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Integration of marker and force data to compute three-dimensional joint moments of the thumb and index finger digits during pinch

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Abstract

This study presents methodology to determine joint moments of the digits of the hand during pinch function. This methodology incorporates steps to identify marker-based kinematic data defining aligned coordinate systems for individual digit segments and joint center locations. The kinematic data are then transformed to a common reference frame along with the force data collected at pinch contact of a customized apparatus in three-dimensions (3-D). These methods were demonstrated with a pilot investigation to examine the static joint moments occurring during two-digit oppositional precision pinch at a particular endpoint force level applied at the digit pads. Notable abduction joint moments at the proximal joints of both digits were observed, which implicate the role of respective intrinsic and extrinsic muscles in maintaining pinch grasp. Examining differences in joint moment results when substituting select steps of this methodological approach suggested greater relative importance for joint center identification and segment coordinate system alignment.

Keywords

hand biomechanics; joint moments; pinch; kinematics; kinetics

1 Introduction

The human hand demonstrates exquisite motor control in manipulating objects for performing everyday functional tasks. Analyzing pinch grasp mechanics provides insight on *how* the hand performs basic object manipulation. Endpoint forces are applied by the two digits to not only secure the object but functionally move it through space. The ability of the digits to produce the necessary endpoint forces at the digit-object interface depends directly on the posture of the digits while grasping the object. At a given posture, the muscles must produce the requisite moments at the digit joints to generate the desired force load. The active roles of particular muscles during hand function tasks have been studied previously (Valero-Cuevas et al. 1998; Johanson et al. 2001; Li et al. 2001). However, it is the

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generation of moments by these muscles about the joints that characterizes fundamental mechanical performance of the digits. Previous studies have investigated the joint moments across digits of the hand in examining anatomical considerations for moment calculations (Chao et al. 1976; Kurillo et al. 2003), contributions from particular muscles (Li et al. 2000; Kamper et al. 2006), and dynamic functions (Jindrich et al. 2004; Grinyagin et al. 2005). It follows that protocols to assess joint moments from experimental measurements are needed in accurately evaluating hand function.

In computing robust estimates of digit joint moments, accurate kinematic descriptions of the digits in a common reference frame to the force data being collected is required. Several previous studies have employed motion capture methods to track three-dimensional (3-D) kinematics of the hand and digits (Vigouroux et al. 2011; Cerveri et al. 2007; Zhang et al. 2003). Potential sources of error have been cited to include marker placement, marker superimposition and occlusion from camera view, and passive skin movement (Ryu et al. 2006; Murgia et al. 2004; Metcalf et al. 2011). To address these issues it is important to consider performing coordinate system segment alignment (Shen et al. 2012), utilizing fewer markers (Nataraj & Li 2012), and identifying centers of rotation between adjacent digit segments (Cerveri et al. 2005; Gamage et al. 2002; Chang et al. 2007; Kuo et al. 2005).

In this study, an approach to determine joint moments of the thumb and index finger during pinch is presented which encompasses considerations for kinematic motion capture along with data synchronization with the respective force sensor coordinate systems. Specifically, we utilize coordinate system alignment, joint center identification, and coordinate system transformation of 3-D kinematic and kinetic data collected from motion capture and a customized pinch apparatus to perform the necessary inverse analyses. To demonstrate this approach, we examine the pinch mechanics that are generated as a function of target endpoint force level. In utilizing our protocol for this pilot investigation, procedures are outlined for determining estimates of digit endpoint force vectors and their location of application on the digits, joint kinematics, and resultant joint moments all expressed in a common coordinate system. This approach was further assessed by the potential errors in joint moment computations and other intermediate variables of interest during a step-wise analysis, whereby each major approach step was replaced with an alternative procedure.

2 Methods

This study included data from five able-bodied male subjects (aged 22 to 39) who neither showed nor reported notable deficit in hand function. All subjects signed informed consent forms approved by the local institution review board.

2.1 Digit Kinematics Measurements

Retro-reflective markers were affixed to the surface of the right hand of each subject to estimate thumb and index finger kinematics. The 3-D position of each marker was tracked using a motion capture system (Model 460, Vicon Motion Systems and Peak Performance, Inc., Oxford, UK). An intermediate marker set (Nataraj & Li 2012) was employed (Figure 1). To explicitly define the position and orientation of each distal digit segment, the marker set included a nail marker cluster originally employed with a digit alignment device (DAD)

(Shen et al. 2012) on the thumb distal phalange (DP1) and the index distal phalange (DP2). These nail cluster markers are designated as DADT1, DADT2, DADT3, DADI1, DADI2, and DADI3 as shown in Figure 1. Another marker cluster (markers H1, H2, and H3) was placed on the second metacarpal (MC2) to serve as a local hand reference coordinate system following ISB convention (Wu et al. 2005). Two additional individual markers were placed on the thumb proximal phalange (PP1 with markers TM1, TM2), first metacarpal (MC1 with markers TP1, TP2), index middle phalange (MP2 with markers IM1, IM2), and index proximal phalange (PP2 with markers IP1, IP2). The individual markers were placed according to experimenter discretion to be readily viewable by cameras of the motion capture system during experiment trials. A total of six cameras were employed and placed in a stagger-surround above and about the expected fixed location for pinching. Cameras were located approximately 3–5 feet away from the expected pinch location. System calibration produced single-point positional errors under dynamic tracking conditions of less than 0.2mm. All marker data were collected at 100 Hz.

2.2 Pinch Force Measurements

A pinch apparatus was employed to measure the contact forces of two digits independently using two six-component force/torque transducers (Nano17, ATI Industrial Automation, Inc., Apex, NC). The apparatus also included an aluminum base with adjustable track, two aluminum mounting supports, and two stainless steel pinch plates. The mounting side of each transducer was attached to a mounting support, and the tool side of the transducer was rigidly fixed to a pinch plate using screws. The pinch span was fixed at 20 mm to approximate pinch of smaller-width objects (Vigouroux et al. 2011). Force/torque signals were amplified and multiplexed using a custom ATI interface box (ATI Industrial Automation, Inc., Apex, NC) and converged to a 16-bit analog-digital converter (PXI-6289, National Instruments, Austin, TX). The base of the pinch apparatus was rigidly affixed to a table. All force data were collected at 100 Hz. An output step function signal was sent from the LabView® data acquisition system to the VICON motion capture system for offline time-synchronization of the collected kinematic and kinetic data.

