Comparison of Genetic Algorithm and Pattern Search Algorithm for Optimization-Based Hand Posture Prediction

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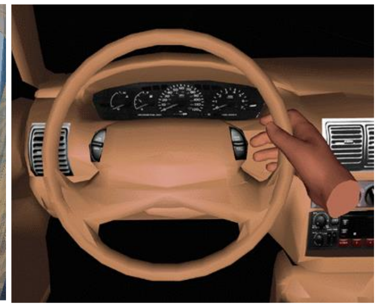
Agenda

- Introduction
  - Background
  - Objectives
- Methods
  - Optimization-based hand posture prediction
  - Algorithms to solve the optimization problem
- Results
- Discussion

Ergonomic Design with Digital Hand Models

- Digital hand models can be applied to hand-held product design.



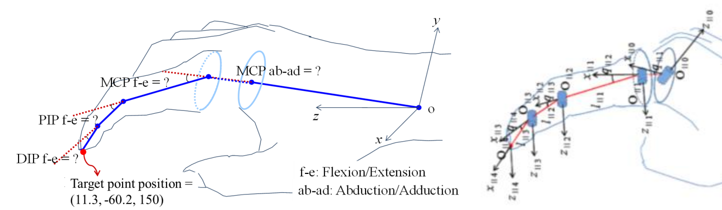



- Hand posture prediction is necessary for hand-held product design.





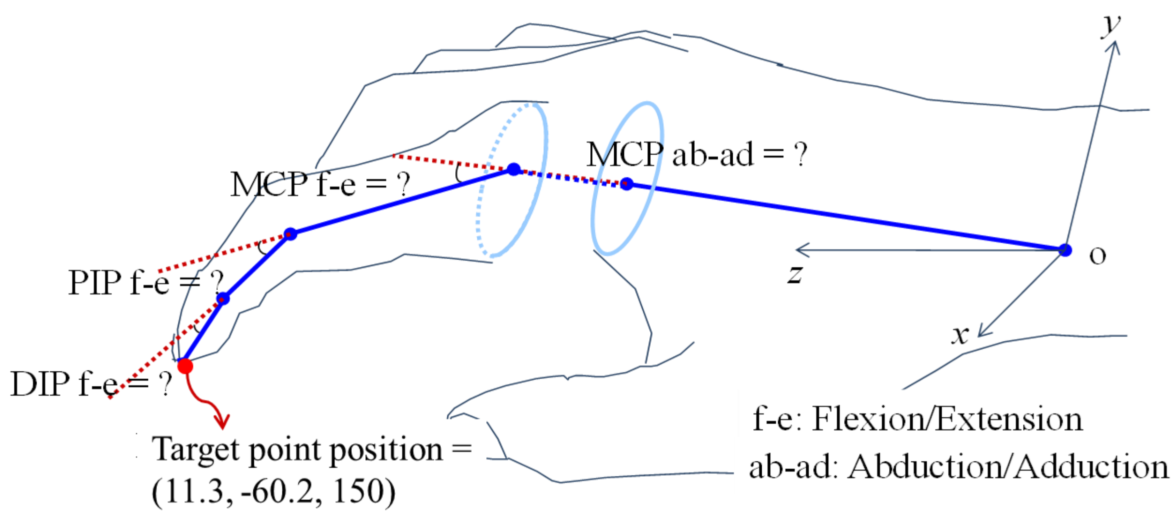
Hand Posture Prediction Methods: Empirical-Based & Mathematical-Based

Classification	Empirical-based	Mathematical-based
Techniques	• Collect empirical data from experiments • Establish regression functions	• Establish geometrical or analytical relationships between hand posture and fingertip position using inverse kinematics method
Limitations or strengths	• Need large data and therefore a lot of experiments to establish regression functions • Easy to use with regression functions	• Experiment not needed • Complex and heavy computation due to (1) highly nonlinearity of the geometrical or analytical relationships and (2) high degrees of freedom (> 20 DOF) of the hand
	 Hand posture = f (age, gender, other human attributes)	 $\mathbf{f}(\mathbf{q}_{II})^{\text{Fingertip}} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} B + l_{II0} \sin\gamma_{II} \\ C \\ A + l_{II0} \cos\gamma_2 \end{bmatrix}$ $A = l_{II3}\cos q_{II1}\cos q_{II4}(\cos q_{II2}\cos q_{II3} - \sin q_{II2}\sin q_{II3}) - l_{II3}\cos q_{II1}\sin q_{II4}(\cos q_{II2}\sin q_{II3} + \sin q_{II2}\cos q_{II3}) + l_{II2}\cos q_{II1}\cos q_{II2}\cos q_{II3} - l_{II2}\cos q_{II1}\sin q_{II2}\sin q_{II3} + l_{II1}\cos q_{II1}\cos q_{II2}$ $B = l_{II3}\sin q_{II1}\cos q_{II4}(\cos q_{II2}\cos q_{II3} - \sin q_{II2}\sin q_{II3}) - l_{II3}\sin q_{II1}\sin q_{II4}(\cos q_{II2}\sin q_{II3} + \sin q_{II2}\cos q_{II3}) + l_{II2}\sin q_{II1}\cos q_{II2}\cos q_{II3} - l_{II2}\sin q_{II1}\sin q_{II2}\sin q_{II3} + l_{II1}\sin q_{II1}\cos q_{II2}$ $C = -l_{II3}\cos q_{II4}(\sin q_{II2}\cos q_{II3} + \cos q_{II2}\sin q_{II3}) + l_{II3}\sin q_{II4}(\sin_{II2}\sin q_{II3} - \cos q_{II2}\cos q_{II3}) - l_{II2}\sin q_{II2}\cos q_{II3} - l_{II2}\cos q_{II2}\sin q_{II3} - l_{II1}\sin q_{II2}$

Objectives of the Study

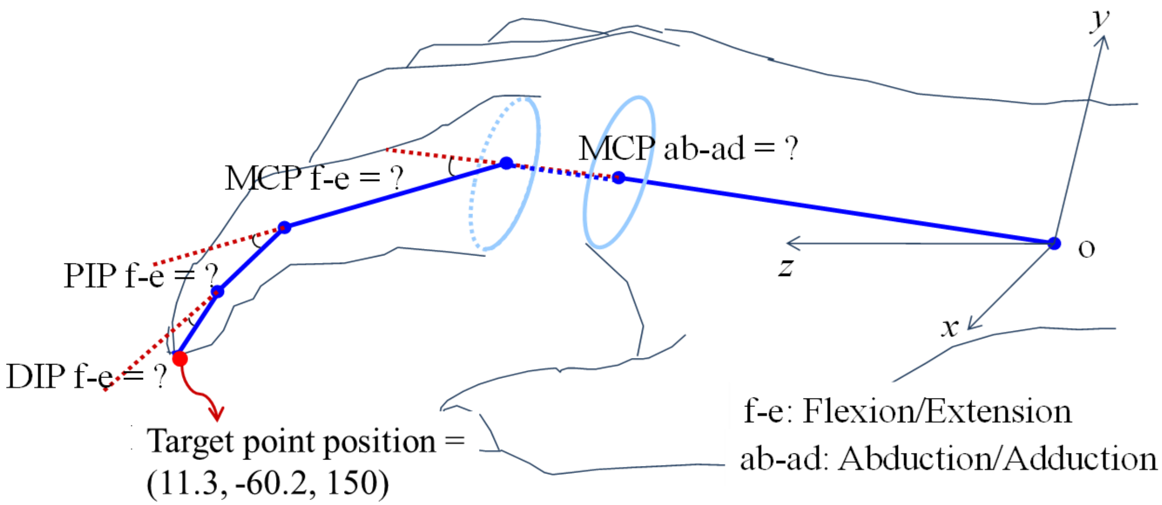
1. Present an optimization-based method for hand posture prediction

