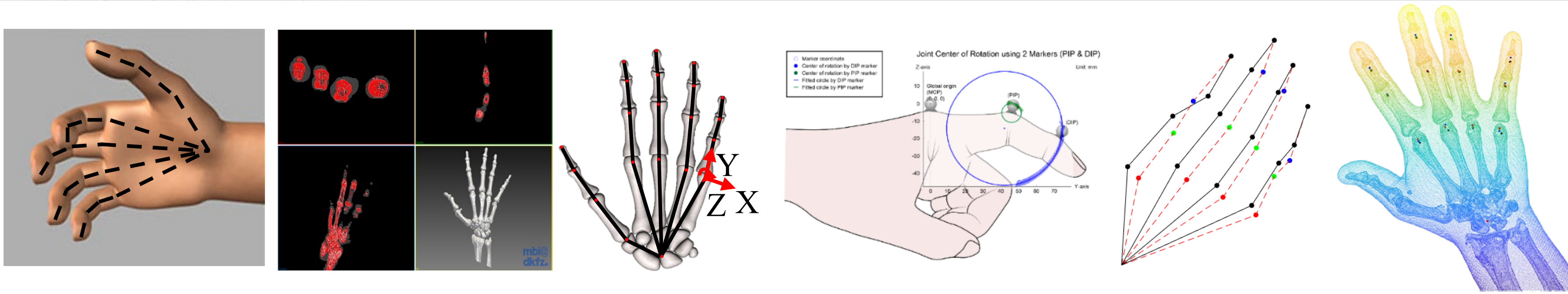
Estimation of Finger Joint Center of Rotation Using Finger Motion



Zhichan Lim, Xiaopeng Yang, Hayoung Jung, Heecheon You

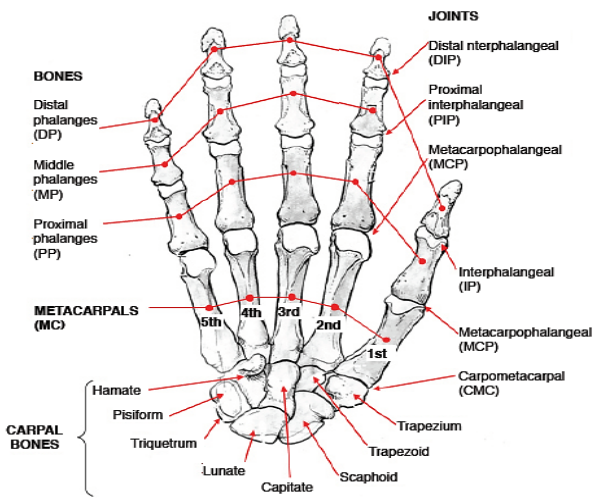
Department of Industrial & Management Engineering, Pohang University of Science and Technology, Korea

CONTENTS

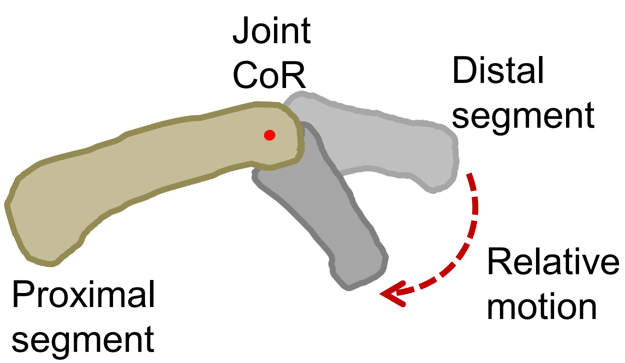
Hand Anatomy

- Hand bone structure: Containing 29 bones at the wrist and fingers
- Joint CoR: The center around which the relative motion of a joint's distal segment occurs

Hand bone structure
(Figueroa et al., 2016)



Joint CoR

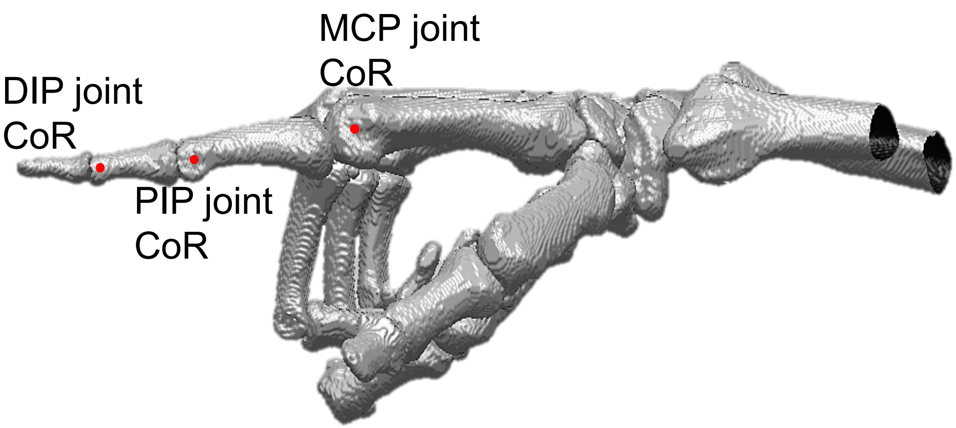


Types of Joint CoR

- Instantaneous joint CoR
  - The joint CoR around which the distal segment moves at certain instant of time from the starting position to the ending position (Challis, 2001)
- Fixed joint CoR
  - No change of Joint CoR location during motion
  - Hand joints: Assumed to have fixed joint CoR in previous studies (Zatsiorsky, 1998)

