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Biomechanical loading on the upper extremity increases from single key tapping to directional tapping

Jin Qin [a], Matthieu Trudeau [a], Jeffrey N. Katz [a,b,c], Bryan Buchholz [d], Jack T. Dennerlein [a,b,*]

[a] Department of Environmental Health, Harvard School of Public Health, Boston, MA 02115, USA
[b] Department of Orthopaedic Surgery, Brigham and Women's Hospital, Harvard Medical School, Boston, MA 02115, USA
[c] Division of Rheumatology, Immunology and Allergy, Brigham and Women's Hospital, Harvard Medical School, Boston, MA 02115, USA
[d] Department of Work Environment, University of Massachusetts, Lowell, MA 01854, USA

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ABSTRACT

Musculoskeletal disorders associated with computer use span the joints of the upper extremity. Computing typically involves tapping in multiple directions. Thus, we sought to describe the loading on the finger, wrist, elbow and shoulder joints in terms of kinematic and kinetic difference across single key switch tapping to directional tapping on multiple keys. An experiment with repeated measures design was conducted. Six subjects tapped with their right index finger on a stand-alone number keypad placed horizontally in three conditions: (1) on single key switch (the number key 5); (2) left and right on number key 4 and 6; (3) top and bottom on number key 8 and 2. A force–torque transducer underneath the keypad measured the fingertip force. An active-marker infrared motion analysis system measured the kinematics of the fingertip, hand, forearm, upper arm and torso. Joint moments for the metacarpophalangeal, wrist, elbow, and shoulder joints were estimated using inverse dynamics. Tapping in the top–bottom orientation introduced the largest biomechanical loading on the upper extremity especially for the proximal joint, followed by tapping in the left–right orientation, and the lowest loading was observed during single key switch tapping. Directional tapping on average increased the fingertip force, joint excursion, and peak-to-peak joint torque by 45%, 190% and 55%, respectively. Identifying the biomechanical loading patterns associated with these fundamental movements of keying improves the understanding of the risks of upper extremity musculoskeletal disorders for computer keyboard users.

1. Introduction

The rapid increase of computer use in the past few decades has often been associated with musculoskeletal symptoms and disorders (MSDs) spanning the entire upper extremity including the neck/shoulder, elbow, forearm, hand, and wrist (Gerr et al., 2002, 2006; Punnett and Bergqvist, 1997). Sustained pain in the upper extremity and specific musculoskeletal disorders, such as wrist tendonitis, epicondylitis, and trapezius muscle strain are higher among computer users. The prevalence of computer use related upper extremity MSDs has been reported to be over 50% in several studies (Eltayeb et al., 2007; Klussmann et al., 2008; Scholossberg et al., 2004). The MSD prevalence around proximal joints is especially high, i.e. the one year prevalence of symptoms of the shoulder region was 38% and 31% among computer workers in two recent studies (Eltayeb et al., 2007; Klussmann et al., 2008), higher than arm, elbow, and hand rates. Among 632 newly hired computer operators, the one year incidence of neck and shoulder symptoms was 58% and of hand/arm symptoms 39%, respectively (Gerr et al., 2002). Force, posture and joint dynamics have been identified in various hand and arm activities to be associated with upper extremity MSDs (Marras and Schoenmarklin, 1993; Marcus et al., 2002; National Research Council, 2001).

Despite the high prevalence of MSDs, the association between computer use and biomechanical loading on the musculoskeletal system is not fully understood due to a limited number of papers. Force exerted during key strike has been shown to be two to four times greater than activation force requirement (Rempel and Gerson, 1991; Rempel et al., 1992). Deviated wrist from the neutral posture during computer keyboarding was observed among those with pain and discomfort and may be associated with increased risks of MSDs (Gerr et al., 2006). While disorders affect various parts of the upper extremity, dynamics analysis for keyboard work has been limited to distal joints of the upper extremity. Fingertip force and the wrist, metacarpophalangeal and proximal interphalangeal joint angles, as well as angular velocity and acceleration during typing have been quantified previously (Baker et al., 2007; Serina et al.,

* Corresponding author at: Harvard School of Public Health, Department of Environmental Health, 401 Park Drive, Room 404L, Boston, MA 02115, USA. Tel.: +1 617 384 8812; fax: +1 617 384 8767.
E-mail address: jax@hsph.harvard.edu (J.T. Dennerlein).

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1999; Sommerich et al., 1996). Lee et al. (2009) showed that subtle changes to the keyswitch force–displacement characteristics affect the finger muscle activity patterns, particularly in the intrinsic hand muscles, in activating the keyboard keyswitches. Kuo et al. (2006) characterized index finger tapping on a keyswitch in terms of finger joint kinetics, kinematics, muscle activation patterns, and energy profiles. They found that while both potential energy and kinetic energy are large enough to overcome the work necessary to press the key switches, nonetheless, the motor control strategies utilize muscle forces and joint torques to ensure a successful keystroke. Another limitation of the current literature is the lack of information on the kinetic aspects of keyboard use, such as joint moment. A more comprehensive profile of the biomechanical loading on the entire upper extremity during computer use needs to be documented. The only study that measured both the kinematic and kinetic characteristics during keying (Dennerlein et al., 2007) suggests that finger, wrist and elbow joints work in synergy to produce fingertip motion with a majority of the movement being generated by the finger and the wrist joint. This study was limited in that subjects were tapping on a single key switch, and the motion occurred mainly in the two-dimensional sagittal plane.

The kinematic analysis of single key switch tapping provided a first step in understanding the fundamental component of the typing action. However, keying typically involves more complicated three-dimensional motions (e.g. on multiple keys or using multiple fingers) during which the motor control strategies and upper extremity movements are likely to be different than single finger tapping on a single key. The coordination of the multiple degrees of freedom of the upper extremity kinematic system during keying activities can provide information on the system constraints and the motor control strategies. Further knowledge of the kinetic and kinematic characteristics, as well as the coordination of the upper extremity multiple degrees of freedom during more complicated keying tasks is necessary to study the biomechanical risk factors of MSDs associated with computer use.

