Robust Identification of Three-Dimensional Thumb and Index Finger Kinematics With a Minimal Set of Markers

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This study presents a methodology to determine thumb and index finger kinematics while utilizing a minimal set of markers. The motion capture of skin-surface markers presents inherent challenges for the accurate and comprehensive measurement of digit kinematics. As such, it is desirable to utilize robust methods for assessing digit kinematics with fewer markers. The approach presented in this study involved coordinate system alignment, locating joint centers of rotation, and a solution model to estimate three-dimensional (3-D) digit kinematics. The solution model for each digit was based on assumptions of rigid-body interactions, specific degrees of freedom (DOFs) at each located joint, and the aligned coordinate system definitions. Techniques of inverse kinematics and optimization were applied to calculate the 3-D position and orientation of digit segments during pinching between the thumb and index finger. The 3-D joint center locations were reliably fitted with mean coefficients of variation below 5%. A parameterized form of the solution model yielded feasible solutions that met specified tolerance and convergence criteria for over 85% of the test points. The solution results were intuitive to the pinching function. The thumb was measured to be rotated about the CMC joint to bring it into opposition to the index finger and larger rotational excursions (>10 deg) were observed in flexion/extension compared to abduction/adduction and axial rotation for all joints. While the solution model produced results similar to those computed from a full marker set, the model facilitated the usage of fewer markers, which inherently lessened the effects of passive motion error and reduced the post-experimental effort required for marker processing. [DOI: 10.1115/1.4024753]

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Introduction

The robust measurement of digit kinematics is critical to accurately characterize the exquisite control and function of the hand. Motion capture methods employing infrared cameras to track three-dimensional (3-D) positions of retro-reflective markers placed at anatomical reference points on the hand and digits are regularly employed [1–3]. From these data, kinematics are derived that describe the positions and orientations of the digit segments. Despite technological advances in camera processing and resolution, quantifying functional movements from skin-surface markers still pose notable challenges. Potential sources of error include inaccurate marker placement, marker superimposition and occlusion from camera view, and passive skin movement [4–6].

Our laboratory has devised methods to mitigate certain errors for digit motion capture by utilizing marker clusters affixed to nails and a device to establish anatomical coordinate systems [7]. Affixing clusters to the nail rather than a more compliant skin surface reduced error from passive marker motion. Next, a unique transformation was reliably derived from a static calibration to determine a virtual digit-aligned coordinate system from an arbitrarily placed nail cluster, thereby nullifying placement error. In this study, the basic approach from Ref. [7] for measuring distal segment orientations has been substantially extended for advanced and comprehensive 3-D kinematic descriptions of

the entire thumb and index finger digits, including determination of the joint center locations, relative joint angles, relative segment positions, and coordinate system alignment of all involved digit segments.

The current study presents a three-step approach to robustly determine 3-D digit kinematics of thumb and index finger precision grasp (i.e., “pinching”) [1] by solving a mathematical model defined by a minimal set of markers as an alternative to direct computations from a more complete marker set. Pinching is a basic manual function for object manipulation [8] and can exhibit precise changes in digit posture, which require rigorous methods of measurement for accurate characterization [9]. The current approach relied more on a mathematical formulation to determine the kinematic quantities of the thumb and index finger during a precision pinch rather than additional marker data susceptible to the aforementioned sources of error and necessitating additional post-experiment time to process these data. The first step identified the 3-D locations of functional joint centers of rotation. The second step was the anatomical alignment of marker-based coordinate systems, as described in Ref. [7]. The third step involved utilizing a mathematical model to solve kinematic quantities not directly measurable from the minimal marker set during a dynamic pinching trial. The solution model utilized optimization and assumptions of rigid-body interactions. While no comparative gold standard was available to assess the absolute accuracy in this study, the solution outputs were compared against results directly computed from a complete marker set to demonstrate a basis for efficacy. The complete marker set data did not represent a definitive standard since they were susceptible to the aforementioned sources of error.

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Fig. 1 Marker sets employed in the current study. (a) The minimal marker set (nine markers total), (b) the intermediate marker set (17 markers total), and (c) the complete marker set (21 markers total).

Methods

Subject and Marker Sets. One session with each of the six able-bodied subjects (1 female, 5 male, ages 22–33) was conducted. The subjects signed informed consent forms approved by the local institutional review board. The subjects neither reported nor showed notable deficits in hand function. The minimal marker set for this study (see Fig. 1(a)) was comprised of two three-marker nail clusters [7] and a skin cluster on the hand serving as a local reference coordinate system, following the ISB convention [10]. Additional details about the nail cluster can be found in Ref. [7], but the nail-cluster has 4 mm diameter markers, a 1 mm diameter connective metal rod, and a base made from Roylan™ splinting material. These dimensions and materials yielded a cluster with negligible inertia and mass (<1.5 g), significantly lower than that of our subject's hand, which is approximately 450 g, according to anthropometric scaling factors reported in Ref. [11].

