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Finger joint coordination during tapping

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Abstract

We investigated finger joint coordination during tapping by characterizing joint kinematics and torques in terms of muscle activation patterns and energy profiles. Six subjects tapped with their index finger on a computer keyswitch as if they were typing on the middle row of a keyboard. Fingertip force, keyswitch position, kinematics of the metacarpophalangeal (MCP) and the proximal and distal interphalangeal (IP) joints, and intramuscular electromyography of intrinsic and extrinsic finger muscles were measured simultaneously. Finger joint torques were calculated based on a closed-form Newton–Euler inverse dynamic model of the finger. During the keystroke, the MCP joint flexed and the IP joints extended before and throughout the loading phase of the contact period, creating a closing reciprocal motion of the finger joints. As the finger lifted, the MCP joint extended and the interphalangeal (IP) joints flexed, creating an opening reciprocal motion. Intrinsic finger muscle and extrinsic flexor activities both began after the initiation of the downward finger movement. The intrinsic finger muscle activity preceded both the IP joint extension and the onset of extrinsic muscle activity. Only extrinsic extensor activity was present as the finger was lifted. While both potential energy and kinetic energy are present and large enough to overcome the work necessary to press the keyswitch, the motor control strategies utilize the muscle forces and joint torques to ensure a successful keystroke.
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Keywords: Finger; Tapping; Energy; EMG; Motor control

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1. Introduction

Upper extremity musculoskeletal disorders associated with computer keyboard use are an important concern in occupational health (Bureau of Labor Statistics (BLS), 2002; Gerr et al., 2002). Since computer keyboard use is characterized by repetitive finger movements as defined by a keystroke, these disorders may arise from cumulative effects of transient loads on the tissue through repetitive muscle activations (National Academy Press (NAP), 2001). Thus, identifying the joint coordination and the specific muscle activation patterns and function associated with such a keystroke, is a crucial step in understanding the injury mechanism.

A keystroke is the fundamental movement associated with typing (Flanders and Soechting, 1992). The movement involves: (1) a downswing to depress keyswitch and then (2) an upswing to release the keyswitch and prepare for the next keystroke. Jindrich et al. (2004a) observed that during the contact period of a keystroke the finger joints move in a coupled, reciprocal manner. As the fingertip presses on the keyswitch, the metacarpophalangeal joint (MCP) flexes while the distal interphalangeal (DIP) and proximal interphalangeal (PIP) joints extend. As the fingertip releases the keyswitch, the joints then move in opposite directions with the MCP joint extending while the interphalangeal (IP) joints flex. Long and Brown (1964) had defined the first pattern of motion as closing-type and the second as

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opening-type reciprocal motion. Nevertheless, it is still unclear if this reciprocal motion is a result of a movement prior to contact or a result of the closed kinematic chain formed by the fingertip's contact with the keyswitch.

Specific finger joint coordination and activities of the extrinsic and intrinsic muscles have been described previously (e.g., Buchner et al., 1988; Close and Kidd, 1969; Darling et al., 1994; Landsmeer and Long, 1965; Long and Brown, 1964; Long, 1968; Valero-Cuevas, 2000). However, most of these studies have only considered free finger movements (Close and Kidd, 1969; Darling et al., 1994; Landsmeer and Long, 1965; Long and Brown, 1964), while other studies have only considered IP joint motions (Buchner et al., 1988) or isometric conditions (Valero-Cuevas, 2000). Among the few studies relating keystroke with muscle activities, Dennerlein et al. (1998) suggested that the role of extrinsic finger flexors during a keystroke on the middle row of the keyboard is to overcome the activation force of the keyswitch, while the role of extrinsic extensors is to perform the upswing rather than stop the downswing. They also observed that the extrinsic flexors were activated after the downswing and thereby suggested that another mechanism may have initiated the movement. Potential sources of this mechanism may include gravity, passive muscle forces and other muscles, specifically intrinsic finger muscles. However, activation patterns of intrinsic muscles with respect to the finger joint coordination during a keystroke were not investigated.

Energy approaches can often elicit specific motor control strategies associated with rapid and complex movements (McMahon, 1984). For example, Dennerlein et al. (1998) suggested that during the downswing of a keystroke, the change of potential energy was large enough such that if it was completely converted to kinetic energy, the fingertip would reach velocities observed in typing. They did not, however, measure the segmental kinematics to calculate the potential and kinetic energy profiles. Jindrich et al. (2004b) examined joint energy by integrating joint torques with respect to the joint excursions observed during contact period and observed that during the loading phase of contact period, the MCP exhibited net positive work while the IP joints exhibited negative work. Moreover, the work generated by the MCP joint exceeded the work done on the keyswitch. However, the kinetic energy and potential energies were not reported for either the contact or the free movement portions of a keystroke.