Therefore, the goal of this study was to quantitatively assess the kinematics and kinetics, as well as the motor behavior of the entire upper extremity during more complicated tapping tasks than previously studied single finger tapping on a single key. Specifically, we wanted to determine how the loading of the finger, wrist, elbow and shoulder joints differ in terms of kinematics, kinetics and contribution to fingertip movements from simple single key switch tapping to directional tapping on multiple keys. We expected the loading to increase, especially for the proximal joints. As the next step in exploring the complicated typing movements of the upper extremity during keying, the results of this study were expected to provide more information on the association between typing tasks and the biomechanical loading on the internal tissues. Such information is essential for the prevention, diagnosis, treatment and intervention of work-related MSDs associated with computer use or similar tasks.

2. Methods

Six graduate students (mean (sd) age 28.3 (±2.0) years), three women and three men tapped on a stand-alone number keypad with their right index finger (Fig. 1). The participants were free of upper extremity MSDs at the time of the experiments. Informed consent was obtained, and all experimental procedures and forms were approved by the Harvard School of Public Health Institutional Review Board. The experiment included three conditions: (1) tapping on a single key switch (the number key 5); (2) left–right–left: tapping back and forth on the number key 4 (Left) and 6 (Right); (3) top–bottom–top: tapping back and forth on the number key 2 (Bottom) and 8 (Top). With a repeated measures study design, each of the participants completed all three conditions with the order of the conditions randomized. The effect of typing skills on kinematics and kinetics was minimized by performing these less familiar tasks.

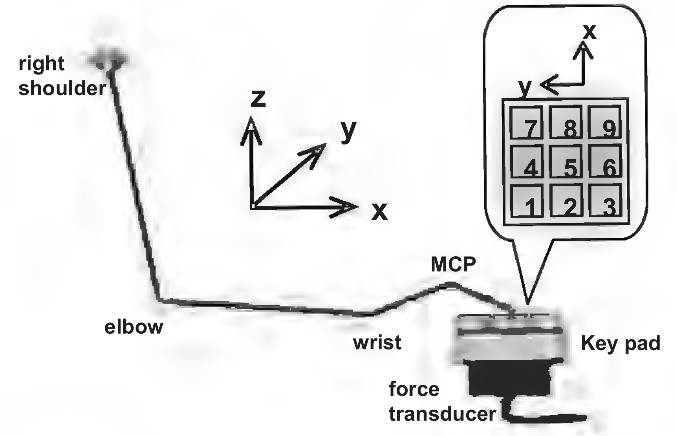


Fig. 1. Schematic view of the sagittal plane of the right upper extremity during tapping.

Taps were identified by the occurrence of a local maximum tapping force on the keypad. A motion cycle was defined as the time between three consecutive taps. For example, the single finger tapping cycle consisted of three consecutive taps on the number key 5. The top–bottom–top cycle consisted of taps on the number key 8 to 2 and back to 8, and the left–right–left cycle consisted of taps on the key 4–6 and back to 4. Eight motion cycles were extracted and averaged (aligned with the taps' maximum force) within each condition for each subject.

All conditions were performed at 3 taps per second by pressing the keys in time with an audio metronome set at 3 Hz. Before each experimental condition, participants were instructed verbally on the task requirements. In addition, they were instructed to keep their other fingers from touching the other keys on the keypad by keeping them in a slightly extended posture, and to minimize the contact time with the key switch in an attempt to mimic the posture associated with typing. During the experiment, participants tapped repeatedly on the key switches as required in each condition and data were collected for approximately 15 s for each condition. Participants rested 1 min between conditions. The key switch's activation force was 0.44 N, and the total travel (the maximum distance the key could be pressed down in the vertical direction) was 3.23 mm. The subjects completed the tapping tasks while seated in a chair adjusted such that their thighs were parallel to the ground and the height of the tapping surface was even with their seated elbow height. No forearm or palm support was provided.

Force vectors applied by the fingertip to the key and keypad were measured by a 6-axis force–torque transducer (ATI Industrial Automation, model Gamma, SI-65-5.5, Apex, NC, USA). The keypad sat on top of a 3 mm-thick dibond plate (Alcan Composites) attached to the force–torque transducer. The amplified signals from the force–torque transducer were recorded onto a personal computer with a National Instruments Board (NI PCI-6040, National Instruments, Austin, TX) at 200 samples per second. The force signal was low pass filtered digitally using a forth order Butterworth filter with a cutoff frequency of 20 Hz and a zero phase shift.

Three-dimensional (3-D) kinematics of the upper extremity were recorded using an active-marker infrared motion analysis system (Optotrak Certus System, Northern Digital, Ontario, CN). Four clusters of three markers secured on a rigid plate were mounted on the hand, forearm, upper arm and torso, which were treated as rigid body segments. A single marker was attached to the fingertip of the right index finger. The 3-D positions of these markers were recorded at 200 samples per second. All kinematic data were low-pass filtered digitally using a fourth order Butterworth filter with a cutoff frequency of 10 Hz and a zero phase shift.

