD-UE); Range of motion; Acceleration; Velocity

1. Introduction

The association between musculoskeletal disorders of the upper extremity and computer use has been a public health concern since the mid 1980s (Hopkins, 1990), and the increasing reliance on computers for many daily tasks places increasing numbers of both workers and non-workers potentially at risk. Several studies have reported on the incidence of musculoskeletal disorders of the upper extremity related to computer use in industry. These reports have been quite consistent across studies, i.e. overall, it appears that approximately 22% of computer users sustain musculoskeletal disorders of the upper extremity including neck, shoulder and hand/wrist disorders (Bergquist et al., 1995; Gerr et al., 2002; Hales et al., 1994).

Studies examining the kinematics of computer use have focused almost exclusively on describing the postures and actions of the wrist and forearm (Rose, 1991; Serina et al., 1999; Simoneau et al., 1999). Little attention has been paid to the kinematics of the fingers, thumb, and hand. Studies that have examined the kinematics of fingers during computer keyboard use have focused on describing

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the motions of single fingers (Dennerlein et al., 1998; Flanders and Soechting, 1992; Ortiz et al., 1997; Soechting and Flanders, 1997). These studies suggest that although computer keyboarding is a highly stereotypical task for an individual user, there is great variability between users. This implies that each computer user has a signature style for interacting with the computer keys. To our knowledge, there has been only one study that described the overall kinematics of the hand during a keyboarding task; Sommerich et al. (1996) evaluated the key strike force, overall joint posture, velocities, accelerations, and tendon travel at the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints of 25 professional typists using attached electro-goniometers. While that study provided important information about the basic kinematics of keyboarding, it did not examine joint postures, velocities, or accelerations of individual finger motions nor look at the differences in kinematics of the right and left hands.

In addition, a new kinematic variable related to hand use, hand/wrist displacement, has not been described elsewhere in the literature. Hand/wrist displacement refers to translational hand movements in which the entire hand/wrist unit is repositioned to strike the keys. Observations of computer keyboard users have identified that they adopt one of two key striking patterns during computer keyboard use: they either "plant" their wrist/forearms in one place by resting their wrists on one spot on the desktop or a wrist rest and reaching for the keys with primarily finger motions, or they "float" over the keys, continuously repositioning their hand/wrist units to reposition their fingers for key strike. The planted pattern will often be associated with increased ulnar and radial deviation angles to reach the keys at the extreme right and left of the keyboard. For the floating pattern, the wrist, hand and fingers essentially act as a single unit (Fig. 1). Since musculoskeletal disorders of the upper extremities are often associated with repetitive use of the joints, it is possible that individuals who "plant" may have increased stress on joints and tendons during computer use due to the increased angles at the wrist. This study provides an initial measurement of average hand/wrist displacement during keyboarding.

The purpose of this research paper is to: (1) provide a quantitative description of the kinematics of the finger joints and translational hand/wrist movements during the

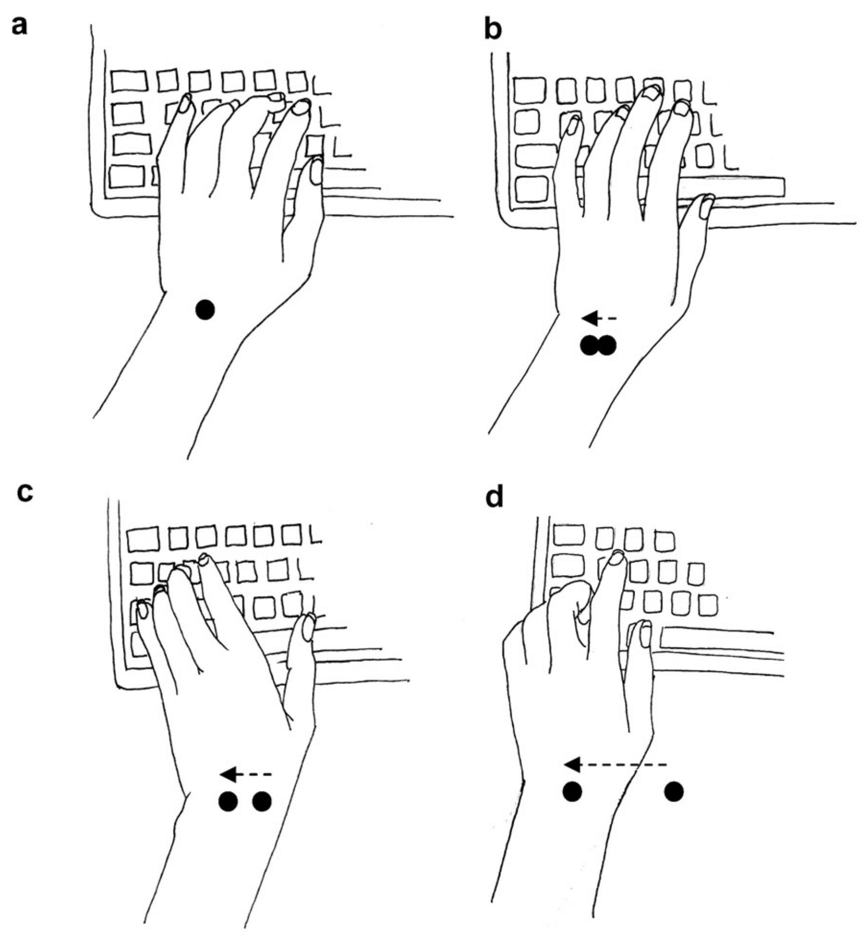

Fig. 1. In this graphical display of hand/wrist displacement the keyboard user is typing the word "gave". In picture (a) he has struck the "g" key. Pictures (b, c, and d) demonstrate three possible methods that can be used to strike the "a" key. In picture (b), the user strikes the "a" key with his 5th digit. This results in almost no displacement of the wrist or hand, and the wrist remains "planted". In picture (c), the user ulnarly deviates the wrist to strike the "a" key with the 3rd digit. Although the hand itself does move, there is minimal wrist displacement, and the wrist remains "planted". In picture (d) the user shifts the hand and wrist as a unit to strike the "a" key. This results in significant wrist displacement and the hand/wrist unit "floats".

