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Joint Contribution to Fingertip Movement During a Number Entry Task: An Application of Jacobian Matrix

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Upper extremity kinematics during keyboard use is associated with musculoskeletal health among computer users; however, specific kinematics patterns are unclear. This study aimed to determine the dynamic roles of the shoulder, elbow, wrist and metacarpophalangeal (MCP) joints during a number entry task. Six subjects typed in phone numbers using their right index finger on a stand-alone numeric keypad. The contribution of each joint of the upper extremity to the fingertip movement during the task was calculated from the joint angle trajectory and the Jacobian matrix of a nine-degree-of-freedom kinematic representation of the finger, hand, forearm and upper arm. The results indicated that in the vertical direction where the greatest fingertip movement occurred, the MCP, wrist, elbow (including forearm) and shoulder joint contributed 10.2%, 55.6%, 27.7% and 6.5%, respectively, to the downward motion of the index finger averaged across subjects. The results demonstrated that the wrist and elbow contribute the most to the fingertip vertical movement, indicating that they play a major role in the keying motion and have a dynamic load beyond maintaining posture.

Keywords: keying task, upper extremity, Jacobian matrix, kinematics

The high prevalence of computer use and its association with upper extremity musculoskeletal disorders impose a substantial public health burden in the US. Epidemiologic studies have demonstrated consistently that more than 50% of computer users sustain musculoskeletal symptoms and disorders of the upper extremity spanning from the neck and shoulder to the hand and wrist.[1–4] Almost all causation models of these disorders include biomechanical strain resulting from the physical demands of work.[5] For computer keying, most studies have focused on the static postural load; however, keying is a dynamic activity with repetitive motions of the fingers activating keyswitches that has yet to be well described beyond simple tapping. However, tapping is a basic cyclic motion that constitutes more complex typing activities. Understanding the kinematics of tapping lays the groundwork for studying the biomechanics of keyboard typing.

The upper extremity is a complex kinematic system with multiple degrees of freedom and as a result all its joints and segments can and do contribute to the fingertip motion required in computer keying activities. Recent studies used three-dimensional (3-dimensional) motion tracking systems to analyze the kinematics and kinetics of the upper extremity and associated biomechanical loading during single finger tapping.[6,7] While the protocol recorded 3-dimensional kinematics, these works use a planar model of the upper extremity to determine the role of the shoulder, elbow, wrist and metacarpophalangeal (MCP) joints in finger tapping on a single key switch and on keys in orthogonal directions by determining joint contribution to fingertip movement. The planar model is sufficient for analyzing simple motions restricted to the plane; however, it is difficult to use for more complicated keying tasks due to the irregular patterns of 3-dimensional trajectories of the fingertips accessing multiple key switches.

This study was designed to determine the dynamic role of the shoulder, elbow, wrist and MCP joints during a number entry task requiring an irregular motion pattern of the index finger. The goal of this study was to assess the contribution of each joint of the upper extremity kinematic system to fingertip movement utilizing 3-dimensional models rather than planar models to understand the kinematics and hence biomechanical loading for more complex movements than previously studied and described.

Methods

Procedure

Six healthy participants, three women and three men (mean age 28.3 ± 2.0 years, mean height 168.4 ± 7.4 cm, mean weight 64.9 ± 12.7 kg), entered a series of random 7-digit phone numbers without brackets or hyphens (presented as a list on a sheet of paper) on a stand-alone numeric keypad using their right index finger (Figure 1). The keypad measured approximately 75 × 75 mm, and the keys measured 12 × 14 mm. No instructions were provided to the participants for the other fingers; however, participants held other fingers in a slightly flexed posture. All subjects were right-handed and none had substantial experience with numeric data entry. Participants preformed the task while seated in a chair adjusted such that their backs were straight and the height of the keypad

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surface was even with their elbow while the upper arm was at the side of the body and shoulders relaxed. The keypad was fixed to a nonadjustable height table. The chair was positioned such that the keypad was directly in front of the right shoulder requiring no internal or external shoulder rotation with the elbow flexed at 90°, and the tip of the middle finger touched the top row of the keypad while the wrist was in a neutral posture and the forearm pronated. Participants were instructed to sustain an upright back posture against the back of the chair during the task. No forearm or palm support was provided. The task was performed at the participant's own comfortable pace. Accuracy was not monitored in the experiment, but the participants were instructed to do their best to type in the right number and not to correct any errors they noticed.

