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A digit alignment device for kinematic analysis of the thumb and index finger

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Abstract

Kinematic analysis of the digits using optical motion capture systems relies on defining accurate coordinate systems for the individual segments. Limitations of previous digit kinematic protocols include marker placement errors, marker occlusion and superimposition, and skin movement artifact. The purpose of this study was to develop a protocol utilizing a digit alignment device (DAD) and nail marker clusters to overcome these limitations. Ten subjects underwent 10 static calibration trials for validation. The orientation of the thumb distal phalange relative to the index finger distal phalange was described using Euler angles of pitch(x), yaw(y'), and roll(z''). The digit calibration protocol demonstrated high accuracy (0.5°, 1.9° and 2.2° for x, y', z'') and precision (1.4°, 2.3° and 3.1° for x, y', z''). The developed protocol provided convenient identification of transformations that determine anatomically relevant coordinate systems for the distal phalanges of the digits. The potential of utilizing this protocol as a standardized tool for digit kinematics was demonstrated using a dynamic task of precision pinching.

Keywords

Kinematic analysis; Motion capture; Precision pinch; Thumb; Index finger

1. Introduction

Accurate quantification of digit kinematics is important for evaluating pathological conditions, surgical interventions, and therapy effectiveness [1]. Optical motion capture has become popular to study digit kinematics [2-6], but there is no universal digit kinematic protocol. Variations in marker placement and coordinate system definitions reduce data compatibility for cross-validation analysis [7]. Furthermore, conventional marker-based protocols have inherent limitations. First, marker placement on the digits is unreliable due to the difficulty in identifying distinct bony landmarks of small phalangeal segments [8]. Second, dynamic errors due to marker occlusion and superimposition occur from capturing many markers in a small volume [5]. Third, passive skin movement [9] yields ill-defined segment coordinate systems [10] and compromises accurate motion analysis [11]. The purpose of this study was to develop a calibration protocol utilizing a digit alignment device and nail marker clusters to overcome these limitations.

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2. Methods

2.1. Digit Alignment Device

A digit alignment device (DAD) was designed to define an anatomically relevant coordinate system for the distal phalanges of the thumb and index finger. It was constructed from a rectangular woodblock (11.0 cm×8.0 cm×4.0 cm) with a round edge (Figure 1a). Both the top and an adjacent face of the block had a groove for alignment of the thumb and index finger, respectively. Three retro-reflective markers were permanently fixed to the top surface of the DAD and were used to define the block coordinate system (BCS) for the index finger. A 90-degree rotation about the z-axis of the index finger BCS yielded the thumb BCS (Figure 1a).

2.2. Nail Marker Clusters

A cluster consisting of three non-collinear markers (4 mm diameter) was attached to a base plate via a rigid metal rod (Figure 1a). The base plate was made of Roylan™ Splinting Materials (Preston Medical Products Inc, Bolingbrook, IL) and fixed to the nail using double-sided tape. Each marker cluster defined a local cluster coordinate system (CCS) for a digit. The specific definition of the origin and axes of each CCS is arbitrary.

2.3. Digit Alignment Calibration Protocol to Determine Virtual Coordinate Systems

A digit calibration protocol utilizing the DAD and marker clusters was developed to determine an anatomically aligned virtual coordinate system (VCS) based on the locally fixed CCS for each digit. For proper alignment, each digit was placed firmly against the inner edge of the groove with its coronal plane aligned parallel to the contacting block face. The assumption was a fully extended digit was straight with all segments aligned in that position. Therefore, each digit was anatomically aligned to its respective BCS axes.

The VCS was created by translating the BCS to the nail, thereby defining a transformation/translation matrix, $[T_{BV}]$. The static calibration also established the transformation matrix between CCS and BCS, $[T_{CB}]$. These matrices then yielded the transformation from CCS to VCS, $[T_{CV}] = [T_{CB}][T_{BV}]$. See Figure 1b. The transformation $[T_{CV}]$ for each digit was invariant and then applied to derive the VCS dynamically from the CCS.