The coordinate direction definitions were as follows: x axis – anterior (+) and posterior (−), y axis – medial (+) and lateral (−), and z axis – superior (+) and inferior (−). From the fingertip 3-D trajectories, the maximum distance traveled by the fingertip were calculated for single key tapping, from left to right, from right to left, from top to bottom, and from bottom to top. Using the relationships of the anatomical landmarks and anthropometrical data, the position of each segment's center of mass, its inertia tensors and orientation were calculated at each instance of time based on the 3-D trajectories of the markers (Cappozzo et al., 1995; McConville et al., 1980; Veldpaus et al., 1988). The finger was approximated as a single segment with the length spanning the metacarpophalangeal (MCP) joint center to the fingertip marker. From the segments orientation, we calculated the joint postures excursions from the reference posture of the forearm fully pronated, the elbow flexed 90°, and the upper arm on the side of the torso. A 3-D multi-segment inverse dynamic model (Kingma et al., 1996; Kuo et al., 2006) calculated net reactive joint forces and moments for the MCP, wrist, elbow and shoulder joints. The unused fingers were assumed to be fixed to the hand and their inertial properties were included in the hand segment. For joint posture excursion and torque sign convention, flexion, adduction, supination and internal rotation were positive, and extension, abduction, pronation and external rotation were negative. The potential and kinetic energy (sum of the translational and rotational kinetic energy) were calculated for each segment. Joint power was calculated based on the joint moment and angular velocity.

The MCP, wrist, elbow and shoulder joint contributions to the fingertip movement were calculated by multiplying the relevant joint excursion with the effective moment arm of the fingertip about the joint axes. With the vector from the joint rotation center to fingertip, the effective moment arm was calculated as the vector projection to the plane that was normal to the rotation axis. Fingertip movement was the distance moved from the maximum position in the z axis to the maximum force applied on the key switch. The relevant joint excursions were the posture change between these two points. The joint contribution to fingertip movements were calculated separately for taps on the number key 4 (Left), 6 (Right), 2 (Bottom), and 8 (Top) between the points of the local maximum fingertip force and the previous local maximum fingertip position in the z axis. The joint torques and contribution to fingertip movements were calculated based on each participant's anthropometry. The mean and standard deviation of the dependent variables across participants were presented.

To determine the difference of joint loading between single key switch tapping and directional tapping, we compared the kinematics and kinetics across three conditions. We evaluated the effect of tapping condition on fingertip force, joint posture excursion, moment in 3-D axes for each joint, and segment energy using multivariate analysis of variance, followed by ANOVA, and then Tukey post hoc testing. Condition and subject effects were examined and the significant level of 0.05 was used.

3. Results

3.1. Fingertip force and movement

The average fingertip tapping forces in the z axis (vertical) were 28–61% greater in magnitude in directional tapping conditions than the single key tapping (Table 1). The greatest fingertip force in the z axis occurred during left–right–left (LRL) tapping, followed by top–bottom–top (TBT) tapping, and the lowest during single key tapping. The x force component on number key 8 (top) was the smallest among all taps. The y force component for taps on key 6 (right) was significantly larger than taps on other keys ($p < .0001$). The fingertip travel in the y axis during LRL and in the x axis during BTB tapping corresponded to the distances between the number key 4 and 6, and between the number key 2 and 8 (4.2 cm), respectively. The fingertip travel in the z axis was between 2.79 (0.48) and 2.91 (1.03) cm. The fingertip force magnitudes were 2.0–2.5 times of the activation force requirement of the keypad (0.44 N).

3.2. Joint kinematics and kinetics

To achieve successful key strikes, the joint postures differed across the three tapping conditions (Fig. 2). Unlike movement during single key and LRL tapping, the wrist moved in the opposite direction to the MCP joint during TBT tapping. Joint posture excursion was greater during directional tapping than single key tapping except the MCP flexion during LRL tapping. In general, joint flexion excursions were the greatest during TBT tapping (Table 2), followed by LRL tapping, and the smallest during tapping on a single key switch ($p \leqslant 0.003$). The greatest joint flexion excursions were 18.9 (2.3), 12.9 (2.9), 5.0 (2.4), and 5.5 (1.4) degrees for the MCP, wrist, elbow and shoulder joint, respectively, while all occurred during TBT tapping. Similarly, the largest adduction excursion of 5.7 (1.8) degrees for the MCP and of 0.8 (0.8) degrees for the shoulder joint occurred during TBT tapping, followed by excursions for LRL tapping. Adduction excursions were significantly smaller during tapping on a single

Table 1
Mean (standard deviation) fingertip force and movement statistics in 3-D across different tapping directions. x, y, z axis directions are illustrated in Fig. 1. Fingertip force is calculated for the duration of contact with the key. Fingertip travel is the maximum absolute distance moved between two successive taps. Conditions with different superscript letters are significantly different, and the corresponding means are represented by the letters such that A > B > C. L – Left (4), R – Right (6), T – Top (8), B – Bottom (2).

	Single (−z)	R → L (+y)	L → R (−y)	T → B (−x)	B → T (+x)	Condition effect p-value
Average (N)						
x	0.04 (0.03)^{AB}	0.06 (0.05)^{AB}	0.08 (0.05)^{A}	0.07 (0.03)^{A}	0.01 (0.04)^{B}	0.002
y	0.02 (0.02)^{B}	-0.01 (0.03)^{C}	0.07 (0.04)^{A}	0.00 (0.03)^{BC}	0.00 (0.03)^{BC}	<.0001
z	-0.69 (0.22)^{A}	-1.06 (0.38)^{B}	-1.10 (0.35)^{B}	-0.92 (0.20)^{AB}	-0.88 (0.20)^{AB}	0.002
Magnitude (N)	0.69^{B}	1.07^{A}	1.11^{A}	0.93^{AB}	0.88^{AB}	0.002
Maximum (N)						
x	0.22 (0.18)^{AB}	0.30 (0.24)^{AB}	0.36 (0.20)^{A}	0.34 (0.15)^{A}	0.10 (0.21)^{B}	0.011
y	0.09 (0.09)^{B}	-0.01 (0.13)^{B}	0.27 (0.14)^{A}	-0.02 (0.13)^{B}	-0.01 (0.13)^{B}	<.0001
z	-1.15 (0.32)^{A}	-1.70 (0.59)^{B}	-1.71 (0.52)^{B}	-1.48 (0.35)^{AB}	-1.52 (0.34)^{AB}	0.002
Travel (cm)						
x	0.41 (0.09)^{B}	0.49 (0.08)^{B}	0.46 (0.09)^{B}	4.26 (0.27)^{A}	4.25 (0.25)^{A}	<.0001
y	0.37 (0.12)^{B}	4.29 (0.06)^{A}	4.27 (0.03)^{A}	0.49 (0.18)^{B}	0.50 (0.20)^{B}	<.0001
z	2.91 (1.03)	2.79 (0.46)	2.79 (0.48)	2.86 (0.43)	2.87 (0.42)	0.991