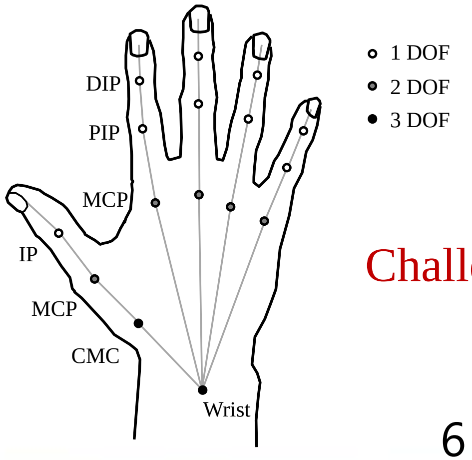
2. Compare the performance of two algorithms, genetic algorithm and pattern search algorithm for solving the optimization problem



Problem Statement

- Hand posture prediction: determining hand joint angles when the fingertip reaches a given target point





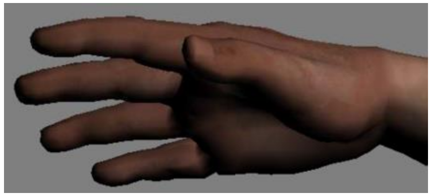
Challenging due to high DOF (>20) of the hand

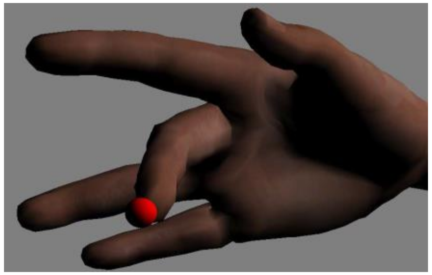
Optimization-Based Hand Posture Prediction Method

- Assumption: human beings use the least motion of the joints to reach the target point

- Optimization problem: finding a posture which minimizing the displacement of joints from the initial neutral posture towards a target point

Initial neutral posture





Predicted posture to reach the target point

$$\underset{\mathbf{q}_{\mathrm{II}}}{\text{Min}} \quad f_d = \sum_{j=1}^{4} w_j \left| q_{\mathrm{II}j} - q_{\mathrm{II}j}^{N} \right|$$

$$\text{s. t.:} \quad \left\| \mathbf{f}(\mathbf{q}_{\mathrm{II}})^{\text{fingertip}} - \mathbf{p}_{\mathrm{II}}^{\text{target point}} \right\| \le \varepsilon,$$

$$q_{\mathrm{II}j}^{L} \le q_{\mathrm{II}j} \le q_{\mathrm{II}j}^{U}; i = 1,2,\ldots,n$$

$$\mathbf{f}(\mathbf{q}_{\mathrm{II}})^{\text{Fingertip}} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} B + l_{\mathrm{II}0} \sin \gamma_{\mathrm{II}} \\ C \\ A + l_{\mathrm{II}0} \cos \gamma_2 \end{bmatrix}$$

$$A = l_{\mathrm{II}3} \cos q_{\mathrm{II}1} \cos q_{\mathrm{II}4} (\cos q_{\mathrm{II}2} \cos q_{\mathrm{II}3} - \sin q_{\mathrm{II}2} \sin q_{\mathrm{II}3}) - l_{\mathrm{II}3} \cos q_{\mathrm{II}1} \sin q_{\mathrm{II}4} (\cos q_{\mathrm{II}2} \sin q_{\mathrm{II}3} + \sin q_{\mathrm{II}2} \cos q_{\mathrm{II}3})$$
$$+ l_{\mathrm{II}2} \cos q_{\mathrm{II}1} \cos q_{\mathrm{II}2} \cos q_{\mathrm{II}3} - l_{\mathrm{II}2} \cos q_{\mathrm{II}1} \sin q_{\mathrm{II}2} \sin q_{\mathrm{II}3} + l_{\mathrm{II}1} \cos q_{\mathrm{II}1} \cos q_{\mathrm{II}2}$$

$$B = l_{\mathrm{II}3} \sin q_{\mathrm{II}1} \cos q_{\mathrm{II}4} (\cos q_{\mathrm{II}2} \cos q_{\mathrm{II}3} - \sin q_{\mathrm{II}2} \sin q_{\mathrm{II}3}) - l_{\mathrm{II}3} \sin q_{\mathrm{II}1} \sin q_{\mathrm{II}4} (\cos q_{\mathrm{II}2} \sin q_{\mathrm{II}3} + \sin q_{\mathrm{II}2} \cos q_{\mathrm{II}3})$$
$$+ l_{\mathrm{II}2} \sin q_{\mathrm{II}1} \cos q_{\mathrm{II}2} \cos q_{\mathrm{II}3} - l_{\mathrm{II}2} \sin q_{\mathrm{II}1} \sin q_{\mathrm{II}2} \sin q_{\mathrm{II}3} + l_{\mathrm{II}1} \sin q_{\mathrm{II}1} \cos q_{\mathrm{II}2}$$

$$C = -l_{\mathrm{II}3} \cos q_{\mathrm{II}4} (\sin q_{\mathrm{II}2} \cos q_{\mathrm{II}3} + \cos q_{\mathrm{II}2} \sin q_{\mathrm{II}3}) + l_{\mathrm{II}3} \sin q_{\mathrm{II}4} (\sin_{\mathrm{II}2} \sin q_{\mathrm{II}3} - \cos q_{\mathrm{II}2} \cos q_{\mathrm{II}3})$$
$$- l_{\mathrm{II}2} \sin q_{\mathrm{II}2} \cos q_{\mathrm{II}3} - l_{\mathrm{II}2} \cos q_{\mathrm{II}2} \sin q_{\mathrm{II}3} - l_{\mathrm{II}1} \sin q_{\mathrm{II}2}$$