2.3 Data Collection Protocol

Each subject was seated comfortably and squarely in front of the table to which the pinch apparatus was affixed. The long-axis of the pinch apparatus base was oriented 45 degrees rotated relative to the medial-lateral dimension of the table. The centerline of the subject was offset laterally from the pinch apparatus according to subject preference such that the subject's arm would point straight forward when actively pinching the apparatus with the right hand.

Each trial was 20 seconds long whereby the subject was presented with a yellow step profile with plateau at a specified force level on a monitor display (Figure 2A). The subject follows the step profile as closely as possible with an active force trace representing the average inwardly-directed *normal* (perpendicular and into respective plate) force the subject applied on the pinch apparatus with the thumb and index finger. Just prior to commencement of the trial, the experimenter instructed the subject to keep the hand in the “ready” position (Figure 2B). The forearm rested comfortably on the table, ulnar-side down, with the hand positioned

behind the designated red marker on the proximal side of the pinch apparatus. The three non-involved digits (middle, ring, little fingers) were naturally curled into the palm of the hand. The remaining two digits (thumb, index finger) employed for active pinch were in a relaxed position. Upon trial commencement (time = 0 sec), the subject transitioned to the “active pinch” position whereby the subject contacts the plates with the respective digits while applying minimal load prior to the rising edge of the step function (time = 4 sec) with forearm elevated from the table surface. At the rising edge, the subject actively generated pinch force upon the apparatus to bring the red force-trace to the specified plateau of the step profile as quickly as possible while minimizing overshoot. The subject then steadily maintained load such that the force trace matches the step profile plateau as well as possible for the remaining duration of the plateau (until time = 19 sec). At the falling edge of the step profile, subject simply releases the pinch apparatus and returns the hand and forearm to the “ready” position.

For each trial, the subject was presented any one of ten plateau force levels (1, 2, 3, 4, 5, 6, 7, 8, 9, or 10 Newtons). Each subject underwent a total of 50 trials (5 trials at each force level). The trial force levels were presented randomly as the subject was blinded to the force-level until trial commencement. Approximately 30 seconds elapsed between consecutive trials, except for the 10th, 20th, 30th, and 40th trials where a 5–10 minute rest break was taken. Subjects did not report or show notable signs of physical fatigue or discomfort over the course of the pinching trials. For subsequent analysis with the presumption of static pinching conditions, only data from time = 9 sec to time = 19 sec were retained for analysis assuming the subject may have been considerably steadying their pinch grip during the first 5 seconds of the plateau phase.

2.4 Computational Approach to Determine Finger Joint Moments

This section describes the step-by-step procedure for transforming the collected kinematic and kinetic data and computing resultant digit joint moments and other intermediate biomechanical quantities.

STEP#1: Transforming Marker Position Data—All marker position data were initially collected with respect to an arbitrary global coordinate system $\{G\}$ specified during calibration of the motion capture system. During post-processing all data were transformed to an explicitly known “base” coordinate system $\{B\}$ defined by three 3-D marker positions $(\vec{B}_1, \vec{B}_2, \vec{B}_3)$ affixed to the table-top surface (Figure 2A). The explicit computations and transformations are detailed in Appendix – **Step#1**.

STEP#2: Identifying Functional Joint Centers—Using the aforementioned marker set, the subject performed one motion trial for each digit to identify functional joint centers of rotation as previously described in Nataraj & Li 2012. For each motion trial, the subject produced near-maximal rotational excursions at each joint. The following joint centers were identified: the interphalangeal (IP1), metacarpophalangeal (MCP1), and carpometacarpal (CMC1) joints of the thumb and the distal interphalangeal (DIP2), proximal interphalangeal (PIP2), and metacarpophalangeal (MCP2) joints of the index finger. In the first trial, the subject performed ten repetitions of thumb opposition (Li et al. 2007) (Figure 3A). In the

second trial, the subject performed ten continuous transitions between *curled* and *uncurled* positions (Figure 3B).

Step-wise spherical fitting and coordinate system transformations were subsequently executed to identify joint center locations. The general procedure involved specifying a reference coordinate system $\{Ref\}$ from a three-marker cluster affixed to one segment and observing the relative motions of markers on the adjacent segment. A transformation matrix for $\{Ref\}$, convention described in Craig, 1989, was defined by rotation matrix R_{Ref} from selected origin $\vec{P}_{Ref}$ expressed in global coordinates:

$$T_{Ref} = \begin{bmatrix} R_{Ref} & \vec{P}_{Ref} \\ 0 & 1 \end{bmatrix} \quad (1)$$

The transform inverse T_{Ref}^{-1} was applied to the motion marker data to express them in $\{Ref\}$. Assuming purely rotational joint motion (Wu et al. 2005), these data trace 3-D spherical paths about that joint. The *Optimization Toolbox* from MATLAB® (*Mathworks, Inc.*, Natick, MA) was employed to perform the spherical fit and calculate the 3-D position of the functional joint center (O) expressed in $\{Ref\}$ that minimized the following objective function used in Cerveri et al., 2005:

$$F(c) = \sum_i^M \sum_j^N \left[(p_{i,j} - {}^{Ref}O) \cdot (p_{i,j} - {}^{Ref}O)^T - R_i^2 \right]^2 \quad (2)$$

where $M = \# \text{markers}$, $N = \# \text{sampling data}$, and where $p_{i,j}$ and R_i are the position of the i th marker at j th time-step and the radius of the sphere defined by marker $p_{i,j}$ around ${}^{Ref}O$, respectively. Applying transform T_{Ref} to ${}^{Ref}O$ yielded the joint center position in global coordinates.