The hand cluster was longitudinally aligned along the second metacarpal and placed at a stable location, both dorsally and proximally, to avoid protrusion of the first dorsal interosseus muscle. An intermediate marker set was employed only for digit motion trials to identify joint centers (see Fig. 1(b)). It additionally included two isolated markers placed dorsal-center on the remaining digit segments (first metacarpal, thumb and index proximal phalanges, and index middle phalanx). The complete marker set included a three-marker cluster on every digit segment (see Fig. 1(c)) for the direct computation of the digit kinematics as comparison values. Compared to the minimal marker set, it additionally included three-marker skin clusters instead of isolated markers on the remaining digit segments. Cluster markers were not collinear in order to define a local 3-D coordinate system affixed to their respective segment where positive $\hat{x}$, $\hat{y}$, and $\hat{z}$ axes pointed right, superior, and proximal, respectively, from a dorsal

perspective [7]. For all motion capture trials, the 3-D positions of the retro-reflective markers were tracked at 100 Hz with respect to a globally-fixed reference specified by the motion capture system (Model 460, Vicon Motion Systems and Peak Performance, Inc., Oxford, UK). Each isolated marker or cluster was affixed onto flat soft plastic adhering to the skin using double-sided adhesive tape.

Step 1: Identification of the Joint Centers. Upon donning the intermediate marker set, the subject performed one motion trial for each digit that produced near-maximal rotational excursions at each joint. These motion data were used to determine the centers of rotation of the following joints: 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 (thumb), the subject performed ten repetitions of thumb circumduction [12]. In the second trial (index finger), the subject performed ten continuous transitions between curled (IP joints maximally extended, MCP joint maximally flexed) and uncurled (IP joints maximally extended, MCP joint maximally flexed) positions.

Step-wise spherical fitting and coordinate system transformations were subsequently executed to identify the average locations of functional joint centers [13,14]. 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 (see Fig. 2(a)). In Fig. 2(a), each rotational joint center was calculated from the motion of the markers on Segment B relative to the marker-based reference coordinate system {Ref} affixed to Segment A. Motion markers traced spherical paths with respective radial distance (dashed lines) from the joint center location to be identified.

Fig. 2 Identifying the joint centers in the distal to proximal direction. (a) General demonstration of how the joint center is identified according to the spherical motions of markers affixed to one segment relative to the reference frame on an adjacent segment. (b) Coordinate systems affixed to each digit segment and the corresponding joint centers for each digit. (Notes: the blue circles indicate the index finger joint centers and the green circles indicate the thumb joint centers; the figure of the hand was generated in Poser software (SmithMicro Inc., Watsonville, CA.)

Fig. 3 Digit alignment protocol. (a) Static calibration of the thumb and index finger was performed using the digit alignment device (DAD) and nail marker clusters. (b) Transformation relationships among the block coordinate system (BCS), cluster coordinate system (CCS), and virtual coordinate system (VCS) were derived. (c) In the current study, the thumb and index finger were interfaced with the digit alignment device (DAD) to align all clusters in the full marker set. (Note: figures (a) and (b) are adapted from [7].

A transformation matrix for {Ref} was defined by the rotation matrix R_{Ref} from the convention described in Ref. [7] fixed to a selected origin $\bar{P}_{\text{Ref}}$ expressed in global coordinates (using notation from Re. [15])

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

The transform inverse T_{Ref}^{-1} was applied to the motion marker data to express them in {Ref}. Assuming purely rotational joint motion [10], 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 [16]

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

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

The nail cluster affixed to the thumb distal phalanx (DP1) defined coordinate system {DP1} with the origin arbitrarily located on the middle of the nail surface to first serve as {Ref} and calculate O_{IP1} from the motion paths of the markers on the thumb proximal phalanx (PP1). The PP1 motion markers and O_{IP1} , serving as a pseudomarker, defined a coordinate system affixed to the thumb proximal phalanx {PP1} to calculate the joint center O_{MCP1} from motion markers on the first metacarpal (MC1). Finally, the MC1 motion markers and O_{MCP1} defined the coordinate system {MC1} to calculate the joint center O_{CMC1} from the motions of the markers constituting the hand cluster. Joint centers were identified from distal to proximal because the nail cluster was the most stable reference that minimized the propagation of calculation errors. Similarly applying the preceding procedure yielded the index finger joint centers (O_{DIP2} , O_{PIP2} , and O_{MCP2}) from the segment coordinate systems for the distal phalanx (DP2), middle phalanx (MP2), and proximal phalanx (PP2). The mean inter-joint distances yielded segment lengths PP1, MC1, MP2, and PP2.