Before data collection, participants practiced the task for about one minute or until they felt familiar with the task. During the experiment, each participant typed for 20 seconds and the middle 15 seconds of data were extracted for analysis. The experimental procedures were approved by Institutional Review Board, and informed consent was obtained.

Experimental Measurements

Three-dimensional kinematic data of the right upper extremity were recorded during the task using an active-marker infrared motion analysis system (Optotrak Certus System, Northern Digital, Ontario, Canada). Clusters of three markers were secured on rigid plates and mounted on the hand, forearm, upper arm and torso using double and single-sided medical tape and adjustable Velcro straps. A single marker was attached to the fingernail of the index finger.[6] The sensor attachment and wire management was performed to minimize interference with joint motion and to make sure that the range of motion was not affected. The 3-dimensional positions of these markers were recorded at 200 samples per second. Anatomical landmark locations relative to the cluster markers were digitized using a probe. The digitized landmarks included incisura jugularis, left and right acromion process, lateral and medial epicondyle, ulnar and radial styloid, metacarpophalangeal joint of the index, middle and little finger, and tip of the middle finger. Anatomical coordinate systems of trunk, upper arm, forearm, hand and finger at each time instant were constructed from the digitized landmarks.[8,9] All kinematic data were low-pass filtered digitally using a 4th order Butterworth filter with a cutoff frequency of 10 Hz and a zero phase shift.[6]

For this study, fingertip force was used to determine the timing of keystrokes. Force vectors applied by the fingertip to the keypad were measured by a 6-axis force-torque transducer (ATI Industrial Automation, model Gamma, SI-65–5.5, Apex, NC, USA) attached underneath the keypad. The amplified signals from the force-torque transducer were recorded onto a personal computer at 200 samples per second with a National Instruments Board (NI PCI-6040, National Instruments, Austin, TX, USA). The force signal was low pass filtered digitally using a 4th order Butterworth filter with a cutoff frequency of 20 Hz and a zero phase shift.[6] The kinematics measured by Optotrak system and fingertip force measured by force transducer were synchronized.

Data Analysis

From the orientation of the upper extremity segments, nine joint angles including flexion/extension at the shoulder, elbow, wrist and MCP joint, adduction/abduction of the shoulder, wrist and MCP joints, internal/external rotation of the shoulder, and forearm pronation/supination were calculated with reference to the anatomical posture (fully extended arm vertical to the ground and palm facing forward). The shoulder internal/external rotation angle was adjusted as suggested by Cutti et al.[10] Joint angular velocity differentiation were derived from the relative rotation of the segments.[11]

To compute the joint contribution, the upper extremity was modeled as a nine degree-of-freedom (DOF) kinematic system with four rigid body segments (upper arm, forearm, hand, and index finger). The finger was approximated as a single segment with the length spanning the MCP joint center to the fingertip. To compute joint contribution, the Jacobian matrix $J(\mathbf{q})$ relating the joint space expressed in joint angles (q) to task space expressed in fingertip Cartesian coordinates (p) was calculated. The symbolic form of $J(\mathbf{q})$ was derived using MatLab Symbolic Math Toolbox (MathWorks Inc., Natick, MA, USA). (Appendix)