In order to examine motor control questions not answered by Dennerlein et al. (1998) and Jindrich et al. (2004a, b), we sought to characterize the joint coordination, kinematics, muscle activation patterns, and energy profiles during the contact and free movement periods of a keystroke with single finger tapping in a middle row posture. In particular, we are interested in the activation patterns of intrinsic muscles, defining their role in the keystroke, as well as describing the finger energy profiles that are observed during specific motor control strategies. We tested the following hypotheses: (1) The reciprocal motion of finger joints reported by Jindrich et al. (2004a) begins before the fingertip contacts the keyswitch; and (2) The intrinsic muscles and extrinsic flexors follow the same pattern of activity. Finally, we describe the energy profiles of the finger during the keystroke to facilitate the explanation of the mechanics and motor control of the keystroke.

2. Materials and methods

Six subjects (three males, three females) with a mean age of 26 years (range: 21–28 years), participated in the study (Table 1). All subjects signed informed consent forms, and the experimental protocol was approved by the Human Subjects Committee at the Harvard School of Public Health.

Subjects tapped with their right index finger while seated at an adjustable workstation and chair, with their elbows, hips, knees, and ankles at approximately 90° (Jindrich et al., 2004a). Subjects were instructed to tap on an isolated keyswitch (IBM PC AT keyboard, buckling-spring design with a 0.3 N activation and 3.7 mm maximal displacement) with a hand and finger posture similar to as if they were typing on the middle row of a computer keyboard. They tapped at a rate of 0.8 taps per second paced by a metronome for 10 s and were instructed to minimize contact time with the keyswitch. To ensure that subjects minimized contact time as instructed, the duration of the taps were observed on an oscilloscope while subjects practiced tapping until their contact was below 150 ms, similar to the duration of keystrokes observed during touch-typing (Dennerlein et al., 1998). No feedback was provided to the subjects once data collection commenced.

Vertical and horizontal fingertip forces were measured using a two-dimensional strain-gauge force transducer

Table 1
Subject data of gender, age, and successful EMG measurements; X indicates successful EMG measurement

Subject	1	2	3	4	5	6
Gender	M	M	F	F	M	F
Age (years)	26	28	21	27	27	26
LUM	X		X	X	X	X
FDI	X	X	X	X	X	X
FDS	X	X	X	X	X	
FDP			X	X		
EDC	X	X	X	X	X	X

mounted underneath the keyswitch. The force transducer was firmly secured to the tabletop and had a resolution of 0.0025 N, with a dynamic bandwidth up to 1000 Hz (Jindrich et al., 2003). The sensor output was linear such that the residual for a straight-line curve fit was less than 0.002 N for the vertical and 0.004 N for the horizontal force. These residuals correspond to a maximum error between the straight-line curve fit and actual measurements during calibration of 0.4 percent and 1.5 percent of the maximum load tested for the vertical and horizontal components, respectively.

Three miniature goniometers (Shape Sensors, Measurand Inc.) measured flexion/extension angles of the right index finger DIP, PIP, and MCP joints. They were attached across the dorsal aspect of the joints and calibrated as described by Jindrich et al. (2004b). The active element of the sensor (a 12 mm segment) was positioned spanning the dorsal side of the joint. Distal to the joint the goniometers were fixed using tape, while proximal to the joint they passed through a narrow plastic tube. This allowed sliding of the goniometer proximal of the joint and ensured that rotation about only one joint caused local bending of the active region. The goniometers were statically calibrated using bent metal rods, with known angles ranging from 0° to 60° at 20° increments. The dynamic response of the miniature goniometers and mounting system was validated by comparing goniometer output to joint angles measured using a high-speed video system (Motionscope, Redlake Imaging) during rapid finger movements (Jindrich et al., 2004a). A digital image of the finger, hand, and keyswitch was acquired after practice taps and before data collection. The images provided estimates of the initial angle between the fingertip and the keyswitch, which in turn provided a reference for the joint angles measured by the goniometers in the coordinate frame of the force sensor (Jindrich et al., 2004b). The vertical position of the keyswitch was measured by an optical tracking system (Jindrich et al., 2003).

Five pairs of bipolar fine-wire electromyography (EMG) electrodes were inserted into the first lumbrical (LUM), first dorsal interosseus (FDI), flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP), and extensor digitorum communis (EDC) muscles using 29-gauge needles prepared as described by Burgar et al. (1997). The electrodes (50 μm stainless steel wires with nylon insulation) were connected to a custom-designed amplifier (14–2000 Hz band pass filter). The placements of the electrodes were confirmed by observing the EMG activities (Burgar et al., 1997).