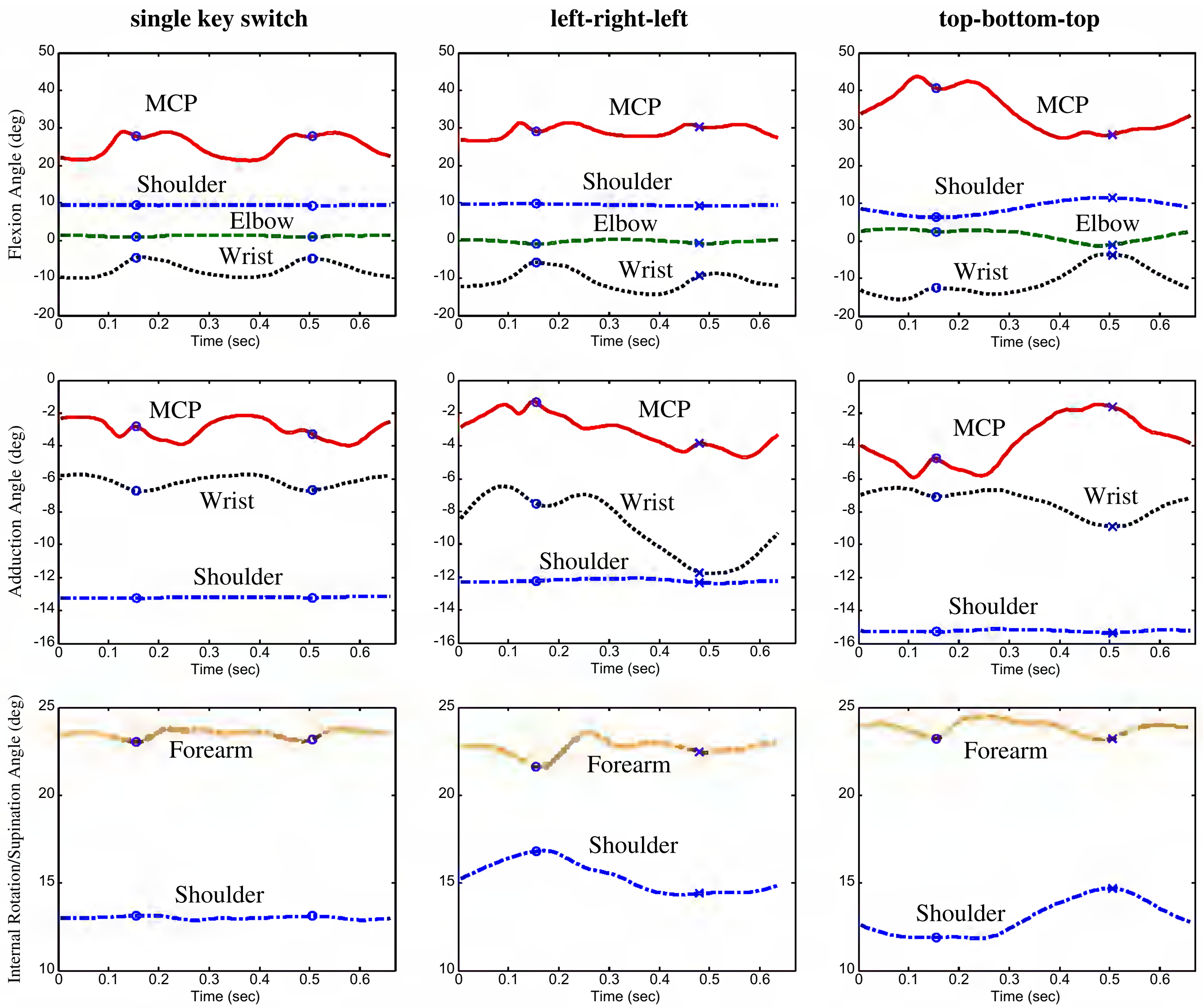


Fig. 2. Average joint angles across six subjects and eight cycles in three experimental conditions. Circles (○) and crosses (×) indicate the maximum fingertip force in *z* axis in the following manner: (1) Single key switch: ○ = taps on the number key 5; (2) left–right–left (LRL): ○ = taps on the number key 4 (left), × = taps on the number key 6 (right) (3) top–bottom–top (TBT): ○ = taps on the number key 2 (bottom), × = taps on the number key 8 (top). Flexion, adduction, supination and internal rotation were positive, and extension, abduction, pronation and external rotation were negative.

key switch ($p \leqslant 0.02$). The wrist joint adduction excursion was significantly larger during LRL tapping (6.3 ± 2.7°) than the other two tapping conditions ($p = 0.001$). Forearm supination ($p = 0.006$) and shoulder internal rotation excursions ($p < .0001$) in directional tapping were greater than single key tapping.