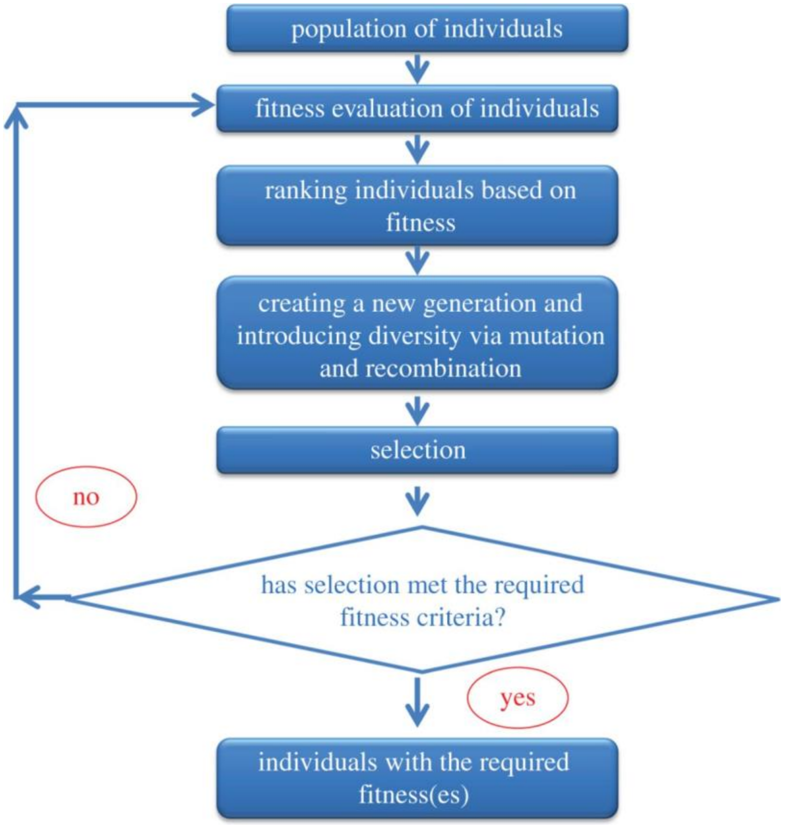
NLP problem

where: $\mathbf{f}(\mathbf{q}_{\mathrm{II}})^{\text{Fingertip}}$: fingertip position

$\mathbf{p}_{\mathrm{II}}^{\text{target point}}$: target point position

Algorithms for Solving Optimization Problem: Genetic Algorithm

- Genetic algorithm
  - Through the crossover and mutation of the genes from two parents, one child with a good gene from both parents is generated; then the same progress is repeated till an exact or approximated optimal solution is obtained.



Algorithms for Solving Optimization Problem: Pattern Search Algorithm

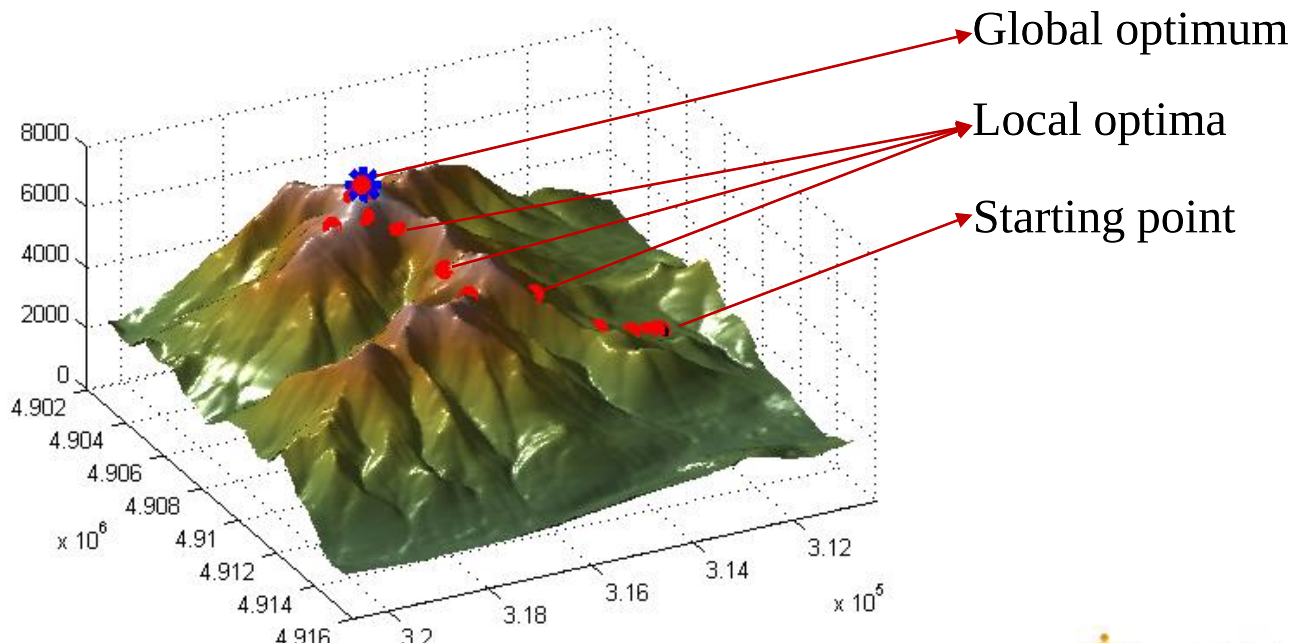
- Pattern search algorithm

  S1. Starting from an initial point, search the formed mesh (called pattern) around the initial point

  S2. Find a point (local optimum) in the mesh that mostly improve the objective function

  S3. From a new mesh around the point found in S2

  S4. Repeat from S1 until no points in a mesh can improve the objective function (global optimum)



Comparison of Genetic Algorithm & Pattern Search Algorithm

- Measures: computation time & prediction error

Prediction error = |predicted joint angles – ground truth joint angles|

- Postures for comparison: 16 postures (joint angles and fingertip positions were given) selected covering the whole reachable region of the fingertip

Initial posture　　Intermediate postures (illustrated)　　Ending posture

Results

- Absolute prediction error
  - Genetic algorithm showed slightly lower error than pattern search algorithm, but not statistically significant ($t(15) = -1.86$, $p = .083$).
- Computation time
  - Pattern search algorithm showed significantly faster computation speed than genetic algorithm ($t(15) = 2.19$, $p < .05$).

Algorithm	Computation time (sec)	Absolute prediction error (degree)
Genetic algorithm	86.2 (± 156.0)	0.3 (± 1.2)
Pattern search algorithm	2.6 (± 3.1)	1.2 (± 5.2)

Discussion

- The optimization-based hand posture prediction method based on the assumption that human beings use the least motion of the joints to reach the target point can predict hand postures accurately (< 1.2° on average)

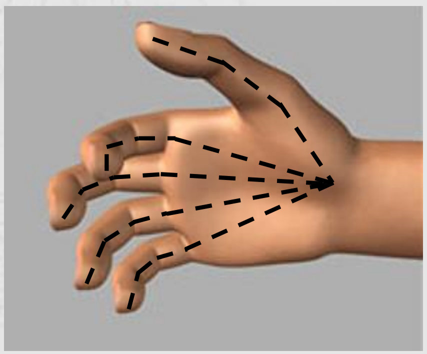
- Pattern search algorithm is preferred to the genetic algorithm for solving the optimization problem because of faster computation (40 times faster) and similar accuracy to the genetic algorithm (difference = 0.9° on average)

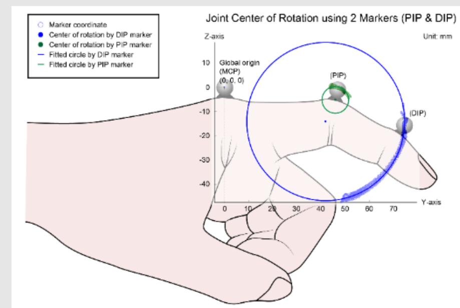
- For 3D computer-aided product design using digital hand models, a faster algorithm (such as deep learning algorithm) than pattern search algorithm (average computation time = 2.6 sec) for real-time processing.

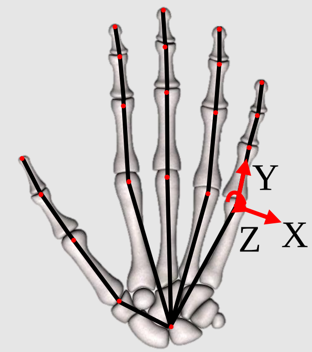
Q & A

Thank you for your attention!