Data from the force transducer, goniometers, keyswitch position sensor, and EMG electrodes were acquired at 10 kHz using a computer data-acquisition hardware and program (SCXI 1121 Isolated Sensor Input Module and LabVIEW, National Instruments, Austin, TX, USA). The recorded EMG signals were digitally band-pass filtered at 30–700 Hz. To minimize noise amplification due to digitally differentiating the data, the kinematics and force signals were digitally filtered (filtfilt function in Matlab, Mathworks, Natick, MA, USA) based on a fourth-order Butterworth low-pass filter (20 Hz) with zero phase shift. Linear and angular velocities as well as accelerations of the joints were calculated by digitally differentiating the filtered position data (Biewener and Full, 1992).

Before EMG patterns were identified, background 60 and 60 Hz harmonic noise was removed using fourth-order Butterworth notch filters. The signal was then normalized to the highest activity level over the entire experimental session for each muscle and then rectified by simply taking the absolute value. Given that the EMG signal exhibited a steep pattern of activation and the presence of background noise (Fig. 1), 0.2 was chosen as the threshold of muscle activation. Therefore, muscle activity was defined when the rectified EMG value exceeded the threshold. Fig. 1 shows the comparison of EMG signals between before and after signal processing.

Net joint torques for the finger joints were calculated based on a closed-form solution to a Newton–Euler inverse dynamical model of the finger (see Appendix; Craig, 1989). The three phalanxes of the index finger were modeled as a three-link system with the pivot of the proximal link anchored to the base reference frame. The finger segments were approximated by uniform cylindrical tubes with ellipsoid cross sections, and their masses and the moments of inertia were estimated using the density of water. A caliper was used to measure hand anthropometry; average finger segment lengths across all subjects were 21 ± 1, 24 ± 1, and 43 ± 3 mm for the

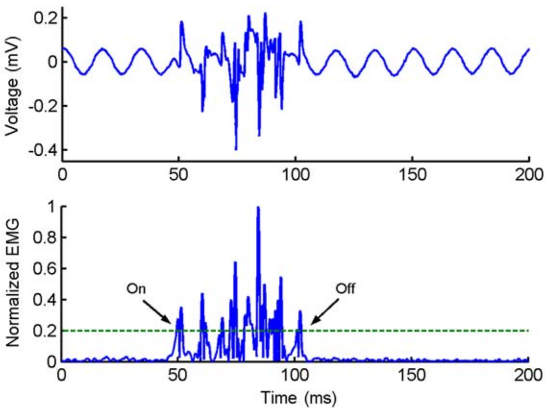

Fig. 1. EMG signals before and after signal processing. Data were adapted from the LUM signal of subject 1. The plot on top represents signal before processing. Note the 60 Hz harmonic noise in the baseline. The bottom plot exhibits the absolute (rectified) values of signal after filtering and normalization. The dotted line denotes the threshold of EMG activation, 0.2. The onset (On) and offset (Off) of the EMG signal are defined when the signal first or last crossed the threshold as illustrated.

distal, middle, and proximal phalanges, respectively. Since the wrist and the other four fingers were supported during the experiment, the position of MCP joint was assumed to be static during tapping.

To describe energy transfer between different components during a keystroke, energy generated by the joints (E_{torque}), gravity ($E_{\text{potential}}$), finger kinetics (E_{kinetic}), and work done on the keyswitch ($E_{\text{keyswitch}}$) were calculated. Work done on the keyswitch ($E_{\text{keyswitch}}$) during the contact period was calculated by integrating vertical fingertip force with respect to position of the keycap. Centers of mass for the three phalanxes were estimated from the link model and used to calculate potential energy of the finger. The total kinetic energy of the finger (E_{kinetic}) was calculated using the sum of each link's translational and rotational kinetic energy. Total work done by the finger joints (E_{torque}) was calculated by integrating joint torque with respect to joint angle for each joint, then summing across the three joints.

From these data individual taps were identified and aligned, using an interactive program and then averaged together. The onset of the downswing movement was defined as the moment when the fingertip began to fall. Contact periods were identified when the vertical force exceeded 0.02 N. The beginning of contact period was defined as the zero time reference, with subsequent time being positive and prior negative. The local maxima of impact and pulp compression phases, as defined by Rempel et al. (1994), were identified and the latter was used to separate the loading and unloading phases of contact periods (Jindrich et al., 2004b). A linear spring and damper model was fitted to the joint torque and joint angle data to characterize the mechanical behavior of each joint during the loading phase of the keystroke (Jindrich et al., 2004b). Taps without the typical force pattern (Rempel et al., 1994) or contact duration longer than 150 ms were discarded. The kinematics, kinetics, energy profiles, and EMG data were then averaged across all keystrokes.

3. Results

The observed tapping keystrokes (Table 2) were consistent with those reported previously (Dennerlein et al., 1998; Jindrich et al., 2004a, b). The averaged tap duration across all subjects was 108 (±SD of 21) ms. The average calculated vertical velocity of fingertip at beginning of the contact period was 0.45 (±0.04) m/s. The average peak vertical force was 2.0 (±0.5) N.