As shown in Figure 4A, the nail cluster affixed to the distal thumb phalanx, DP1, defined coordinate system $\{DP1\}$ with origin arbitrarily chosen as the position of the second marker of the nail cluster to first serve as $\{Ref\}$ and calculate O_{IP1} from motion paths of markers on the proximal thumb phalanx, PP1. The PP1 markers and O_{IP1} , serving as a pseudo-marker, defined a coordinate system $\{PPI\}$ to calculate joint center, O_{MCPI} , from motion markers on the first metacarpal, MC1. Finally, the MC1 markers and O_{MCPI} defined coordinate system $\{MC1\}$ to calculate joint center, O_{CMC1} , from motions of markers constituting the hand cluster on the second metacarpal, MC2. Joint centers were identified from distal to proximal because the nail cluster was the most stable reference that minimized propagation of calculation errors. Similarly applying the above procedure yielded index finger joint centers (O_{DIP2} , O_{PIP2} , O_{MCP2}) from segment coordinate systems for the distal phalanx, DP2, the middle phalanx, MP2, and the proximal phalanx, PP2. The mean inter-joint distances yielded segment lengths for DP1, PP1, DP2, and MP2.

STEP#3: Calibration for Coordinate System Alignment—The subject interfaced the thumb and index finger with a block apparatus (“digit alignment device”, Figure 4B) at a static calibration position as outlined in Shen et al. 2012 during a 3-second motion capture

trial. A pure rotational transformation ${}^{SCS}R_{BCS}$ (equation 3) was determined for each segment coordinate system $\{SCS\}$ for alignment with a block coordinate system $\{BCS\}$ serving as the standardized alignment reference. Applying this static transform during dynamic trials produced the corresponding anatomically-aligned virtual rotation matrix $\{VCS\}$ for that digit segment, given as R_{VCS} (equation 4).

$$\text{Static calibration: } {}^{SCS}R_{BCS} = R_{SCS}^{-1} R_{BCS} \quad (3)$$

$$\text{Dynamic trials: } R_{VCS} = R_{SCS} {}^{SCS}R_{BCS} \quad (4)$$

At the static calibration position, constrained flexion at the MCP joint of the index finger resulted in an orientation bias between the hand cluster and the block coordinate system. To compensate, the rotation angle between the pre-aligned z-axes of the hand and proximal phalange of index finger was calculated at this position. The aligned hand coordinate system was then rotated by this angle about its x-axis (i.e., flexion/extension axis).

STEP#4: Definition and Alignment of Digit Segment Coordinate Systems—

Each segment coordinate system was defined by three non-colinear markers presumed affixed to that segment. Coordinate systems on the distal segments for each digit $\{DP1\}$, $\{DP2\}$ and the second metacarpal $\{MC2\}$ were defined by the respective markers of the adjoining marker cluster. The remaining digit segment coordinate systems were defined by the two individual markers respectively affixed and the referenced location of the distal joint center. For example, the coordinate system for the thumb proximal phalange $\{TP1\}$ was defined by markers TM1 and TM2 and the referenced position for the thumb interphalangeal joint (O_{TP1}). Initially, these coordinate systems were arbitrarily defined where the z-axis was specified as the unit vector pointed from the distal joint center to the first marker. The y-axis was defined as the unit vector cross-product of the z-axis and the vector pointed from the first marker to the second marker. The x-axis was then defined as the unit vector cross-product of the y-axis and z-axis. This arbitrary segment coordinate system $\{SCS\}$ was then aligned to their respective $\{VCS\}$ for pinch trials according to the alignment calibration procedure described in STEP#3. Joint angles were computed as Euler rotations between adjacent (distal relative to proximal) digit segment coordinate systems in X-Y-Z order.

STEP#5: Transforming Pinch Force Data—Since all force data was initially expressed with respect to its respective sensor coordinate system $\{S\}$, a series of transformations were necessary to express these data in the same base coordinate system $\{B\}$ as the marker data. Marker-based digitization using a customized lab digitizer was performed to define points on the pinch apparatus plates expressed. Utilizing equations for tabulating center of pressure, COP, defined these points expressed in $\{S\}$, and transformations between $\{B\}$ and a marker-based coordinate system affixed to the digitizer, $\{D\}$, define these same points in $\{B\}$. Finally, in order to transform pinch force data from $\{S\}$ to $\{B\}$, the origin and axes of the sensor coordinate system expressed in $\{B\}$ needs to be explicitly solved. These procedures are detailed in Appendix – **Step#5**.

STEP#6: Computing Static Joint Moments—Once all force and position data were collected, time-synchronized, and expressed in the same base system $\{B\}$, a static, massless approach for computation of joint moments was applied. Specifically, the net three-dimensional force vector for each digit was represented to act entirely on the distal segment of each digit and through the measured COP location. It was assumed each digit segment was represented as a massless, inertialess rigid body connected to adjacent segments by 3-D rotational joints. Each digit was modeled as a three-link model with the most proximal segment assumed to be affixed the second metacarpal (MC2) serving as the local ground reference. The assumption of massless segments was justified since the magnitude of even the lowest endpoint force plateau level (1N) was notably greater than the typical static weight of the involved digit segments (Delp et al. 1996). The mean angular accelerations during pinch were less than 1deg/sec^2 , justifying assumption of negligible dynamic, inertial contributions. As such, the 3-D moment externally applied at each joint was directly computed as:

$$\vec{M} = \vec{r} \times \vec{F} \quad (5)$$

where the 3-D moment vector ($\vec{M}$) is the cross-product of the torque arm vector ($\vec{r}$) onto the force vector ($\vec{F}$) for the respective joint and digit (Figure 5). By convention, $\vec{r}$ was designated as the vector from the joint center to the COP of the endpoint force vector acting on that digit.

ADDENDUM STEP: Error Analysis—In order to quantify the potential improvement in measurement accuracy by executing each of the three *optional* methodological steps (Step 2 = joint center identification, Step 3 = digit coordinate system alignment, Step 5 = explicit solution of force sensor coordinate systems), the joint moment computations were performed 4 times for an additional data collection. The first iteration follows the presented approach exactly as previously described and serves as a “gold-standard” for comparison. Each of the next three iterations follows the same approach except, in each respective case, one of the methodological steps was substituted with an alternative procedure. This protocol was performed with one healthy subject (male, age 33) undergoing the aforementioned pinching protocol at the 5 Newton force-level for 15 trials. The subject donned the marker set previously described plus additional markers placed on the dorsal-side of the digit joints as described in Braido et al. 2004. These additional markers on the thumb from distal-to-proximal were denoted as TE1, TE2, and TE3 (see Figure 6A). The additional markers on the index finger from distal-to-proximal were denoted as IE1, IE2, and IE3.