Instantaneous joint CoR
(Reuleaux, 1875)

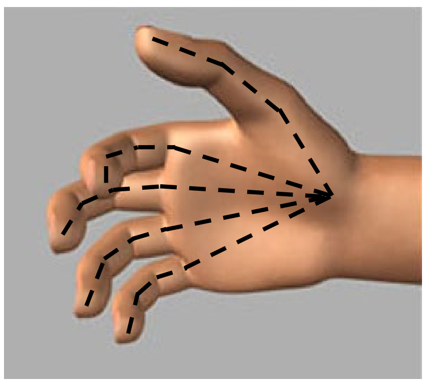
Fixed joint CoR
(Fowler, 2001)

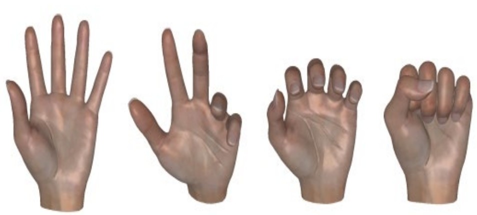


Applications of Finger Joint CoR

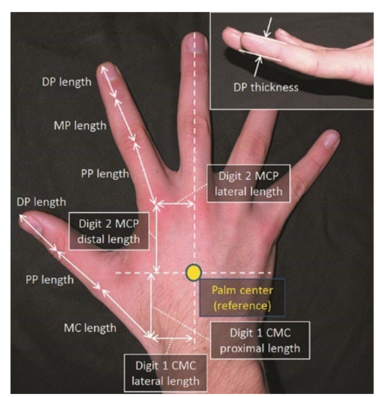
- Hand animation, hand posture recognition
- Ergonomic product designs
- Clinical assessment for hand surgery

Posture visualization & recognition

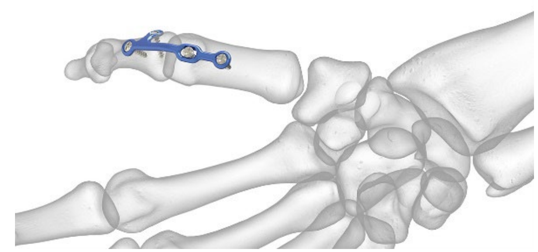




Ergonomic product design



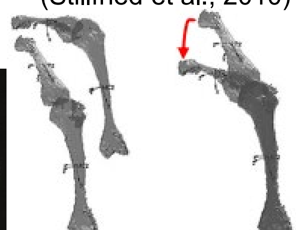
Post-operative medical evaluation

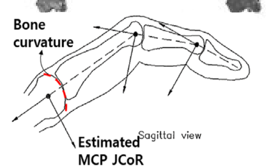


Existing Methods of Joint CoR Estimation

Type	Skeleton-based Estimation	Surface-based Estimation
Data type	Medical images data (MRI/CT)	Surface motion data
Techniques	• Reuleaux, bone curvature, PCA	• Circle fitting, optimization
Strengths	• Easy to visualize position of joint CoR • Accurate joint CoR	• Easy to collect data • Cost-effective • Safe
Limitations	• Expensive • Risk of exposure to ionizing radiation • Difficult to collect data • Long data processing	• Less accurate • Existing techniques not validated • Complex calculation

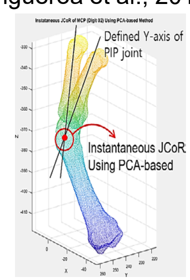
(Stillfried et al., 2010)

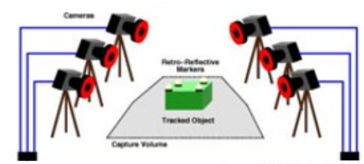


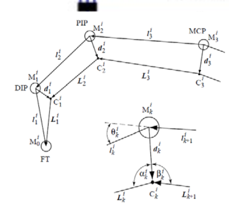


(Fowler et al., 2001)

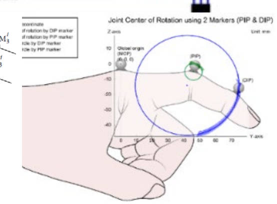
(Figueroa et al., 2016)







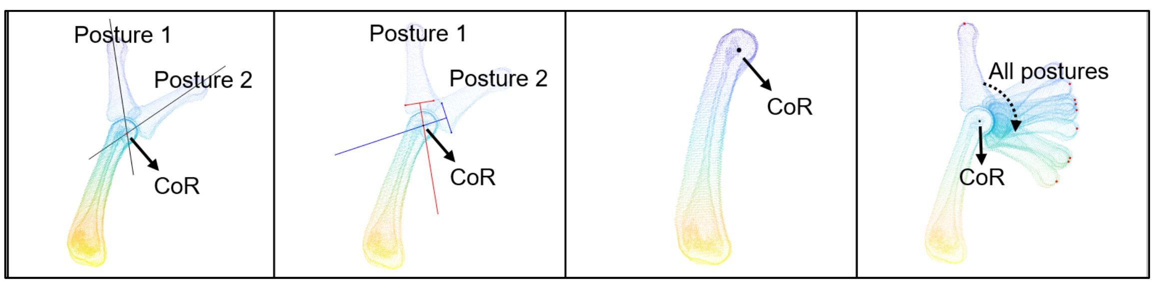
(Zhang et al., 2003)