Joint contributions to fingertip movement in the *z* axis (vertical) were similar between single key and LRL tapping with the wrist contributing the most among all the joints (Fig. 3). The contributions among joints changed substantially for TBT tapping. The MCP joint and shoulder produced the most fingertip vertical movement for taps on the number key 2 (Bottom). The wrist and elbow joint contributed positively while the shoulder contributed negatively to the fingertip vertical movement for the taps on the number key 8 (Top). For fingertip movement in *y* direction (medial–lateral), shoulder and wrist were the major contributing joints, while the shoulder was the dominant contributing joint for fingertip movement in the *x* axis (anterior–posterior).

The average joint torques were similar while the peak-to-peak torque varied largely among the three tapping conditions (Table 3). Joint torques variations were generally significantly greater in directional tapping than single key tapping. The magnitude was especially large for the proximal joints. Shoulder peak-to-peak torques during directional tapping were as much as 2.3, 1.6 and 2.4 times greater than the torques during single key tapping for flexion, adduction and internal rotation respectively.

3.3. Segment energy and joint power

This varying pattern of the system dynamics and joint kinetics across the three tapping conditions was also seen in the segment energy and joint powers. Segment average and maximum kinetic energy and the change of potential energy during TBT tapping were significantly larger than single key tapping for the hand, forearm and upper arm (Table 4). The same results were found for the hand energy during LRL tapping. Joint power was also affected by different tapping conditions with TBT tapping producing the highest power at the wrist, elbow and shoulder joint (Fig. 4).

Table 2
Mean (standard deviation) joint posture excursion across six subjects for three tapping conditions: single key switch (S), left–right–left (LRL), top–bottom–top (TBT). Conditions with different superscript letters in the same row within a joint movement direction (e.g. Flexion) are significantly different, and the corresponding means are represented by the letters such that A > B. Flexion, adduction, supination and internal rotation were positive, and extension, abduction, pronation and external rotation were negative.

	Flexion			Adduction			Internal rotation/Supination		
	S	LRL	TBT	S	LRL	TBT	S	LRL	TBT
Posture excursions									
MCP (deg)	10.2 (5.4)^{B}	7.7 (1.4)^{B}	18.9 (2.3)^{A}	2.9 (0.8)^{B}	4.4 (1.5)^{AB}	5.7 (1.8)^{A}			
Wrist (deg)	6.7 (3.1)^{B}	8.9 (2.6)^{B}	12.9 (2.9)^{A}	1.6 (1.1)^{B}	6.3 (2.7)^{A}	3.2 (1.7)^{B}			
Forearm (deg)							1.3 (0.7)^{B}	2.8 (1.1)^{A}	2.3 (0.6)^{A}
Elbow (deg)	1.0 (0.5)^{B}	1.7 (0.9)^{B}	5.0 (2.4)^{A}						
Shoulder (deg)	0.4 (0.1)^{B}	0.9 (0.3)^{B}	5.5 (1.4)^{A}	0.3 (0.1)^{B}	0.6 (0.2)^{AB}	0.8 (0.4)^{A}	0.5 (0.2)^{B}	2.7 (0.6)^{A}	3.2 (0.9)^{A}

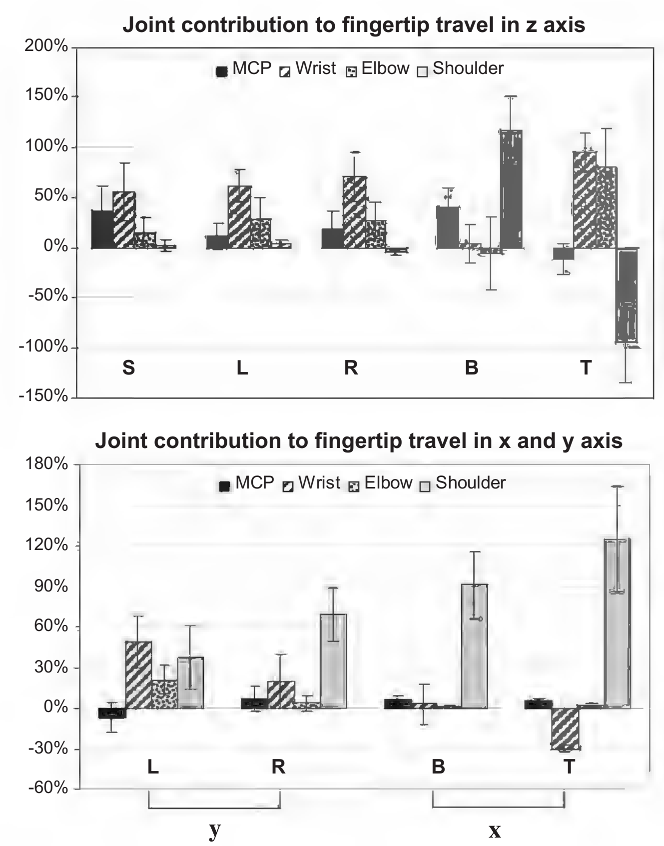


Fig. 3. Percentage of joint contribution (±SD) to fingertip three-dimensional movement averaged across subjects for the three experimental conditions. x, y, z axis directions are illustrated in Fig. 1. Contribution was calculated between the points of maximum fingertip position in z axis and the maximum force on the number key 5 (S), 4 (L), 6 (R), 2 (B), and 8 (T). Positive sign indicated that the joint motion contributed in the same direction as the fingertip movement, and vice versa.

4. Discussion

The 3-D kinetics and kinematics during directional tapping on a stand-alone computer numeric keypad were described in this study to determine how the MCP, wrist, elbow and shoulder joints are loaded differently from single key switch tapping. The results suggested that top–bottom–top tapping led to the largest biomechanical loading on the upper extremity especially for proximal joints, followed by left–right–left tapping, and the lowest loading was observed during single key switch tapping. An earlier study where only sagittal plane motion of the upper extremity was captured during single key tapping (Dennerlein et al., 2007) suggested that tapping involves not only the finger and wrist joint, but dynamic loading of the elbow and to a lesser extent the shoulder. Our results indicated the contributions to fingertip movement during directional tapping came mainly from the shoulder joint and to a lesser extent the more distal joints.

