Journal of Biomechanics 48 (2015) 672–680

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Digit mechanics in relation to endpoint compliance during precision pinch

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ARTICLE INFO

Article history:
Accepted 18 December 2014

Keywords:
Hand
Pinch
Compliance
Joint
Mechanics

ABSTRACT

This study investigates the mechanics of the thumb and index finger in relation to compliant endpoint forces during precision pinch. The objective was to gain insight into how individuals modulate motor output at the digit endpoints and joints according to compliance-related sensory feedback across the digits. Thirteen able-bodied subjects performed precision pinch upon elastic resistance bands of a customized apparatus instrumented with six degree-of-freedom load-cells. Compliance levels were discretely adjusted according to the number of bands connected. Subjects were provided visual feedback to control the rate of force application. Fifteen repetitions of low-to-moderate force (<20 N) pinches were analyzed at each of five compliance levels, during which force and motion data were collected. Joint angles and moments normalized by pinch force magnitude were computed. Second-order polynomials were used to characterize joint mechanics as a function of compliance. The joint degrees-of-freedom (DOFs) at the finger showed greater dependence on compliance for angular position while the thumb joint DOFs demonstrated greater dependence for normalized joint moment. The digits also adjusted coordination of their endpoint forces according to compliance. Overall, the finger may be altering its position to increase load to the joints of the thumb with changing compliance. These findings describe naturally emergent changes in digit mechanics for compliant precision pinch, which involves motor execution in response to endpoint sensory feedback. Identifying and understanding these motor patterns may provide theoretical basis for restoring and rehabilitating sensorimotor pathologies of the hand.

1. Introduction

Precision pinch is a fundamental action in executing various activities of daily living. It involves fine and dexterous manipulation of smaller objects utilizing the thumb and index finger. To ensure secure pinch grasp, the mechanics associated with these digits depend on physical properties of the object. While properties such as object shape and size (Vigouroux et al., 2011) can be registered visually, the compliance of the object is typically discriminated upon tactile interaction and functional manipulation (Annaswamy and Srinivasan, 1990; Tiest and Kappers, 2009). Thus, pathological afflictions to sensation at the fingertips are commonly associated with functional clumsiness (Keith et al., 2009). Therefore, assessing the biomechanics of precision pinch as a function of compliance may help identify mechanical behaviors of the digits that are hallmarks in natural hand sensorimotor function. With this understanding, better paradigms for clinical treatment and rehabilitation may be formulated for restoring natural grasp.

Previous studies have examined the joint mechanics associated with precision pinch in response to object properties including size, shape, contact location, and surface friction (Chao et al., 1976; Cadoret and Smith, 1996; Schettino et al., 2003; Domalain et al., 2008; Vigouroux et al., 2011). These properties contribute to mechanical constraints to be satisfied for successful object manipulation. Compliance in relation to hand function has largely been studied for developing advanced hand controllers to mimic the digit-pads (Michelman and Allen, 1993; Kao et al., 1997; Al-Gallaf, 2006; He et al., 2013), the ability of humans to accurately discriminate compliance in psychomotor experiments (Tan et al., 1995), and stability evaluation using buckling springs (Valero-Cuevas et al., 2003). However, the role of object compliance in mediating the

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http://dx.doi.org/10.1016/j.jbiomech.2014.12.040
0021-9290/

naturally-emergent mechanics of the thumb and index finger during precision pinch has not yet been well studied.

This study examines changes in digit mechanics as a function of compliance during precision pinch. *Compliance* was defined as the property allowing the digits to displace the surface in proportion to grasp force. Executing compliant pinch requires the sensorimotor system to integrate sensation and proprioception with motor function. Compliance is discriminated not only according to mechanoreceptors at the digit pads, but also force information transmitted through golgi organs and muscle spindles as the pinching surfaces are displaced. We hypothesized that the digits will exhibit motor behaviors that are quantifiably dependent on surface compliance. To characterize changes across the digit linkages, traditional biomechanical metrics of joint angles and moments were analyzed. To evaluate mechanical adjustments at the endpoint interface between each digit and respective touch-surface, metrics describing relative changes in the endpoint force vector magnitude and direction, such as force coordination angle (Li et al., 2013), were examined. The angle between the digit endpoint force vectors indicates how the thumb and index finger modulate the force directions relative to one another to accomplish the specified pinch task. Understanding these motor patterns may provide a foundation for advanced designs of rehabilitation paradigms for precision pinch grasp.

A novel pinch apparatus with six degrees-of-freedom (DOFs) load-cells and suspension elastic bands was developed to apply resistive force onto each digit-pad proportional to the "interpad distance" (i.e., space between the thumb and index finger pads) during loaded precision-pinch grasp. Force and motion data were collected for offline determination of joint angles and endpoint force magnitudes and locations. A musculoskeletal model was then used to compute corresponding changes in joint moments as functions of endpoint compliance.

2. Methods

2.1. Subject

Thirteen right-handed healthy subjects, aged 31.2 ± 6.3 years with maximum pinch aperture of 18.0 ± 1.0 cm, participated in this study. All subjects were male to remove possible gender effects. Subjects had normal or corrected-to-normal vision and did not report or demonstrate indications of disease, injury, or complications involving the hand or wrist. All participants signed an informed consent approved by the Institutional Review Board.

2.2. Collection of marker position data for digit kinematics

A set of retro-reflective markers (Nataraj and Li, 2013a) (Fig. 1**A**) were affixed to the surface of the right hand to obtain digit kinematics. A motion capture system (Vicon Inc., Oxford, UK) measured the 3D position of each marker at 100 Hz. A nail marker-cluster on each distal phalanx defines the position and orientation of each distal digit segment (Shen et al., 2012) (Fig. 1**B**). Another marker-cluster (H1, H2, and H3) on the second metacarpal served as a local hand reference coordinate system following ISB convention (Wu et al., 2008). Additional markers were placed on the thumb proximal phalange (TM1, TM2), first metacarpal (TP1, TP2), index middle phalange (IM1, IM2), and index proximal phalange (IP1, IP2).