performance of keyboarding tasks, and (2) examine potential differences between the left and right hands. The findings presented here are part of a larger study that is developing an observational instrument that can be used by clinicians and researchers to document the kinematics of the fingers and hands during typing.

2. Methods

This descriptive study was approved by the University of Pittsburgh Institutional Review Board.

2.1. Subjects

Twenty subjects were recruited from the University of Pittsburgh and the University of Pittsburgh Medical Center via flyers and word of mouth. The subjects were 70% female and all but one were right-handed. Table 1 provides the demographics and hand anthropometric data (size, measured via a tape measure and strength measured via a dynamometer) for the subjects. All subjects reported using a computer an average of 6 h per day, and approximately two thirds of that time was spent keyboarding. Inclusion criteria consisted of typing at least 40 words per minute over a continuous 25 min period (expert typists). Individuals with active musculoskeletal discomfort or who had been diagnosed with a musculoskeletal disorder of the upper extremity were not excluded from this study and four reported that they were experiencing discomfort at the time of the trial.

Table 1
Subject demographics

	Mean (s.d.)	Range	
		Minimum	Maximum
Age	27.8 (11.0)	20	54
Comp. use (h/day)[a] ($n = 18$)	5.3 (2.6)	2	10
Time using keyboard during computer use (%) ($n = 19$)	64.2 (25.4)	25	100
Time using mouse during computer use (%) ($n = 19$)	37.9 (25.7)	0	75
R grip strength (kg)	34.2 (9.8)	19.6	61.1
L grip strength (kg)	31.4 (9.8)	20.4	60.6
R tip pinch (kg)	9.3 (3.3)	1.4	6.4
L tip pinch (kg)	7.8 (3.0)	1.8	5.9
R wrist circum (cm)	15.3 (2.9)	5.2	20.0
L wrist circum (cm)	15.5 (2.9)	5.3	19.7
R hand circum (inc. thumb) (cm)	22.9 (1.4)	20.9	25.5
L hand circum (inc. thumb) (cm)	22.6 (1.6)	19.0	25.0
R hand length (cm)	18.5 (0.9)	16.4	20.0
L hand length (cm)	18.6 (1.0)	17.0	20.0
Subject BMI ($n = 19$)	24.8 (6.5)	18.6	42.0
Gross typing speed (wpm)	56.9 (15.8)	34	92
Accuracy (% words correct)	88.9 (5.8)	76	97
Female	70.0%		
Race–white	90.0%		
Right hand dominant	95.0%		

[a] Computer use was self-reported.

2.2. Equipment

Kinematics data were collected using a VICON™ motion measurement system (VICON 612 system with 5 M2 cameras) (VICON Motion Systems Inc, Lake Forest, CA, USA – http://www.vicon.com/jsp/index.jsp) positioned around a computer workstation, two on either side between 168 and 177 cm above the floor, and one positioned facing head on over the hands at 188 cm above the floor. The hand, wrist, and finger movements were derived from the tracking of 21 passive markers positioned on the dorsal surface of each hand as described in Fig. 2. The passive characteristic of the system (no wires) and small size of the markers (sphere of 4 mm in diameter) allowed subjects to type naturally. Data were collected at 60 Hz during the three 1-min intervals.

The computer work station and chair were fully adjustable. The monitor height and keyboard height were set at 71 cm to maintain the relative position of the VICON™ and video cameras to the position of the hands during keyboarding. The chair was adjusted by each subject prior to keyboarding to their preferred configuration. A foot rest was provided as necessary as was a wrist rest. Forty-five percent of the subjects chose to use the wrist rest.

All keyboarding was completed solely on a GoldTouch™ keyboard positioned in a "standard" (i.e. flat and un-angled) position (Goldtouch Technologies Inc., Goldtouch US Corporate Headquarters, Irvine, CA, USA – http://www.goldtouchtechnologies.co.uk/contact/index.html). Alternate input devices (i.e. mouse) were not used. Productivity data were gathered using an electronic keyboarding program, Typing Master Pro™ (Typing Master Finland, Inc., Helsinki, Finland – http://www.typingmaster.com/index.asp?go=company). This program displays text which advances as the keyboard user types. All subjects used the same typing paragraph (a fourth grade reading level).

2.3. Protocol

As this was a descriptive study, there was no experimental intervention. Subjects were instructed to type at their normal rate on the keyboard, using their usual method. Correction of errors was discouraged. First, subjects typed for 15 min to acclimate to the workstation. Three 1-min trials of motion data were captured at 15-min, 20-min and 24-min of keyboarding. Subjects were not informed when motion data were being collected.