During the free movement of the downswing, closing-type reciprocal motions of finger joints were observed across all subjects (Fig. 2). The downswing and the reciprocal motion began prior to the onset of contact by, on average, 96 (±30) and 38 (±4) ms, respectively. This reciprocal motion continued during the loading phase with positive stiffness for the MCP and negative values for the PIP and DIP joints (Table 2). During the removal of the fingertip, the finger joints exhibited an opening-type reciprocal motion (Fig. 2).

Prior to contact of the keyswitch, coupled activities between the intrinsic muscles and the extrinsic flexors were repeatedly observed among all subjects (Fig. 3). Inspecting individual taps revealed that the onset of both the extrinsic flexors and the intrinsic muscles occurred after the downswing motion began. Although both muscles were co-activated throughout the downswing, the intrinsic muscles slightly preceded the extrinsic muscles. On average, activity of the intrinsic muscles preceded the beginning of reciprocal motion and the activity of the extrinsic flexors by 33±18 and 16±14 ms, respectively. During the unloading phase, only the EDC was active.

The peaks in the kinetic energy profile correspond to the downswing and upswing (Fig. 4); however, the changes in kinetic energy were smaller than the changes in potential energy (Fig. 5 and Table 3). Note that the minimum of potential energy was defined as zero, which occurred around the end of the loading phase (Fig. 5). The keyswitch is not a purely elastic system and the residual energy of $E_{\text{keyswitch}}$ at the end of contact period represents the loss of energy due to damping. The overlapping of the first peak of E_{kinetic} and the $E_{\text{keyswitch}}$ during the early loading phase indicates energy transfer between these two components; however, not all kinetic energy was transferred to $E_{\text{keyswitch}}$. Likewise, the slight lag of the second peak of E_{kinetic} at the end of the contact period indicates that not all the kinetic energy of lifting finger was contributed by the elastic energy of the keyswitch.

Table 2
Mean values and standard deviations of torque and mechanical model parameters of finger joints during tapping

	Averaged joint torque during contact period (N mm)	k_{load} (N mm rad^{-1})	b_{load} (N mm rad^{-1})
DIP	5 (1)	−170 (130)	3 (4)
PIP	15 (2)	−368 (146)	11 (6)
MCP	37 (4)	335 (266)	−17 (6)

k_{load}: spring constant; b_{load} damper constant.

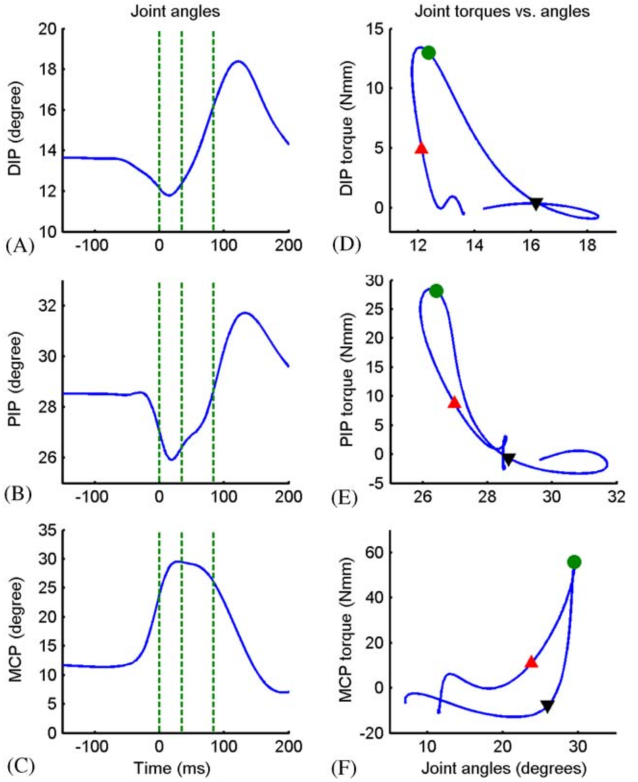

Fig. 2. Typical finger joint motions in a tap (A–C) and joint torques vs. angles (D–F). Data were averaged from eight taps of subject 2. The first vertical dotted line denotes the beginning of the contact period while the second dotted line separates the loading and unloading phase, and the third dotted line highlights the end of the contact period. Joint angles and torques are positive for flexion. In plot D–F, the upward and downward triangles denote the beginning and end of contact periods, respectively. The circles represent the separation of loading and unloading phase. The MCP and IP joints exhibit a closing-type then an opening-type reciprocal motion.

Fig. 5 further illustrates the transfer of energy between different components starting from 150 ms prior to the beginning of contact period. The E_{torque} and $E_{\text{potential}}$ had parallel profile before the downswing. During the downswing the $E_{\text{potential}}$ dropped with the increase of E_{kinetic}, while a local maxima of E_{torque} occurred concurrently with the first peak of E_{kinetic}. E_{torque} increased considerably after the beginning of contact, and continued to increase during the release of the keyswitch. The magnitude of the second peak of E_{kinetic} is relatively smaller than that of the first peak and could not fully cover the restoring of $E_{\text{potential}}$ as the finger lifted. These patterns of energy changes were similar across all subjects (Table 3).