Alternative for Step#2: Rather than the series of spherical fittings to identify centers of joint rotation, the additional markers placed on the dorsal-side of the respective joints served as the estimated joint center locations.

Alternative for Steps#3: Segment coordinate systems were defined utilizing the dorsal-side joint markers in conjunction with markers from the original marker set for each digit. For the distal segment, the normal (y) axis was simply defined using the markers along the long-stem of the nail-cluster (e.g., DADT2, DADT3 for thumb). The lateral (x) axis was performed applying a cross product between the y-axis and a unit-vector defined between

the lower nail-cluster marker (e.g., DADT3 for thumb) and corresponding adjacent joint marker (e.g., TE1 for thumb). An additional cross-product produces the longitudinal (z) axis. For the middle and proximal segments, the respective z-axis was defined between the distal and proximal adjacent joint markers. The y-axis was determined from the unit cross-product between the z-axis and the other segmental marker closest to the z-axis (e.g., TM1, TP1 for thumb segments). Again, an additional unit cross-product produces the remaining x-axis. *No alignment* with the digit alignment device was performed upon these defined coordinate systems.

Alternative for Step#5: Instead of explicit quantitative synchronization of the force sensor coordinate systems with the base coordinate system defined in kinematic space as previously described, the sensor coordinate systems were visually estimated. Markers were manually placed to be aligned with the edges of the apparatus base plate assuming the sensors were orthogonal to the plate as ensured by manual utilization of a T-square tool. These two markers were used to define the presumed direction of the *normal* (perpendicular to plate surfaces) axis of the sensor coordinate systems (Figure 6B). A third marker served as a coplanar marker from which subsequent cross-products yielded the remaining coordinate system axes. The origin of these sensor coordinate systems were approximated by first digitizing a point that is visually estimated to be along the normal axis of the sensor. This point is then projected in the direction of the presumed normal axis a distance equaling the thickness of the support plate plus sensor (~2.1cm).

3 Results

Linear regression models were fitted to select biomechanical variable data for each subject to determine offset (bias) and trend (slope) values as a function of normal endpoint force during pinch for each subject. The summary linear regression parameter values across all subjects are shown in Table 1 for joint angles, joint moments, endpoint force, and joint moment arm magnitudes defined as the perpendicular distances from joint locations to respective endpoint force line of action. Subjects were able to accurately and precisely maintain the task-designated normal force as the normal component slope was 1.0 and standard deviation was 0.0, despite a measure of imprecision in the collateral shear forces with slope standard deviations > 0.1.

The dependence of the joint angle changes with endpoint normal force were relatively small as the mean absolute linear regression slope < 0.6 deg/N for all joint DOFs. In this investigation, the slopes were significant for the following joint DOFs: MCP1-Ext, CMC1-Abd, and MCP2-Abd. The joint angle bias values for the linear regression model fits serve as the universal setpoint values across these subjects. Notable observations include all joints being in flexion except MCP1. The joint DOF exhibiting the largest change in setpoint from the neutral positions defined from the static calibration was CMC1-rotation.

The joint moment slope for 13 of the 18 joint DOFs was statistically significant ($p < 0.05$), employing a threshold of $p = 0.05$ without correction for multiple comparisons to prioritize avoidance of Type II errors. The largest (> 70 N-mm/N) absolute changes in joint moments as a function of normal endpoint force occurred at the most proximal joints (CMC1, MCP2)

for both digits in abduction. This is demonstrated visually in Figure 7A. The changes in the magnitudes of the joint moment arms as a function of normal force are shown in Figure 7B. All slope trends were significant ($p < 0.05$) for thumb joint DOFs but only MCP2 for the index finger. A downward trend was observed for all joints except MCP2, which all demonstrated the largest slope ($|\text{slope}| > 0.5\text{mm/N}$). The fitted mean values for significant joint moment or moment arm slopes followed the resultant linear regression model well with R^2 value > 0.85 .

Table 2 summarizes results from the error analysis session. The presented results are all “differentials” for each variable quantity when one of the methodological steps was substituted with the alternate mode compared to the “gold standard”. For each step substitution, results for the variable most directly affected by the substitution (joint center location for step 2; joint angles for step 3, joint forces for step 5) are shown along with the corresponding differential effect on resultant joint moment computations. Across the 15 trials for this subject, most component (i.e., individual joint degree-of-freedom, DoF) differentials were shown to be significantly different from the gold standard for $p < 0.05$. For substitutions of steps 2, 3, 5, the mean component changes in respective joint variables of interest were approximately 7mm, 9deg, and 0.04N. The respective mean component changes in result joint moment computations were approximately 20, 30, and 3 N-mm.

4 Discussion

In this study, we have developed methodology to compute joint moments of the thumb and index finger during pinch. Considerations for determining accurate and anatomically-relevant coordinate system transformations across position and force data spaces have been made in order to measure digit joint mechanics during the fine motor task of precision pinch. The methodology identified subtle changes in hand and digit postures and related these data to the endpoint force vector to infer the reaction joint moments created by the force vector assuming static conditions. The task of steady precision pinch at various stable load levels was chosen for investigation in demonstrating this methodology since it represents a most fundamental level of function.

For this pilot investigation, digit postures defined by joint angles had small but significant dependence on endpoint normal force magnitude for certain joint DOFs. This suggests these joint DOFs may be especially compliant in accommodating the pinch grip with increasing pinch force. Since the relative variations in joints angles were small, the resultant joint moments followed significant linear trends in proportion to the endpoint force being applied. The values for the postural set-points indicate a base configuration for the two pinching digits to be well opposed to exert coordinated endpoint forces pointing inwardly upon the apparatus being grasped. The thumb was largely brought into opposition with the index finger by notable rotation at the CMC1 joint. Furthermore all joints except MCP1 were in flexion, indicating a posture that brings to the two digits towards one another for grasp. The lack of flexion setpoint at the MCP1 joint likely results to accommodate a pinch configuration whereby the distal segments of the thumb and index finger are position aligned to exert endpoint forces more equal and opposite to hold the grasped object in a stable configuration.