2.4. Data processing

Marker data collected in the first 5 s of every trial were eliminated. Joint angles were derived as described in Cook et al. (in press). Briefly, we considered that the MCP or PIP joint was neutral (or 0°) when the metacarpal bones and/or phalanges formed a straight line (see Fig. 3). The hand was modeled as a rigid segment and its orientation was derived

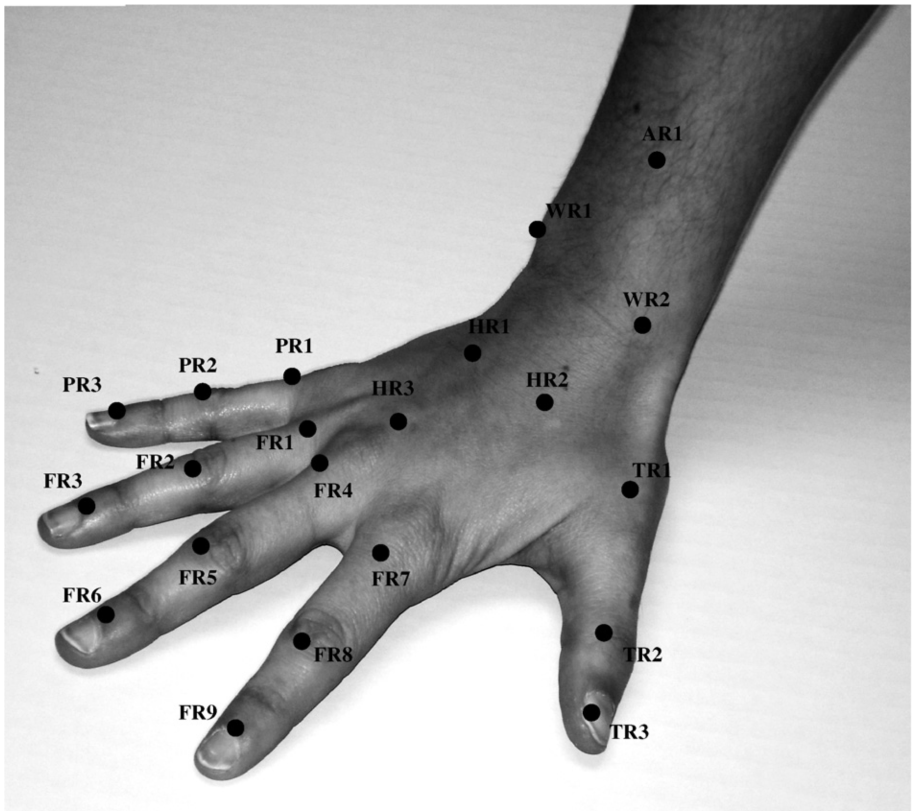

Fig. 2. Placement of VICON™ reflective markers on the dorsum of the right wrist, hand, and fingers. AR1 – distal forearm (between radius and ulna); WR1 – ulnar styloid; WR2 – radial styloid; HR1 – hand marker (proximal 4th metacarpal); HR2 – hand marker (proximal 2nd metacarpal); HR3 – hand marker (distal 2nd metacarpal); PR1 – 5th digit (distal MCP joint); PR2 – 5th digit (distal PIP joint); PR3 – 5th digit (distal phalange); FR1 – 4th digit (distal MCP joint); FR2 – 4th digit (distal PIP joint); FR3 – 4th digit (distal phalange); FR4 – 3rd digit (distal MCP joint); FR5 – 3rd digit (distal PIP joint); FR6 – 3rd digit (distal phalange); FR7 – 2nd digit (distal MCP joint); FR8 – 2nd digit (distal PIP joint); FR9 – 2nd digit (distal phalange); TR1 – 1st digit (lateral aspect of MP); TR2 – 1st digit (lateral aspect of IP); TR3 – 1st digit (lateral aspect of nail). (The left is mirror image).

by tracking its local reference frame constructed on the three hand markers (HR1, HR2, HR3 in Fig. 2). Five vectors (PR1–PR2, FR1–FR2, FR4–FR5 and FR7–FR8 and TR1–TR2 in Fig. 2) representing the proximal phalanges were projected onto the hand's local saggittal and coronal planes to compute the MCP flexion–extension (MCP f/e) and abduction-adduction (MCP ab/ad) angle, respectively. Conversely, PIP joints were assumed to be 1-DOF hinge joints and, thus, PIP flexion–extension angles were computed using the 3D angle between the appropriate distal and proximal phalanges vectors (e.g. angle between FR4–FR5 and FR5–FR6 in Fig. 2).

To compute angular velocity and acceleration, angle data were lowpass filtered using a 7th-order Butterworth lowpass filter with a cut-off frequency of 5 Hz and then numerically differentiated in Matlab. Filtering biomechanical data is common and necessary to compute numerical derivatives of position or angle data. We used a Butterworth filter with a cut-off at 5 Hz based upon the frequency content of the signals being filtered. Over 98% of the power in the signals were below 5 Hz. In addition, we compared the filtered signals to the original angle data to ensure that the filters did not remove critical components of the motions. We also compared filtered velocity and acceleration signals with different cut-off frequencies to ensure that we fully captured the kinematics of the fingers while still reducing errors induced by noise in the angular data. Finally, the filtering method used was the Matlab routine (FILTFILT) to ensure that there was no phase distortion induced in the signal by the filter process. After filtering the absolute values of the velocity and acceleration time series were taken and the means were computed for each trial, similar to the methods described by Sommerich et al. (1998).

Means (standard deviations), minima and maxima were found for the angle, velocity and acceleration time series. Also, the root-mean-squares (RMS) for joint angle movements during each 1-min period were calculated as an estimate of the overall joint motions. Finally, translational hand/wrist movements (hand/wrist displacements) were calculated by tracking the linear movement of the markers placed on the wrist. Wrist markers were used as keyboard users who had a "planted" style rarely moved their wrists, and keyboard users who had a "floating" style continuously moved them. This provided pathlength, describing the overall distance the hand traveled in mm, and x-axis RMS and y-axis RMS which described the variability of motion in the lateral–medial and anterior–posterior directions, respectively.