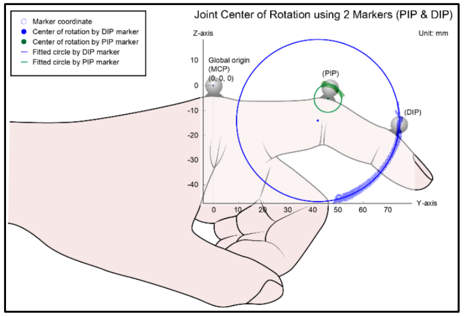


(Delonge, 1972 ; Kasa, 1976)

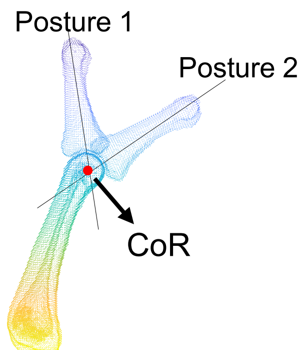
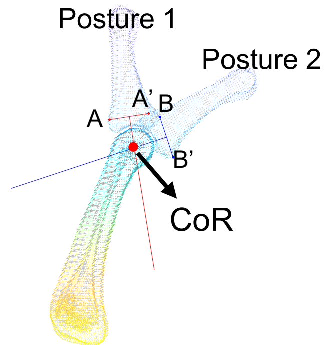
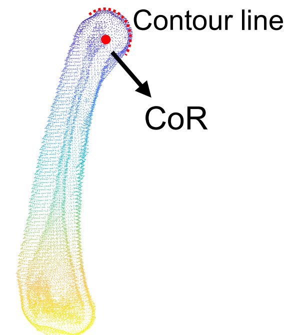
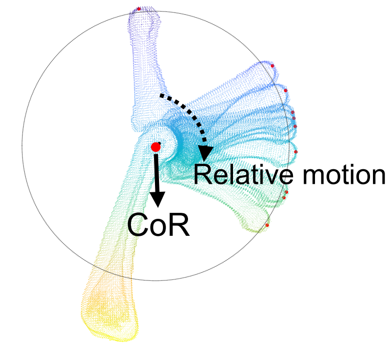
Objectives

Compare different CT-based joint CoR estimation techniques and identify those techniques provide similar results





CT-Based Joint CoR Estimation: Techniques

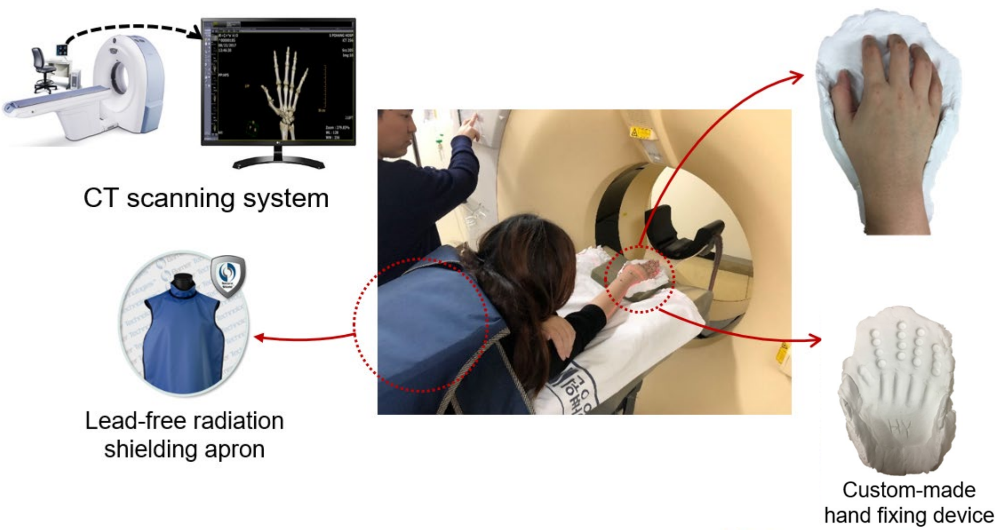
	PCA	Reuleaux	Bone Curvature	Delonge-Kasa (D-K)
Techniques	 (Figueroa et al., 2016)	 (Reuleaux, 1875)	 (Fowler et al., 2001)	 (KASA, 1976)
Type of joint CoR	Instantaneous & Fixed	Instantaneous & Fixed	Fixed	Fixed
Description	Intersection of centerlines of 2 distinct distal bones	Intersection of perpendicular bisectors of landmark A to A' and B to B'	Center of contour line defined on bone head surface	Fit a circle to the trajectory of landmark motion
Required input data	**Centerline** of each bone	Distinct coordinate of **landmark A to A' and B to B'**	**Contour line** of bone head	**Landmark** and its **displacement vector**