The large abduction moments imply that the index finger and thumb were not kinetically opposed in grasping the apparatus along the respective flexion-extension plane for each digit. This may be to exploit anatomical mechanical advantages whereby the large reaction moments by the proximal joints (CMC1, MCP2) can best be balanced by the strong abductor muscles. Specifically, passive properties and active force-generation by musculature about the CMC1 and MCP2 joints need to produce abduction moments to maintain a stable pinch configuration at load levels typically observed for activities of daily living (Fowler et al. 1999). This implicates significant roles for the thenar muscles of the thumb and first dorsal interosseus of the index finger during pinching.

The trends towards shorter moment arms with increasing normal pinch force across most joints indicate general postural movements for physiological mechanical efficiency. Shorter moment arms would require smaller joint moments to be exerted by the muscles and surrounding structures to produce a given endpoint force. The notable exception was at MCP2 of the index finger, which may suggest the role of this joint in accommodating the other joints in the pinch task. The MCP2 joint may be supported by more redundant musculature (e.g. the first dorsal interosseous) to generate the moment required at its joint more readily than the other involved joints for precision pinch.

Ultimately, the presented methodology could be employed for any manual function involving digits uniquely coming into contact with a surface affixed to a force transducer. While the methodology mimics that traditionally employed in inverse analysis of gait (Liu et al. 2006), it has been customized for manual function and could be applied to any task involving digit motion and contact to a similarly instrumented surface.

A limitation in this study was the consideration of only the endpoint force contribution to the resultant moment at the digit joints. Assumptions of negligible inertial and dynamic effects were justified given the static nature of the functional task and the involved digit segments being relatively small with low mass. In the future, if more dynamic tasks were to be investigated, this methodology could still be largely employed, but more comprehensive computation of the joint moments would be required. This step could be directly performed utilizing additional available software (Delp et al. 2007) capable of generating three-dimensional equations of motion for the applicable subject-specific model of the hand and digits.

Furthermore, these methods can be applied to perform inverse dynamics analyses of digit mechanics during other investigations of pinch function. Inverse analysis parameters would include not only estimation of joint moments but also theoretical muscle forces required to perform functional pinch tasks. In order to elucidate pinch mechanics that emerge under various experimentally controlled conditions such as systematic perturbation or addition of compliance to the pinch surface, these methods for determination of digit mechanics will be valuable. Ultimately, these applications are also important in clinical settings to assess performance of individuals who have pathologies (e.g. stroke, dystonia, carpal tunnel syndrome) affecting hand function.

Notable differentials in joint moment computations were observed with substitution of any of the three major methodological steps (steps 2, 3, and 5) with the greatest differentials produced with substitution of steps 2 or 3. This suggests greater importance in executing joint center identification and digit alignment relative to explicit solution of the force sensor coordinate system. For step 2, an external, i.e., skin surface, representation of the joint center locations can potentially produce greater errors for joint moment DOFs sensitive to shear force components at the interface surface. Therefore, a representation of the joint center location *internal* to the digit would be critical to reduce this type of error. The joint moment differentials produced due to substitution of step 3 demonstrates the notable effects of relying only on experimenter visual discrimination of marker placements in defining segment axes. Directional sensitivity of these axes to marker placement is amplified since markers must be placed in such close proximity given the relatively small segment sizes. Substitution of step 5 clearly generated the smallest joint moment differential. This small differential is directly explained by the relatively small mean differential in joint force components (0.04N) compared to the target normal force level of 5N required for the specified experimental task. However, it is reasonable to expect the joint moment differentials to grow for tasks requiring either greater grip forces or relatively higher shear loads. While substitution of any of these steps can produce changes in the resultant computations of joint moments, it is recommended that all steps as presented are employed to better compute digit mechanics of the thumb and index finger during pinch function experiments.

In the future, these methods can be applied and extended to produce inverse analyses results which elucidate the underlying joint biomechanics of the digits during various tests of hand function. In order to streamline processing, our laboratory has developed a customized graphical user interface (GUI) in MATLAB® which automatically performs the procedures outlined in the presented methodological approach. This GUI is depicted in Figure 8, and, following numeric trial inputs and push-button execution of data processing, it includes options for graphical display of select data along with motion visualization of individual pinching trials.

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7 Appendix

Step#1 – Transformations of Marker Position Data

This section details determination of the transformation matrix to express all marker data to the “base” coordinate system. The origin was arbitrarily selected as $\vec{B}_2$ with coordinate system axes $(\hat{x}, \hat{y}, \hat{z})$ defined as:

$$\hat{x}_B = \frac{\vec{B}_1 - \vec{B}_2}{\|\vec{B}_1 - \vec{B}_2\|} \quad (\text{A.1})$$

$$\hat{z}_B = \frac{\hat{x} \times (\vec{B}_3 - \vec{B}_2)}{\|\hat{x} \times (\vec{B}_3 - \vec{B}_2)\|} \quad (\text{A.2})$$

$$\hat{y}_B = \frac{\hat{z} \times \hat{x}}{\|\hat{z} \times \hat{x}\|} \quad (\text{A.3})$$

Each time-frame (i) of marker position data (${}^G\vec{P}_i$) expressed in $\{G\}$ was then transformed to be expressed in $\{B\}$ as follows:

$${}^B\vec{P}_i = {}^B_G T {}^G\vec{P}_i \quad (\text{A.4})$$

where ${}^B_G T$ is the inverse of the transformation matrix relating coordinate system $\{B\}$ to $\{G\}$ using column vector notation from Craig, 1989:

$${}^G_B T = \begin{bmatrix} \hat{x}_B & \hat{y}_B & \hat{z}_B & {}^G\vec{B}_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (\text{A.5})$$

Ultimately, *all* marker-based position data were initially collected in $\{G\}$, but immediately transformed to $\{B\}$.