When utilizing the minimal marker set, the distal joint centers remain referenced from the respective nail-cluster coordinate systems as ${}^{\text{DP1}}O_{\text{IP1}}$ and ${}^{\text{DP2}}O_{\text{DIP2}}$. Since the proximal segment coordinate systems {MC1} and {PP2} would be unavailable, joint centers O_{CMC1} and O_{MCP2} need to be alternatively referenced from the hand-cluster coordinate system {MC2} whose origin was

arbitrarily selected as the average position of its three markers. The alternative references could be derived by the chain-rule relationships

$${}^{\text{MC2}}O_{\text{CMC1}} = T_{\text{MC2}}^{-1} T_{\text{MC1}} {}^{\text{MC1}}O_{\text{CMC1}} \quad (3)$$

$${}^{\text{MC2}}O_{\text{MCP2}} = T_{\text{MC2}}^{-1} T_{\text{PP2}} {}^{\text{PP2}}O_{\text{MCP2}} \quad (4)$$

It was observed that ${}^{\text{MC2}}O_{\text{CMC1}}$ was not dynamically stable due to the relative CMC motion to the MC2. For correction, a simple linear regression utilizing the 3-D position data of the nail-cluster markers expressed in {MC2} as inputs and the ${}^{\text{MC2}}O_{\text{CMC1}}$ as outputs was formulated and applied for the identification of ${}^{\text{MC2}}O_{\text{CMC1}}$ in subsequent dynamic trials. An additional motion trial involving ten continuous repetitions of maximal thumb opposition [12] was performed in order to validate the estimate of ${}^{\text{MC2}}O_{\text{CMC1}}$ by the linear regression model.

As shown in Fig. 2(b), the nail-cluster coordinate systems {DP2} and {DP1} for the index finger (blue) and thumb (green), respectively, served as the initial reference {Ref} to calculate the distal joint centers (DIP2 and IP1, respectively). The distal joint center and middle digit motion markers defined the coordinate systems {MP2} and {PP1} to calculate the centers of the PIP2 and MCP1 joints. Finally, {PP2} and {MC1} were established to calculate the centers of the MCP2 and CMC1 joints. When utilizing the minimal marker set, the PIP2 and MCP1 joint centers (lighter filled areas) cannot be directly referenced but were solved by mathematical formulation and the MCP2 and CMC1 joint centers were alternatively referenced by the hand coordinate system {MC2} affixed to the second metacarpal.

Step 2: Static Calibration for Coordinate System Alignment. The isolated markers were removed and replaced with marker clusters to form the complete marker set. The subject interfaced the thumb and index finger with a block apparatus (“digit alignment device,” (DAD); see Fig. 3) at a static calibration position, as outlined in Ref. [7], during a 3 s motion capture trial. A pure rotational transformation ${}^{\text{CCS}}R_{\text{BCS}}$ (see Eq. (5)) was determined for each cluster coordinate system {CCS} for alignment with a block coordinate system {BCS} serving as the standardized alignment reference. Applying this static transform during dynamic trials produced the corresponding digit-aligned virtual rotation matrix {VCS}, given as R_{VCS} (see Eq. (6))

$$\text{Static calibration: } {}^{\text{CCS}}R_{\text{BCS}} = R_{\text{CCS}}^{-1} R_{\text{BCS}} \quad (5)$$

$$\text{Dynamic trials: } R_{\text{VCS}} = R_{\text{CCS}} {}^{\text{CCS}}R_{\text{BCS}} \quad (6)$$

This transformation procedure was applied to the initial arbitrary coordinate system affixed to each digit segment. At the static

Fig. 4 Dynamic pinch trial. (a) Hand in the open position to initiate (and terminate) pinch cycle. (b) Hand in the closed tip-pinch position. The tip-pinch configuration position approximated the functional grip of small-width objects, resulting in the exertion of low finger joint forces [1].

calibration position, all index finger digit segment coordinate systems were aligned with the coordinate system affixed to the top of the DAD, while those for the thumb were aligned with the coordinate system affixed to the side of the DAD. However, unlike in the study in Ref. [7], a coordinate system was also created based on the hand marker cluster on the second metacarpal serving as the local hand reference frame. For this coordinate system, another rotational transformation was performed in order to consider the constrained flexion at the MCP joint of the index finger in the calibration position. This resulted in an orientation bias between the hand cluster and the block coordinate system. To compensate for this, the rotation angle between the prealigned z -axes of the hand and proximal phalanx of the 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 3: Applying the Solution Model

Dynamic Pinching Trial. The subject performed 10 consecutive cycles of pinching at a comfortable self-selected pace during a single motion capture trial. A cycle began with the hand in the open position (see Fig. 4(a)) with digits fully, but comfortably, extended. The thumb and index finger smoothly transitioned to a closed tip-pinch configuration (see Fig. 4(b)) and returned to the open position to complete the cycle.

Mathematical Solution Model. A mathematical model was created for each digit. Each digit was assumed to be composed of three rigid-body segments serially connected from the hand reference segment by 1-, 2-, or 3-DOF rotational joints. The index finger was assumed to have 2, 1, and 1 DOFs, at the MCP2, PIP2, and DIP2 joints, respectively, and the thumb was assumed to have 3, 2, and 1 DOFs at the CMC1, MCP1, and IP1 joints, respectively [17] (see Fig. 5(a)). Known and unknown kinematic quantities were parsed for the index finger model in Fig. 5(b). Coordinate systems affixed to the hand {MC2} and index distal phalanx {DP2} were explicitly known from the marker data and served as references to estimate O_{MC2} and O_{DIP2} , as previously determined. The proximal (L_{PP2}) and middle (L_{MP2}) phalanx segment lengths were also previously estimated. The remaining unknown kinematic quantities of interest were joint center location O_{PIP2} and the segment coordinate systems {PP2} and {MP2}.