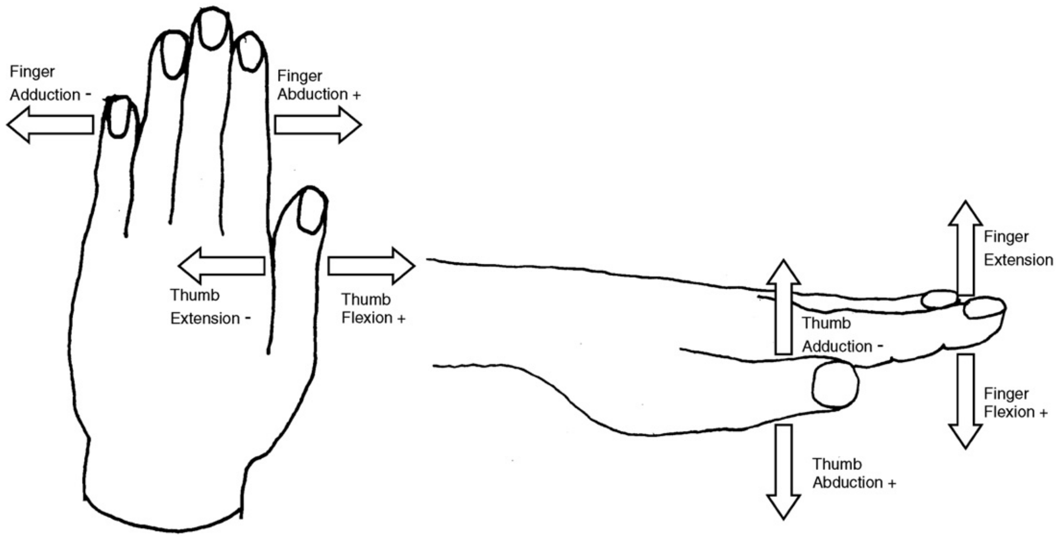

Fig. 3. Hand diagrams showing 0° of flexion/extension and 0° abduction/adduction for the fingers and thumbs as well as the planes of movement and the direction of positive and negative numbers.

2.5. Data analyses

We found no significant difference for any variable across the three 1-min trials. Therefore, we combined that data and calculated the mean and standard deviation for each kinematic variable for each joint and movement. This provided an overall quantitative description of the kinematics of the finger joints and hand/wrist displacement during keyboarding. We analyzed the differences at the MCP and PIP joints for f/e joint angle, joint velocity, and joint acceleration between hands (right vs. left) and between each hand's finger using 3-way, repeated measures ANOVAs. The independent variables consisted of hand [right vs. left], joint [MCP vs. PIP] and finger [digits 1–5]. The analyses for ab/ad differences at the MCP joints for joint angle, joint velocity, and joint acceleration were completed using a 2-way repeated measures ANOVA [right vs. left hands, digits 1–5]. Differences in hand/wrist displacement (pathlength, x-axis RMS, y-axis RMS) between the two hands were assessed using a 1-way repeated measures design. Because Mauchly's tests of sphericity were significant, F ratios using Greenhouse and Geisser's corrections were used. If an overall ANOVA was significant, we used post-hoc analyses to examine potential differences in kinematics between the left and right hands and between individual fingers for each hand using t-tests calculated using pooled error terms as the denominators (Winer et al., 1991) and the estimated marginal means obtained for the overall interactions as the numerator.

3. Results

3.1. Joint angles

Mean MCP joint flexion angles of digits 2 through 5 ranged from 14.8° to 37.3° (Fig. 4a). The mean MCP f/e angles were progressively smaller from the 2nd to the 5th digit, with a significant difference between all MCP f/e angles except between the 4th digit and the 3rd and 5th digits for both hands. Mean MCP joint ab/ad angles of digits 2 through 5 ranged from −2.2° to −16.6°, with adduction increasing from the 2nd MCP to the 5th MCP (Fig. 4b). There were significant differences between the 5th digit and all other digits for both hands. Mean PIP flexion angles were greater than mean MCP angles, with a range of 14.4° to 47.5° across digits. Like the MCP joints, the PIP joint angles were significantly different from each other except for the 2nd and 5th digits, and 3rd and 4th digits for both hands.

The thumb (1st digit) had significantly higher mean abduction angles (27.7°) compared to the other MCP flexion angles (1.9°). Mean thumb PIP flexion angles were about 20° less than the other digits. All thumb angles were significantly different from the other digits for both MCP and PIP joints.

The only significant differences between the right and left hand joint angles were for the 3rd digit MCP f/e and 1st digit ab/ad (Fig. 4a and b). The overall trend was for the right side to have greater MCP flexion and smaller PIP flexion.

Movements of the fingers were estimated by the root-mean-square (RMS) of the time series (Fig. 4c and d). The RMS ranged between 2.2° and 10.4° across joints. All subjects had similar levels of movement noted by the small standard deviations, ranging from 0.7° to 3.6°. There were significant differences between the right and left sides for RMS for 1st and 2nd MCP f/e, 1st and 4th PIP f/e, and 1st digit ab/ad.

