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Digit mechanics in relation to endpoint compliance during precision pinch

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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.

Keywords

hand; pinch; compliance; joint; mechanics

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5 Conflict of Interest

The authors have no conflicts of interest to disclose.

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 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 via 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

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.

Collection of Marker Position Data for Digit Kinematics

A set of retro-reflective markers (Nataraj and Li 2013a) (**Figure 1A**) 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) (**Figure 1B**). 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 phalanx (TM1, TM2), first metacarpal (TP1, TP2), index middle phalanx (IM1, IM2), and index proximal phalanx (IP1, IP2).

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 (**Figure 1C**). 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).

Pinch Apparatus

A customized pinch device was constructed to interface with elastic bands (McMaster-Carr® natural rubber bands, $7''L \times 5/8''W$) that provide the compliance-based resistance during pinching (**Figure 2A**). 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.

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 (**Figure 2B**). 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 (**Figure 2C**). 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 (**Figure 3A**), 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 (**Figure 3B**). 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 (**Figure 3C**). The peak of the ramp corresponds to the subject having an interpad distance of approximately 4 cm. The ramp durations 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 (**Figure 3D**). 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.

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 (**Figure 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 the nail marker-clusters attached to the digits (Nataraj et al. 2014a). To avoid considering the variability at initial pinch and final pinch-release, only data collected between the “target” range of 25-75% the pinch-force ramp were analyzed. This target range was selected based on experimenter observations from pilot data to consistently capture a linear profile. Thus, the smallest and largest pinch forces analyzed across all compliance levels in this study was 1.2N and 18N, respectively.

The force coordination angle (FCA) was computed as the angle between the 3-D force vectors of the thumb (F_T) and index finger (F_I) during precision pinch (Li et al. 2013):

$$FCA = \cos^{-1} \left(\frac{F_T \bullet F_I}{\|F_T\| \|F_I\|} \right)$$

The Pearson's coefficient was utilized to assess correlation between the fitted polynomial model and the experimentally-observed data points for each variable of interest. After confirming normality using the Kolmogorov-Smirnov test, the one-sample t-test was applied to test for non-zero values at significance $p=0.05$. When comparing across digits, the unpaired two-sample t-test was applied at significance $p=0.05$.

3 Results

Within the target range of the force ramps, the applied forces demonstrated highly linear results as desired, confirming the robustness of the apparatus and subject ability to perform the experimental task (**Figure 4**). Linear regression ($y = mx + b$) was applied where y =pinch force (N), x =interpad distance (cm), and m and b are slope and bias/offset

parameters, respectively. The regression showed high coefficient of determination ($R^2 > 0.99$) for all five compliance levels. For the baseline case of 1 band, slope (m_{base}) and offset (b_{base}) were -0.81 N/cm and $+8.0$ N, respectively. Methodological robustness was demonstrated as fitted slope and offset for the remaining cases were within 3% of their respective values predicted from baseline, i.e., $NB \cdot m_{base}$ and $NB \cdot b_{base}$, where NB=number of bands. The slope and offset results with each compliance level was within 3% of the respective baseline prediction. All regression parameters were non-zero and significant ($p < 0.001$).

Mean forces applied by each digit in each directional-component against interpad distance are shown in **Figure 5A/B**. The total pinch force is expressed as the sum of the magnitudes of the 3D force vectors of both digits (**Figure 5C**). Relative contributions of the thumb (49.3%) and finger (50.7%) to total pinch force were nearly equal. However, the contribution of finger normal force to total pinch force was significantly greater than that of the thumb (index 36.0% > thumb 31.7%; $p < 0.05$). Furthermore, the index finger was functionally more efficient by exerting more force in the normal direction (71.0%), which was desirable to the specified task, compared to only 64.3% by the thumb ($p < 0.05$). For both digits, the off-normal axis along which greater relative forces were exerted was the proximal axis ($p < 0.01$), but in opposite directions.