Solution Optimization. The unknown kinematic quantities composed 21 solution elements (3-D location of O_{PIP2} and three 3-D rotation axes ($\hat{x}, \hat{y}, \hat{z}$) for {MP2} and {PP2})

Fig. 5 Solution modeling of the thumb and index finger digits. (a) Presumed solution model for each digit formed a 3-segment serial-link open chain from the hand segment treated as a grounded reference. Moving proximal-to-distal, the index finger joints were assumed to have 2, 1, and 1 degrees of freedom (DOFs). The corresponding thumb joints have 3, 2, and 1 DOFs. (b) Sagittal view for the index finger showing the joint positions (O_i , where i indicates proximal, middle, or distal) and aligned coordinate system axes ($\hat{x}, \hat{y}, \hat{z}$) affixed to the corresponding segment. (Note: lateral axes ($\hat{x}$) are not shown but assumed to point into the page). (c) Parameterized index finger model was used for optimization with unknown quantities parameterized to be a function of only three unknowns (axial rotation angles θ_{L1} , θ_{L2} , θ_{P2}). (Note: the figure of the hand is from pixelperfectdigital.com)

$$s = [O_{PIP2} \hat{x}_{MP2} \hat{y}_{MP2} \hat{z}_{MP2} \hat{x}_{PP2} \hat{y}_{PP2} \hat{z}_{PP2}] \quad (7)$$

The $\hat{z}$ for each segment was defined to equal the unit vector directed longitudinally to the segment by connecting adjacent joint center locations

$$z_{ij} = \frac{O_{ij} - O_{i+1j}}{\|O_{ij} - O_{i+1j}\|} \quad (8)$$

where i is the segment, j is the direction component expressed in {MC2}. Note that ' $i-1$ ' and ' $i+1$ ' denote the segment "proximal" and "distal" to ' i ', respectively.

The $\hat{x}$ and $\hat{y}$ rotation axes were unit vectors perpendicular to $\hat{z}$ by definition

$$x_{ij} = \frac{x_{ij}}{\|x_{ij}\|}, \quad y_{ij} = \frac{y_{ij}}{\|y_{ij}\|}, \quad \hat{x}_i = \hat{y}_i \times \hat{z}_i, \quad \hat{y}_i = \hat{z}_i \times \hat{x}_i \quad (9)$$

Presuming rigid-body kinematics and nontranslational joints, the previously specified segment lengths L_{PP2} and L_{MP2} were assumed to be invariant.

The remaining system equations specify the number of rotational DOFs at each joint and were treated as constraints to be satisfied within tolerance. Joint rotations were calculated as order-dependent ($\hat{x} - \hat{y} - \hat{z}$) Euler angles between aligned coordinates systems of adjacent segments. Aligned axes of rotations were assumed to correspond to anatomical flexion/extension ($-\hat{x}, +\hat{x}$), abduction/adduction ($-\hat{y}, +\hat{y}$), and axial rotation ($+\hat{z}$ is clockwise from the anterior perspective). Therefore, the DOF constraint equation for the joint at O_i was

$$\hat{x}_i = \hat{x}_{i-1} \text{ for 1-DOF or } \hat{y}_i \cdot \hat{x}_{i-1} = 0 \text{ for 2-DOF} \quad (10)$$

There were no additional constraints for 3-DOFs.

Parameterized Form of Solution. The dimensionality of the optimization solution vector was parametrically reduced to three axial rotation angles for faster solution convergence

$$s'(\theta) = [\theta_O \ \theta_{L1} \ \theta_{L2}] \quad (11)$$

The original solution vector s was then derived from these angles (see Fig. 5(c)). As per convention, $\hat{z}_{PP2}$ and $\hat{z}_{MP2}$ initially belonged to the plane containing $\hat{y}_{DP2}$ and $\hat{a}$, the vector connecting O_{MCP2} to O_{DIP2} . A known rotation of θ_O about $\hat{a}$ explicitly determined O_{PIP2} . Subsequent rotations of θ_{L1} and θ_{L2} about $\hat{z}_{PP2}$ and $\hat{z}_{MP2}$ fully determine {PP2} and {MP2}.

The constrained optimization routine '*fmincon*' from the Optimization Toolbox was applied to solve $s'(\theta)$ using the Levenberg-Marquardt algorithm [18]. The objective function

quadratically minimized the parameterized axial rotation angles as

$$F = \frac{1}{n} \sqrt{\sum_{i=1}^n \theta_i^2} \quad (12)$$

where i is the angle index and $n=3$ for the total number of angles. The solution and objective function tolerance was 0.05 rad, which was <1% of the full angular range $[0, 2\pi]$. The constraint tolerance was 0.1, which was 5% of the domain $[-1, 1]$ over which the unit vectors lie. Both the maximum allowable number of iterations and function evaluations was 1000. These tolerance values were manually selected in order to facilitate a vast majority of solution points to converge for the presumed number of DOFs assigned to each joint.