4. Discussion

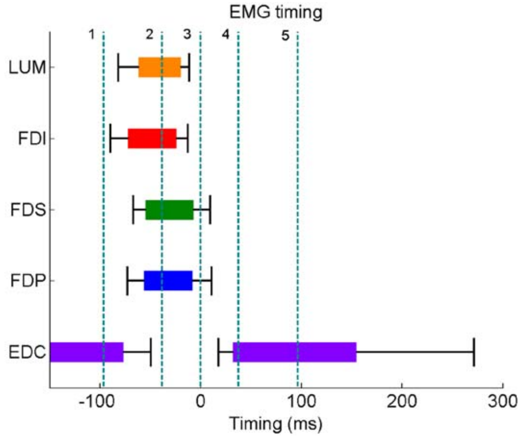

Fig. 3. Mean values of muscle activities onset and cessation in a tap. The error bars represent one standard deviation. Data were averaged across all subjects. The first vertical dotted line denotes the beginning of the downswing (1). The second dotted line represents the onset of reciprocal motion (2). The events for the remaining three dotted lines (3–5) are the same as Fig. 2. While the activity of the intrinsic muscles mostly overlaps with the extrinsic flexor muscles, their activity preceded them by 16 ms, suggesting that their role is to initiate the reciprocal motion prior to contact with the keyswitch.

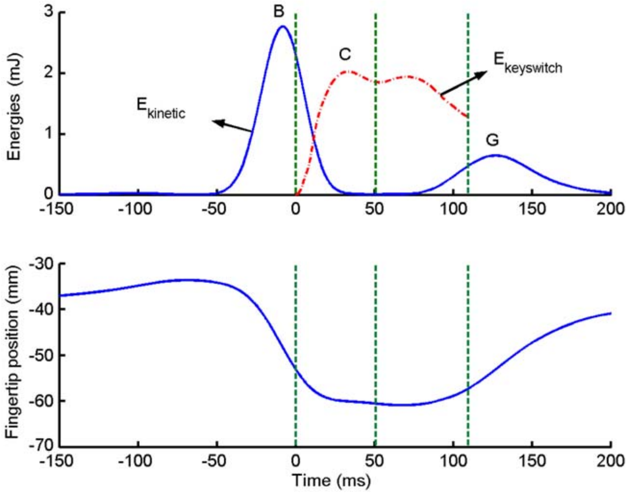

Fig. 4. Top: kinetic and keyswitch energy profiles during a keystroke. Bottom: fingertip vertical position during a keystroke. Data were averaged from eight taps of subject 3. The dotted lines denote the same periods as Fig. 2. Note that keyswitch energy is only considered at the contact period. At the end of contact period, the keyswitch did not return all the energy stored during loading phase due to internal friction effect. Letters B, C, and G highlight parameters as defined in Table 3.

The finger joint coordination during tapping on a keyswitch followed a reciprocal motion during the downswing beginning prior to contact; however, it initiated after the finger started to move downward. The muscle activities during the keystroke coincided with the movement patterns in that the activity of intrinsic muscles began slightly before the closing-type reciprocal motion. Similar to the intrinsic muscles, the activity of the extrinsic flexor started after the initiation

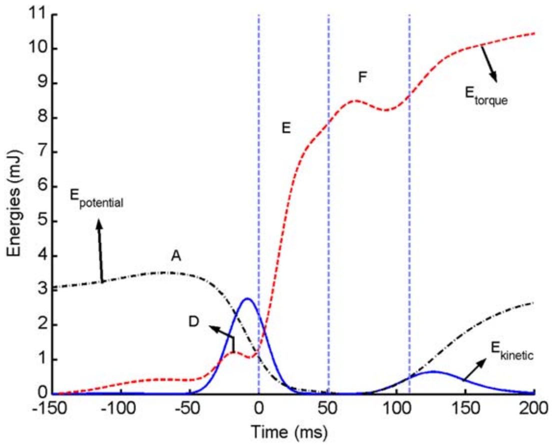

Fig. 5. Energy profiles of kinetic, potential and joint torques energy during a keystroke. Data were averaged from eight taps of subject 3. The dotted lines denote the same periods as Fig. 2. The minimum of potential energy occurring around the end of loading phase was defined as zero. Work done on the joints was calculated from 150 ms prior to the onset of contact. Letters A, D, E, and F specify parameters as defined in Table 3.

