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Mechanical properties of the human hand digits: Age-related differences

Jaebum Park [a,b], Nemanja Pažin [c], Jason Friedman [d], Vladimir M. Zatsiorsky [a], Mark L. Latash [a,*]

[a] *Pennsylvania State University, University Park, PA, USA*
[b] *Montana State University, Bozeman, MT, USA*
[c] *University of Belgrade, Belgrade, Serbia*
[d] *Tel Aviv University, Tel Aviv, Israel*

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ABSTRACT

Background: Mechanical properties of human digits may have significant implications for the hand function. We quantified several mechanical characteristics of individual digits in young and older adults.
Methods: Digit tip friction was measured at several normal force values using a method of induced relative motion between the digit tip and the object surface. A modified quick-release paradigm was used to estimate digit apparent stiffness, damping, and inertial parameters. The subjects grasped a vertical handle instrumented with force/moment sensors using a prismatic grasp with four digits; the handle was fixed to the table. Unexpectedly, one of the sensors yielded leading to a quick displacement of the corresponding digit. A second-order, linear model was used to fit the force/displacement data.
Findings: Friction of the digit pads was significantly lower in older adults. The apparent stiffness coefficient values were higher while the damping coefficients were lower in older adults leading to lower damping ratio. The damping ratio was above unity for most data in young adults and below unity for older adults. Quick release of a digit led to force changes in other digits of the hand, likely due to inertial hand properties. These phenomena of "mechanical enslaving" were smaller in older adults although no significant difference was found in the inertial parameter in the two groups.
Interpretations: The decreased friction and damping ratio present challenges for the control of everyday prehensile tasks. They may lead to excessive digit forces and low stability of the grasped object.

1. Introduction

Age-related changes within the neuromotor system (reviewed in Cole et al., 1999; Grabiner and Enoka, 1995) affect a variety of activities of daily living including prehensile tasks (Francis and Spirduso, 2000; Olafsdottir et al., 2008; Parikh and Cole, 2012; Rantanen et al., 1999; Shim et al., 2004). These behavioral changes may get contributions from changes both within the central nervous system and in mechanical characteristics of the digits. In particular, healthy aging is known to be associated with a significant decrease in the friction coefficient between the digit tips and surfaces of typical grasped objects; this factor has been discussed as a contributor to the higher grip forces typical of older adults (Cole, 1991; Cole et al., 1999; Gorniak et al., 2011).

Changes in mechanical properties of the digits may contribute to safety and stability of prehensile actions. In a first approximation, we consider each digit tip as a point object that can be characterized by such parameters as mass, apparent stiffness, and damping with a clear understanding that estimates of these parameters reflect properties of more proximal portions of the digits and the involved muscles.

We used two newly developed devices in the experiments. The earlier described device (Savescu et al., 2008) was used for estimation of the friction coefficient, which was expected to be lower in older subjects across all five hand digits (Hypothesis 1). The other device involved a handle equipped with spring-loaded force sensors that could be engaged and disengaged during steady-state normal force production leading to a quick, small-amplitude unloading of one of the digits. We used the recorded changes in the digit tip force and trajectory to compute its effective mass, apparent stiffness, and damping. Further, we computed the damping ratio. We expected the ratio to be smaller in older subjects (Hypothesis 2).

Despite the fact that only one digit was unloaded in each trial, we observed nearly instantaneous changes in the forces produced by the other digits involved in the task. These changes were not small and resembled the well-known phenomena of finger enslaving (lack of individuation; Kilbreath and Gandevia, 1994; Zatsiorsky et al., 2000). Older adults have been described as having lower enslaving expressed in percent to the maximal force-generation capability of the fingers (Kapur et al., 2010; Shinohara et al., 2003). Based on those studies, we expected the new phenomenon (we call it "mechanical enslaving",

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* Corresponding author at: Department of Kinesiology, Rec.Hall-268N, The Pennsylvania State University, University Park, PA 16802, USA.
E-mail address: mll11@psu.edu (M.L. Latash).

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ME) to follow the same pattern, that is, show proportionally smaller effects in the older group (Hypothesis 3).

2. Methods

2.1. Subjects

Ten healthy elderly subjects and ten healthy young subjects (age: mean = 76.1, SD = 5.6 years for the elderly; mean = 26.9, SD = 4.9 years for the young; 5 females in each group) were recruited. All subjects were right-handed determined by the Edinburgh Handedness Inventory (Oldfield 1971). None of the subjects had a previous history of neuropathies or traumas to their upper extremities. The elderly participants were screened with a cognition test (mini-mental status exam $\geq$ 24 points), a depression test (Beck depression inventory $\leq$ 20 points), a quantitative sensory test (monofilaments $\leq$ 3.22), and a general neurological examination. Prior to the experiment, the subjects signed a consent form approved by the Office for Research Protection of the University.