A second-order polynomial model was applied to the FCA data at each compliance level (**Figure 6**). Utilizing this simple model for detecting non-linear dependence of FCA, a strong correlation ($R > 0.97$) was observed between model and data points at compliance levels involving two or more resistance bands. At one band, the correlation was relatively low ($R < 0.40$), suggesting that a compliance threshold between one and two bands has been exceeded to produce a smoother application of FCA across the target force range. Additionally, a significant non-zero linear trend (slope = $1.25 \pm 1.35^\circ/\text{band}$, $p < 0.01$) is observed in mean value of FCA across compliance levels.

Mean and range values for joint angles at each compliance level are shown in **Figure 7**. Mean values are from neutral (i.e., 0°) to indicate absolute posture information from an invariant anatomical reference, and range values indicate excursions from the initial grip posture at rest. The largest ($>20^\circ$) offsets in mean values occur at the DOFs of Index-MCP (flexion) and Thumb-CMC (flexion, rotation). The offsets for these joint-DOFs were also all significantly different from zero ($p < 0.01$). Similarly, the largest ($>5^\circ$) excursions in range also occurred at the DOFs of Index-MCP (flexion, abduction) and Thumb-CMC (flexion, rotation), and were significantly different from zero ($p < 0.01$). The 2nd-order polynomial models for these joint angle profiles showed good correlations ($R > 0.9$) for all cases except mean for Thumb-IP flexion ($R = 0.72$) and range for Thumb-CMC flexion ($R = 0.87$).

After normalizing by the applied pinch force, mean and range (M&R) values of joint moments (**Figure 8**) were relatively large (>3 N-cm/N) for all DOFs *except* Thumb-CMC (abduction) M&R, Index-MCP (abduction) M&R, Index-DIP (flexion) M&R, Index-MCP (flexion) range, and Index-PIP (flexion) range. Relative to all other joint-DOFs ($p < 0.05$), the greatest M&R values were observed at Thumb-CMC (flexion, rotation) and Index-MCP (flexion). It was observed that the M&R values for *all* normalized joint moments across both

digits move towards zero with decreasing compliance (i.e., increasing number of resistance bands). The 2nd-order polynomials to model joint moment profiles, exhibited high correlation ($R>0.99$) for all cases.

Mean parameter values for 2nd-order polynomial models for observed joint data (angles, moments) across subjects as a function of compliance level are listed in **Table 1**. Significance as a non-zero value for each parameter is also shown and indicates existence of a non-zero bias (p_o), linear dependence (p_l), and non-linear dependence (p_2) in relation to compliance level. All three parameters for both M&R values of normalized joint moments were significant for all joints ($p<0.05$) except Thumb-CMC abduction mean. Typically, only non-zero bias parameters were significant for joint angle data except mean Thumb-MCP (flexion, abduction) and Thumb-IP (flexion). When observing the mean of absolute parameter values across all DOFs for each digit, the finger exhibited greater values than the thumb for joint angle measures while the thumb DOFs were greater for joint moment measures whenever significant differences ($p<0.05$) existed. Across both digits, the DOFs having greatest parameter values, thereby greatest dependence on compliance, were associated with the Thumb-CMC joint. For the finger, the joint DOFs with greatest compliance dependence were at the Index-MCP joint.

A 100-point data set interpolating between compliance levels 0 and 5 was used as input to the 2nd order polynomial models for joint moments. The covariance matrix for the resultant model output data with each joint moment serving as an observed variable is shown in **Table 2**. The largest positive and negative variance values are associated with the joint-DOFs of Thumb-CMC flexion and Thumb-CMC rotation.

4 Discussion

We examined the mechanics (joint angles/moments, endpoint force vectors) at the thumb and index finger as a function of endpoint compliance during precision pinch. Robust procedures were applied for joint identification, anatomical alignment of segment-affixed coordinate systems, transforming force and motion data to a common coordinate system, musculoskeletal model computation of joint moments, and implementation of a novel pinch apparatus. Specific patterns in digit mechanics were apparent functions of endpoint compliance, suggesting that digits are sensitive in making mechanical adjustments according to sensed compliance. Since the maximum pinch forces within target ranges for analysis (<20 N) were well below able-bodied maximums (57.2 N, Nataraj, et al. 2014b), these adjustments were not necessarily due to mechanical constraints, but rather naturally emergent and self-selected behaviors.