Data Collection and Pre-Processing

Experiment

- 9 participants
  - No neurological or musculoskeletal disorder in dominant hand
  - 3 hand size categories (Size Korea, 2010)
    - Large: > 188.5 mm
    - Medium: 178.3 ~ 188.4 mm
    - Small: < 178.2 mm

- Apparatus
  - CT scanning system
  - Custom-made hand fixing device
  - Radiation shielding apron



Experiment Protocol

1. Preparation

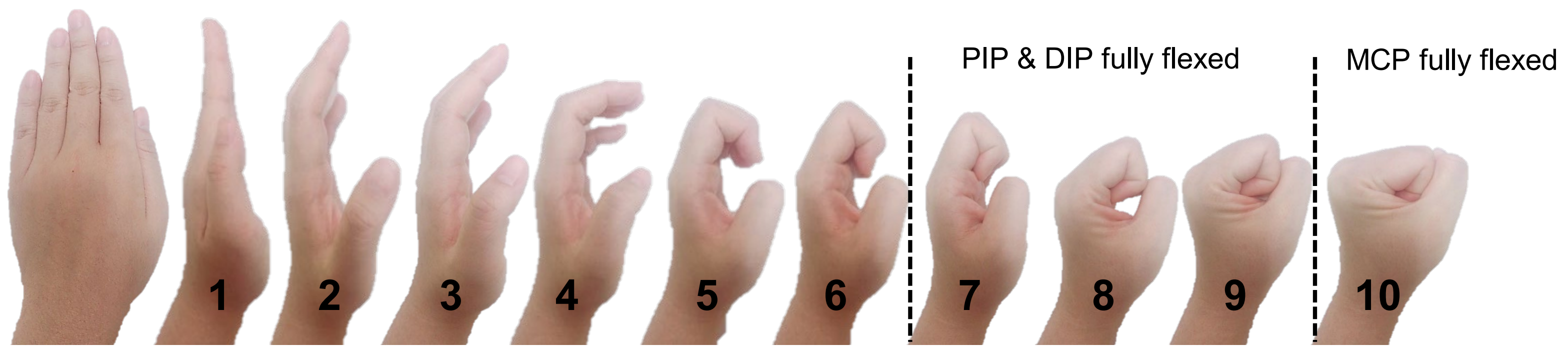
- Measure hand length
- Build a custom-made hand fixing device
- Practice hand posture

Custom-made hand fixing device

2. Main experiment

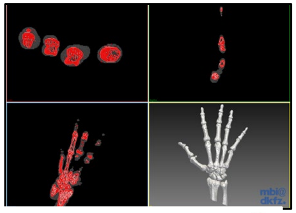
- Fix hand and each posture (10 postures) at the fixing device
- CT scan of each hand posture

3. Debriefing



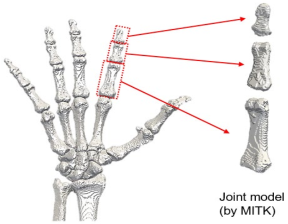
CT Data Pre-Processing

- Reconstruct the 3D skeletal models of different postures that share the same bone surface



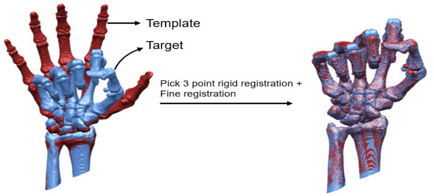
S1. **Segmentation of hand skeleton**

1. Masking: Remove skin region
2. Segmentation of skeleton: Extract bone region



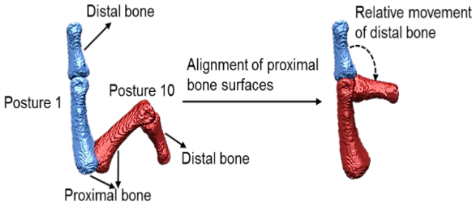
S2. **Preparation of Template bone**

Subtraction tool: Remove pixels at the contact region between 2 distinct bones



S3. **Registration of template to target bones**

1. Pre-alignment: pick-3-point rigid registration
2. Fine-alignment: Fine rigid registration



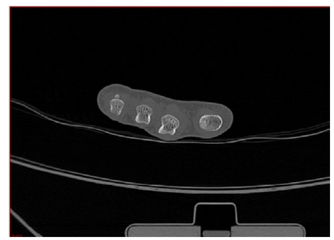
S4. **Alignment of proximal bone**

Precise alignment: Pick-3-points rigid registration

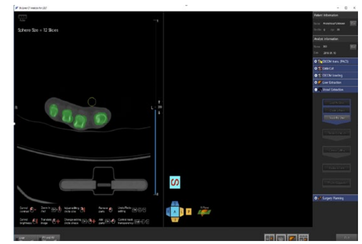
S1. Segmentation of Hand Skeleton

- 2-step procedure for segmentation of hand skeleton from CT images
  - S1: Masking
    - Exclude the skin region using a 3D sphere tool of Dr.Liver