Development of a Hand Link Model by Estimation of Joint Center of Rotation Using Surface Marker Motion







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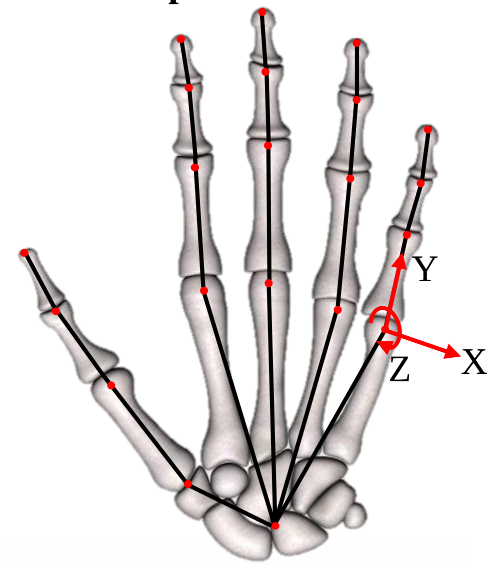
AGENDA

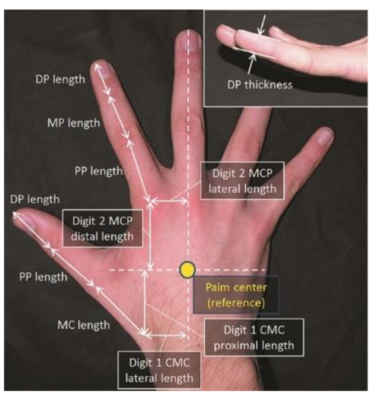
- Introduction
  - Background
  - Objectives of the study
- Method
  - Existing approaches of estimation of JCoR
  - Experimental protocol
  - Data pre-processing
  - Estimation of JCoR
- Result
- Discussion

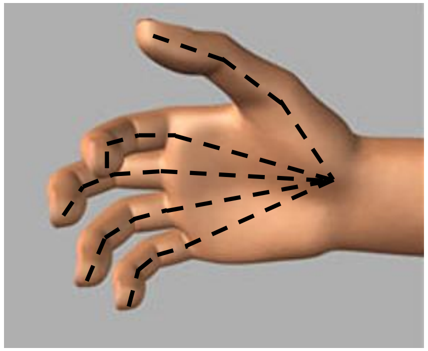
Usefulness of Hand Link Model

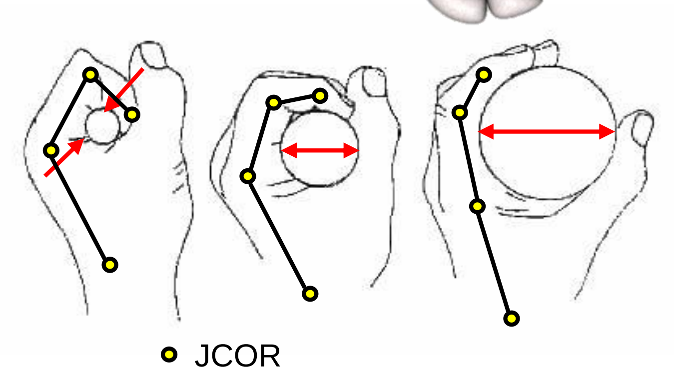
- Digital Human Modeling
  - Well-animated motion, posture recognition
  - Ergonomic product design
  - Clinical assessment of hand surgery

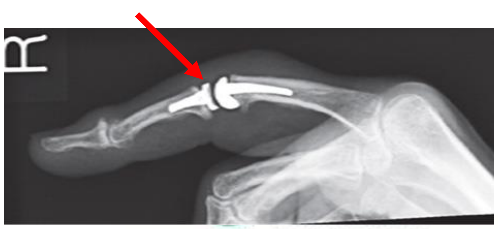
Examples of hand link model











Research Goal

Develop Hand Link Model Using Accurate Estimated Joint Center of Rotation (JCoR)

- ❑ Estimation of JCoR using Delonge-Kasa circle fitting method
- ❑ Development of experimental protocol for MCP, PIP and DIP JCoR
- ❑ Visual validation of estimated JCoR results

Existing Approaches of Estimating JCoR

- Various method to estimate the JCoR
  - Literature survey

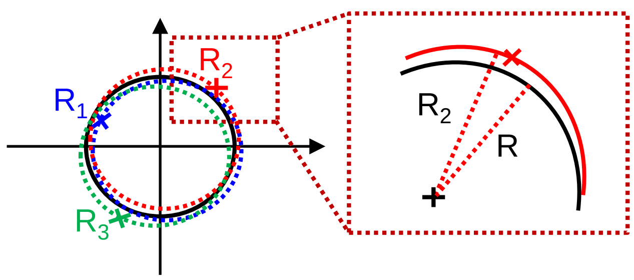
ROM = Range of motion

Author	Year	Joint COR	Method used	Description (Limitations)
Piazza et al.	2004	Ball & socket joint	Non-linear problem without closed solution	▪ Need to be solved iteratively. ▪ Initial guess of COR is required. ▪ Large ROM is required.
Zhang et al.	2003	Hinge joint	Optimization routine minimizing the time-variance of the internal link lengths	▪ Few parameters need to be deter mined to estimate COR.
Kasa	1976	Hinge joint	Algebraic least square method	▪ Large ROM is required.
Halvorsen et al.	1999	Hinge/ ball and socket joint	Reuleaux method	▪ Few parameters need to be deter mined to estimate COR.

  - **Delonge-Kasa method** provides a simple and fast closed solution without require any initial guess and additional parameters to be determined.

Existing Approaches of Estimating JCoR

- Various method to estimate the Joint CoR (Cont.)
  - Knight & Semwal (2010) proposed generalized Delonge-Kasa method that reduced bias for larger ROM, the formula has proven to be 100 times faster than traditional non-linear Maximum likelihood method.
- Delonge-Kasa method
  - Circle fitting method: Minimization of least square error between observed and estimated radius of circle.
  - Limitation of the method
    - Require large motion to estimate the CoR (small arc may generate small (incorrect) radius of circle)
    - Additional data processing is required to ensure the motion lies only in 2 axis planes.