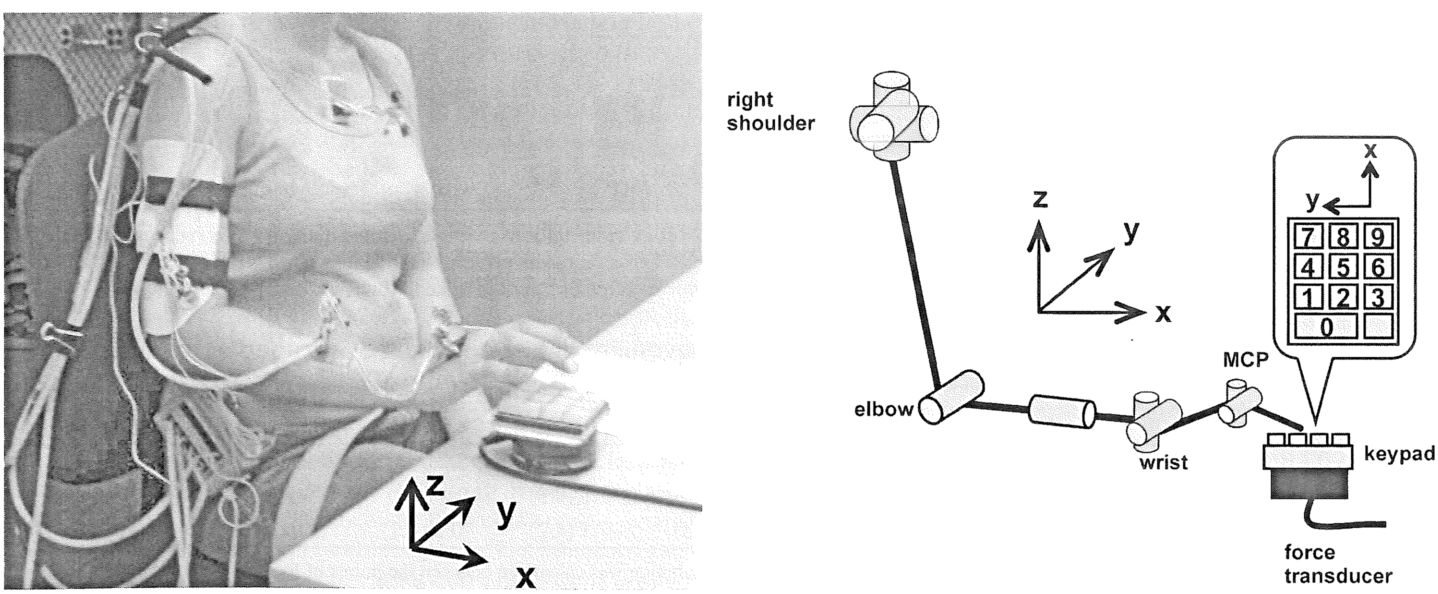

Figure 1 — Experimental setup. (a) Marker attachment: rigid bodies of clusters of three infrared markers were attached on the top of sternum, upper arm, forearm and hand. (b) Schematic view of the right upper extremity kinematic system during experiment defining the global coordinate system.

The Jacobian matrix provides mapping information between joint angular velocity and fingertip movement velocity in 3-dimensional space:

$$\dot{\mathbf{p}} = J(\mathbf{q})\dot{\mathbf{q}} \qquad (1)$$

where $\dot{\mathbf{p}}$ is a 3 × 1 vector of fingertip linear velocity in Cartesian space, $\dot{\mathbf{q}}$ is a 9 × 1 vector of joint angular velocities, and $J(\mathbf{q})$ is a 3 × 9 Jacobian matrix. At each time instant the numerical form of $J(\mathbf{q})$ is calculated by inputting the instant joint angles to the symbolic form of $J(\mathbf{q})$.