Original CT image



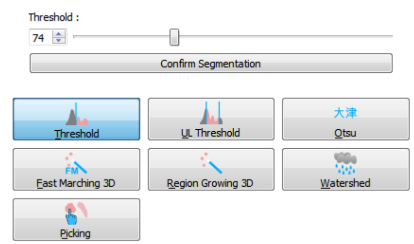
Masking



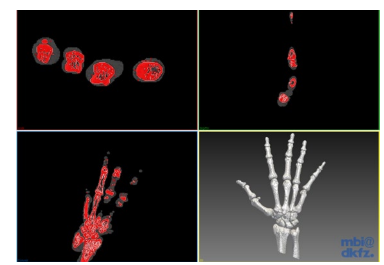
Masked CT image

  - S2: Segmentation
    - Extract the skeleton region using a **threshold-based technique** of MITK by manually adjust threshold value

Threshold selection



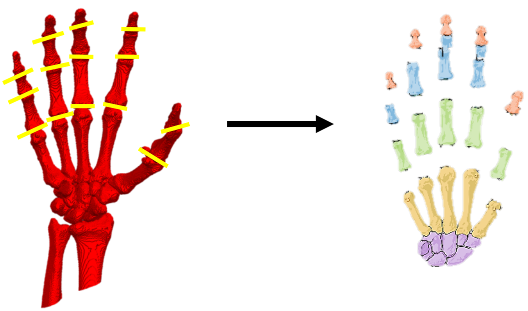
Segmented bone



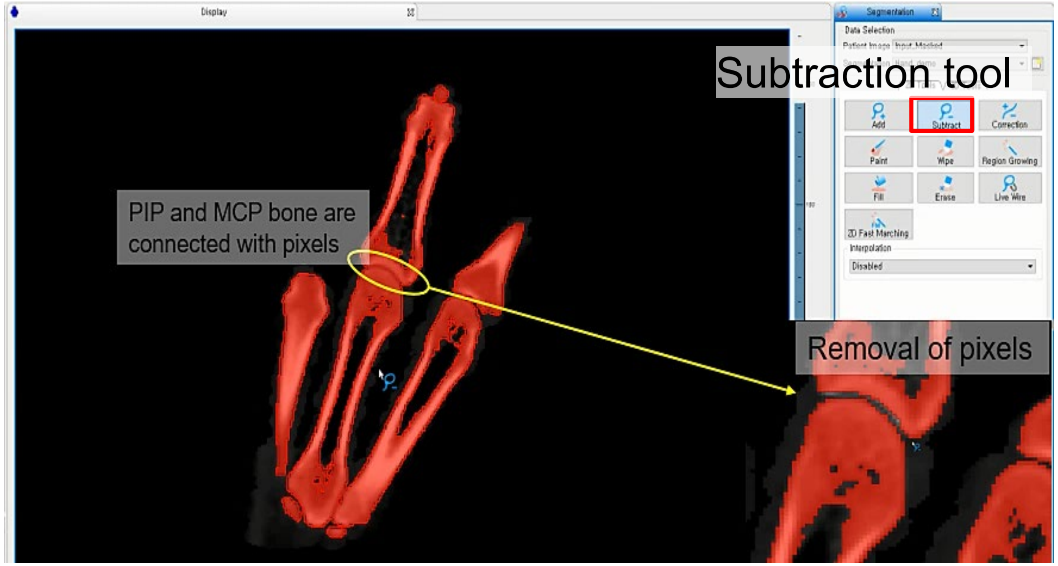
S2. Preparation of Template Bone

- 2-step procedure for extraction of the bone segments from one skeleton model as template bone
  - S1: Select the skeleton at the initial posture
  - S2: Remove the connected pixels between 2 bone segments using a subtraction tool of MITK