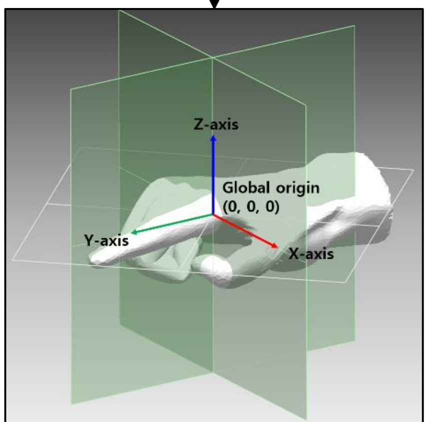
Least square error criterion:

$$Min \sum_{i=1}^{N} (R_i - R)^2$$

Algorithm Flows of Determining Joint COR

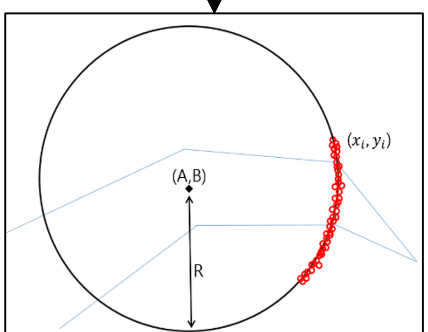
Data Collection (Flexion-extension of all fingers for 3 times with 2 different finger tip reaching point)

- 3 columns of marker trajectory data is collected (X, Y, Z)



Data Processing (Coordinates translation & transformation) using MATLAB

- Generate hand global coordinate system with wrist as the origin
- Set wrist as local origin (0, 0, 0): translation
- Project motion of coordinate of each marker to desire YZ plane
- Generate hand local coordinate system



$$v = \sum_{i=1}^{N}[(x_i - A)^2 + (y_i - B)^2 - R^2]^2 = min$$

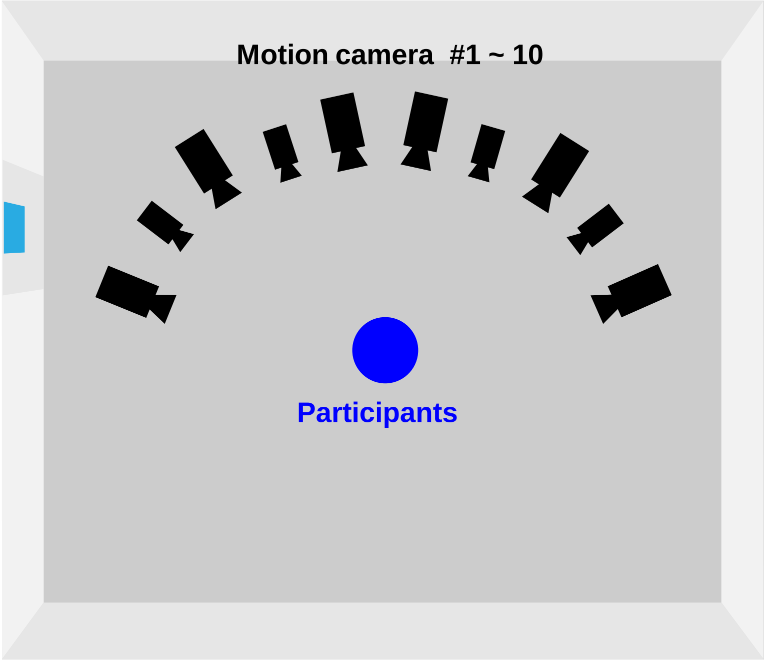
Determine JCoR coordinate and distance between JCoR and marker coordinates using Delonge Kasa estimator using MATLAB

- Input: marker trajectories of x, y, z data (3 columns of matrix) for all markers
- Output
  - ➢ Estimated CoR coordinate
  - ➢ R_i (average distance between CoR at joint i and initial surface marker that attached at joint i)

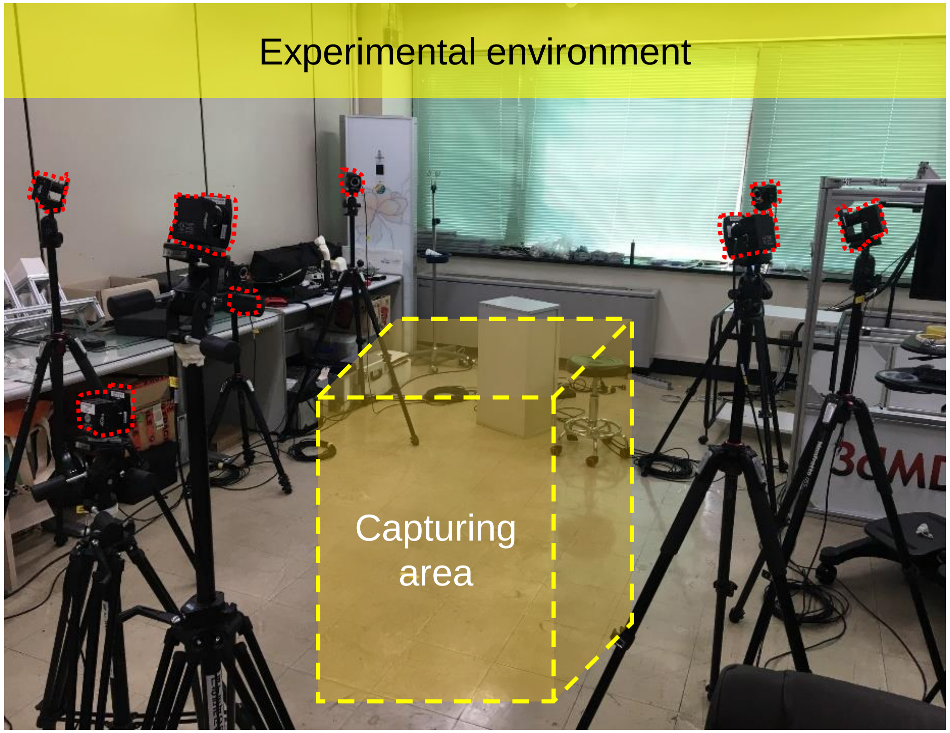
Experiment Layout

❑ 10 motion cameras (Motion Analysis Inc., USA) was used to capture the index finger motion at 60 Hz.

Top view: layout of motion cam.



Perspective view: experimental environment



Participants & Experimental Task

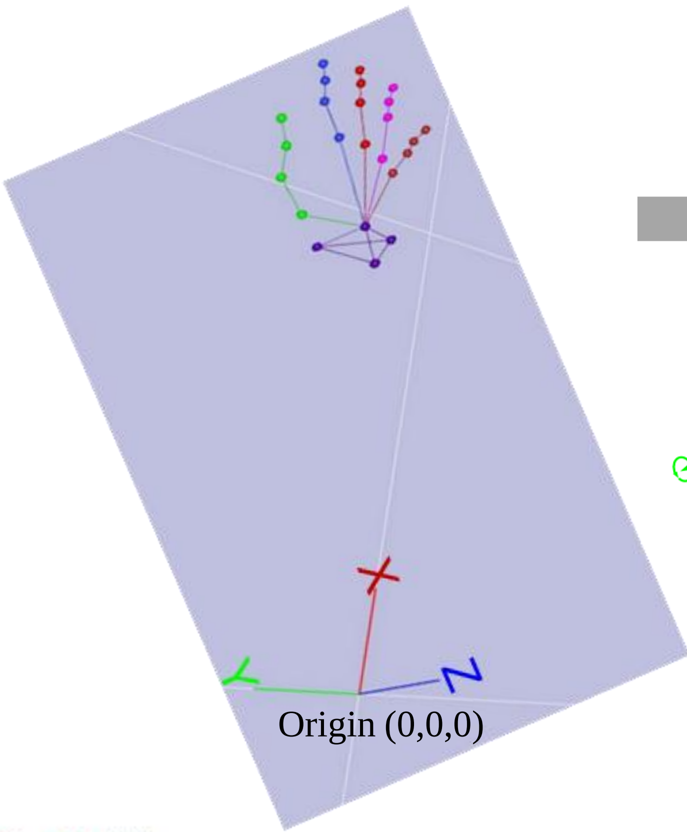
- One healthy male subject were recruited (no neurological or musculoskeletal disorder in the hand).
- 23 retro-reflective markers (Ø = 7 mm) were attached on the dorsal part of each finger joint of the hand.