The main findings of this study involve how each digit applied force and modulated joint mechanics against the presented endpoint compliance. While the thumb and index finger applied near equal total loading, the index finger produced more load in the normal direction, which was functionally specific to the experimental task. Greater total loading has been shown for the index finger than thumb during “static” precision pinch against a rigid surface (Li et al. 2013), but the task-specific load in the normal direction was approximately equal. Our study suggests the index finger produces greater task-specific loading under

compliant conditions. Specifically, with compliance, the index finger is not motion constrained by the rigid surface and is able to rely on force sensation to identify and more efficiently apply load in the desired normal direction. The ability of the finger to physically orient itself in a coordinated manner may stem from the dependence of tip-pinch manipulability on posture of the finger (Yokogawa and Hara 2004) along with natural anatomy of the finger to produce flexion movements along the pinch plane.

The applied force vectors of the pinching digits were nearly in direct *opposition* (FCA=180°) across all compliance levels; however, a significant trend towards higher FCA with lower compliance was observed. The mean FCA was >160° and significantly greater ($p<0.05$) at all compliance levels than the asymptotic maximum value of 156° reported for precision pinch against a rigid surface (Li et al. 2013). Thus, with a compliant endpoint, there appears propensity for the digits to direct their respective force vectors more in opposition compared to static precision pinch. Despite this clear distinction in FCA between compliant and non-compliant conditions, this study shows a similar trend of increasing FCA with increasing force. These observations indicate that, under compliant conditions, the sensorimotor system utilizes stronger force cue to augment task-specific performance as measured by FCA. However, when the surface is rigid, the digits do not as readily adjust their net grip-force pattern towards better opposition as digits cannot continually change postures to this end. This suggests the digits can, with compliance, better utilize their proprioception with force sensation to better naturally direct their grip forces. Grip force patterns can be modulated against rigid surfaces even with sensorimotor dysfunction (Seo et al. 2010; Kutch and Valero-Cuevas 2011). Compliant grip, however, may make available additional sensory cues to enhance task performance of matching the normal-force profile. These cues may emanate from online regulation of the covariance in decreasing grip aperture with transient force buildup across the moving digits.

Since the highest compliance level tested (i.e., one resistance band), the changes in FCA with increasing force did not show a smooth profile compared to lower compliance levels, a modicum of endpoint resistance may be needed to stabilize coordination of the digit force vectors. The presented experimental methodology better allowed subjects to generate a self-selected motor control pattern to emerge against a given compliance level since only matching a target force was required. This differs from paradigms requiring subjects to also balance an object as a functional co-constraint in addition to applying increasing force (Valero-Cuevas et al. 2003). In this study, maximum ramp forces were chosen to be low-to-moderate, consistent with low-force tasks common to precision pinch grip such as buttoning, writing, and using utensils (Levine et al. 1993).

While the postures assumed by the digits against changing compliance involved small angular changes (<5°) at most joints, the bias (p_o) parameters for joint angle ranges at all DOFs for both digits indicate notable angular excursions. Since the largest M&R values for angles were observed at Index-MCP and Thumb-CMC joints, these joints are clear motion-drivers for the digits during compliant precision pinch. Bringing together the digit tips could be accomplished with an alternative strategy of minimal excursions at these proximal joints while producing notably greater flexion at Index-PIP and Thumb-IP. While this alternate motion pattern may have transpired anecdotally, the overall trends observed in this study

clearly indicate utilization of Index-MCP and Thumb-CMC to produce the necessary excursions at the tips against endpoint resistance. The other joints may serve to follow and support the actions of these proximal joints while maintaining a stable posture regardless of compliance level. Motion-driving from these proximal joints may result from the naturally larger effective moment arms relative to the endpoint force to better facilitate adjustments that efficiently distribute joint moment loads across both digits.