2.4. Experimental Tasks

Ten healthy subjects (seven males and three females; age: 28 ± 5 years) participated in two experimental sessions in accordance with informed consent procedures approved by the local institutional review board. The subjects had hand sizes in a range that would be accommodated by the current DAD device. An optical motion capture system (VICON Nexus T40) recorded marker position data at a 100 Hz sampling rate. In the first session, the digit alignment protocol was performed for ten static trials by each subject. For each static trial, data were recorded for 3 seconds and averaged to establish the CCS and BCS for calibration. In the second session, one static calibration trial was performed, followed by a dynamic trial of 10 precision pinch cycles at a self-selected pace. The subject was instructed to rest the elbow on the testing table with the wrist in a neutral position, and pinch in space as if he/she were picking up a tiny object.

2.5. Data Analysis

Order-dependent Euler angles (pitch about x, yaw about y', roll about z'') of the thumb VCS relative to the index finger VCS were computed by MATLAB®. Pitch, yaw, and roll indicated the relative orientation between the distal segments of the two digits. The expected values for the validation trials were pitch(x)=0°, yaw(y')=0°, and roll(z'')=90°. A 10-fold

cross-validation analysis was performed using each static trial as a calibration to determine the outcomes of the remaining 9 trials. Accuracy was defined as the difference between the predicted and expected angle values. Precision was defined as the standard deviation of the predicted angles. One-way repeated measures ANOVA was performed to determine the effects of “fold” on accuracy and precision.

3. Results

Accuracy and precision were not significantly affected by the factor “fold” ($p>0.10$). Therefore, any of the 10 static trials could be selected for calibration to establish the transformation between CCS and VCS. Representative results of 10-fold cross-validation are shown in Figure 2. Accuracy and precision results were calculated using one-fold validation data. For pitch, yaw, and roll, the accuracy values were $0.5\pm2.1^\circ$, $1.9\pm4.0^\circ$, and $2.2\pm5.5^\circ$, respectively. The corresponding precision values were $1.4\pm0.7^\circ$, $2.3\pm1.6^\circ$, and $3.1\pm1.2^\circ$.

Representative dynamic task data are shown in Figure 3. At pulp contact, the thumb distal phalange was orientated relative to the index finger distal phalange with a pitch of $68.0^\circ\pm8.2^\circ$, a yaw of $-11.3^\circ\pm4.5^\circ$, and a roll of $137.7^\circ\pm2.0^\circ$.

4. Discussion

A digit calibration protocol utilizing the DAD and nail marker clusters was developed as a standardized tool to study digit kinematics. Static validation trials showed that this protocol was accurate and precise. Successful application of this protocol to a dynamic functional task was also demonstrated.

The developed protocol addressed major limitations of previous kinematic methods. First, the DAD eliminated the need to place markers accurately along the digit longitudinal axis [8]. The grooves on the DAD effectively aligned the digit to the longitudinal axis of the DAD. Second, the marker cluster was not restricted to the surface of the digit and therefore was spatially arranged to avoid marker occlusion and superimposition [5]. Third, skin movement artifact [9] was avoided by attaching the marker clusters to the rigid nails.

Dexterous manipulation of the hand is made possible by thumb-finger opposition, which is anatomically facilitated by the pronated position of the thumb relative to the fingers. The orthogonal surfaces of the DAD provide this special alignment of the thumb and index finger, allowing for the establishment of anatomically relevant coordinate systems for the distal phalanges of the thumb and index finger.

In the future, the DAD can be modified to accommodate other fingers, the left hand, and different hand sizes. Furthermore, while the current study was limited to the distal phalanges, inverse kinematics [12] could be applied to derive kinematic descriptions of the more proximal digit segments from the motion data of the nail marker clusters.

Acknowledgments

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Figure 1.

Digit calibration protocol. (a) Static calibration of the thumb and index finger 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).

Figure 2.
Rotation angle errors of 10-fold cross-validation from one representative subject.

Figure 3.
The average rotation angle trajectories (solid lines) and standard deviations (dotted lines) across the closing phases of all pinch cycles from one subject.