2.2. Equipment

2.2.1. The handle with yielding sensors

A handle was designed to provide a quick, low-amplitude release of a digit producing a pressing force on one of the four force/moment sensors. The subjects grasped the handle with three fingers in opposition to the thumb (Fig. 1B). The digit combinations were '*Thumb–Index–Middle–Ring*' (*TIMR*) or '*Thumb–Middle–Ring–Little*' (*TMRL*). The handle was fixed to the immovable table, and four miniature force sensors (Nano-17, ATI Industrial Automation, Garner, NC, USA) were used to measure forces exerted by the digits. The force signals were digitized using a 16-bit A/D converter (PCI-6225, National Instruments, Austin, TX, USA) and a customized LabVIEW program at 500 Hz. The force sensors were connected to a rod (Fig. 1C), which was screwed into an electromagnet. The rod passed through a circular hole in a circular disc, made of a ferromagnetic material. A compression linear spring was placed between the force sensor and the ferromagnetic disc. The force sensor and the rod were effectively rigid when the electromagnet was turned on. Turning the electromagnet off caused the force sensor to yield resulting in a quick (<40 ms), low-amplitude (<10 mm) translational motion of the sensor and the corresponding digit. The spring between the sensor and the disc was compressed providing resistive force. As a result, the digit stopped in a new equilibrium position. The electromagnet was turned-off unexpectedly for the subject at a time defined by the experimenter. After each trial, the electromagnet was reloaded.

A three-dimensional (3D) motion capture system with three cameras (ProReflex MCU 240, Qualisys AB, Sweden) was used to capture the 3D coordinates of the fingertips at 240 Hz. Reflective markers (5 mm in diameter) were placed on the centers of the fingertips (Fig. 1A). Before each trial, the force transducer signals were set at zero and the force and motion capture recordings were synchronized using the LabVIEW program.

2.2.2. The setup for friction coefficient estimation

The device was designed to measure digit downward force (normal force) and shear force (tangential force) simultaneously while the force sensor was moved horizontally by a linear motor with respect to the digit (Fig. 2; see Savescu et al., 2008). A multi-axis force sensor (Nano-25, ATI Industrial Automation, Garner, NC, USA) was attached to the frame to measure the normal and tangential forces. The top of the sensor (25 mm in diameter) was covered with 320-grit sandpaper. Forearm and wrist movement was prevented by Velcro straps, while a wooden piece placed underneath the subject's palm ensured a constant hand and finger configuration. The sampling frequency of the force sensor was 500 Hz, and the motor speed was 6 mm/s. Before each trial, all sensor signals were set to zero with the task-digit on the sensor and the hand relaxed; the sensor recorded only active downward force during the data acquisition.

2.3. Experimental procedures

Subjects washed their hands with soap and wiped the fingertips with alcohol to normalize the skin condition. After the 10–20 min orientation session, the subjects sat in a chair facing the 19 LCD screen, which provided force feedback. The entire experiment including orientation and main sessions for each subject lasted approximately 1 h.

2.3.1. Maximal voluntary contraction (MVC) tasks

The MVC forces of the right-hand digits were measured using the handle. Subjects were instructed to grasp the handle (Fig. 1B) with the four digits together and produce maximal total gripping force in a self-paced manner within 8 s. The subjects were instructed to relax immediately after reaching a maximal level of force. Two trials were given to subjects for each of the two digit combinations (*TIMR* and *TMRL*). Further, the trial with higher MVC_{TOT} was selected, and the forces of individual digits (MVC_i; $i = T,I,M,R,L$) at the time of reaching MVC_{TOT} were used to set the next tasks.

2.3.2. Trials with the handle with yielding sensors

There were fifteen conditions: 5 target digits (*Thumb*, *Index*, *Middle*, *Ring*, and *Little*) × 3 steady-state force levels (15, 30, and 45% of MVC_i). For each condition, the subjects were required to grasp the handle naturally and then to produce a prescribed steady-state force level for about 5 s. The feedback was provided on the target digit force only, but the subjects did not know this. The normal force (along z-axis in Fig. 1A) of the target digit was displayed in %MVC on the computer screen. At a random time, which was uniformly distributed between 5 and 8 s, the electromagnet holding the target digit was turned off, causing the digit to move into flexion. The displacement of the digit tip along z-axis was approximately 5–10 mm. The perturbation caused the target digit normal force to drop. The subjects performed three attempts for each perturbation condition, and the order of target digit (5 levels) and %MVC (3 levels) combinations was randomized.

2.3.3. Trials for friction coefficient estimation

There were fifteen experimental conditions: Five digits (*Thumb*, *Index*, *Middle*, *Ring*, and *Little*) × three normal force levels (15, 30, 45% of MVC_i). Each trial was 10-s long. The subjects were instructed to press on the sensor with one of the digits and match the given %MVC level as accurately as possible within the first 5 s. Then, the experimenter turned the linear motor on. The subjects were required to keep the steady level of normal force against the horizontal motion of the sensor ($-y$ direction in Fig. 2) without moving the hand/digits within the next 5 s. If the deviation of the normal force from the target level exceeded 10% for more than 1.5 s, the subject repeated the trial. The tip of instructed digit and the sensor surface were wiped with alcohol at the end of each trial to regulate the moisture level at the fingertip and contact surface. Each subject performed three consecutive trials for each digit and force level in a randomized order.

2.4. Data analysis

Data processing was performed using customized software written in Matlab (The MathWorks, Natick, MA, USA). The digit tip force and displacement data were digitally low-pass filtered with a zero-lag, 4th-order Butterworth filter at 200 Hz. The force data were down-sampled to 240 Hz to match the frequency of the motion capture system.