Table 3
Mean values and standard deviations of energy parameters during a keystroke

A	$E_{\text{potential}}$ at beginning of downswing (mJ)	2.6 (1.1)
B	1st peak of E_{kinetics} (mJ)	2.0 (0.9)
C	Maxima of $E_{\text{keyswitch}}$ (mJ)	1.7 (0.2)
D	E_{torque} local maxima at 1st peak of E_{kinetics} (mJ)	0.7 (0.3)
E	Averaged E_{torque} during loading (mJ)	3.6 (1.5)
F	Averaged E_{torque} during unloading (mJ)	3.2 (1.5)
G	2nd peak of E_{kinetics} (mJ)	0.6 (0.3)

See Figs. 4 and 5 for the locations of each parameter.

of the downward finger movement. While there existed enough kinetic energy to overcome the keyswitch, work done by the joints was added to ensure the keyswitch was fully pressed.

The results presented illustrate that the closing-type reciprocal motions observed by Jindrich et al. (2004a) originate prior to the contact; they are not solely observed when the fingertip forms a closed kinematic chain with the keyswitch. This early onset of IP extension allows the fingertip to move in such a way to align the fingertip with the motion of the keyswitch. Once contact is made the closed kinematic chain mechanism may further contribute to these IP extensions. As the constraint at the fingertip was removed, the activation of EDC dominated and an opening-type reciprocal motion was observed as expected (Long and Brown, 1964).

The timing of the EMG activities along with the joint movements illustrates that the downswing precedes any extrinsic flexor and intrinsic muscle activity and begins when the extrinsic extensor ceases activity. This observation indicates that the downswing is not initiated by the intrinsic muscles or extrinsic flexors; rather, it must be initiated by passive mechanisms such as gravity or passive muscle forces. Since the palm was supported it is assumed that the wrist could not contribute to the downward movement in this case. The finding that the intrinsic muscles are activated prior to the reciprocal motion by 33 ms also indicates that they initiate reciprocal motions, as hypothesized previously (Long and Brown, 1964). Furthermore, the later co-activation of extrinsic flexors suggests that these muscles serve to overcome the activation force of the keyswitch, which occurs 55 ms after the onset of flexor activity (Dennerlein et al., 1998). They may also control the fast extension of IP joints during the downswing as suggested by Darling and Cole (1990). During the early loading phase, they may add to further IP extension through the closed kinematic chain mechanism. All of these possible behaviors originate from the complex dynamics of the multi-linked system of the finger.

Considering energy profiles showed that the finger movement during a keystroke is not a 'pendulum' type, where the total mechanical energy is conserved and the motion is achieved by the exchange between potential and kinetic energies (Zatsiorsky and Gregor, 2000); rather, the energy created by the joint torques (joint work) substantially contributes to the movements and the completion of the keystroke. The closed-form equations reveal that the dynamic behavior of joint torques before contact is primarily dominated by the inertia (mass) terms. This indicates that in addition to gravity, either passive muscle force or early activation of the intrinsic muscles accelerate the downswing. In addition, joint work begins to increase rapidly at the moment of contact, suggesting that the role of the joint flexors is to do work in order to overcome the resistance of the keyswitch. Joint work also contributes to the potential and kinetic energy during the release of keyswitch. This agrees with the activation pattern of extrinsic extensor and indicates that the role of extrinsic extensor is only to lift the finger but not stop the downward motion of the finger as suggested by Dennerlein et al. (1998).

Several aspects of the study design place our conclusions into a specific context. First, we studied tapping instead of typing. We did this in order to isolate a single finger and a keystroke. The tapping frequency was selected to represent the expected average keystroke frequency of single finger during touch-typing (60 words per minute translates to 6 characters per second, which translates to, on average, each finger completing a keystroke every 1.3 s). In order to simulate the similar mechanics of a keystroke during touch-typing, subjects were instructed to minimize contact time. The kinematics and forces observed were qualitatively consistent with keystroke data reported during touch typing (Dennerlein et al., 1998). So while this average tapping rate provided a good representation of average taps in touch-typing, it did not explore differences in kinematics and kinetics across different tapping frequencies ranging the typical intervals experienced by the right index finger during typing. Along these lines, the primary goal of this study was to examine hypotheses developed from previous motor control research of the finger during typing and tapping. A next logical step is the variation of specific task requirements, such as tapping frequency and keyswitch designs.

Second, the amplitudes of the EMG signals were not normalized to an EMG value associated with a reference contraction (common practice is for the reference contraction to be a maximum voluntary contraction or MVC). This limitation makes it difficult to interpret relationships between EMG amplitude and force across different muscles both within the same subject and across subjects. Third, the MCP joint was assumed to only rotate without translation, given that the palm was supported. The dynamics of the finger, particularly the energy profiles, will be changed if the MCP joint is in fact moving (i.e., during touch-typing and single-finger typing). In addition, the indwelling electrodes and goniometers may have interfered with the movement and resulted in a kinematics pattern that differs from finger movement without these constraints. Finally, the coordination patterns observed in our study were not affected by the movement of other fingers, as they would be in touch-typing.