The various contributions across the different tapping conditions were consistent with the joint constraints and anthropometric characteristics of the upper extremity kinematic structure. We modeled the upper extremity with four rigid segments and joints that limit the degrees of freedom to nine. In the typing postures with the forearm fully pronated and the elbow flexed at a right angle, all joints can contribute to almost pure vertical movement of the fingertip through flexion and extension, except for the shoulder, which produced both vertical (z) and forward/backward (x) motion of the fingertip. During top–botttom–top tapping movements, the system relied on the shoulder flexion/extension to move the finger along the x axis. For the taps on the number key 2 (Bottom), the wrist contributed very little to the vertical movement in the z axis but the shoulder did contribute significantly. For the taps on the number key 8 (Top), pure shoulder flexion contributed to fingertip movement in both the positive x (away from the participant) and z direction (up away from the keypad). Therefore, the wrist and the elbow joint flexed in order to keep the fingertip on the same horizontal level as the keypad. For the left–right movements, abduction/adduction of the wrist and shoulder, as well as internal/external rotation of the shoulder moved the fingertip to the two locations. The motor control preference of utilizing the proximal joints during directional tapping was also manifested by the segment energy profile and joint power. Increased kinetic and potential energy on the hand, forearm, and upper arm were found during top–bottom–top tapping, and the hand energy increased during left–right–left tapping. The wrist, elbow and shoulder joint generated significantly greater power during top–bottom–top tapping than other conditions. Except the kinematic constraints of the upper extremity, the increased use of more proximal joints could also be related to the cognitive demands of the tasks. Using a torque-matching task, Hamilton et al. (2004) demonstrated that the motor output from the stronger, more proximal joints in the human arm showed less variability than the output from the weaker, more distal joints. The cognitive demands and the motor output variability during the simple cyclic left–right and top–bottom motions were low in this study. Increased cognitive demands and mental load during keying, such as typing at a higher speed, may affect the joint contribution to the fingertip movements.

The biomechanical loading on the proximal joints increased during unsupported tapping on multiple keys. However, whether and how this increase is correlated with increased risks of MSDs is unknown and needs to be further evaluated in epidemiological studies. Though the muscles articulating the more proximal joints are stronger and therefore will likely to have larger tolerances to these biomechanical loadings, they still have to maintain sustained static loads indicated by the large potential

Table 3
Mean (standard deviation) of joint torque statistics across six subjects for three tapping conditions: single key switch (S), left–right–left (LRL), top–bottom–top (TBT). Conditions with different superscript letters are significantly different, and the corresponding means are represented by the letters such that A > B. Flexion, adduction, supination and internal rotation were positive, and extension, abduction, pronation and external rotation were negative.

	Flexion			Adduction			Internal rotation/Supination		
	S	LRL	TBT	S	LRL	TBT	S	LRL	TBT
Average torque									
MCP (Ncm)	0.94 (0.35)^{B}	1.64 (0.74)^{A}	1.34 (0.78)^{AB}	−0.33 (0.12)	−0.43 (0.18)	−0.55 (0.32)			
Wrist (Ncm)	−25.6 (10.0)^{B}	−23.1(9.8)^{A}	−24.1 (9.1)^{AB}	3.63 (2.4)	3.34 (3.0)	2.84 (2.1)			
Forearm (Ncm)							−30.6 (28.3)	−32.4 (29.0)	−29.7 (34.0)
Elbow (Ncm)	−200 (73.5)	−196 (72.2)	−195 (72.1)						
Shoulder (Ncm)	−316 (145)	−315 (171)	−307 (161)	−132 (55.4)	−109 (53.5)	−144 (37.5)	0.30 (0.87)	1.19 (1.40)	0.07 (1.89)
Peak to peak torque									
MCP (Ncm)	8.0 (2.2)^{B}	12.3 (3.8)^{A}	9.9 (3.3)^{AB}	3.1 (0.9)^{B}	4.5 (1.0)^{A}	4.3 (1.6)^{A}			
Wrist (Ncm)	18.2 (6.9)^{B}	24.7 (7.8)^{A}	25.0 (7.8)^{A}	7.8 (4.6)^{B}	16.3 (6.8)^{A}	9.2 (2.9)^{B}			
Forearm (Ncm)							12.8 (8.8)^{B}	19.2 (9.8)^{AB}	23.1 (7.3)^{A}
Elbow (Ncm)	48.1 (26.1)^{B}	63.1 (36.2)^{AB}	72.1 (32.2)^{A}						
Shoulder (Ncm)	68.0 (29.3)^{B}	83.6 (35.5)^{B}	154.2(55.2)^{A}	53.2(23.4)^{B}	84.0 (48.4)^{A}	60.4 (29.7)^{AB}	34.5 (19.3)^{B}	82.2 (42.9)^{A}	66.7(26.6)^{A}

energy, which is due to segment weight. In addition, the increased dynamic loads added additional stress on the proximal joints during directional tapping. These results are in line with the high prevalence of MSDs in the shoulder region among computer users. Two systematic reviews of the literature (Larsson et al., 2007; National Research Council, 2001) found strong evidence for a causal relationship between neck and shoulder disorders and highly repetitive work, forceful exertions, high levels of static contractions, prolonged static load, and extreme postures, as well as combinations of these risk factors. This study identified specific motion during keying that increases biomechanical loadings on the shoulder joint and indicated that not only the static but also the dynamic loading on the shoulder joint were increased during directional tapping without support.