Step#5 – Transformations of Marker Position Data

This section details marker-based digitization of the pinch apparatus and the solution of the sensor coordinate system $\{S\}$, i.e., origin and axis directions, expressed in the base coordinate system $\{B\}$.

Marker-based digitization

A customized lab digitizer was created to define points on the pinch apparatus plates simultaneously in the respective sensor coordinate system $\{S\}$ and the marker coordinate system $\{B\}$. The digitizer was composed of a metal stylus affixed to a planar plastic plate with retro-reflective markers, located remotely to the stylus tip (Figure 9A). The plate was screw connected to four non-collinear retro-reflective markers (D1, D2, D3, D4), each 14 mm in diameter. Similarly to $\{B\}$, an arbitrary coordinate system for the digitizer $\{D\}$ was created from corner markers D1, D2, and D3.

$${}^B_D T = \begin{bmatrix} \hat{x}_D \hat{y}_D \hat{z}_D & {}^B \vec{D}_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (\text{A.6})$$

D4, the slightly off-corner marker, was not required for coordinate system definition but was utilized for offline identification of all digitizer markers in the motion capture software.

The stylus tip was manually interfaced with a grounded metal base at a tapped location (Figure 9A) during a single motion capture trial to determine the tip location relative to $\{D\}$. The digitizer was manually tilted and rotated with the stylus tip in place at the tapped location according to experimenter discretion for approximately 30 seconds. Since it was assumed the digitizer tip was in a fixed position during manual rotations, the motion paths traced for each marker were presumed to be along a spherical surface centered about that tip. A spherical fit was applied to determine the location of the stylus tip ($\vec{x}$) at the tap as expressed in the base coordinate system $\{B\}$. The objective function, again similar to that in Cerveri et al. 2005 was:

$$F(c) = \sum_i^M \sum_j^N \left[(p_{i,j} - \vec{x}) \cdot (p_{i,j} - \vec{x})^T - R_i^2 \right]^2 \quad (\text{A.7})$$

where $M = \# \text{markers}$, $N = \# \text{sampling data}$, and where $p_{i,j}$ and R_i are the position of the i th marker at j th time-step and the radius of the sphere defined by marker $p_{i,j}$ around the location of the stylus tip, $\vec{x}$, respectively, all expressed in $\{B\}$. Once $\vec{x}$ is solved, the position of the stylus tip can be referred from $\{D\}$ for each time-point by:

$${}^D \vec{x} = {}^B_D T^{-1} \vec{x} \quad (\text{A.8})$$

The average ${}^D \vec{x}$ across all collected time-points was taken as the standard reference location, ${}^D \vec{x}_{ref}$, of the stylus tip with respect to $\{D\}$ for all subsequent digitization trials. *Digitization* of an experimenter-selected location subsequently occurred by placing the stylus tip at a designated location and maintaining it in that fixed position over the course of a short (e.g., 3 seconds) motion capture trial. The location of each digitized point, ${}^B \vec{x}_{dig}$, in the base coordinate system $\{B\}$ was then given by:

$${}^B \vec{x}_{dig} = {}^B_D T {}^D \vec{x}_{ref} \quad (\text{A.9})$$

The average $\vec{B}_{x_{dig}}$ was used across all time-points during the digitization trial since it was presumed that the stylus tip was in a fixed position throughout motion capture.

Solving for Sensor Coordinate System

In order to transform force data to be expressed in a common coordinate system with the marker data, it was necessary to calibrate points common to both the force sensor coordinate system $\{S\}$ and that of the base marker coordinate system $\{B\}$. First, the pinch apparatus was constructed such that the plane of each contacting plate was coincident with the origin of its respective sensor. Second, the center of pressure (COP) location of any net force vector applied to the affixed plate was calculated in reference to its respective sensor coordinate system $\{S\}$ as follows:

$$^S x_{COP} = \frac{-(M_y + F_x * c)}{F_z} \quad (\text{A.10})$$

$$^S y_{COP} = \frac{-(M_x + F_y * c)}{F_z} \quad (\text{A.11})$$

$$^S z_{COP} = c \quad (\text{A.12})$$

where F_x , F_y , and F_z were the forces acting in the x-, y-, and z-directions of the sensor local coordinate system, respectively. M_x and M_y were the torques about the x- and y-axes, respectively, and c was the thickness of the sandpaper covering the pinch plate surface ($c = -0.6$ mm).

In order to solve for each sensor coordinate system $\{S\}$ with respect to $\{B\}$, the experimenter digitized three non-collinear points (P_1, P_2, P_3) on the respective, affixed plate in $\{B\}$. In order to explicitly follow the remaining steps for directly solving $\{S\}$, the experimenter needed to digitize points such that P_1 was located below and left of P_2 , and P_3 was located below and right of P_2 when facing the contact-side of the plate. An arbitrary plate coordinate system, $\{P\}$ expressed in $\{B\}$, was created by specifying its x-axis as the unit vector in the direction of $P_2 - P_1$, the z-axis as the unit vector in the direction of the cross-product vector between vector $P_2 - P_1$ and vector $P_3 - P_1$. The y-axis was the resultant cross-product of the aforementioned z-axis with x-axis. The location of each digitized point was determined in both the base coordinate system, $\{B\}$, and that of the sensor coordinate system, $\{S\}$ using the digitizer relationship (equation A.9) and calculation of COP (equations A.10–A.12), respectively. Using the assumption that the plate and sensor coordinate systems share a plane containing their respective x- and y-axes, the location of any point, P_0 , expressed in $\{S\}$ can be determined with respect to $\{B\}$ using the series of trigonometric relationships seen in Figure 9C. The distance d (equation F9.1) and the distances (r_1, r_2 , equation F9.2) between digitized points P_1, P_2 and the point to be solved, P_0 , form a triangle as seen in Figure 9C. Using these distance values and the law of cosines, the angle θ (equation F9.3) was subsequently determined. The direction vector r was determined as a unit-vector initially coincident with the x-axis of $\{P\}$ but rotated by the

angle theta about the negative z-axis of $\{P\}$ and is expressed in $\{B\}$ as described by **equation F9.4**. Finally, translating from P_I expressed in $\{B\}$ a distance r_I along r yields the point of interest P_O (**equation F9.5**), initially specified in $\{S\}$, but now expressed in desired base system $\{B\}$. Therefore, to determine the x-axis and y-axis of $\{S\}$, the above procedure was applied onto $P_O = [1, 0]$ and $P_O = [0, 1]$, respectively. The subsequent cross-product the x-axis onto y-axis yielded the z-axis of $\{S\}$ with respect to base system $\{B\}$.