In summary, we characterized finger tapping on a keyswitch in terms of joint kinetics, kinematics, activation patterns of muscles, and energy profiles. The downswing exhibited a closing-type reciprocal motion, which is attributed to the activation of intrinsic muscles and their role in extension of the IP joints. The extrinsic flexors, which are co-activated with the intrinsic, generate flexion joint torques, and together with the kinetic energy overcome the resistance of the keyswitch.

Appendix. Two-dimensional equations of motion to calculate finger joint torques

Calculation is based on Newton–Euler inverse dynamic for a three-link system; frame $\{x_0, y_0, z_0\}$, $\{x_1, y_1, z_1\}$, $\{x_2, y_2, z_2\}$, $\{x_3, y_3, z_3\}$ are references of level base, proximal phalanx, middle phalanx, and distal phalanx, respectively (Fig. A1).

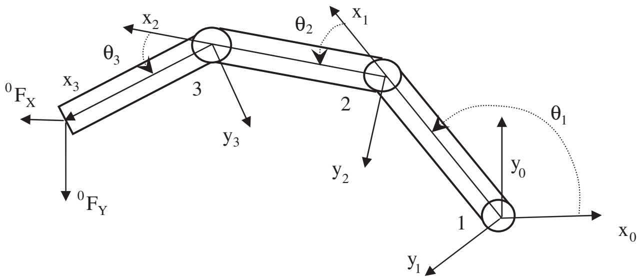

Fig. A1. Schematic representation of a three-link model of finger. Each link has its own reference frame with the x-axis parallel to the lengthwise axis, while the level base frame is anchored to the pivot of link 1. See text for definition of variables.

1. Notation
   (1) Finger segments are approximated by cylindrical tubes with ellipsoid cross sections. ${}^iI_{XX}$, ${}^iI_{YY}$, and ${}^iI_{ZZ}$ represent components of the inertia tensor applied on center of mass of the ith link along x-, y-, and z-axis, respectively, and are expressed by

   $$ {}^iI_{XX} = \tfrac{1}{2}(a_i^2 + b_i^2)m_i, \quad {}^iI_{YY} = \tfrac{1}{6}(3b_i^2 + 4l_i^2)m_i, \quad {}^iI_{ZZ} = \tfrac{1}{6}(3a_i^2 + 4l_i^2)m_i, \tag{A.1} $$

   where a_i, b_i, l_i and m_i denote the half of depth, the half of width, the longitudinal length, and the mass of the ith link, respectively.
   (2) n denotes torque exerted on the joint of each link; ${}^0F_X$ and ${}^0F_Y$ denote the x- and y-axis component of the force exerting on the end of the third link with respect to the base frame $\{x_0, y_0, z_0\}$, respectively.
   (3) Except the force and inertial term, leading superscripts and subscripts identify the reference coordinate system (frame); trailing subscripts indicate which link is referenced to. For example, ${}^1n_1$ represents the joint torque of the first link referenced to frame $\{x_1, y_1, z_1\}$.
   (4) θ denotes the angle of rotation of the $i+1$th link with respect to the ith link.
   (5) c is short for cosine; s is short for sine; thus, $c_1 = \cos\theta_1$, $c_{12} = \cos(\theta_1 + \theta_2)$.
2. Torque of each joint is expressed in terms of mass M, centrifuge R, coriolis C, gravity G, and external force F; namely,

   $$ {}^in_i = M + R + C + G + F. \tag{A.2} $$

3. Torque of the third joint (DIP), ${}^3n_3$, is represented by

   $$ M = \left({}^3I_{ZZ} + \frac{1}{4}m_3l_3^2\right)(\ddot{\theta}_1 + \ddot{\theta}_2 + \ddot{\theta}_3) + \frac{1}{2}m_3l_2l_3c_3(\ddot{\theta}_1 + \ddot{\theta}_2) + \tfrac{1}{2}m_3l_1l_3c_{23}\ddot{\theta}_1, \tag{A.3} $$

   $$ R = \tfrac{1}{2}m_3l_2l_3s_3(\dot{\theta}_1^2 + \dot{\theta}_2^2) + \tfrac{1}{2}m_3l_1l_3s_{23}\dot{\theta}_1^2, \tag{A.4} $$