Joint moments were normalized according to the endpoint force magnitude to remove the proportional scaling of larger joint moments with larger endpoint forces and isolate changes due to compliance. Larger normalized joint moments for the thumb compared to the finger were observable across all compliance levels. This suggests that during compliant pinch, grip is regularly oriented to more greatly load thumb joints. The largest variances for joint moment range values occurring at the CMC joint corroborate this notion. The finger may orient itself to exhibit shorter moment arms at its active joint DOFs by not only more greatly shifting load to the thumb joints but also to the passive DOFs of its own joints. Specifically, finger joint loads appear to be distributed to DOFs which are effectively constrained and not modeled for this digit (e.g., axial rotation). This pinch-control strategy may be explained by musculature spanning the thumb joints being relatively strong (Li et al. 2005) and more capable of generating forces necessary to support sustained compliant pinch grip. The clear trend towards zero in both mean and range of normalized moments across *all* joints with decreasing endpoint compliance may also be indicative of compensations towards efficiency.

This study identified mechanical hallmarks of the digits during precision pinch against compliant loading with the following primary implications:

- The index finger may be modulating angular position with changes in compliance to better orient its force loading in the normal direction and ensure the thumb generates relatively greater joint moments.
- Both digits appear to adjust coordination of their endpoint force vectors as a function of compliance, and do so more effectively than against rigid surfaces.
- Improved functional performance with compliant grip may be due to fewer motion constraints on the digits, thereby providing more ability to make online postural adjustments and additional sensory cues associated with motions against compliant loading.

Compliant pinch is a high-level dexterous motor task that involves dynamic co-modulation of proportionally increasing endpoint loads against decreasing pinch span between the thumb and index finger. Identifying key patterns in regulating precision pinch grip against a compliant surface may provide bio-inspired bases for rehabilitation and robotics applications for restoring hand function. Understanding the unique role of each digit in executing the task and how they coordinate their actions may provide insight into how to target rehabilitation therapies or design prostheses that replicate natural patterns of hand function.