2.3. Computation of joint angles

Subjects performed digit motion trials to identify functional joint centers of rotation as described in (Nataraj and Li, 2013a). Joint centers were identified for the interphalangeal (T-IP), metacarpophalangeal (T-MCP), and carpometacarpal (T-CMC) joints of the thumb and the distal interphalangeal (I-DIP), proximal interphalangeal (I-PIP), and metacarpophalangeal (I-MCP) joints of the finger (Fig. 1**C**). Using the markers and referenced joint center locations, a coordinate system was defined and aligned for each digit segment as described in (Nataraj and Li, 2013a). The X-Y-Z rotation axes corresponded to anatomical bi-directional DOFs for flexion(+), abduction(+), and internal axial rotation(+), respectively, and joint angles were computed as order-dependent (X-Y-Z) Euler angles between aligned coordinates systems of adjacent segments. Thumb and finger digits had DOFs defined at each joint as follows: T-IP=flexion; T-MCP=flexion, abduction; T-CMC=flexion, abduction, rotation; I-DIP=flexion; I-PIP=flexion; I-MCP=flexion, abduction (Gonzalez et al., 2005).

2.4. Pinch apparatus

A customized pinch device was constructed to interface with elastic bands (McMaster-Carr® natural rubber bands, 7″L x 5/8″W) that provide the compliance-based resistance during pinching (Fig. 2**A**). The apparatus was instrumented with 6-DOF load-cells (Mini40, ATI Industrial Automation, Apex, NC, USA). The initial pinch span was adjusted to equal 10 cm, which was 50–60% of the maximum pinch aperture for all subjects. We deemed this aperture range sufficiently small to obviate the need to re-adjust the initial pinch span for each subject. Subjects initially placed the thumb and index finger on small, plastic washers located at the center of the lateral side of each respective set of bands. To apply increasing pinch force upon the bands, subjects would bring the thumb and index finger towards one another as if to execute pinching grasp. Compliance levels were adjusted according to the equal number of parallel elastic bands affixed to each side of the pinch device. The aforementioned elastic bands and mode of affixation facilitated examination of compliance levels that ranged from low to moderate pinch forces that should be readily exerted by most able-bodied adults. Since the bottom-ends of the bands were screw-fixed, bands were added or removed easily by securing the top-ends to the device with a fastener-clip. The top-ends of the desired number of bands were initially held by the experimenter and pulled vertically a predetermined distance to create desired tension based on a predetermined visual marking on the bands to match with the top of the apparatus. The portions of bands above the marking were then laid over the apparatus, while maintaining tension, and then fastened. In this study, up to five elastic bands were utilized on each side.

2.5. Data collection protocol

Each subject was seated facing a monitor-screen providing visual feedback of the pinch force applied to the bands of the apparatus, which was affixed to the mounting table and aligned at a 45° offset to the subject and monitor (Fig. 2**B**). The screen showed a fixed yellow ramp profile along with a dynamic red force-trace indicating the pinch force being applied upon the bands along the "normal" axis of the of the apparatus coordinate system (Fig. 2**C**). A customized LabView® (National Instruments, Austin, TX, USA) program was developed to collect the force signals and provide visual presentation of the force-trace superimposed upon the test-ramp.

At initial rest (Fig. 3**A**), the subject placed their forearm on the table aligned parallel to a line connecting the subject and monitor with the hand 15 cm away from the apparatus. The hand is ulnar-side down with the thumb and finger lightly in contact and the three other digits comfortably curled into the palm. Each pinch trial began with presentation of a force-ramp profile onto the screen and audible "go" command. The subject would then move the hand from rest to lightly contact the digits with the bands without deflection within three seconds (Fig. 3**B**). Three seconds following trial commencement, the subject steadily brought the thumb and finger together to apply increasing pinch force and visually match the moving force-trace against the static ramp to the best of the subject's ability (Fig. 3**C**). The peak of the ramp corresponds to the subject having an interpad distance of approximately 4 cm. The ramp duration was three seconds for all trials, which was deemed to be a "slow" pinch and comfortable for subjects to perform without strain or fatigue across all compliance test levels. Each band approximately added 0.8 N of resistive force per centimeter of interpad displacement. Once the force-trace passed the ramp peak, subjects returned the hand to the resting position to complete the trial (Fig. 3**D**). Each subject executed five blocks of pinch trials, one at each compliance level. Fifteen pinch trials were repeated for each block with brief rest between consecutive trials. Trial blocks were presented randomly.

2.6. Additional computations and analysis

Following data collection of all marker and force data and aforementioned computation of joint angle kinematics, additional analyses were necessary to characterize the endpoint force vector data for subsequent computation of joint moments and relative directional coordination of digit forces. The effective location (x,y) where the measured 3-D force vector passes the X-Y plane, parallel to 45-degree offset from sagittal plane of subject, of the respective local sensor coordinate system (Fig. 2) was computed as follows:

$$x = \frac{-M_y}{F_z}, \quad y = \frac{-M_x}{F_z}$$

Transformations were applied to relate the sensor-measured 3-D force vector to the endpoint force applied by each digit expressed in the coordinates local to the distal segment of that digit (Nataraj and Li, 2013b). The joint kinematics (angles, angular velocities, and angular accelerations) and the endpoint forces were then used as inputs to an inverse dynamics solver for a musculoskeletal model of the hand developed in SIMM® (Musculographics Inc., Santa Rosa, CA, USA) to determine the joint moments required to generate those given inputs. The interpad distance was computed based on