3.2. Joint angular velocity

MCP f/e joint angular velocities for the 2nd through 5th digits averaged from between 37.6°/s and 47.8°/s, with the

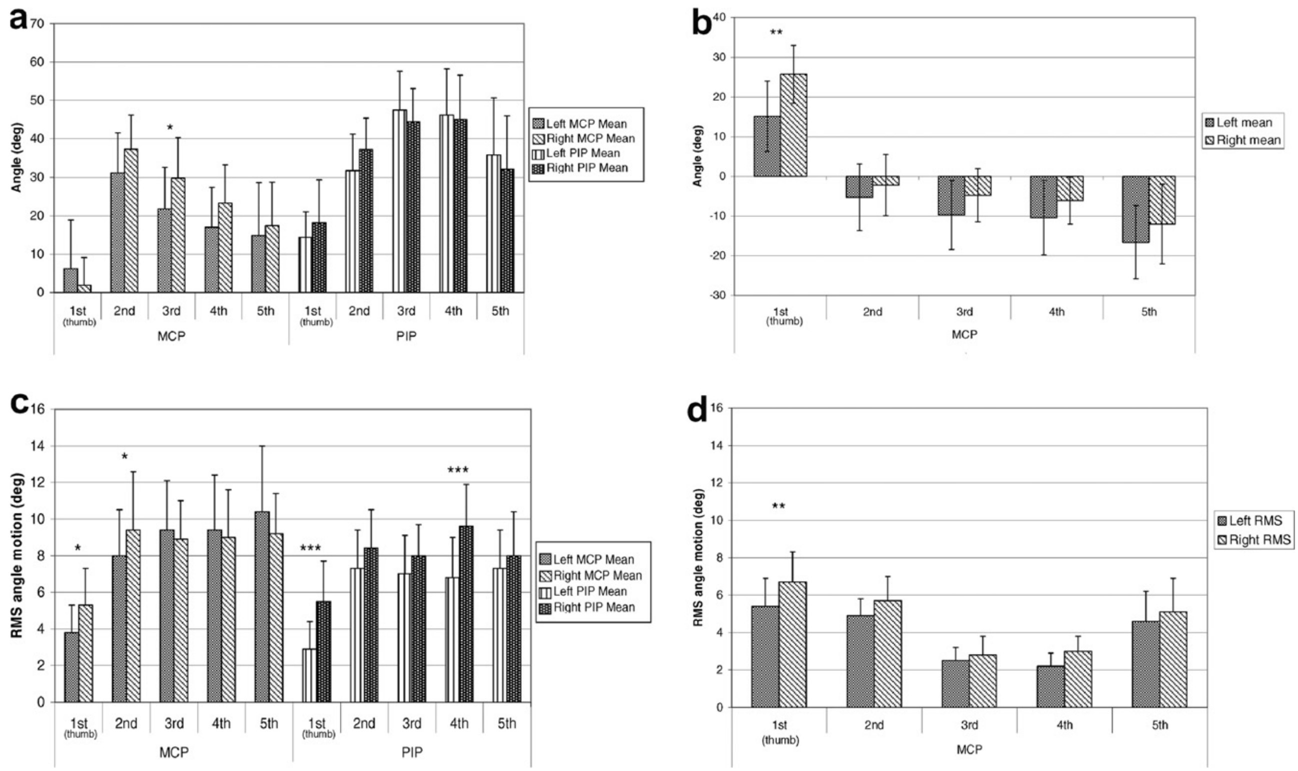

Fig. 4. Mean joint angle and mean RMS of the right and left digits during three 1-min computer keyboarding tasks (in f/e negative numbers indicate extension, in ab/ad negative numbers indicate adduction). $N = 20$. The error bar represents the standard deviation between subjects. Joint angles and joint angle RMS with a significant difference between the right and left hands are represented by an asterisk; $^{*} = P \leqslant .05$; $^{**} = P \leqslant .01$; $^{***} = P \leqslant .001$. (a) Mean joint angles for MCP and PIP digit f/e; (b) mean joint angles for MCP ab/ad; (c) mean joint angle RMS for MCP and PIP digit f/e; (d) mean joint angle RMS for MCP ab/ad.

greatest range of velocities occurring at the 5th digits (Fig. 5a). There was a significant difference between 2nd and 5th digits for left MCP f/e. Mean PIP f/e velocities averaged between 30.7°/s and 45.6°/s. There was a significant difference in PIP f/e velocity between the right 3rd digit and all other right digits, but no significant differences between digits on the left. MCP ab/ad 2nd through 5th velocities were generally considerably smaller than MCP f/e velocities and ranged from 11.9°/s to 24.7°/s. There were significant differences in ab/ad velocities between all digits except the right 3rd digit with the 4th and 5th digits, and the 2nd with the 5th digits and 3rd with the 4th digits on the left.

The 1st digit's mean angular velocities were greatest for right MCP ab/ad (37.2°/s) and lowest for left MCP f/e (16.2°/s). There were significant differences between the 1st digit and all other digits' velocities except for the right PIP f/e and left MCP ab/ad, where only the 3rd digit was significantly different from the 1st. There were significant differences between the 1st digits of the right and left hands for all joints/motions (Fig. 5a and b).

Post-hoc analyses of the differences between the right and left hands suggests that there were significant differences in velocity between the right and left 1st digits for all joints/motions, the 3rd digits for PIP f/e and MCP ab/ad, as well as a the 5th digits MCP f/e (Fig. 5a and b).