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7 References

- Al-Gallaf EA. Multi-fingered robot hand optimal task force distribution - Neural inverse kinematics approach. *Robot Auton Syst.* 2006; 54:34–51.
- Annaswamy, AM.; Srinivasan, MA. Manipulation of Compliant Objects with Compliant Fingerpads - Identification and Control Issues. *Proceedings of the 29th IEEE Conference on Decision and Control*; 1990. p. 1966-1967.
- Cadoret G, Smith AM. Friction, not texture, dictates grip forces used during object manipulation. *J Neurophysiol.* 1996; 75:1963–1969. [PubMed: 8734595]
- Chao EY, Opgrande JD, Axmear FE. Three-dimensional force analysis of finger joints in selected isometric hand functions. *J Biomech.* 1976; 9:387–396. [PubMed: 932052]
- Domalain M, Vigouroux L, Danion F, Sevez V, Berton E. Effect of object width on precision grip force and finger posture. *Ergonomics.* 2008; 51:1441–1453. [PubMed: 18802824]
- Gonzalez MH, Mohan V, Elhassan B, Amirouche F. Biomechanics of the Digit. *J Am Soc Surg Hand.* 2005; 5:13.
- He X, Du YF, Lan N. Evaluation of Feedforward and Feedback Contributions to Hand Stiffness and Variability in Multijoint Arm Control. *Ieee T Neur Sys Reh.* 2013; 21:634–647.
- Kao I, Cutkosky MR, Johansson RS. Robotic stiffness control and calibration as applied to human grasping tasks. *Ieee T Robotic Autom.* 1997; 13:557–566.
- Keith MW, Masear V, Chung K, Maupin K, Andary M, Amadio PC, Barth RW, Watters WC 3rd, Goldberg MJ, Haralson RH 3rd, Turkelson CM, Wies JL. Diagnosis of carpal tunnel syndrome. *J Am Acad Orthop Surg.* 2009; 17:389–396. [PubMed: 19474448]
- Kutch JJ, Valero-Cuevas FJ. Muscle redundancy does not imply robustness to muscle dysfunction. *J Biomech.* 2011; 44:1264–1270. [PubMed: 21420091]
- Levine DW, Simmons BP, Koris MJ, Daltroy LH, Hohl GG, Fossel AH, Katz JN. A self-administered questionnaire for the assessment of severity of symptoms and functional status in carpal tunnel syndrome. *J Bone Joint Surg Am.* 1993; 75:1585–1592. [PubMed: 8245050]
- Li K, Nataraj R, Marquardt TL, Li ZM. Directional coordination of thumb and finger forces during precision pinch. *PLoS One.* 2013; 8:e79400. [PubMed: 24236128]
- Li ZM, Harkness DA, Goitz RJ. Thumb strength affected by carpal tunnel syndrome. *Clin Orthop Relat Res.* 2005; 441:320–326. [PubMed: 16331021]
- Michelman, P.; Allen, P. Compliant Manipulation with a Dexterous Robot Hand. *Proceedings : Ieee International Conference on Robotics and Automation*; 1993. p. C711-C716.
- Nataraj R, Evans PJ, Seitz WH Jr. Li ZM. Pathokinematics of precision pinch movement associated with carpal tunnel syndrome. *J Orthop Res.* 2014a; 32:786–792. [PubMed: 24536036]
- Nataraj R, Evans PJ, Seitz WH Jr. Li ZM. Effects of carpal tunnel syndrome on reach-to-pinch performance. *PLoS One.* 2014b; 9:e92063. [PubMed: 24632925]
- Nataraj R, Li ZM. Robust identification of three-dimensional thumb and index finger kinematics with a minimal set of markers. *J Biomech Eng.* 2013a; 135:91002. [PubMed: 23775305]
- Nataraj R, Li ZM. Integration of marker and force data to compute three-dimensional joint moments of the thumb and index finger digits during pinch. *Comput Methods Biomech Biomed Engin.* 2013b
- Schettino LF, Adamovich SV, Poizner H. Effects of object shape and visual feedback on hand configuration during grasping. *Exp Brain Res.* 2003; 151:158–166. [PubMed: 12783144]
- Seo NJ, Rymer WZ, Kamper DG. Altered digit force direction during pinch grip following stroke. *Exp Brain Res.* 2010; 202:891–901. [PubMed: 20186401]
- Shen ZL, Mondello TA, Nataraj R, Domalain MF, Li ZM. A digit alignment device for kinematic analysis of the thumb and index finger. *Gait Posture.* 2012; 36:643–645. [PubMed: 22633016]

- Tan HZ, Durlach NI, Beauregard GL, Srinivasan MA. Manual Discrimination of Compliance Using Active Pinch Grasp - the Roles of Force and Work Cues. *Percept Psychophys.* 1995; 57:495–510. [PubMed: 7596747]
- Tiest WMB, Kappers AML. Cues for Haptic Perception of Compliance. *Ieee T Haptics.* 2009; 2:189–199.
- Valero-Cuevas FJ, Smaby N, Venkadesan M, Peterson M, Wright T. The strength-dexterity test as a measure of dynamic pinch performance. *J Biomech.* 2003; 36:265–270. [PubMed: 12547365]
- Vigouroux L, Domalain M, Berton E. Effect of object width on muscle and joint forces during thumb-index finger grasping. *J Appl Biomech.* 2011; 27:173–180. [PubMed: 21844605]
- Wu JZ, An KN, Cutlip RG, Krajnak K, Welcome D, Dong RG. Analysis of musculoskeletal loading in an index finger during tapping. *J Biomech.* 2008; 41:668–676. [PubMed: 17991473]
- Yokogawa R, Hara K. Manipulabilities of the index finger and thumb in three tip-pinch postures. *J Biomech Eng.* 2004; 126:212–219. [PubMed: 15179851]

Figure 1.

(A) The marker set employed to measure digit kinematics, (B) The digit-alignment device used to calibrate digit coordinate systems, (C) The digit joints to be identified and about which to compute 3-D joint moments.

Figure 2.