Computing Kinematic Quantities From the Full Marker Set for Comparison. For the full marker set, the orientation kinematics was also represented as Euler angle rotations between adjacent segment coordinate systems defined directly by the affixed marker cluster. However, O_{PIP2} needed to be estimated by averaging the position along $\hat{z}_{MP2}$ a distance L_{MP2} from O_{DIP2} and the position along $-\hat{z}_{PP2}$ a distance L_{PP2} from O_{MCP2} . While these two positions should theoretically be similar, this condition is not guaranteed in the presence of any passive motion or alignment errors.

All of the preceding procedures were analogously applied to the thumb model case to determine the O_{MCP1} and rotation axes for {PP1} and {MC1}.

Results

Estimation of Joint Centers and Segment Lengths. Standard deviations on the fitted spherical radius were <1.5 mm for all identified joint centers and the respective coefficients of variation were <5% (see Table 1). The corresponding segment lengths estimated from the inter-joint distances were shown to be stable with the mean standard deviations (SD) < 2.0 mm during the identification trial. To estimate solution dependence on this variation of segment length, the mean angular errors were estimated as changes in the angles of the triangle formed in the solution plane (see Fig. 5(c)) following a 1 SD increase in the middle and proximal segment lengths from the mean kinematic posture observed during the dynamic pinching trial, as computed by the law of cosines. All estimated solution planar angles due to a 1 SD increase in both segment lengths were <10 deg. When the CMC position was referenced from {MC2} instead of {PP1} for the validation trial, the SD on the proximal segment length was notably high (>10 mm for all subjects). However, applying the linear regression reduced the length SD to <2 mm for all subjects, which

Table 1 Joint center identification and segment length estimation results across six subjects

	Index finger			Thumb		
	R_{DIP2}	R_{PIP2}	R_{MCP2}	R_{IP1}	R_{MCP1}	R_{CMC1}
Mean error of fitted spherical radius, mm	0.49 ± 0.36	0.68 ± 0.55	1.32 ± 0.98	1.62 ± 0.66	0.65 ± 0.19	1.74 ± 0.86
Mean coefficient of variation on radius, %	1.6	2.3	2.6	3.1	1.7	4.7
	Index finger		Thumb			
	Middle phalanx (L_{MP2})	Proximal phalanx (L_{PP2})	Proximal phalanx (L_{PP1})	Metacarpal (L_{MC1})		
Mean length, mm	37.1 ± 14.4	48.9 ± 14.6	44.7 ± 9.1	49.4 ± 12.3		
SD on length, mm	1.2 ± 0.9	1.6 ± 1.2	2.0 ± 0.9	2.4 ± 1.1		
Estimated mean angular error due to 1 SD on length, deg ^a	6.1, 7.6, -9.3		4.9, 2.9, -6.6			

^aThe three angle values reported denote the planar triangle angle near the distal, proximal, and middle joints, respectively, due to 1 SD increase in both the middle, and proximal digit segments of model.

Fig. 6 Plots are shown of the sample data of the solution model versus the comparison (from full marker set) values for the estimation of the index finger middle joint (PIP2) position and angles for the MCP2, PIP2, and DIP2 joints

is similar to that observed for the identification trial with reference from {PP1}.

Solution Model. Over 90% of the data points tested satisfied the constraint tolerance and over 85% satisfied the objective function and solution tolerance for convergence. Sample solution results for the index finger digit (PIP2 position, MCP2/PIP2/DIP2 Euler angles) for two complete pinch cycles are shown in Fig. 6. These results compared well visually to those computed from the full marker set in terms of similar initial (at time=0) set point values and a high correlation in dynamic trajectories. There are notable (>20 deg) phasic dynamic differentials for the PIP2 extension and MCP2 axial rotation.

A summary of the results for the solution model output of position kinematics for both digits are shown in Table 2. Observing the mean angle values across digit joints, the PIP2, MCP2, MCP1, and IP1 joints were typically in flexion (>15 deg) during pinching. The CMC1 joint was typically flexed, abducted, and axially rotated. Observing the root mean square (RMS) about the mean value, the pinching trial produced significant (>10 deg) excursions of all digit joints in extension-flexion. Although MCP2 was constrained to only have 2 DOFs, notable changes in the axial rotation were obtained within the specified constraint tolerances. The mean position components of the middle joint for both digits (PIP2, MCP1) indicate the joints were anterior and left to the hand coordinate system translated to the respective proximal joint. The position component demonstrating the highest RMS for the thumb and index middle joints were along the posterior and superior axis, respectively. These position results were intuitive for pinching as the digits make contact on the palmar side of the hand.