3.3. Joint angular acceleration

Mean MCP flexion acceleration between the 2nd and 5th digits was lowest for the right 5th digit (609.2°/s^2) and highest for the left 5th digit (776.5°/s^2) (Fig. 5c). There was a significant difference between the 4th digit and all other digits for right MCP f/e. PIP f/e accelerations ranged from 547.2°/s^2 to 672.6°/s^2. Mean ab/ad ranged from 223.8°/s^2 to 396.0°/s^2. There was a significant difference in ab/ad acceleration between the 2nd digit and all other digits for the right MCP. On the left there was a significant difference in MCP ab/ad for the 2nd digit with the 3rd and 4th digits as well as the 5th digit with the 3rd and 4th digits (Fig. 5c and d).

There was a significant difference between the 1st digit and all other digits for right MCP f/e and ab/ad, and left MCP f/e and PIP f/e. There were no significant differences between right PIP 1st digit motion and other digits, and only one significant difference, between the 1st and 4th joints, for left MCP ab/ad. The right 1st digit's acceleration was almost double the acceleration of the left for all joints and motions.

Post-hoc comparisons between the right and left hand found significant difference between the right 1st digit for MCP f/e, ab/ad and PIP f/e, as well as the MCP joint f/e for the 5th digits (Fig. 5c and d).

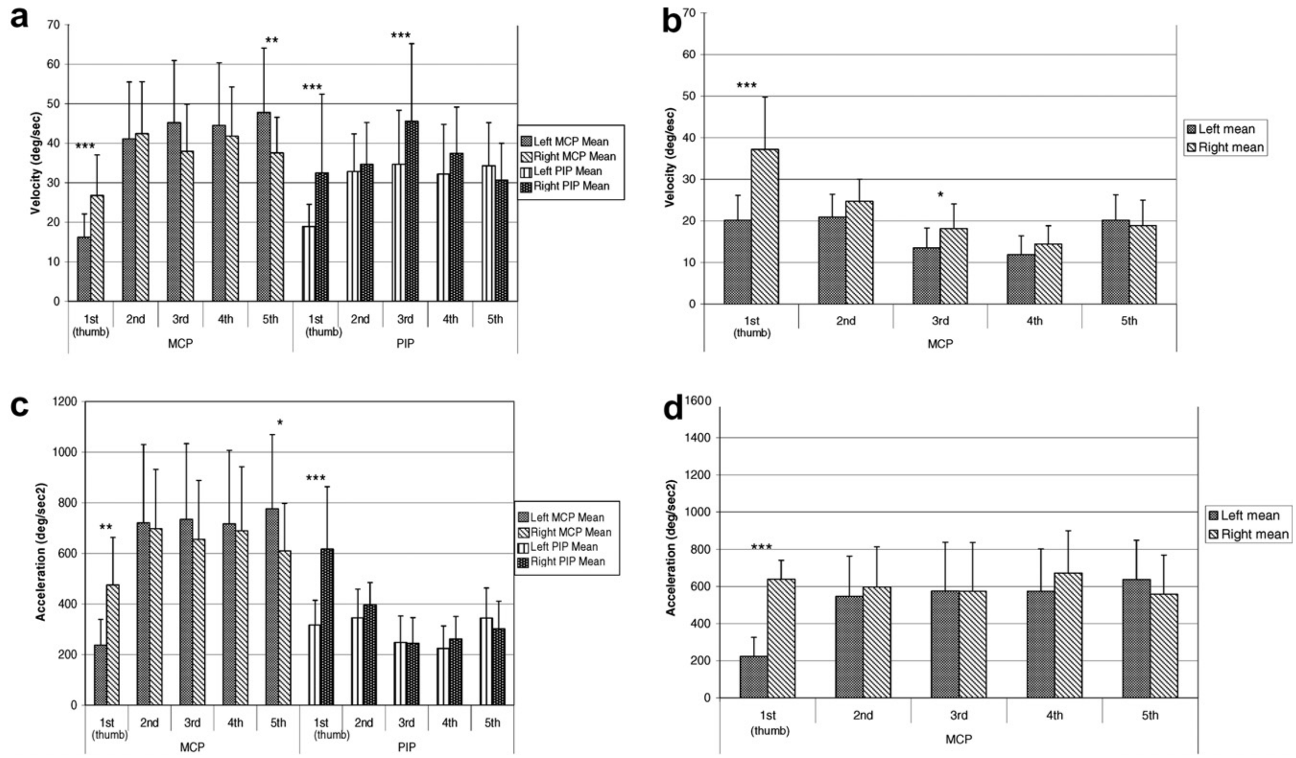

Fig. 5. Mean joint angular velocities and accelerations of the right and left digits during three 1-min computer keyboarding tasks. The error bar represents the standard deviation between subjects. $N = 20$. (a) Mean joint angular velocities for MCP and PIP digit f/e; (b) mean joint angle velocities for MCP ab/ad. (c) mean joint angular accelerations for MCP and PIP digit f/e; (d) mean joint angle accelerations for MCP ab/ad.

3.4. Hand/wrist displacement

There was a significant difference between right hand pathlength (1368.8 mm, s.d. 760.8 mm, min 485.7 mm, max. 3035.9 mm) and left hand pathlength (1051.1 mm, s.d. 528.6 mm, min. 317.7 mm, max 1945.6 mm) ($P = 0.02$) suggesting that the right hand was more likely to be moved as a unit (float) while the left hand was more likely to have a "planted" pattern. Right and left x-axis RMS (movement side to side) was also significantly different (right 4.3 mm, s.d. 2.8, min. 1.3 mm, max. 11.1 mm; left 3.0, s.d. 1.4, min. 0.8 mm, max. 5.0 mm; $P = 0.007$) but right and left y-axis RMS (movement front to back) was not (right 4.7 mm, s.d. 3.1, min 1.0 mm, max. 13.5 mm; left 3.4, s.d. 2.3, min. 0.7 mm, max. 9.9 mm; $P = 0.08$).