The larger loading of the proximal joints suggest that adding a forearm support may reduce the static as well as the dynamic loading on the proximal joints. Arm support was found to be associated with reduced risks of upper extremity musculoskeletal symptoms and disorders in many epidemiological studies (Gerr et al., 2006; Rempel et al., 2006; Visser, 2004). Arm support has also been reported to reduce the shoulder and forearm muscle activities during computer use (Nag et al., 2009). We did not measure changes in load due to forearm support; however it should be noted that adding the support may also change the loading on the distal joints as has been observed elsewhere (Kotani et al., 2007).

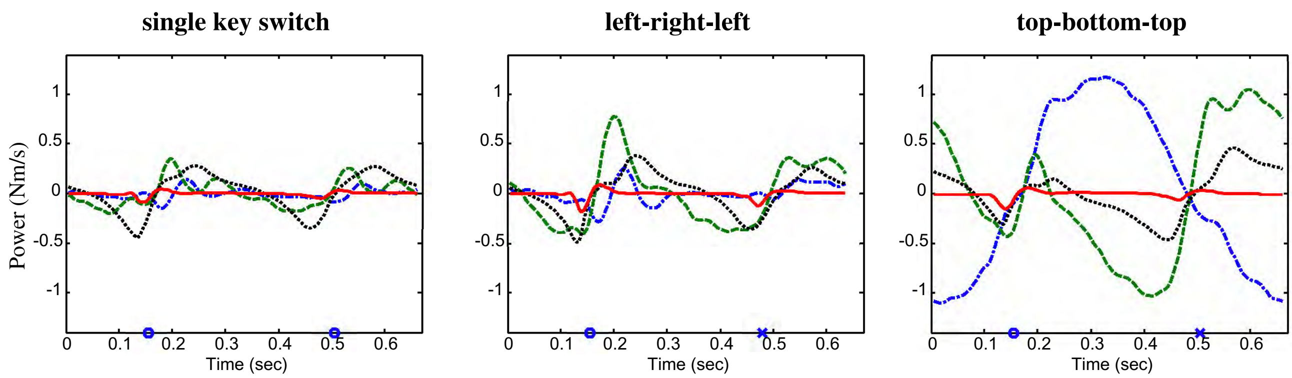
The study limitations should be taken into consideration when interpreting the results. The tapping tasks were performed unsupported which do not represent all keying works. Future research is warranted to investigate the effect of arm and wrist support on the upper extremity kinematics and kinetics during keying activities. We used the unsupported upper extremity because of several reasons. It has been reported that the traditional recommendation for typist to "hover or float" over the keyboard while keying, in which a neutral wrist posture is maintained without supporting the arm is still advocated and used (Cook and Burgess-Limerick, 2002, 2004; Cook et al., 2004; WorkSafe Victoria, 2001).

This study was a part of a progressive research endeavor to provide comprehensive profiles of the biomechanical characteristics and motor behaviors of the entire upper extremity during keying. We started by studying single finger tapping on a single key switch without any support (Dennerlein et al., 2007). Based on the findings on previous studies, we will continue building up the understanding on various aspects on this issue, such as use of the support, typing styles, and keyboard design. In addition, the conclusion can be generalized into other tasks with similar upper extremity motions where support is not feasible, e.g. quality control job on an assembly line.

Direct application of the results should be taken cautiously because the magnitude of the biomechanical loading may change due to the differences between controlled laboratory conditions and real work environment. However, with the repeated measures design controlling for subjects' variances, the biomechanical loading differences observed among experimental conditions were believed to be mainly due to task differences. In this study, the finger was modeled as a rigid body from the MCP joint to fingertip. This simplification may overestimate the MCP joint angle; however this error is likely to be small. The measured MCP joint angles were in a similar range reported by other studies (Baker et al., 2007; Sommerich et al., 1996). The kinematic and kinetic characteristics of the proximal and distal interphalangeal joints during single finger tapping have been studied previously (Kuo et al., 2006). In addition, the data were collected in the laboratory for a short period of time (about 15 s for each condition). Repetition over a longer duration may cause muscular fatigue. The muscular fatigue then could alter the kinematic and kinetic behaviors of the upper extremity and cause alterations in muscle activation patterns.

Table 4
Upper extremity kinetic energy and potential energy mean (standard deviation) across three tapping conditions: single key switch (S), left–right–left (LRL), top–bottom–top (TBT). Conditions with different superscript letters are significantly different, and the corresponding means are represented by the letters such that A > B > C.

	S	LRL	TBT	Condition effect *p*-value
Average kinetic energy (mJ)				
Finger	0.21 (0.11)	0.26 (0.10)	0.26 (0.06)	0.405
Hand	1.06 (0.66)^{B}	1.78 (0.75)^{A}	2.12 (0.65)^{A}	<.001
Forearm	0.08 (0.04)^{B}	0.27 (0.16)^{B}	0.50 (0.24)^{A}	0.002
Upper Arm	0.03 (0.02)^{B}	0.12 (0.07)^{B}	0.81 (0.34)^{A}	<.001
Max kinetic energy (mJ)				
Finger	1.26 (0.78)	1.45 (0.63)	1.37 (0.35)	0.748
Hand	4.93 (3.36)^{B}	7.26 (3.63)^{A}	8.01 (2.83)^{A}	0.003
Forearm	0.35 (0.15)^{B}	0.93 (0.82)^{AB}	1.40 (0.58)^{A}	0.006
Upper Arm	0.13 (0.08)^{B}	0.32 (0.18)^{B}	1.89 (0.91)^{A}	<.001
Change of potential energy (mJ)				
Finger	4.89 (1.30)	5.46 (1.14)	5.92 (0.87)	0.170
Hand	37.55 (12.64)^{C}	49.41 (15.68)^{B}	64.59 (17.49)^{A}	<.001
Forearm	14.45 (3.27)^{B}	19.85 (7.53)^{B}	68.74 (32.54)^{A}	<.001
Upper Arm	14.79 (4.91)^{B}	24.91 (12.44)^{AB}	62.14 (52.71)^{A}	0.049