Separation of bone segments



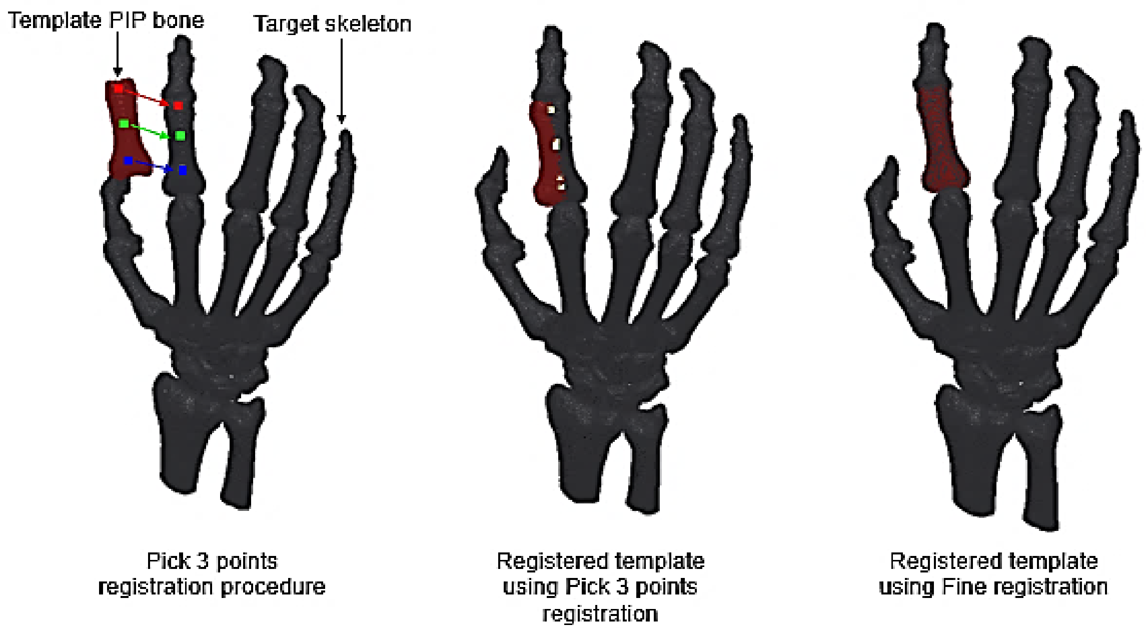
Subtraction Tool by MITK



S3. Registration of Template to Target Bones

- 2-step procedure for template bone alignment
  - S1: Pre-alignment by the Pick-3-Point rigid registration tool of RapidForm 2006
  - S2: Fine-alignment by the Fine rigid registration tool of RapidForm 2006

Example of template bone alignment



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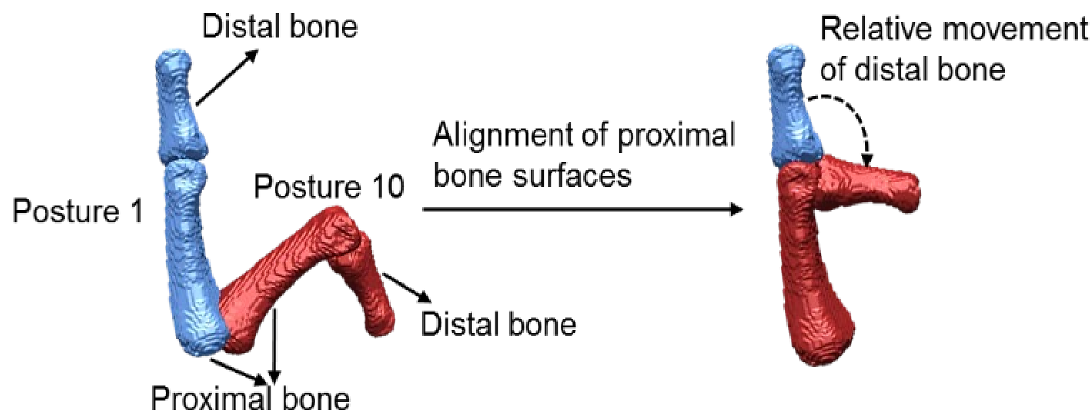
S4. Alignment of Proximal Bone

- Align the proximal bone segments of all postures to examine the motion of distal bone segments using Pick-3-Point rigid registration tool of RapidForm 2006

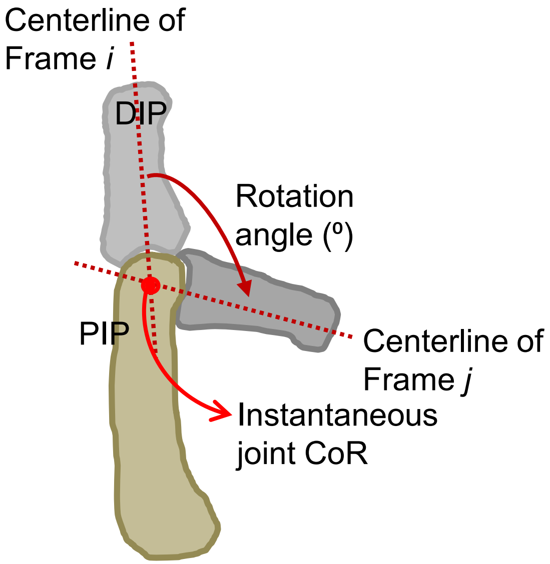
Alignment of proximal bone



CT-Based
Instantaneous Joint CoR Estimation

Instantaneous Joint CoR Estimation: PCA

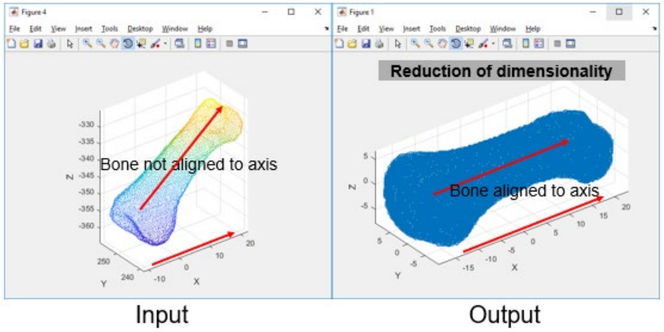
- **Principal Component Analysis** (**PCA** method)
  - Estimates instantaneous joint CoR between 2 postures using bone centerlines
  - Steps
    - S1. Determine the centerline of the distal segment at each posture
    - S2. Find the intersection point between the centerlines of the distal segment at 2 different postures



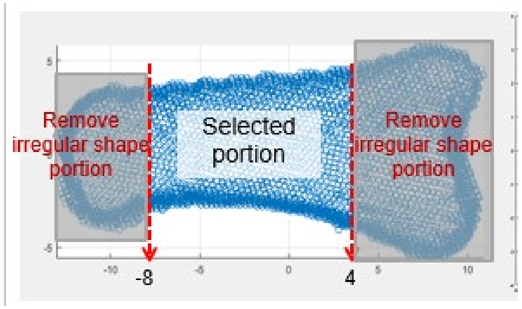
Rosemarie Figueroa 1, T. J. (2016). DETERMINING INSTANTANEOUS CENTERS OF ROTATION FOR FINGER JOINTS THROUGH DIFFERENT POSTURES USING THE ITERATIVE CLOSEST POINT ALGORITHM (ICP). Proceedings of the Human Factors and Ergonomics Society, 1470-1474.