For a key striking cycle, the time of the local maximum index fingertip position in the z axis (vertical direction) before each keystroke (t_a) and the time of the local maximum force exerted on the keypad (t_b) were identified. Joint contribution to fingertip motion was calculated for the periods between t_a and t_b, the movement of the fingertip to activate the keys. Joint contribution to fingertip movement can be computed by integrating Equation (1):

$$p_{ij} = \sum_{t_a}^{t_b} \left(J_{ij}(\mathbf{q}(t)) \cdot \dot{\mathbf{q}}_j(t) \cdot \frac{1}{F_s}\right) \qquad (2)$$

where i = x, y, z, j = 1–9 *df* (degrees of freedom), and p_{ij} is the fingertip movement in the axis i due to the movement of *df* j, and F_s is the sampling frequency. The contribution from each degree of freedom was computed for every index finger tap, and then the contribution was averaged across all index finger taps and all participants. The contribution from each joint to fingertip movement was calculated (contributions from multiple degrees of freedom at each joint were summed).

Results

Participants typed 28 (SD = 5) taps on average within 15 seconds of number entry task. In the z axis (vertical direction) where the main fingertip movement occurred, the MCP/wrist flexion and the elbow/shoulder extension contributed to the downward movement (in negative sign) of the fingertip (Table 1). The majority of the fingertip movement in z axis was contributed by the wrist and the elbow joints (Figure 2). The MCP, wrist, elbow (including forearm) and shoulder joints contributed 10.2% (SD = 12.1%), 55.6% (SD = 9.5%), 27.7% (SD = 10.5%) and 6.5% (SD = 10.7%), respectively, to the fingertip movement in the z axis averaged across all subjects.

Shoulder internal rotation and wrist flexion contributed to medial movement (in positive sign), while wrist ulnar deviation and elbow extension contributed to lateral movement (in negative sign) of fingertip movement in the y axis (Table 1). Fingertip motion in the x axis (anterior-posterior direction) was small in general (≤1.4 mm in absolute magnitude).

Discussion

This study assessed quantitatively the dynamic roles of the shoulder, elbow, wrist and MCP joints during a data entry task on a numeric keypad. Using the experimentally measured 3-dimensional upper extremity motion and the 9-DOF kinematic chain along with its mathematical Jacobian matrix, the contribution from each joint during keystrokes was calculated. In general, the wrist joint contributed the most to the fingertip movement, followed by the elbow. The MCP and shoulder joints played relatively less important roles in the task.

Comparing these results to other studies, this study showed that during typing, the wrist joints contributed 55.6% of the fingertip's vertical motion, similar to the 56% reported by Dennerlein et al;[6] however, in this data entry task the MCP joint's contribution is considerably small with only 10.2% compared with, the 27% reported for the single key tapping task. This difference of MCP contribution may be due to different task requirement. In Dennerlein's study, the tapping speed was strictly controlled at 3 taps/sec, whereas in the current study participants were allowed to type at their own comfortable speed (1.9 ± 0.3 taps/sec). Moving smaller distal joint (MCP) could facilitate movement at faster speed. Dennerlein[6] suggested that since the shoulder contributed very little to the fingertip motion, the shoulder joint acted like a mechanical base for the kinematic chain to maintain stability rather than actively contributing to the

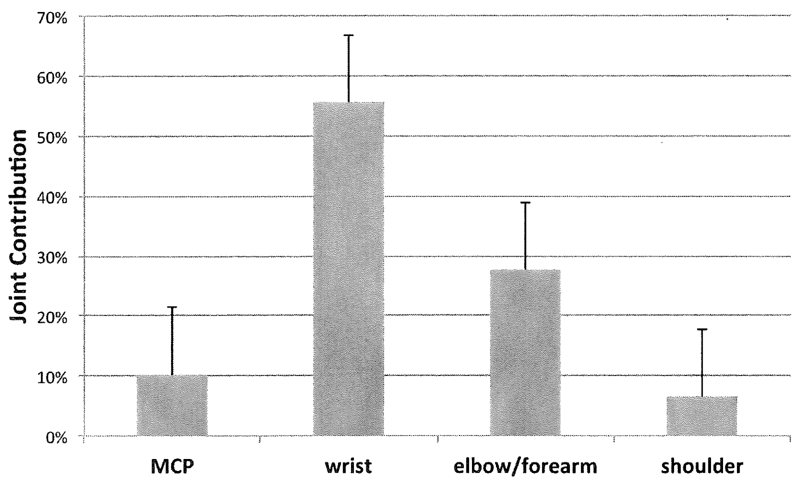

Figure 2 — Joint contributions to fingertip movement in z axis (vertical) as percentages averaged across subjects presented in means and SDs (error bar). Contribution from multiple degrees of freedom at each joint was summed together.