When comparing the solution model to the full marker set, the computed results demonstrated clear similarities and notable differences. The mean joint angle difference across all DOFs was 11.4 ± 5.5 deg. The analysis of variance (ANOVA) indicated that mean joint angle differences across all DOFs for the thumb was greater than the difference across all DOFs for the index finger. It should be noted that, ultimately, comparisons were made only between the proposed model solution output and that from the complete marker set, as opposed to the intermediate marker set. Since the individual markers from the intermediate marker set were replaced by marker clusters, the intermediate marker set was no longer available for explicit representation during the functional trials. The correlations (ρ) between the joint angle

trajectories ranged from 0.65–0.92, but were typically higher for extension-flexion trajectories, which also demonstrated higher RMS values. The mean differences (Δ) for the PIP2 and MCP1 ranged over [2.6,4.8] and [4.4,5.8] mm, respectively. A one-way ANOVA suggested that these position differences were greater for the thumb than the index finger ($p < 0.01$). The correlations for the PIP2 and MCP1 positions were 0.85–0.96 for all components.

Discussion

The current study presents an alternative approach to compute 3-D kinematics of the thumb and index finger during pinching by relying more on mathematical formulation in order to reduce the amount of marker data required. This inverse kinematics approach assumed rigid-body mathematical models such that the explicit description of digit kinematics by affixed markers was not required for all segments. Specific considerations were outlined as part of a comprehensive three-step approach in order to determine quantitative kinematic values of the pinching digits corresponding to assumptions of constant segment lengths, aligned segment coordinate systems, identified joint center locations, and the number of degrees of freedom at each joint. Requiring fewer markers inherently mitigated errors associated with traditional motion capture by decreasing the likelihood of superimposition and occlusion while reducing the total amount of data susceptible to passive motion. Furthermore, requiring less marker data notably reduces the post-experiment processing time. While the joint center identification trials did require a total of 17 markers, only four short of the designated full marker set, the eight additional markers beyond the minimal marker set (nine total) were only required for the two digit motion trials. Presumably, many subsequent dynamic pinching trials may be executed in which only the minimal marker set is needed when utilizing the current approach. The only additional required step to the overall approach includes a single calibration trial with the digit alignment device block. Overall, once the materials and methods of the approach have been established, the additional effort for online data collection is minimal, while the post-processing of marker data has been substantially reduced.

The solution models produced intuitive reliable results for pinching kinematics in assuming the rigid-body interaction, conventional notions of digit joint DOFs, and the aligned coordinate system definitions. Joint center identification was demonstrated to

Table 2 Kinematic quantities determined by the solution model across six subjects

General kinematics during pinch						
Joint	Index finger			Thumb		
	MCP2	PIP2	DIP2	CMC1	MCP1	IP1
Extension angle mean, deg	-30 ± 8	-20 ± 8	-16 ± 6	-24 ± 10	-15 ± 7	-34 ± 22
Abduction angle mean, deg	-5 ± 10	-2 ± 8	2 ± 12	25 ± 6	4 ± 3	5 ± 7
Axial rotation angle mean, deg	-1 ± 12	-1 ± 2	3 ± 10	95 ± 7	-1.5 ± 2	1 ± 8
Extension angle RMS ^a deg	26 ± 2	19 ± 4	13 ± 2	16 ± 4	10 ± 4	34 ± 10
Abduction angle RMS ^a deg	9 ± 4	10 ± 4	7 ± 2	14 ± 5	4 ± 3	9 ± 6
Axial rotation angle RMS ^a deg	11 ± 5	8 ± 4	2 ± 1	41 ± 28	1 ± 1	8 ± 6
Joint		PIP2			MCP1	
Rightward (+x) position ^b mean, mm		-7 ± 12			-6 ± 36	
Superior (+y) position ^b mean, mm		-22 ± 8			-12 ± 26	
Posterior (+z) position ^b mean		-36 ± 7			-26 ± 10	
Rightward (+x) position ^b RMS, ^a mm		6 ± 4			11 ± 10	
Superior (+y) position ^b RMS, ^a mm		17 ± 4			12 ± 9	
Posterior (+z) position ^b RMS, ^a mm		19 ± 10			9 ± 8	
Comparison of kinematics computed by solution model to complete marker set values						
Joint	Index finger			Thumb		
	MCP2	PIP2	DIP2	CMC1	MCP1	IP1
Δ in extension angle, deg	17 ± 7	14 ± 4	10 ± 4	15 ± 6	19 ± 7	13 ± 7
Δ in abduction angle, deg	12 ± 5	12 ± 8	8 ± 3	13 ± 3	12 ± 4	9 ± 4
Δ in axial rotation angle, deg	9 ± 6	9 ± 8	10 ± 6	9 ± 8	9 ± 6	11 ± 3
ρ for extension angle	0.89 ± 0.2	0.93 ± 0.1	0.74 ± 0.3	0.85 ± 0.3	0.72 ± 0.3	0.92 ± 0.1
ρ for abduction angle	0.88 ± 0.2	0.88 ± 0.2	0.71 ± 0.3	0.80 ± 0.3	0.72 ± 0.3	0.79 ± 0.3
ρ for axial rotation angle	0.87 ± 0.2	0.84 ± 0.3.	0.65 ± 0.3	0.86 ± 0.3	0.65 ± 0.3	0.86 ± 0.1
Joint		PIP2			MCP1	
Δ in rightward (+x) position ^b , mm		2.6 ± 1.5			4.4 ± 2.8	
Δ in superior (+y) position, ^b mm		4.8 ± 0.8			5.6 ± 1.8	
Δ in posterior (+z) position, ^b mm		3.6 ± 1.3			5.8 ± 2.4	
ρ for rightward (+x) position ^b		0.95 ± 0.1			0.87 ± 0.1	
ρ for superior (+y) position ^b		0.96 ± 0.1			0.88 ± 0.1	
ρ for posterior (+z) position ^b		0.95 ± 0.1			0.85 ± 0.1	

Note: Δ denotes the 'difference' between results for the solution model and complete marker set and ρ denotes the Pearson 'correlation' coefficient at the 95% confidence interval between results for the solution model and complete marker set.