Figure 1.

A marker set consisting of individual and marker clusters was employed for computation of thumb and index finger kinematics.

Figure 2.

Experimental set-up for pinch tasks **A**: Experiment components include: *monitor display* for subject to follow force trace, *pinch apparatus* for applying forces, and marker cluster affixed to table to define “base” coordinate system $\{B\}$ to which all position and force data will be expressed. Also shown are *alignment reference* to orient apparatus 45 degrees to table edge and *starting position* for hand, approximately 10 cm behind apparatus. **B**: Subject hand shown in “ready” (left panel) position prior to trial onset and in “active pinch” (right panel) position after force profile presented.

Figure 3.

Digit motions for determining functional joint centers of rotation. **A:** Subject performed thumb opposition. **B:** Subject transitioned index finger between *curled* (IP joints maximally flexed, MCP joint maximally extended) and *uncurled* (IP joints maximally extended, MCP joint maximally flexed) positions. *Note:* transparent overlays demonstrate time-dependent transitional states.

Figure 4.

Steps for processing of digit kinematics **A: Identifying joint centers:** Each rotational joint center was calculated from motion of markers on segment proximal to joint relative to marker-based coordinate system affixed to segment distal to joint. **B: Digit alignment:** Static calibration performed using the digit alignment device (left panel) to define anatomical reference for each digit defined by respective block coordinate system (BCS) relative to digit segment markers. Transformations (R) between BCS and each marked-based segment coordinate system (SCS) applied (right panel) to generate analogous anatomically-aligned virtual coordinate system during dynamic pinching trials.

Figure 5.

Overhead view schematic for determination of joint moments. Depicted are the reaction forces acting on each digit through the respective center of pressure location along with the identified joint centers and respective torque arm vectors to the force vectors. All force and position data were time-synchronized and expressed in base coordinate system $\{B\}$.

Figure 6.

Modifications for error analysis session **A**: Additional markers used as surrogate joint center locations for error analysis. TE1 = IP1, TE2 = MCP1, TE3 = CMC1, IE1 = DIP2, IE2 = PIP2, IE3 = MCP2. **B**: Example of digitizer placement and definition of normal axis to estimate location of thumb sensor origin.

Figure 7.

Mean linear regression slopes for joint moment and moment arm distance as a function of mean endpoint normal force for thumb and index finger **A:** Joint moment about aligned axes of coordinate system affixed to segment proximal to joint **B:** Perpendicular moment arm distance from identified joint center location to endpoint force vector passing through measured center of pressure location.

Figure 8.

Graphical User Interface (GUI) for automated processing of digit mechanics utilizing methodological approach **A**: Numeric inputs identify the specific trial data sets required for processing. **B**: Push-buttons utilized to apply step-by-step processing of described methodology. **C**: Options are available in GUI to graphically display select biomechanical variables. **D**: Motion display can be used to show dynamic point locations (moving markers, joint centers, aligned segment coordinate systems) of pinching digits approaching pinch apparatus (shown by digitized points on plate and normal-directed axis of both force sensor coordinate systems) with respect to base coordinate system {B} for each pinch trial.

Figure 9.

Marker-based digitization **A**: Customized lab digitizer with markers D1, D2, D3, and D4 serve to define local "digitizer" coordinate system $\{D\}$ was placed with tip at precision tap for motion trial to determine location of tip expressed in $\{D\}$. **B**: Three point locations (P_1 , P_2 , P_3) digitized on pinch apparatus plate to define arbitrary plate coordinate system $\{P\}$. Locations of points recorded in both base system $\{B\}$ and local sensor coordinate system $\{S\}$. **C**: Trigonometric relationships applied to solve for location of sensor origin (P_0) in $\{P\}$.

Table 1
Linear regression parameters (bias, slope) for select biomechanical variables versus increasing digit endpoint force

JOINT	JOINT ANGLE BIAS (deg)			JOINT ANGLE SLOPE (deg/N)		
	<u>Ext</u>	<u>Abd</u>	<u>Rot</u>	<u>Ext</u>	<u>Abd</u>	<u>Rot</u>
IP1	-23* ± 10	6* ± 5	4 ± 12	-0.01 ± 0.5	-0.18 ± 0.2	0.37 ± 0.3
MCP1	13 ± 11	-7* ± 4	14* ± 3	0.53* ± 0.2	0.21 ± 0.4	0.05 ± 0.2
CMC1	-55* ± 7	5 ± 9	97* ± 17	-0.09 ± 0.1	-0.23* ± 0.1	-0.10 ± 0.3
DIP2	-17* ± 12	11* ± 5	-8* ± 5	-0.15 ± 0.4	-0.04 ± 0.1	0.1 ± 0.2
PIP2	-24* ± 4	2 ± 4	11 ± 12	0.39 ± 0.4	-0.05 ± 0.2	-0.03 ± 0.3
MCP2	-54* ± 7	-1 ± 5	-20* ± 12	-0.37 ± 0.3	0.28* ± 0.1	0.14 ± 0.4
JOINT	JOINT MOMENT BIAS (N-mm/N)			JOINT MOMENT SLOPE (N-mm/N)		
	<u>Ext</u>	<u>Abd</u>	<u>Rot</u>	<u>Ext</u>	<u>Abd</u>	<u>Rot</u>
IP1	-11 ± 8	5* ± 3	-4 ± 9	-1 ± 5	11* ± 6	-2 ± 4
MCP1	-3 ± 5	9* ± 5	-11 ± 24	-8* ± 3	43* ± 9	-21* ± 4
CMC1	-11 ± 24	22* ± 14	6 ± 9	19* ± 9	73* ± 8	14 ± 13
DIP2	2 ± 3	1 ± 7	2 ± 4	4* ± 2	-0.0 ± 2	16* ± 3
PIP2	4 ± 13	-5 ± 12	-0 ± 10	12* ± 5	-17* ± 4	35* ± 7
MCP2	12 ± 25	-4 ± 10	-3 ± 9	-29* ± 6	-76* ± 5	10 ± 10
DIGIT	ENDPOINT FORCE BIAS (N)			ENDPOINT FORCE SLOPE (N/N)		
	<u>Shear-Up</u>	<u>Shear-Prox</u>	<u>Normal</u>	<u>Shear-Up</u>	<u>Shear-Prox</u>	<u>Normal</u>
THUMB	-0.1 ± 0.4	0.3* ± 0.1	0.1 ± 0.1	-0.1 ± 0.1	-0.1 ± 0.2	1.0* ± 0.0
INDEX	0.2 ± 0.2	0.1 ± 0.3	0.1 ± 0.1	0.0 ± 0.1	0.1 ± 0.1	1.0* ± 0.0
DIGIT	MOMENT-ARM MAGNITUDE BIAS (mm)			MOMENT-ARM MAGNITUDE SLOPE (mm/N)		
	<u>IP1/DIP2</u>	<u>MCP1/PIP2</u>	<u>CMC1/MCP2</u>	<u>IP1/DIP2</u>	<u>MCP1/PIP2</u>	<u>CMC1/MCP2</u>
THUMB	16* ± 7	53* ± 10	84* ± 8	-0.28* ± 0.2	-0.35* ± 0.2	-0.51* ± 0.3
INDEX	17* ± 2	40* ± 6	75* ± 6	-0.06 ± 0.1	-0.01 ± 0.2	0.61* ± 0.4