M	0.028 (0.022)^{B}	0.051 (0.024)^{A}	0.046 (0.018)^{AB}
W	0.212 (0.163)^{B}	0.239 (0.143)^{AB}	0.276 (0.140)^{A}
E	0.232 (0.132)^{B}	0.408 (0.221)^{B}	0.667 (0.234)^{A}
S	0.134 (0.062)^{B}	0.244 (0.110)^{B}	0.844 (0.412)^{A}

*M – MCP, W – wrist, E – elbow, S – shoulder

Fig. 4. Average joint power (Nm/s) across six subjects and eight cycles in three experimental conditions and their RMS (standard deviation) values. MCP: solid red line (––), Wrist: dotted black line (...), Elbow: dash green line (- -), and Shoulder: dash-dot blue line (–·). Conditions with different superscript letters are significantly different, and the corresponding means are represented by the letters such that A > B. (For interpretation of the references to colours in this figure legend, the reader is referred to the web version of this paper.)

Lastly, the experimental condition investigated single finger tapping while typing activities involves multiple finger movements. Therefore, future studies should include multiple fingers during typing over longer periods of time to further understand the biomechanical loading on the upper extremity. Because of the smaller force components in the *x* and *y* axes, the resolution of the force transducer used (0.025 N) was relatively large. However, differences between conditions were observed even with the current resolution.

In conclusion, this study determined the biomechanical loading on the upper extremity and the role of each joint during single finger tapping on multiple keys. Increased loading during directional tapping was observed compared to single key switch tapping, especially on the proximal joints. By parsing the tapping movement into left–right and top–bottom movements, we were able to identify the potential risks to upper extremity MSDs associated with these fundamental movements and keying activities. The results also provided kinetic and kinematic evidence supporting intervention designs such as the forearm support. Such interventions must be evaluated in rigorous randomized control trails.

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Jin Qin recently completed her Doctoral degree in Occupational Health at Harvard University, School of Public Health in 2010. She received her M.S. degree in Industrial Engineering from Rochester Institute of Technology in 2005, and B.E. degree in Mechanical Engineering from Tianjin University, Tianjin, China in 2003.

Matthieu Trudeau is currently a doctoral student at the Harvard School of Public Health, majoring in Ergonomics. He obtained his B.Eng. from Dalhousie University (Halifax, NS, Canada) in 2003 before obtaining his M.Sc.A. in Bioengineering from Université de Sherbrooke (Sherbrooke, QC, Canada) in 2007.

Jeffrey N. Katz, graduated from Princeton University in 1980, attended Yale Medical School, and completed a medical internship and residency at Yale-New Haven Hospital and a Rheumatology fellowship at Brigham and Women's Hospital. He received a Master's Degree in 1990 at Harvard School of Public Health. Dr. Katz is currently Professor of Medicine and Orthopaedic Surgery at Harvard Medical School and Professor of Epidemiology and Environmental Health at HSPH.
Dr. Katz has focused his research on the evaluation and outcomes of musculoskeletal disorders including carpal tunnel syndrome, lumbar spinal stenosis and osteoarthritis and lower extremity joint replacement. Dr. Katz is Director of the Orthopaedic and Arthritis Center for Outcomes Research in the Department of Orthopaedic Surgery and Division of Rheumatology, Immunology and Allergy at Brigham and Women's Hospital. He is Principal Investigator of the Brigham Multidisciplinary Clinical Research Center (an NIH P60 Center), the MeTeOR Trial (a seven center RCT of the efficacy of arthroscopic partial meniscectomy) and a NIAMS funded T32 clinical research training program. He is Deputy Editor for Methodology of the Journal of Bone and Joint Surgery. He served on the National Academy of Sciences Panel on Musculoskeletal Disorders and the Workplace.
Dr. Katz lives in Brookline, MA with his wife Susan Zeiger, PhD, a 20th Century American historian, two teenage sons and a much-loved Springer Spaniel.

Bryan Buchholz is professor of occupational biomechanics and ergonomics. He has earned doctoral and master's degrees in bioengineering, a master's in applied mechanics and a bachelor's in chemical engineering, all from The University of Michigan. He is director of the new University of Massachusetts system-wide doctoral program in Biomedical Engineering and Biotechnology. His research efforts focus primarily on the development of biomechanical models that provide a better understanding of the pathomechanics of work-related musculoskeletal disorders so that effective interventions may be perfected. His continuing work on the development of biomechanical models of the human hand for evaluation of its prehensile capabilities and the design of tool handles has expanded since his initial work on his doctoral dissertation. He is also interested in the development of ergonomic exposure assessment tools, especially those employing bioinstrumentation. Dr. Buchholz is part of the Construction Occupational Health Project and involved in an initiative to understand and help control work-related musculoskeletal disorders in the construction industry. He has also been involved in ergonomic exposure assessment in the fishing industry.

Jack T. Dennerlein obtained his Ph.D, degree in from the University of California - Berkeley in 1996 and completed a post-doctoral training at the School of Engineering at Harvard University. Currently he is an Associate Professor in the Department of Environmental Health Sciences at the Harvard School of Public Health where he is also the co-director for the Occupational Injury Prevention Research Training Program supported by the United States National Institute for Occupational Safety and Health. From 2004 to 2005, Dr. Dennerlein was a visiting Scientist in the Faculty of Human Movement Sciences at the VU University, Amsterdam in the Netherlands. His primary research interests are in neuromuscular and occupational biomechanics with application in exposure assessment of work-related musculoskeletal disorders.