^aThe RMS is the root mean square taken about the mean value across the entire pinch trial.

^bPosition coordinates are expressed in {MC2} but with the origin translated to the proximal joint for the digit.

be feasible by the small variations on the spherical fits, which was also critical in assuming invariant segment lengths. Solution convergence was reliable since over 85% of the data points met the specified tolerances. The RMS angle values were highest for flexion/extension, indicating that the index finger and thumb moved towards one another primarily along their respective flexion/extension planes. The thumb was notably rotated about all three axes at CMC1 to oppose and meet the index finger. The markers that composed the minimal marker set were also convenient and well-designed for this application. The nail clusters and small markers have negligible weights and there were no notable differences observed or perceived by the subject in performing pinching movements while donning the markers.

Ultimately, this study did not have a "gold standard" for the absolute assessment of the method accuracy. Therefore, solution results were presented for demonstration as "differences" to a conventional approach utilizing the full marker set and were not characterized as "errors" to indicate solution accuracy. The basic differences between the two methods may be attributable to approach. Both methods relied on data referenced from the nail and hand clusters, but the solution model determined the remaining kinematic quantities utilizing mathematical formulation. The full marker set directly yielded these quantities from the

remaining skin clusters, which were still susceptible to typical sources of error. The thumb skin clusters were particularly prone to passive motion errors generated by adjacent bulky musculature and interposing tendons. Our results indeed showed a relatively larger discrepancy between the kinematic output of the solution model and that from the full marker set for the thumb. Since this discrepancy may be, in large part, due to motion artifact, it cannot be concluded that the solution model necessarily better represents true skeleton kinematics, given the lack of a comparative gold-standard. For the index finger, the differences in kinematic output were relatively smaller, which is consistent with the less severe artifact to be expected. The sample data of Fig. 6 visually shows the good agreement in the set point and correlation between the two methods. The notable phasic joint angle differentials observed in certain cases (e.g., PIP2 extension) may be due to a skin motion artifact, accentuated during larger, more dynamic movements.

The DAD protocol [7] should have nullified *initial* misalignment errors for the skin clusters, but passive motion *during* dynamic activity can produce orientation changes of the cluster independent of its respective segment. Purely longitudinal skin motion may preserve orientation [19], but relative tilting or twisting of the entire skin cluster would not. Although isolated markers

could be employed instead, unlike a cluster, these markers may incur relative motion *between* themselves. This inter-marker motion would corrupt coordinate system axis definitions [7] since the small position errors of markers in close proximity can produce significant directional errors of the correspondingly defined axes. For maximal spacing, routines could be applied to compute flexion/extension kinematics using markers placed only at the digit segment endpoints [3]. However, 3-D kinematics would still require tracking markers outside the flexion-extension plane.

Additional limitations of this study included reliance on one skin cluster serving as the hand reference, additional trials for joint center identification, and presumed digit mechanics. Although prone to passive motion, the hand cluster was designed and positioned to mitigate those effects. A stable position could be readily found because of the greater length of its affixed segment (second metacarpal) and a larger cluster substrate was utilized to increase inter-marker spacing, making related axis definitions more robust. Although joint center identification required additional trials and markers, the digit motion trials were facile to execute and did not add notable experimental time or effort. The eight additional single markers over the minimal marker set were required for only one additional motion trial for each digit. These single markers can then be removed for every subsequent motion capture trial. This reduced marker set can significantly reduce experimenter post-processing time in performing tasks such as identifying and discriminating additional markers, gap-filling trajectories, and correcting mis-labeling due to occlusions and superimpositions. It should be noted that the intermediate marker set theoretically could also be utilized for direct computation of digit kinematics if the identified joint centers again serve as pseudomarkers, but this would require re-introduction of those eight additional markers for additional motion capture trials.

Regarding the presumed digit mechanics, the mathematical formulation was fundamentally constrained by the DOFs specified at each joint and by the defined objective function and their respective tolerance values. Although MCP2 was constrained to only 2DOFs (flexion-extension, abduction-adduction) by assumption, the selected constraint tolerance values allowed notable axial rotation. This suggested that axial displacements of the DP2 relative to MC2 were present. Additionally, while our assumption of nontranslating joint centers may be sufficient to provide reasonable gross descriptions of joint angle kinematics, it is a potential source of error, as previous studies [20,21] have indicated, translating joint centers of rotation for the hand digits. Certainly, the experimental trade-off to consider this effect is potentially greater model complexity and requiring more marker data for highly accurate localization. However, in this study, our spherical fitting results for joint center identification typically showed coefficients of variation of less than 5%. The standard deviations on the segment lengths from the referenced joint center locations during digit motion trials were <2 mm. It was determined that the planar angular errors associated with an increase of one standard deviation of respective length for the proximal and middle segments were generally <10 deg.