(A) Subject seated as instructed relative to pinch apparatus and monitor providing visual feedback of applied (red trace) and target force (yellow trace), (B) Close-up of pinch apparatus including affixed markers (A1, A2, A3) utilized to define global coordinate system.

Figure 3.

Example pinch-trial showing progressive pinching actions of subject: **(A)** Hand initially at resting position upon trial commencement **(B)** Placing digits in light contact with bands without exerting notable force as presented by red trace, **(C)** Pinching to exert force upon bands and bringing digits together to match the linear ramp as presented by yellow trace, **(D)** Releasing bands and bringing hand to original position upon end of trial.

Figure 4.

Mean force applied by all subjects as a linear function of interpad distance for the target range (25-75%) of the presented force-ramps for each of the five compliance levels as specified by the number of resistance bands.

Figure 5.

Mean force components for each digit along axes of global apparatus coordinate system versus interpad distance shown across decreasing compliance levels (i.e., increasing number of resistance-bands).

Note: Percentages in panels A and B correspond to digit and component contributions to the total pinch force exerted in panel C.

Figure 6.

Mean force coordination angle over target ramp forces (normalized by respective maximum force) for each compliance level.

Figure 7. Mean (top) and range (bottom) of joint angles over target pinch forces at each compliance level. A 2nd order polynomial model was applied for each joint-DOF data set.

Figure 8.

Mean (top) and range (bottom) of joint moments over target pinch forces at each compliance level. Joint moments were normalized by total pinch force. A 2nd-order polynomial model was applied for each joint-DOF data set.

Table 1

Parameters for 2nd-order polynomial models for observed output “y” at each joint DOF as a function of compliance level “x”, number of resistance bands:
 $y = p_2x^2 + p_1x + p_0$

Digit joint DOF	Observed Output											
	Mean Joint Angle (deg)			Joint Angle Range (deg)			Mean Normalized Joint Moment (N-cm/N)			Normalized Joint Moment Range (N-cm/N)		
	p ₂	p ₁	p ₀	p ₂	p ₁	p ₀	p ₂	p ₁	p ₀	p ₂	p ₁	p ₀
T-CMC Flexion	0.034 ±0.28	0.057 ±1.6	52 ±7	0.00 ±0.22	-0.06 ±1.5	2.1 ±2.3	-1.9 ±1.1	15 ±10	-38 ±24	2.5 ±1.4	-20 ±13	50 ±31
T-CMC Abduction	0.49 ±0.67	-2.7 ±5.2	15 ±8	-0.13 ±0.38	0.51 ±2.2	8.6 ±3.3	0.0 ±0.13	0.4 ±1.1	-2.1 ±2.8	0.12 ±0.10	-1.0 ±0.8	2.7 ±2.0
T-CMC Rotation	0.26 ±0.36	-2.3 ±2.8	102 ±13	-0.21 ±0.35	1.7 ±2.6	4.2 ±3.8	1.4 ±0.27	-11 ±2.9	28 ±7	1.9 ±0.3	-15 ±4	37 ±10
T-MCP Flexion	0.02 ±0.38	-0.63 ±3.2	-6.3 ±11	0.01 ±0.27	0.03 ±1.8	2.6 ±2.7	-0.9 ±0.5	7.5 ±4.8	-17 ±12	1.2 ±0.7	-9.9 ±6.3	24 ±15
T-MCP Abduction	0.00 ±0.48	0.40 ±3.5	-0.41 ±8	0.02 ±0.21	0.23 ±1.4	1.8 ±2.5	0.4 ±0.3	-3.3 ±2.2	7.3 ±5.4	0.5 ±0.4	-4.4 ±2.9	11 ±6.8
T-IP Flexion	0.12 ±0.84	-0.53 ±5.7	-3.4 ±14	0.00 ±0.47	0.25 ±2.8	4.0 ±3.6	-1.0 ±0.5	8.3 ±4.4	-20 ±11	1.4 ±0.7	-11 ±6	27 ±14
MEAN ABS THUMB	0.40 ±0.41	2.9 ±2.8	33 ±36	0.25 ±0.22	1.7 ±1.4	4.0 ±3.6	0.95 ±0.80	7.8 ±6.9	19 ±17	1.3 ±1.1	10 ±9	25 ±22
I-MCP Flexion	-0.12 ±0.65	1.7 ±3.9	38 ±8	0.29 ±0.58	-1.7 ±4.2	21 ±8.8	0.13 ±0.10	-1.1 ±0.84	6.0 ±1.8	0.11 ±0.10	-0.96 ±0.84	2.6 ±1.9
I-MCP Abduction	-0.25 ±0.78	2.8 ±5.1	-20 ±15	-0.23 ±0.56	2.1 ±3.3	4.5 ±5.4	0.07 ±0.05	-0.57 ±0.37	2.5 ±1.0	0.10 ±0.07	-0.80 ±0.60	1.9 ±1.2
I-PIP Flexion	-0.20 ±1.1	0.01 ±5.8	25 ±9	0.05 ±0.64	0.4 ±3.5	4.8 ±5.4	0.15 ±0.06	-1.2 ±0.54	4.5 ±1.2	0.08 ±0.10	-0.77 ±0.86	2.2 ±1.9