Hand Global Coordinate System

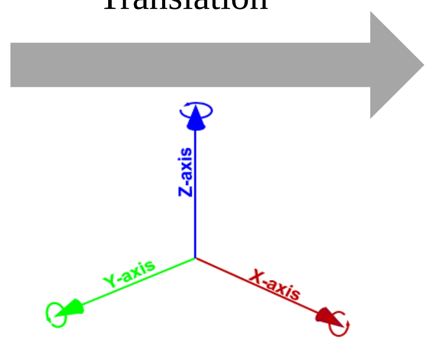
❑ Set global coordinate system

- Transformation (translation and rotation) of the raw data to hand global coordinate system

Raw data from motion capture

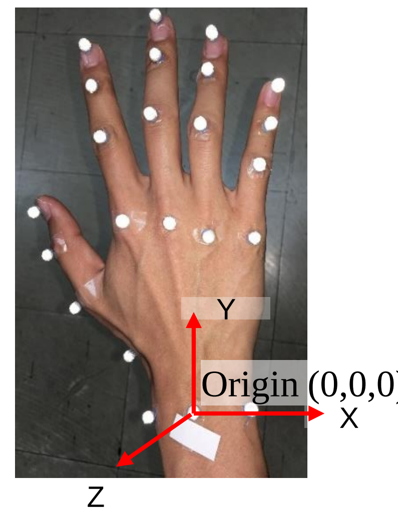


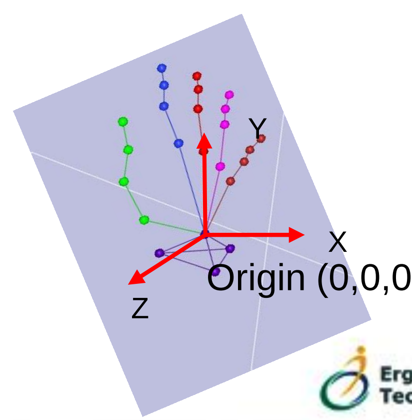
Translation



Rotation

Global coordinate system

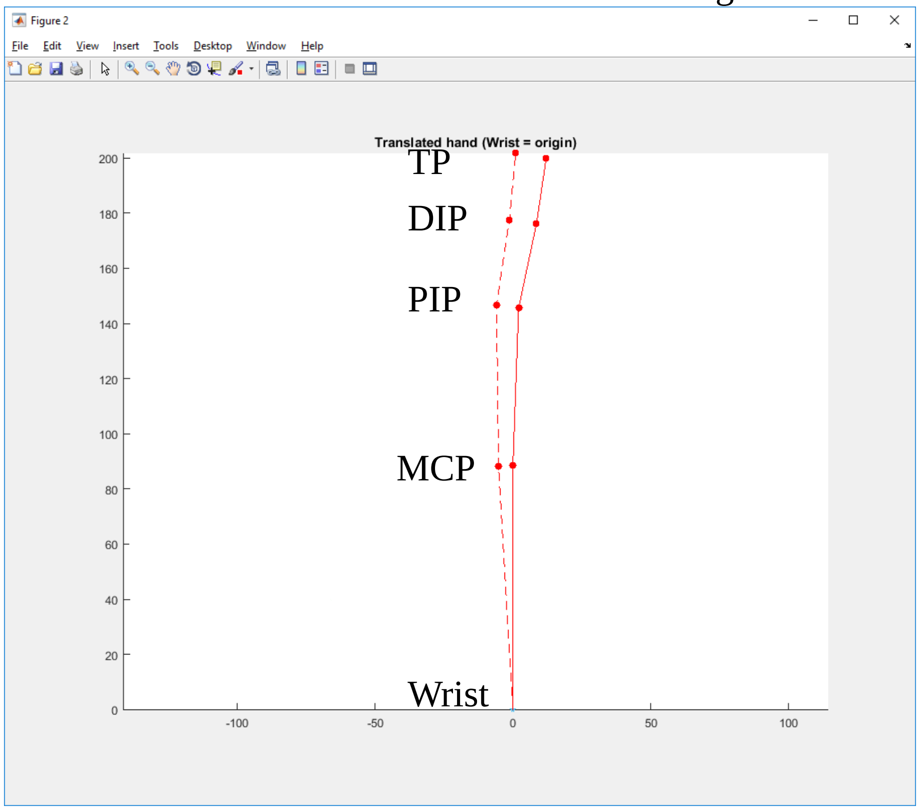




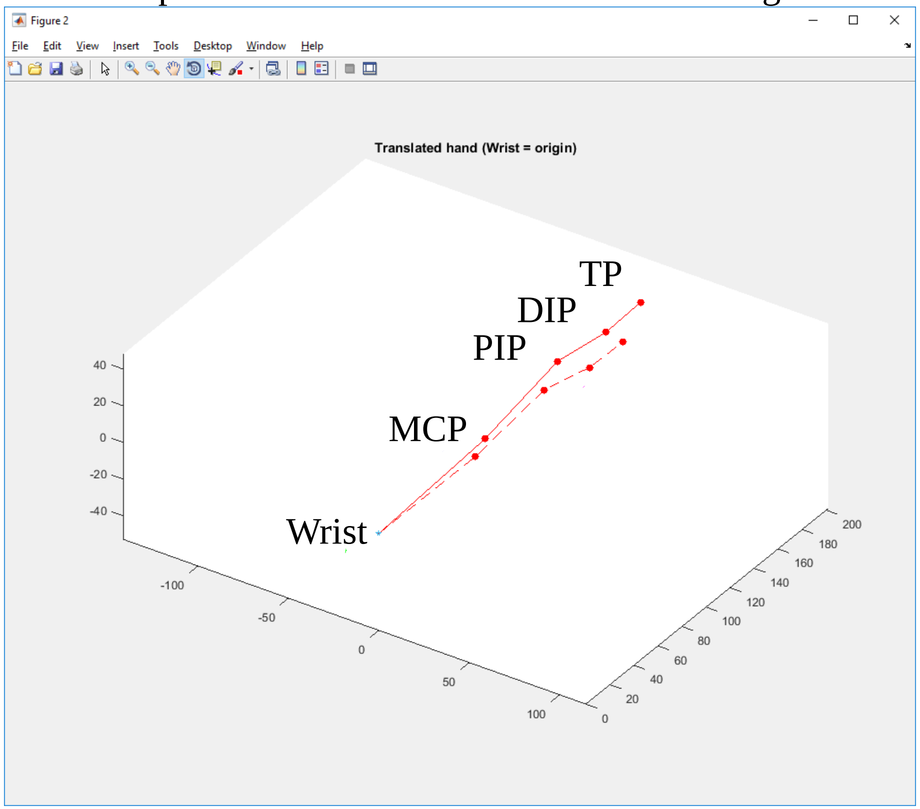
Hand Link Model Using Initial Surface Marker

- Middle finger of hand link model in global coordinate system with initial posture