4. Discussion

The goals of this research paper are twofold: (1) provide a quantitative description of the kinematics of the finger joints and hand/wrist displacement during the performance of keyboarding tasks, and (2) examine potential kinematic differences between the left and right hand.

4.1. Joint positions

The overall values reported in this study were in good agreement with the only other study of finger kinematics (Sommerich et al., 1996). Table 2 provides a comparison between the general joint angles, velocities, and accelerations reported by Sommerich et al. and the mean kinematics across the fingers from this study. The joint angles for MCP and PIP were very similar.

An examination of the mean joint angles of the fingers and hand revealed some interesting finger postures. The mean MCP flexion angle was twice as great at the 2nd digit (right 36.1°, s.d. 10.3°; left 29.6°, s.d. 12.5°) than the angle at the 5th digit (right 16.6°, s.d. 11.6°; left 14.0°, s.d. 14.0°). The variability of the 5th digit suggests that this flexion angle varies a great deal among keyboard users. This decreasing flexion across fingers may be related to several factors. First, keyboard users must pronate their hands to engage the keys. Pronation during keyboarding may exceed 60° (Simoneau et al., 1999). Computer keyboard users may intuitively attempt to reduce pronation, increasing the distance from the 2nd digit to the keyboard. A posture of less pronation requires increased flexion of the 2nd and 3rd digits. A second possible reason for MCP flexion to decrease towards the 5th digits is the tendency of some keyboard users to hyperextend (i.e. extension at the MCP joint of greater than 0°) the 5th, 4th, and sometime even the 3rd digits while holding the fingers above the keys to prevent unintended key activation (Rose, 1991) (see Fig. 6a). A hyperextended 5th MCP joint was noted in 50% of the right hands and 68% of the left hands of this sample and a hyperextended 4th MCP joint was noted in

Table 2
Comparison of joint kinematics between Sommerich et al. (1996) and results from this study for the wrist and digits during a computer keyboarding task

Joint/motion	Joint position (°)			Joint velocity (°/s)			Joint acceleration (°/s^2)		
	Sommerich mean	Study results mean (s.d.)		Sommerich mean *max*	Study results mean (s.d.) *max*		Sommerich mean *max*	Study results mean (s.d.) *max*	
		Right	Left		Right	Left		Right	Left
MCP flex	22.0	25.9 (11.2)	20.0 (12.3)	41.7	40.0 (11.7)	44.6 (15.6)	881	660.9 (236.4)	709.2 (236.4)
				222.5	*267.3*	*288.5*	*5567*	*4624.0*	*4939.1*
PIP flex	39.0	39.8 (10.5)	40.4 (11.4)	34.8	37.2 (12.9)	33.5 (11.6)	717	626.4 (322.1)	588.0 (270.5)
				235.2	*344.1*	*304.3*	*5204*	*5602.6*	*5208.4*

Sommerich et al. (1996) data taken from word-processing group. For joint position, positive values indicate flexion. s.d. is the average standard deviation for all joints. 1st digit numbers were excluded from the mean for the results as there was no corresponding data from the Sommerich et al. study. The max joint position was excluded from the table as there was no corresponding data from the Sommerich et al. article.

23% of the right hands and 46% of the left hands. This hand position has been noted to cause a muscle contraction that exceeds 25% of the computer users maximum voluntary contraction in the extrinsic extensor muscles (Rose, 1991) putting the finger extensor tendons at risk for musculoskeletal disorders of the upper extremity. Some keyboarders also abduct as well as hyperextend their 5th digits continuously during keyboarding (Pascarelli and Kella, 1993), thereby maintaining tension on the 4th dorsal interosseous and abductor digiti minimi.

Descriptions of keyboard kinematics have documented that the wrist is often maintained in ulnar deviation (Rose, 1991; Serina et al., 1999; Simoneau et al., 1999). This study suggests that the MCP joints are also positioned towards the ulnar side of the hand. The 5th digit in particular is on average at 12.5° of adduction (s.d. 9.9) on the right and at 16.7° of adduction (s.d. 9.0) on the left, which was significantly different from all other digits' adduction. The 5th digit is frequently adducted to reach the more extreme keys, so this degree of adduction was not unexpected. However, although the right 5th digit is often used to reach the backspace and enter keys, it was not significantly greater than the left. Keyboard users may choose to reposition the right hand rather than adduct the 5th digit to reach extreme keys.

Overall there were few significant differences between the right and left hand. The notable exception was the right 1st digit (thumb) which had a significantly greater degree of abduction (24.7°, s.d. 8.5) than the left 1st digit (14.5°, s.d. 9.2), probably to activate the spacebar. The difference between the two angles may also reflect another postural habit of some computer keyboard users, that of the "alienated" or "isolated" thumb (Pascarelli and Kella, 1993) (see Fig. 6b). Twenty-seven percent of this sample maintained their left thumb "hyperadducted" and extended above the palm of the hand during computer keyboarding. As with the hyperextended 5th digit, this posture has the potential to put tension on extrinsic musculature, the extensors of the thumb (the abductor pollicis longus, extensor pollicis brevis and the extensor pollicis longus). The abductor pollicis longus and extensor pollicis brevis are associated with the development of deQuervain's tenosynovitis.