Digit joint DOF	Observed Output											
	Mean Joint Angle (deg)			Joint Angle Range (deg)			Mean Normalized Joint Moment (N-cm/N)			Normalized Joint Moment Range (N-cm/N)		
	<i>p</i> 2	<i>p</i> 1	<i>p</i> 0	<i>p</i> 2	<i>p</i> 1	<i>p</i> 0	<i>p</i> 2	<i>p</i> 1	<i>p</i> 0	<i>p</i> 2	<i>p</i> 1	<i>p</i> 0
L-DIP Flexion	0.53 ±0.71 *	-3.4 ±4.3 *	15 ±8 ***	0.01 ±0.64	-0.02 ±4.3	4.6 ±5.8 *	0.03 ±0.04 *	-0.26 ±0.22 ***	0.76 ±0.41 ***	0.02 ±0.02 **	-0.23 ±0.20 ***	0.8 ±0.5 ***
MEAN ABS INDEX	0.67 ±0.54 ***	4.2 ±3.1 *	25 ±13	0.47 ±0.40 ***	3.1 ±2.4 ***	9.0 ±9.0 ***	0.10 ±0.07 ***	0.84 ±0.61 ***	3.4 ±2.3 ***	0.09 ±0.08 ***	0.73 ±0.67 ***	1.9 ±1.6 ***

Note:

* $p < 0.05$,** $p < 0.01$,*** $p < 0.001$ for individual joint-DOF parameters being non-zero value *or* for mean absolute value of parameter (bolded) across all DOFs of given digit being different from that of other digit.

Table 2

Estimated covariance matrix between mean normalized joint moment (N-cm/N) as a function of increasing compliance level

JOINT-DOF;	T-CMC Flexion	T-CMC Abduction	T-CMC Rotation	T-MCP Flexion	T-MCP Abduction	T-IP Flexion	I-MCP Flexion	I-MCP Abduction	I-PIP Flexion	I-DIP Flexion
T-CMC Flexion	<i>90</i>	3	-67	44	-19	49	-7	-3	-7	-2
T-CMC Abduction	3	0	-2	1	-1	1	0	0	0	0
T-CMC Rotation	-67	-2	<i>49</i>	-33	14	-36	5	3	5	1
T-MCP Flexion	44	1	-33	22	-9	24	-4	-2	-4	-1
T-MCP Abduction	-19	-1	14	-9	4	-10	2	1	2	0
T-IP Flexion	49	1	-36	24	-10	26	-4	-2	-4	-1
I-MCP Flexion	-7	0	5	-4	2	-4	<i>1</i>	0	1	0
I-MCP Abduction	-3	0	3	-2	1	-2	0	0	0	0
I-PIP Flexion	-7	0	5	-4	2	-4	1	0	<i>1</i>	0
I-DIP Flexion	-2	0	1	-1	0	-1	0	0	0	0

Note:

Diagonal terms (variance) are italicized; Largest positive and negative of off-diagonal (covariance) values across columns are bolded