Front view of link model of middle finger



Perspective view of link model of middle finger



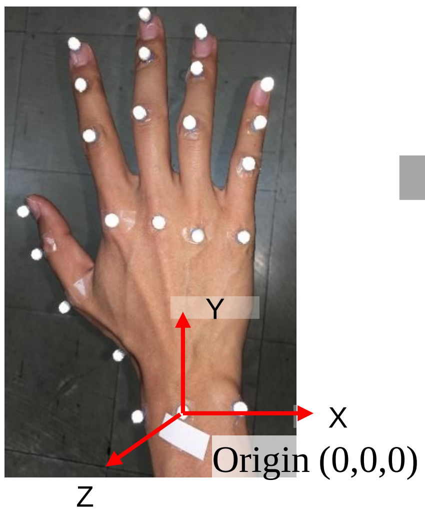
- - - - - - Initial raw surface marker (Unprocessed data)

——— Initial transformed surface marker (Processed data)

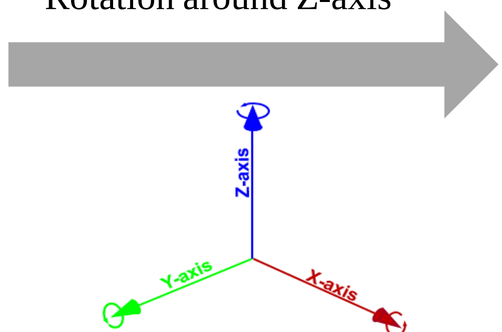
Hand Local Coordinate System

- Transformation of global coordinate to local coordinate for each joint to estimate its COR.

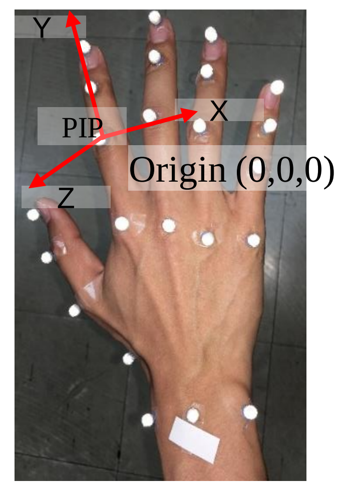
Global coordinate system

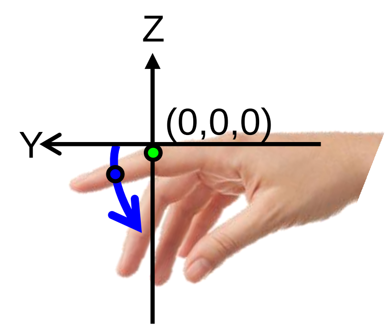


Rotation around Z-axis

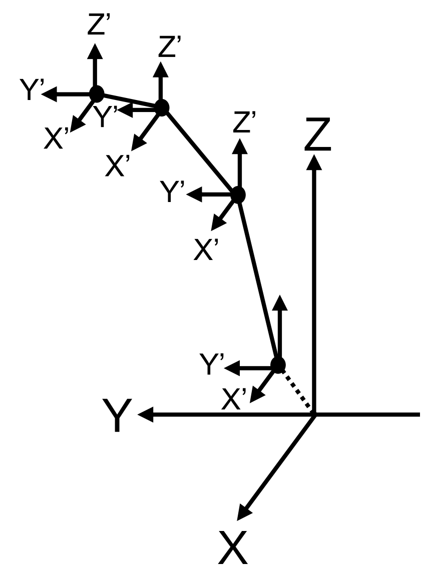


Local coordinate system





Example of one finger



Delonge-Kasa Circle Fitting Method

- Let (x_i, y_i) be the marker locations, the joint CoR (A, B) can be estimated by minimizing the difference between the squared distance of (x_i, y_i) to (A, B) and the squared radius (R) of the fitted circle over the trajectory of marker motion.

From the criterion $$Min \sum_{i=1}^{N} (R_i - R)^2$$

$$* \; Where \;\; R_i = (x_i - A)^2 + (y_i - B)^2$$

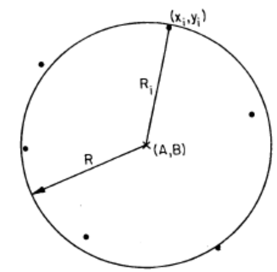


Fig. 1. The measured points and the parameters of the fitted circle.

Objective function: $$v = \sum_{i=1}^{N} [(x_i - A)^2 + (y_i - B)^2 - R^2]^2 = min$$

$$\frac{\partial v}{\partial A} = \frac{\partial v}{\partial B} = \frac{\partial v}{\partial R} = 0$$

$$\frac{\partial v}{\partial R} = -4R \sum_{i=1}^{N} [(x_i - A)^2 + (y_i - B)^2 - R^2] = \sum_{i=1}^{N} [(x_i - A)^2 + (y_i - B)^2 - R^2] = 0$$

$$\frac{\partial v}{\partial A} = -4 \sum_{i=1}^{N} \{[(x_i - A)^2 + (y_i - B)^2 - R^2](x_i - A)\} = \sum_{i=1}^{N} [(x_i - A)^2 x_i + (y_i - B)^2 x_i - R^2 x_i] = 0$$

$$\frac{\partial v}{\partial B} = -4 \sum_{i=1}^{N} \{[(x_i - A)^2 + (y_i - B)^2 - R^2](y_i - B)\} = \sum_{i=1}^{N} [(x_i - A)^2 y_i + (y_i - B)^2 y_i - R^2 y_i] = 0$$

After 1st derivative | After simplified

Delonge-Kasa Circle Fitting Method

- After simplifications, the equations of each derivative function can be rewritten as a linear equation system for A, B and C, where C is a constant.

$$C = R^2 - A^2 - B^2$$

$$A2\Sigma x_i + B2\Sigma y_i + CN = \Sigma({x_i}^2 + {y_i}^2)$$

$$A2\Sigma {x_i}^2 + B2\Sigma x_i y_i + C\Sigma x_i = \Sigma({x_i}^3 + x_i {y_i}^2)$$

$$A2\Sigma x_i y_i + B2\Sigma {y_i}^2 + C\Sigma y_i = \Sigma({y_i}^3 + y_i {x_i}^2)$$