Table 1 Joint contribution to fingertip three-dimensional movement in x, y and z axes averaged across subjects presented as means (SD), in millimeters

Axis	MCP AD	MCP F	Wrist AD	Wrist F	Forearm S	Elbow E	Shoulder E	Shoulder AD	Shoulder IN
x	−0.1 (0.3)	−1.4 (1.2)	1.1 (1.4)	−0.9 (0.9)	0.1 (0.1)	1.2 (1.1)	0.0 (1.3)	0.0 (0.0)	−1.3 (1.1)
y	0.0 (1.3)	0.4 (0.5)	−4.3 (2.5)	1.6 (1.5)	−0.4 (0.4)	−2.1 (0.9)	0.0 (0.0)	−1.2 (0.9)	3.4 (1.9)
z	−0.1 (0.2)	−3.2 (3.1)	−0.7 (0.6)	−14.8 (3.9)	−0.7 (0.8)	−7.3 (4.2)	−0.2 (2.1)	0.0 (0.2)	−1.2 (0.6)

Note. F, flexion; E, extension; AD, adduction; S, supination; IN, internal rotation. Contribution was calculated between the points of local maximum fingertip position in the z axis (vertical) and the local maximum force on the keypad for each of the index finger taps. The positive and negative directions indicate that the joint motion contributed to the fingertip movement in the positive and negative direction of the corresponding axis, respectively. Mean of zero and non-zero SD indicate that the joint did contribute to the fingertip movement, but the contribution in the positive and negative directions has been averaged out over subjects.

fingertip movement, which is also likely the case in this study. In the case of single finger tapping on keys in orthogonal directions and, especially in the anterior-posterior direction, the shoulder contributed significantly to the fingertip 3-dimensional movements.[7] It should be noted that relatively small contribution from the shoulder joint indicated small joint motion, but not necessarily corresponded to small biomechanical loading. The shoulder joint still needs to balance the torque due to the weight and dynamic motion of the upper extremity. This is a possible reason for the high prevalence of shoulder complaints among computer users. Sustained static contractions have been found to be a risk factor of neck and shoulder disorders.[12] Wrist/forearm support can be an effective intervention to reduce biomechanical loading in the shoulder muscles.[13]

The dynamic roles the upper extremity joints played in simple tapping tasks[6,7] and in this study showed that the shoulder, elbow, wrist and MCP joint contributions vary in different tasks. Those patterns were associated with the kinematic advantages and constraints of the upper extremity linkage system set out in the Jacobian matrix and the specific task requirement. For example, shoulder internal/external rotation contribution increases when more medial-lateral movement of the fingertip is required. The longer moment arms of the more proximal joints relative to the fingertip require much less joint motion to achieve the same fingertip movement distance than the more distal joints. On the other hand, activating larger muscles at the shoulder joint is likely to require more energy than activating smaller muscles articulating distal joints. Therefore, participants may tend to rely more on distal joints to conserve energy, especially for longer tasks. It is also possible that distal joint motion may facilitate the control of more complicated and accurate fingertip movement. In the end it is unclear what type or how much of a biomechanical load is associated with risk for injury; however, these data provide further evidence that the wrist and elbow play an important role in keying, which could help us understand the kinematics and joint biomechanical loading in such tasks.