4.2. Joint angular velocity and acceleration

Mean angular velocities of the MCP and PIP joints for f/e were comparable to those reported by Sommerich et al. (1996) (Table 2), while mean angular acceleration was somewhat slower. At present there is no literature that examines the association between finger joint angular velocities and accelerations and musculoskeletal disorders of the upper extremity. Further modeling is required to understand the effect of kinematics on the underlying structures of the wrist, hand, and fingers, and to examine the cumulative effects of joint position, joint angular velocity and joint angular acceleration of the fingers.

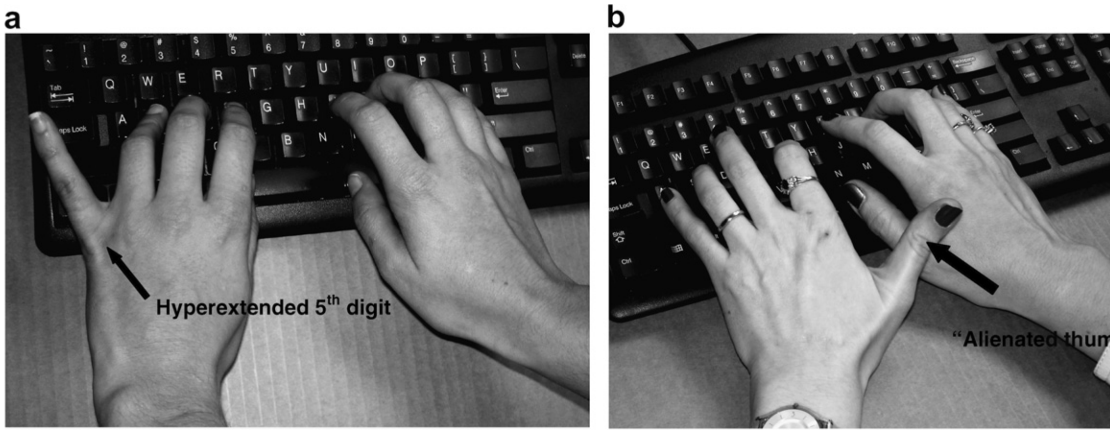

Fig. 6. Stereotypical postures assumed by the digits during typing. (a) 5th digit MCP hyperextension during "resting" portion of keyboard typing task. (b) 1st digit "hyperadduction" during keyboard typing task. Note that for many keyboard users the left 1st digit remains in this posture throughout the entire keyboarding task. (The keyboard used in these photographs was not a GoldTouch™ keyboard).

4.3. Hand/wrist displacement

Observations of computer keyboard users have identified that some keyboard users rarely reposition their hands; instead they alter the postures of the wrists and fingers, while other users almost always reposition their hands. This translational key strike pattern, called hand/wrist displacement, has not been discussed in the literature, but seems to be a potentially useful kinematic variable when studying musculoskeletal disorders of the upper extremity. Keyboard users who reach with their fingers rather than move their wrist/forearms may increase non-neutral posture, such as wrist extension, ulnar deviation, and pronation which are believed to be an important risk factor for MSD-UE. (Goldstein et al., 1987; Marklin et al., 1999; Rempel et al., 1992, 1997; Schuind et al., 1990; Sommerich et al., 1998; Tanzer, 1999; Werner et al., 1997).

In this study, hand/wrist displacement was operationalized as both the overall distance the hand traveled (pathlength) as well as the overall variability in the x- and y directions (x-axis RMS and y-axis RMS). The large standard deviations for pathlength and x-axis RMS as well as the wide range of scores for these variables suggest each keyboard user varies in the amount of hand movement they use during keyboarding when compared to another user, while the non-significant between-trial effect suggests that these users were very consistent in their own hand movement while keyboarding. That the right hand had a significantly larger pathlength and side to side (x-axis) RMS supported clinical observations that the right hand is used to strike keys on the extremes of a standard keyboard (delete, arrow keys, backspace key) which generally causes the keyboard operator to reposition the hand to strike. Since 5th MCP adduction was not significantly different between the right and left hand, it is not surprising that the hand is repositioning to strike these extreme keys. Movements in the y-axis tended to be to reach upward to the top row of keys, a task which both hands do.

4.4. Study limitations

This observational study was conducted to provide further information concerning the joint positions, and joint angular kinematics of the fingers during computer keyboard use. It does not provide information concerning other important biomechanical variables that have been related to MSD-UE such as keying force, carpal tunnel pressure, tendon travel, and muscle activity. Further assessment of these variables as they relate to the task of keyboarding would be an important part of understanding and modeling finger and hand used during keyboarding. This study has only a limited number of subjects ($N = 20$) who were measured while keying at an unfamiliar workstation set-up. The unfamiliar work station in addition to the presence of the VICON™ measuring apparatus may have altered the subject's motor behavior.

5. Conclusion

This study provides the greatest detail to-date on the kinematics of the fingers during keyboarding, including the postures, velocity, and acceleration of each MCP and PIP joint as well as the overall displacement of the hand. There were some differences between the right and left hand, specifically the velocity of the 5th MCP flexors, the 3rd PIP flexors, and the acceleration of the 4th MCP joints. The right and left thumb joint angles were significantly different for MCP abduction, while the velocity and acceleration of the thumb joints were significantly different at all joints and angles. A previously undiscussed kinematic variable, hand/wrist displacement, was found to be highly variable between computer users, but very stable within each users own style. The right and left pathlengths and x-axes RMS were significantly different, suggesting that computer users move their right hand further than their left hand while keying, and with greater variability in the lateral transverse plane. Further research is needed to examine how these kinematic and other variables contribute to the development of musculoskeletal discomfort and musculoskeletal disorders of the upper extremity in computer users, and how these variables can be manipulated to reduce the risk of computer keyboard use.

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