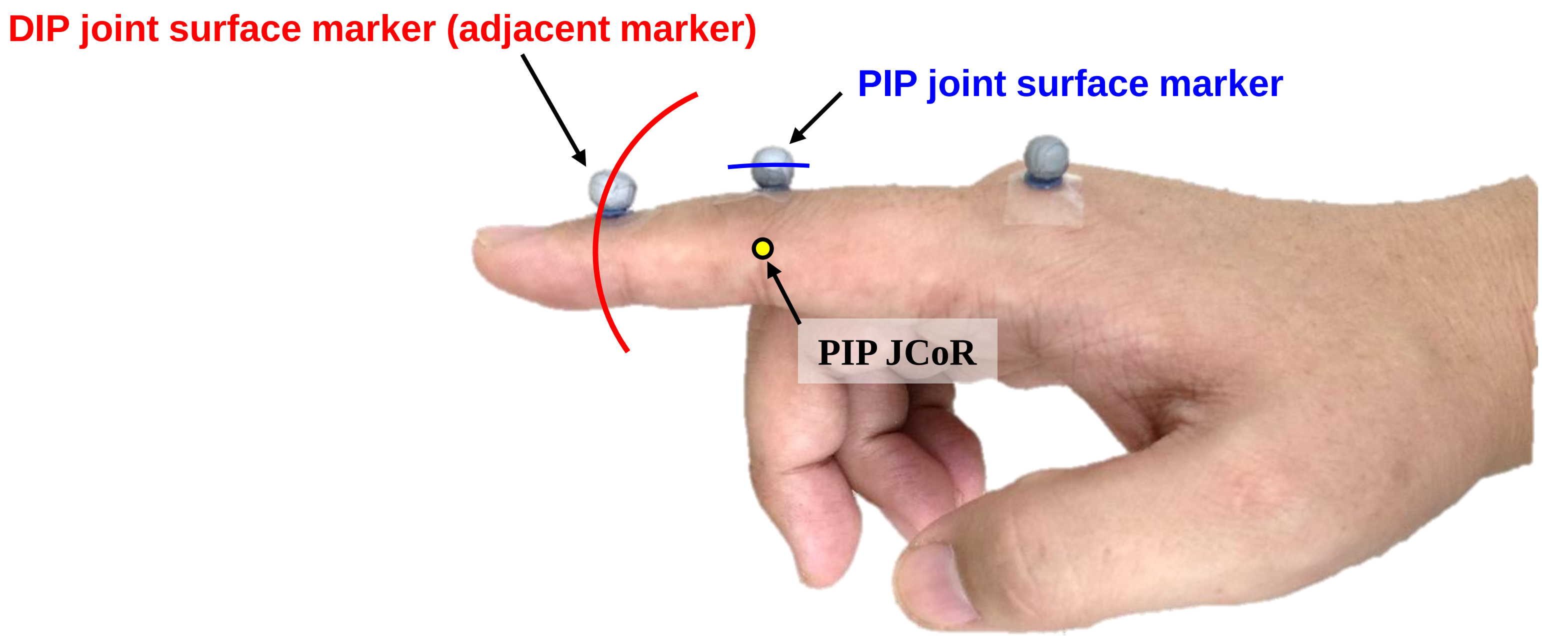
- The linear equations are simply defined by using the classical Gaussian method.

$$\begin{bmatrix} 2\Sigma x_i & 2\Sigma y_i & N \\ 2\Sigma {x_i}^2 & 2\Sigma x_i y_i & \Sigma x_i \\ 2\Sigma x_i y_i & 2\Sigma {y_i}^2 & \Sigma y_i \end{bmatrix} \begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} \Sigma({x_i}^2 + {y_i}^2) \\ \Sigma({x_i}^3 + x_i {y_i}^2) \\ \Sigma({y_i}^3 + y_i {x_i}^2) \end{bmatrix}$$

To be determined

Estimation of JCoR Using Delonge-Kasa

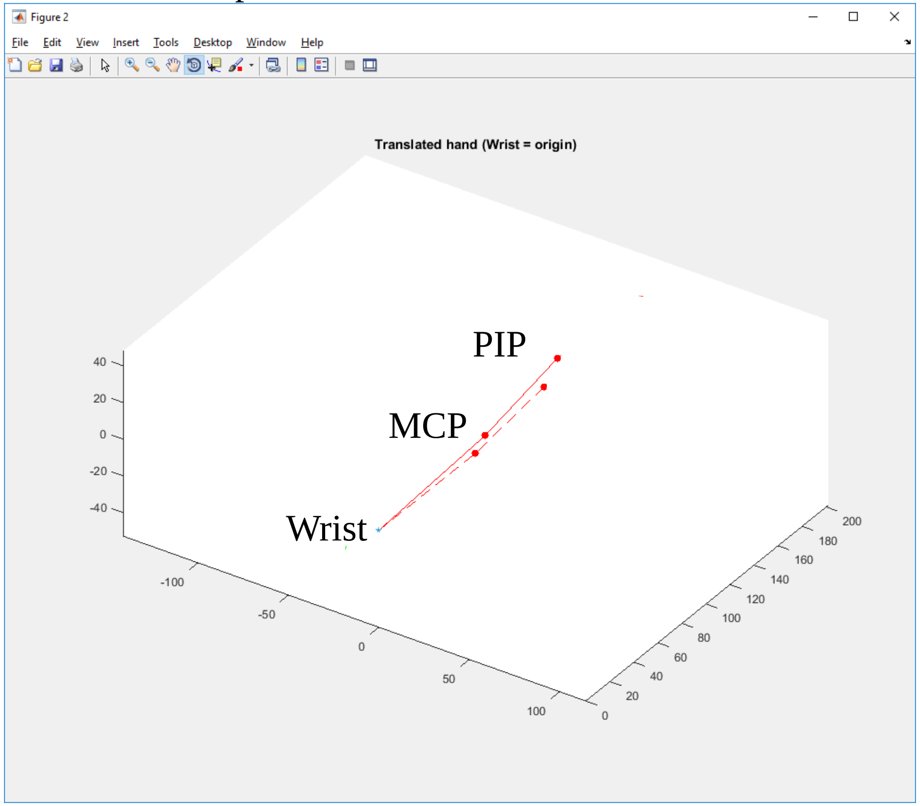
- The present study used Delonge-Kasa method to estimate the PIP joint CoR by a circle fitting method with its adjacent marker on the hand.
  - MCP JCoR is determined using PIP surface marker coordinate
  - PIP JCoR is determined using DIP surface marker coordinate
  - DIP JCoR is determined using TP surface marker coordinate



Hand Link Model Using Estimated JCoR

- Hand link model in global coordinate system with ideal hand posture

Perspective view of hand link model



Link using Initial surface marker

Link Using JCoR

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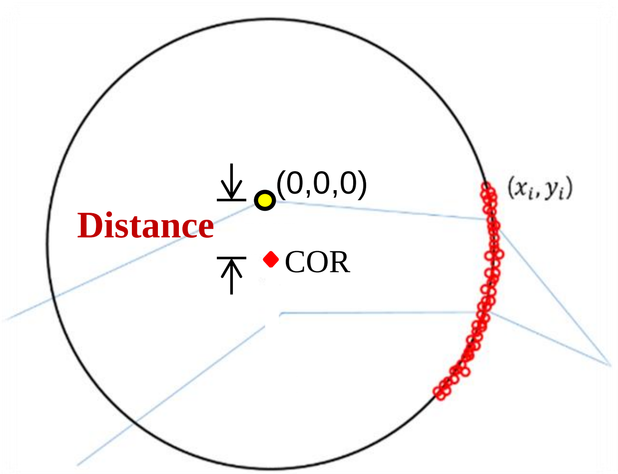
Visual Validation

- Distance from initial surface marker to COR
- Real distance = (Finger depth /2) + radius of reflective marker



radius of reflective marker = 3.5 mm
Unit: mm

Finger	Joint	Measured Distance	Real Distance
Ring	MCP	19.61	24.6
	PIP	12.75	11.5
	DIP	1.5	7.05

Discussion

- In previous study, the method of estimating the JCoR using adjacent marker has proven to be applicable using PIP joint of index finger with flexion/ Extension motion.
- In present study, the proposed method of generating hand model using JCoR that obtained using similar approach validate that the suitability of applying the JCoR estimation method on MCP, PIP and DIP joint.

Limitation & Future Study

- Several transformation steps are required to determine each JCoR.
- More participants need to be recruited for a further study.
- For further validation, true JCoR should be determined using Gold Standard (i.e. CT, fluoroscopy, X-ray etc.) as ground truth for comparison.

CT scan data in frames with different posture

Q & A

THANK YOU FOR YOUR ATTENTION

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