This study is limited in that the index fingertip was modeled as one segment. Future research could include the joint contributions from the distal and proximal interphalangeal joints and from multiple fingers by adding additional markers on the fingers. The Jacobian matrix relationship provided a quantitative assessment of the contribution from each of the 9 *df* of the system to 3-dimensional motion of the fingertip, which facilitates our understanding of the dynamic interactions between joints in various task conditions. It should be noted that this method cannot be applied for extreme postures of the arm (eg, fully extended arm) because the Jacobian matrix reaches singularities. Extrapolating the results to experienced users should be cautious because skill and experience may affect the motor response and, subsequently, the kinematics of performing the same task. Unlike single finger keying in this study, typical typing tasks often involve multiple fingers. By adding more fingers, the travel distances of fingertip for individual fingers are likely to be shorter compared with single finger keying, especially in the medial-lateral direction. We speculate that the relative contribution would increase from the MCP joint and decrease from the wrist joint. Future research should also evaluate the effect of the cognitive demand of the task on joint contribution to fingertip movements.

The single finger typing motion studied here is one step further in deciphering the biomechanics of keying from tapping tasks investigated previously. The mathematical Jacobian matrix derived in this study can be applied in future research about kinematics and motor strategies of upper extremity tasks with a fixed trunk posture. In addition, it can be used for investigating motor synergy of upper extremity movement under the framework of uncontrolled manifold analysis.[14] Uncontrolled manifold analysis studies the motor synergies by decomposing kinematic variability.[15] To do so, one needs to know the specific Jacobian matrix obtained at the mean joint configuration across trials.

Acknowledgments

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Appendix: Parameter Nomenclature and Abbreviations

Note. Symbolic form of the Jacobian matrix is presented in the file Jacobian.mat, available upon request from the corresponding author.

Table A1 Local coordinate system for measured body segments

Segment	Bony Landmarks	Axis	Local Coordinate System*
Trunk	right acromion	y	vector from the right to left acromion process
	left acromion	x	vector through the incisura jugularis and parallel to the global z axis
	incisura jugularis	z	vector parallel and opposite to the global x axis
Arm	right acromion	y	vector from the lateral to the medial epicondyle
	lateral epicondyle	x	vector from the lateral epicondyle to the right acromion
	medial epicondyle	z	vector directed toward the triceps
Forearm	lateral epicondyle	y	vector from the ulnar to the radial styloid
	ulnar styloid	x	vector from the ulnar styloid to the lateral epicondyle
	radial styloid	z	vector directed toward the dorsal side of the forearm
Hand	2nd metacarpal	y	vector from the 5th to the 2nd metacarpal
	3rd metacarpal	x	vector from the dactylion to the 3rd metacarpal
	5th metacarpal	z	vector directed toward the dorsal side of the hand
	dactylion (fingertip)		

*The z axis is defined from the cross-product of the first two defined axes; x axis is then redefined as the cross-product of the y and z axis to ensure all axes are orthogonal.

Table A2 Joint angle definition

Joint	*df*	Angle	Rotation Axis	+ Angle Motion	– Angle Motion
MCP	1	β_m	x	Adduction	Abduction
	2	α_m	y	Extension	Flexion
Wrist	3	β_w	x	Adduction	Abduction
	4	α_w	y	Extension	Flexion
Ulnar	5	γ_u	z	Pronation	Supination
Elbow	6	α_e	y	Extension	Flexion
Shoulder	7	α_s	y	Extension	Flexion
	8	β_s	x	Adduction	Abduction
	9	γ_s	z	Internal rotation	External rotation

Note. degrees of freedom, *df*.

Table A3 Abbreviations of anthropometric parameters

Lfz	Length from fingertip to MCP
Lhy	Length from MCP to wrist joint in the y axis of the hand segment
Lhz	Length from MCP to wrist joint in the z axis of the hand segment
Lpy	Half of the length from ulnar to radial head in the y axis of the forearm segment
Llz	Length from elbow to radial head
Laz	Length from shoulder to elbow