   $$ C = m_3l_2l_3s_3\dot{\theta}_1\dot{\theta}_2, \tag{A.5} $$

   $$ G = \tfrac{1}{2}m_3l_3c_{123}g, \tag{A.6} $$

$$F = -l_3 s_{123}{}^0F_X + l_3 c_{123}{}^0F_Y. \tag{A.7}$$

4. Torque of the second joint (PIP), ${}^2n_2$, is represented by

$$\begin{aligned} M = &\left({}^3I_{ZZ} + \frac{1}{4}m_3 l_3^2 + \frac{1}{2}m_3 l_2 l_3 c_3\right)(\ddot{\theta}_1 + \ddot{\theta}_2 + \ddot{\theta}_3) \\ &+ \left({}^2I_{ZZ} + \left(\frac{1}{4}m_2 + m_3\right)l_2^2 + \frac{1}{2}m_3 l_2 l_3 c_3\right)(\ddot{\theta}_1 + \ddot{\theta}_2) \\ &+ \left(\left(\frac{1}{2}m_2 + m_3\right)l_1 l_2 c_2 + \frac{1}{2}m_3 l_1 l_3 c_{23}\right)\ddot{\theta}_1, \end{aligned} \tag{A.8}$$

$$\begin{aligned} R = &-\frac{1}{2}m_3 l_2 l_3 s_3(\dot{\theta}_1^2 + \dot{\theta}_2^2 + \dot{\theta}_3^2) + \frac{1}{2}m_3 l_2 l_3 s_3(\dot{\theta}_1^2 + \dot{\theta}_2^2) \\ &+ \left(\left(\frac{1}{2}m_2 + m_3\right)l_1 l_2 s_2 + \frac{1}{2}m_3 l_1 l_3 s_{23}\right)\dot{\theta}_1^2, \end{aligned} \tag{A.9}$$

$$C = -m_3 l_2 l_3 s_3(\dot{\theta}_2\dot{\theta}_3 + \dot{\theta}_3\dot{\theta}_1), \tag{A.10}$$

$$G = \left(\frac{1}{2}m_2 l_2 c_{12} + m_3\left(l_2 c_{12} + \frac{1}{2}l_3 c_{123}\right)\right)g, \tag{A.11}$$

$$F = -(l_2 s_{12} + l_3 s_{123})^0F_X + (l_2 c_{12} + l_3 c_{123})^0F_Y. \tag{A.12}$$

5. Torque of the first joint (MCP), ${}^1n_1$ is represented by

$$\begin{aligned} M = &\left({}^3I_{ZZ} + \frac{1}{2}m_3 l_3\left(l_1 c_{23} + l_2 c_3 + \frac{1}{2}l_3\right)\right)(\ddot{\theta}_1 + \ddot{\theta}_2 + \ddot{\theta}_3) \\ &+ \left({}^2I_{ZZ} + \left(\frac{1}{4}m_2 + m_3\right)l_2^2 + \frac{1}{2}m_3 l_2 l_3 c_3 + \left(\frac{1}{2}m_2 + m_3\right)l_1 l_2 c_2\right) \\ &\times(\ddot{\theta}_1 + \ddot{\theta}_2) + \left({}^1I_{ZZ} + \left(\frac{1}{4}m_1 + m_2 + m_3\right)l_1^2 + \left(\frac{1}{2}m_2 + m_3\right) \right. \\ &\left. \times l_1 l_2 c_2 + \frac{1}{2}m_3 l_1 l_3 c_{23}\right)\ddot{\theta}_1, \end{aligned} \tag{A.13}$$

$$\begin{aligned} R = &-\frac{1}{2}m_3 l_3(l_1 s_{23} + l_2 s_3)(\dot{\theta}_1^2 + \dot{\theta}_2^2 + \dot{\theta}_3^2) \\ &- \left(\left(\frac{1}{2}m_2 + m_3\right)l_1 l_2 s_2 - \frac{1}{2}m_3 l_2 l_3 s_3\right)(\dot{\theta}_1^2 + \dot{\theta}_2^2) \\ &+ \left(\left(\frac{1}{2}m_2 s_2 - m_3 s_3\right)l_1 l_2 + \frac{1}{2}m_3 l_1 l_3 s_{23}\right)\dot{\theta}_1^2, \end{aligned} \tag{A.14}$$

$$\begin{aligned} C = &-m_3 l_1 l_3 s_{23}(\dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_2\dot{\theta}_3 + \dot{\theta}_3\dot{\theta}_1) \\ &- m_3 l_2 l_3 s_3(\dot{\theta}_2\dot{\theta}_3 + \dot{\theta}_3\dot{\theta}_1) - (m_2 + 2m_3)l_1 l_2 s_2\dot{\theta}_1\dot{\theta}_2, \end{aligned} \tag{A.15}$$

$$\begin{aligned} G = &\left(\frac{1}{2}m_1 l_1 c_1 + m_2\left(l_1 c_1 + \frac{1}{2}l_2 c_{12}\right)\right. \\ &\left. + m_3\left(l_1 c_1 + l_2 c_{12} + \frac{1}{2}l_3 c_{123}\right)\right)g, \end{aligned} \tag{A.16}$$

$$F = -(l_1 s_1 + l_2 s_{12} + l_3 s_{123})^0F_X + (l_1 c_1 + l_2 c_{12} + l_3 c_{123})^0F_Y. \tag{A.17}$$

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