S1. Centerline of Bone (2/2)

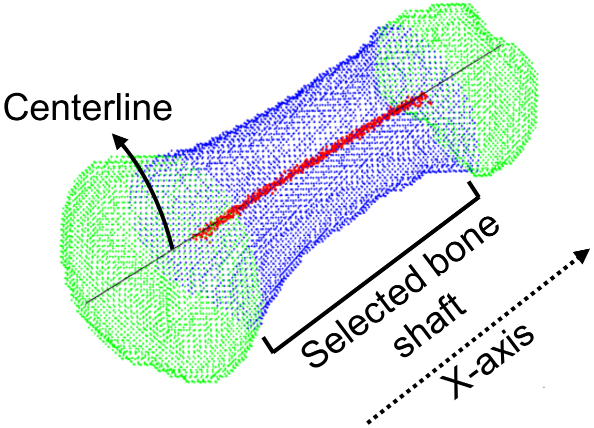
1. Reduce dimensionality of bone using PCA
   - Principle component 1 → X-data
   - Principle component 2 → Y-data
   - Principle component 3 → Z-data



2. Select a bone shaft
   - Remove irregular bone regions at the extreme sides of the bone for bone shaft

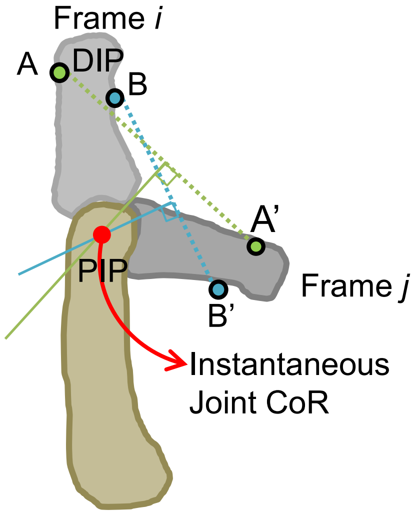


3. Identify a centerline
   - Find the centroid of each YZ plane along x-axis perpendicular to the bone shaft
   - Linearly fit a line which passes through the centroids along x-axis



Instantaneous Joint CoR Estimation: Reuleaux

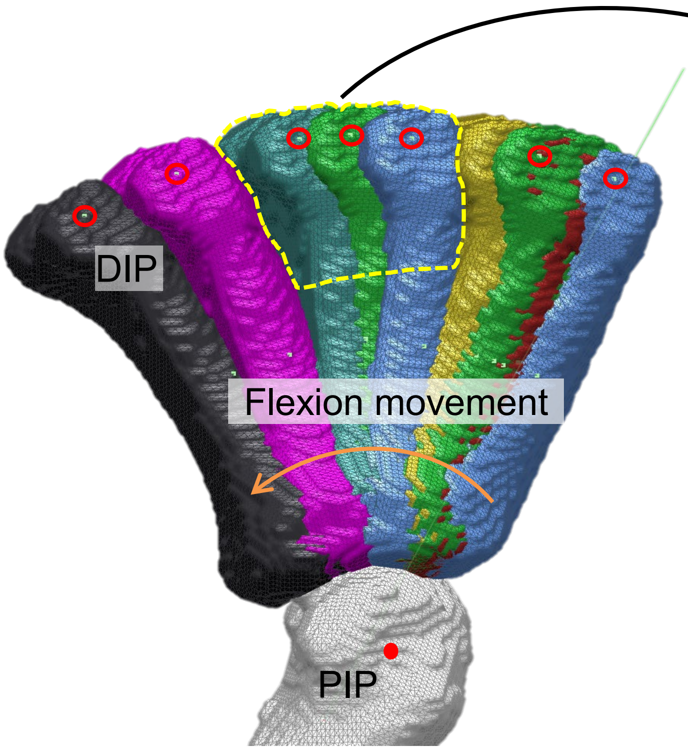
- **Reuleaux** method
  - Estimate an instantaneous joint CoR from 2 postures using the displacement vectors of 2 landmarks
    - S1. Select landmarks A and B and their displacement vectors
    - S2. Find an intersection point between the perpendicular bisectors of the 2 landmarks