While only six subjects were investigated, this was not, in itself, a presumed limitation in this study. The methodology was constructed in closed-form to be conceptually self-evident and facilitate a reduction in the number of markers required. As such, the solution accuracy is predicated only on the assumed constraints (i.e., segment lengths, rigid-body dynamics, rotational joints, and DOFs at each joint) and the model solution cannot serve as a gold standard. The full marker set also does not represent a gold standard due to its own susceptibility to inaccuracy from a passive motion artifact. The corresponding full marker set results were only shown for a basic comparative reference as the presumably conventional conceptual alternative. Without a gold standard based purely on empirical observation, true accuracy or robustness metrics cannot be derived in this study. As such, the collection and analysis of additional data subject sets only provides mean $\pm$ standard deviation information about the function (e.g.,

pinching) being performed and do not yield accuracy, precision, or robustness measures of the proposed method itself. However, the small sample size does provide some measure of the transferability of this method. In the future, it may be desirable to consider a rigorous validation model, which is outside the scope of this study, that serves as a gold standard, and which may involve advanced imaging, robot, or cadaver techniques. Utilizing such a paradigm would better justify reported robustness and accuracy metrics across a larger subject population.

Overall, the fundamental value of this approach is the presentation of a complete set of steps to determine digit kinematics but with less marker data, which has well-known confounding issues during collection and post-processing. To compensate for less marker data, thorough considerations were made regarding the digit segment coordinate system alignment, joint center and corresponding segment length identification, and mathematical model structuring. In the future, we seek to apply this methodology to multiple hypothesis-driven projects that include adequate sample sizes. Once the initial time and effort is made to establish these methods in practice, the additional time or steps in following this protocol should be marginalized and theoretically provide more reliable advanced kinematic descriptions of the hand digits. These procedures are especially valuable given the intrinsic challenge of tracking complicated motion patterns of the relatively small segments of hand digits.

Ultimately, the concepts outlined in this study can also be applied for active marker motion capture systems. While active marker clusters have advantages over passive motion tracking regarding occlusion and labeling, active-marker clusters are typically restrictive in terms of fixed size/shape or wire cluttering that limit their applications, such as those involving instrumentation of relatively small hand digit segments. Given their unconstrained and customizable (e.g., variation in size and modes of fixation) characteristics, passive markers may be more appropriate for the study of hand kinematics and the proposed methodology of this study for marker minimization provides even greater value in this case.

The objective function to minimize axial deviations of a chain of segments derives from the traditional observation of interphalangeal joints exhibiting only 1DOF [17]. However, axial rotations at these joints may be notable [22]. In this case, the solution model would need to be modified with fewer joint constraints, which results in greater solution dependence on the selected objective criterion. We had also assumed that joint rotations primarily occurred about the axes of the digit-aligned coordinate systems, which is not necessarily true. For example, the thumb CMC joint can exhibit nonperpendicular axes of rotation [23]. Furthermore, additional potential sources of error from the procedure to align the digit coordinate systems in this study could be inferred from Ref. [7].

In the future, the presented methodology could be further extended. The current methodology applies optimization and represents functional digit joint kinematics as purely rotational with the rotational axes assumed to be orthogonal to the presumed anatomical planes defined by the digit alignment device. However, even if the true axes of rotation are skew from the anatomical planes of the digit alignment device, if these skew angles are known *a priori* according to presumed anatomical definitions as those utilized in musculoskeletal models [24], these rotations could also be applied accordingly. Alternatively, true dominant axes of rotation or instantaneous changes in the center of rotation could also be identified [20,21,25] from the digit motion trials with an additional cost function optimization. While advanced optimization could be employed for more nuanced characterization of joint kinematics, this likely requires additional markers for truly robust determinations.

While the presented methodology of this study was developed with hand kinematics and the thumb-index precision grasp in mind, the fundamental concepts are generalizable and not absolutely restricted to thumb-index finger digit kinematics. Kinematic

analyses could be performed on the remaining digits (middle, ring, and little) with the addition of respective nail clusters and modifications to the digit alignment device to accommodate those additional digits. This would facilitate studies in multidigit pressing synergies [26] or whole-hand grasp [27]. Furthermore, the optimization objective function for the kinematics could be modified according to energy metrics [28], task-specific objectives [29], or functional couplings [30]. Previous studies have investigated inverse kinematics techniques to validate objectives in predicting natural or likely arm and hand postures [31–33]. In substantially extending the protocol from Ref. [7], this study employed such techniques to robustly determine digit kinematics from the designated minimal marker set in an analytical manner without consideration of individualized motion [34]. The next natural extension of this protocol would be to incorporate these procedures for tabulating digit kinematics with protocols that include applied force measurements such that inverse analyses to determine joint kinetics, such as those for gait, could be employed [35].

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