Development and Evaluation of a 25-DOF Hand Kinematic Model

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Agenda

- Introduction
  - Background
  - Objectives

- Hand Kinematic Model Development

- Hand Kinematic Model Evaluation
  - Methods
  - Results

- Discussion
Background

- Importance of human hand: object manipulation (grasping, positioning, holding, etc.), communication (sign language, gestures), etc.

- Importance of virtual human hand: applications in 3D computer-aided ergonomic design, virtual surgery, computer games, etc.

![Computer-aided ergonomic design (Left: Automobile; Right: Helicopter)](image)

Virtual surgery
Hand model used for ergonomic design

- Hand model can adjust every hand segment length according to an arbitrary individual hand length, and the model is accurate.

- Limitations of the existing commercial hand models, like the hand model in Jack™: Lacking accuracy, and ambiguous in defining the sizes of percentile models.

*Nierop, 2007
Objectives

1. Develop a hand kinematic model which is adjustable at each hand bone segment length according to the hand length

2. Evaluate the accuracy of the hand model with hand motion data collected by an optoelectronic motion capture system
Hand Kinematic Model

- Hand kinematic model development process

Hand Anatomy (DOF)  Hand Anthropometry (BL, Joint ROM)  Kinematic Algorithm (Denavit-Hartenberg)

Hand Kinematic Model

Note: DOF: Degree of freedom
BL: Bone length
ROM: range of motion
Hand Anatomy

**DOFs survey**

<table>
<thead>
<tr>
<th>Joints</th>
<th>Fingers</th>
<th>Wrist joint</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thumb</td>
<td>Index</td>
<td>Middle</td>
</tr>
<tr>
<td>Carpometacarpal (CMC)</td>
<td>2[3*]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metacarpophalangeal (MCP)</td>
<td>2<a href="2">1**</a></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Interphalangeal (IP)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximal interphalangeal (PIP)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Distal interphalangeal (DIP)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

* Buchholz, 1989; ** Jack™

(): DOFs of the new model

**Features of the new model**

✓ Comprehensive DOFs (25 totally)
## Hand Anthropometry

- **Comparison study on ratio of the bone length to hand length**

<table>
<thead>
<tr>
<th>Source</th>
<th>Classification</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MCP</td>
</tr>
<tr>
<td>Buchholz, 1992¹</td>
<td>Ratio*HL</td>
<td>0.46*HL</td>
</tr>
<tr>
<td>Greiner, 1991²</td>
<td>Ratio*HL</td>
<td>0.32*HL</td>
</tr>
<tr>
<td>Buchholz, 1992¹</td>
<td>R²</td>
<td>0.96</td>
</tr>
<tr>
<td>Greiner, 1991²</td>
<td>R²</td>
<td>0.43</td>
</tr>
</tbody>
</table>

¹Based on 2 female and 4 male hands  
²Based on 59 male hands

- **Buchholz’s data were adopted, later a study for measuring hand bone length would be conducted by another member using X-ray.**
Forward Kinematics (Denavit-Hartenberg Method)

- Decide fingertip position given hand posture (i.e., joint angles)

\[ \mathbf{P} = f(\mathbf{\Theta}) \]

\( \mathbf{P} \): Fingertip Position Vector, \( \mathbf{\Theta} \): Vector of Joint Angles

- MCP FE = 30°
- MCP AA = 0°
- PIP FE = 30°
- DIP FE = 10°

Fingertip Position = ?

FE: Flexion/Extension
AA: Abduction/Adduction
The 25-DOF Hand Model

Control the hand posture

Hand Length: 194 mm
Hand Breadth: 90 mm
Evaluation Process

- Experiment
- Data Processing
  - Measured Fingertip Positions
- Joint Angles
- Forward Kinematics
  - Predicted Fingertip Positions
- Prediction Error
Participants

- Five male and right-handed participants

<table>
<thead>
<tr>
<th>Classification</th>
<th>Mean (S.D.)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>26.4 (2.1)</td>
<td>24 - 29</td>
</tr>
<tr>
<td>Hand Length (cm)</td>
<td>19.2 (10.1)</td>
<td>17.8 - 20.6</td>
</tr>
<tr>
<td>Hand Width (cm)</td>
<td>9.0 (5.1)</td>
<td>8.4 - 9.8</td>
</tr>
</tbody>
</table>