* denotes parameter value is non-zero at $p < 0.05$

Table 2

Error analysis differentials for joint variables of interest for substitutions of select methodological steps

Joint DoF	Step#2 Substituted		Step#3 Substituted		Step#5 Substituted	
	Joint Center Position, mm	Joint Moment, N-mm	Joint Angle, Deg	Joint Moment, N-mm	Joint Force, N	Joint Moment, N-mm
<i>CMCI-x</i>	7.6 ± 1.8*	6.2 ± 2.7*	9.5 ± 0.5*	45.3 ± 2.7*	0.01 ± 0.01*	1.5 ± 0.7*
<i>CMCI-y</i>	1.7 ± 1.1*	97.9 ± 2.9*	14.7 ± 0.5*	8.6 ± 0.9*	0.005 ± 0.002*	6.0 ± 0.4*
<i>CMCI-z</i>	20.3 ± 1.2*	39.0 ± 6.0*	32.5 ± 0.3*	10.4 ± 2.9*	0.04 ± 0.01*	3.6 ± 0.4*
<i>MCP1-x</i>	6.2 ± 1.6*	54.3 ± 3.0*	4.3 ± 0.4*	54.3 ± 2.6*	0.02 ± 0.01*	2.8 ± 0.4*
<i>MCP1-y</i>	4.2 ± 0.8*	10.7 ± 2.0*	15.5 ± 0.8*	23.0 ± 2.4*	0.001 ± 0.003	6.9 ± 0.5*
<i>MCP1-z</i>	5.2 ± 1.1*	53.0 ± 3.8*	2.0 ± 0.3*	38.0 ± 2.5*	0.04 ± 0.01*	1.2 ± 0.6*
<i>TIP1-x</i>	3.3 ± 2.0*	53.2 ± 1.0*	16.8 ± 0.2*	8.2 ± 0.6*	0.14 ± 0.04	3.6 ± 0.4*
<i>TIP1-y</i>	8.3 ± 2.2*	0.2 ± 2.7	2.1 ± 0.3*	3.3 ± 0.4*	0.16 ± 0.76	7.2 ± 0.4*
<i>TIP1-z</i>	1.2 ± 5.3	12.5 ± 1.9*	1.9 ± 0.1*	11.5 ± 0.8*	0.21 ± 0.77	0.5 ± 0.3*
<i>MCP2-x</i>	6.6 ± 1.2*	1.0 ± 1.9*	8.6 ± 0.5*	10.3 ± 2.6*	0.01 ± 0.01*	2.0 ± 0.2*
<i>MCP2-y</i>	24.8 ± 1.2*	9.1 ± 4.3*	7.8 ± 1.2*	7.4 ± 1.3*	0.01 ± 0.01*	7.3 ± 0.4*
<i>MCP2-z</i>	7.9 ± 1.2*	4.3 ± 5.4*	0.3 ± 0.6	38.0 ± 3.2*	0.04 ± 0.01*	0.5 ± 0.3*
<i>PIP2-x</i>	4.5 ± 1.5*	16.7 ± 6.2*	18.3 ± 1.3*	34.0 ± 2.4*	0.01 ± 0.01*	2.4 ± 0.2*
<i>PIP2-y</i>	1.8 ± 0.8*	72.0 ± 5.0*	11.6 ± 1.1*	7.9 ± 1.4*	0.00 ± 0.01	0.1 ± 0.3
<i>PIP2-z</i>	5.0 ± 1.5*	42.6 ± 4.6*	2.3 ± 1.5*	14.2 ± 2.1*	0.04 ± 0.01*	5.0 ± 0.4*
<i>DIP2-x</i>	12.6 ± 1.4*	16.9 ± 4.3*	4.2 ± 1.1*	16.4 ± 1.7*	0.00 ± 0.01	1.7 ± 0.3*
<i>DIP2-y</i>	1.0 ± 0.8*	1.4 ± 5.8	7.9 ± 1.8*	23.8 ± 0.6*	0.01 ± 0.01*	0.3 ± 0.3*
<i>DIP2-z</i>	4.4 ± 1.4*	45.7 ± 1.7*	2.3 ± 0.6*	1.4 ± 1.6*	0.04 ± 0.01*	5.0 ± 0.3*
MEAN	7.03	29.80	9.04	19.78	0.04	3.21

Notes:

- (1) Only 'absolute' differentials are given
- (2) For DoFs, x = flexion-extension, y = abduction-adduction, z = axial rotation
- (3) * indicates significant differential from 'gold standard' for $p < 0.05$