- Selection criteria
  - ✓ Age: 20-30 years old
  - ✓ Health conditions: No history of injuries at the hand or wrist
Apparatus

- Optoelectronic motion capture system: 6 Eagle Digital Cameras® (Motion Analysis Corporation, CA, USA)

- Spherical retro-reflective markers

A Layout of Motion Capture System

Marker Set

Diameter = 7mm

$n = 27$
Participants were asked to grasp two different cylinders:

- Diameter = 50 mm
- Diameter = 40 mm
Data Processing

- Transform the captured 3D coordinates in order to be consistent with the 3D coordinate system of the hand model.

Construction of a wrist coordinate system

Translation

Rotation
Joint Angle Calculation: 1 DOF

Example of calculating PIP joint angle

\[ \theta_{\text{flexion}} = \arccos \left( \frac{\vec{a} \cdot \vec{b}}{|\vec{a}| \cdot |\vec{b}|} \right) \]
Joint Angle Calculation: 2 DOF

Example of calculating MCP joint angles

Orthogonal projection of PIP onto YZ plane
Predicted Fingertip Position

Input:
Joint angles

Output:
Predicted fingertip position
Evaluation Criteria

- Prediction Error: Distance between the measured fingertip position \((X_M, Y_M, Z_M)\) and predicted fingertip position \((X_P, Y_P, Z_P)\)

\[
\text{Error} = \sqrt{(X_P - X_M)^2 + (Y_P - Y_M)^2 + (Z_P - Z_M)^2}
\]

Unit: mm

<table>
<thead>
<tr>
<th>Participants</th>
<th>Classification</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>Measured</td>
<td>-2.9</td>
</tr>
<tr>
<td>5</td>
<td>Predicted</td>
<td>-2.9</td>
</tr>
<tr>
<td></td>
<td>Prediction error</td>
<td></td>
</tr>
</tbody>
</table>
The prediction error is from 10.6 mm to 20.9 mm. The model has less prediction error of fingertip position at longer finger.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Fingertip position prediction error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Index</td>
</tr>
<tr>
<td>P1</td>
<td>14.9</td>
</tr>
<tr>
<td>P2</td>
<td>11.7</td>
</tr>
<tr>
<td>P3</td>
<td>11.2</td>
</tr>
<tr>
<td>P4</td>
<td>11.3</td>
</tr>
<tr>
<td>P5</td>
<td>13.4</td>
</tr>
<tr>
<td>Mean</td>
<td>12.5</td>
</tr>
<tr>
<td>S.D.</td>
<td>1.6</td>
</tr>
<tr>
<td>Grand mean</td>
<td>13.1</td>
</tr>
</tbody>
</table>
Evaluation Result for the Small Cylinder

- The prediction error is from 10.5 mm to 19.2 mm. The model has less prediction error of fingertip position at longer finger.

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<thead>
<tr>
<th>Participants</th>
<th>Fingertip position prediction error (mm)</th>
</tr>
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<tbody>
<tr>
<td></td>
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<tr>
<td>Mean</td>
<td>13.5</td>
</tr>
<tr>
<td>SD</td>
<td>2.1</td>
</tr>
<tr>
<td>Grand mean</td>
<td></td>
</tr>
</tbody>
</table>
The new hand model has comprehensive degrees of freedom, especially at the CMC and MCP of the thumb and the wrist.

The Model can predict each bone length of the hand according to an specific individual hand length.

Sources of the prediction error

- Regression of the bone length to the hand length (Small sample size)
- Offset between captured coordinates data and bone data
Future Work

- Big Picture of developing a novel inverse kinematic model which can predict natural hand postures

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Hand Anatomy

Hand Anthropometry (X-ray)

Hand Joint ROM Study

Kinematic Algorithm (D-H method)

Forward Kinematics

Evaluation (Motion Data)

Accurate?

Application

Natural?

Evaluation (Motion Data)

Novel Inverse Kinematics
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Q & A

Thank you!