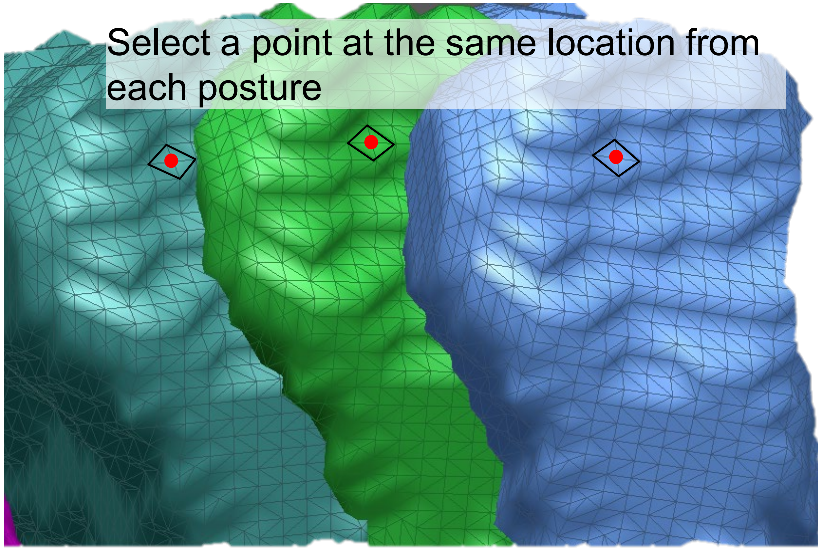


- Challis, J. H. (2001). Estimation of the finite center of rotation in planar movements. Medical Engineering & Physics, 23, 227-233.
- Silmara Nicolau Pedro da Silva, R. M. (2005). Measurement of the flexing force of the fingers by a dynamic splint with a dynamometer. CLINICS, 60(5), 381-388.
- Reuleaux, F. (1875). Theretische Kinematik. Braunschweig.

S1. Select Landmark (2/2)

- Select a point using RapidForm from each posture at the same location of the bone surface data as landmark





Measures of Joint CoR Estimation Method

- Consistency
  - Measured using mean distance between CoRs (mm)

$$\boldsymbol{Mean}\ \textbf{distance}\ (\textbf{MD}), \boldsymbol{mm} = \frac{\sum_{i=1}^{N}\sum_{i\neq j}^{N}\left|\boldsymbol{X_i} - \boldsymbol{X_j}\right|^2}{\boldsymbol{C_N^2}}$$

↓ $\boldsymbol{Mean}$ **distance** ↑ $\boldsymbol{Consistency}$

- Variability
  - Measured using standard error (mm)

$$\boldsymbol{Standard}\ \textbf{error}, \boldsymbol{mm} = \sqrt{\frac{\sum_{i=1}^{N}(\boldsymbol{X_i} - \overline{\boldsymbol{X}})^2}{\boldsymbol{n}-\boldsymbol{1}}}$$

↓ $\boldsymbol{Standard}$ **error** ↑ $\boldsymbol{Variability}$

Results

- 96% of joints were significantly different in consistency between PCA method and Reuleaux method ($p < 0.001$) for majority of joints based on paired t-test.

Hand size: Large / Medium / Small

Large

P1

Finger	P-Value of Paired T-test of PCA with Realeaux		
	MCP	PIP	DIP
Index	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Middle	$p < 0.0005$	$p < 0.0005$	$p = 0.003$
Ring	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Little	$p < 0.0005$	$p < 0.0005$	$p = 0.005$

P2

Finger	P-Value of Paired T-test of PCA with Realeaux		
	MCP	PIP	DIP
Index	$p < 0.0005$	$p = 0.003$	$p = 0.059$
Middle	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Ring	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Little	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$

P3

Finger	P-Value of Paired T-test of PCA with Realeaux		
	MCP	PIP	DIP
Index	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Middle	$p < 0.0005$	$p = 0.162$	$p < 0.0005$
Ring	$p < 0.0005$	$p = 0.029$	$p < 0.0005$
Little	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$

Medium

P4

Finger	P-Value of Paired T-test of PCA with Realeaux		
	MCP	PIP	DIP
Index	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Middle	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Ring	$p = 0.008$	$p < 0.0005$	$p < 0.0005$
Little	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$

P5

Finger	P-Value of Paired T-test of PCA with Realeaux		
	MCP	PIP	DIP
Index	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Middle	$p < 0.0005$	$p < 0.0005$	$p = 0.995$
Ring	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Little	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$

P6

Finger	P-Value of Paired T-test of PCA with Realeaux		
	MCP	PIP	DIP
Index	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Middle	$p < 0.0005$	$p = 0.009$	$p < 0.0005$
Ring	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Little	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$

Small

P7

Finger	P-Value of Paired T-test of PCA with Realeaux		
	MCP	PIP	DIP
Index	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Middle	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Ring	$p < 0.0005$	$p < 0.0005$	$p = 0.002$
Little	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$

P8

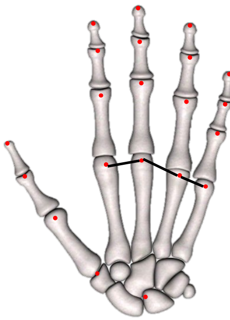
Finger	P-Value of Paired T-test of PCA with Realeaux		
	MCP	PIP	DIP
Index	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Middle	$p < 0.0005$	$p = 0.404$	$p < 0.0005$
Ring	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Little	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$

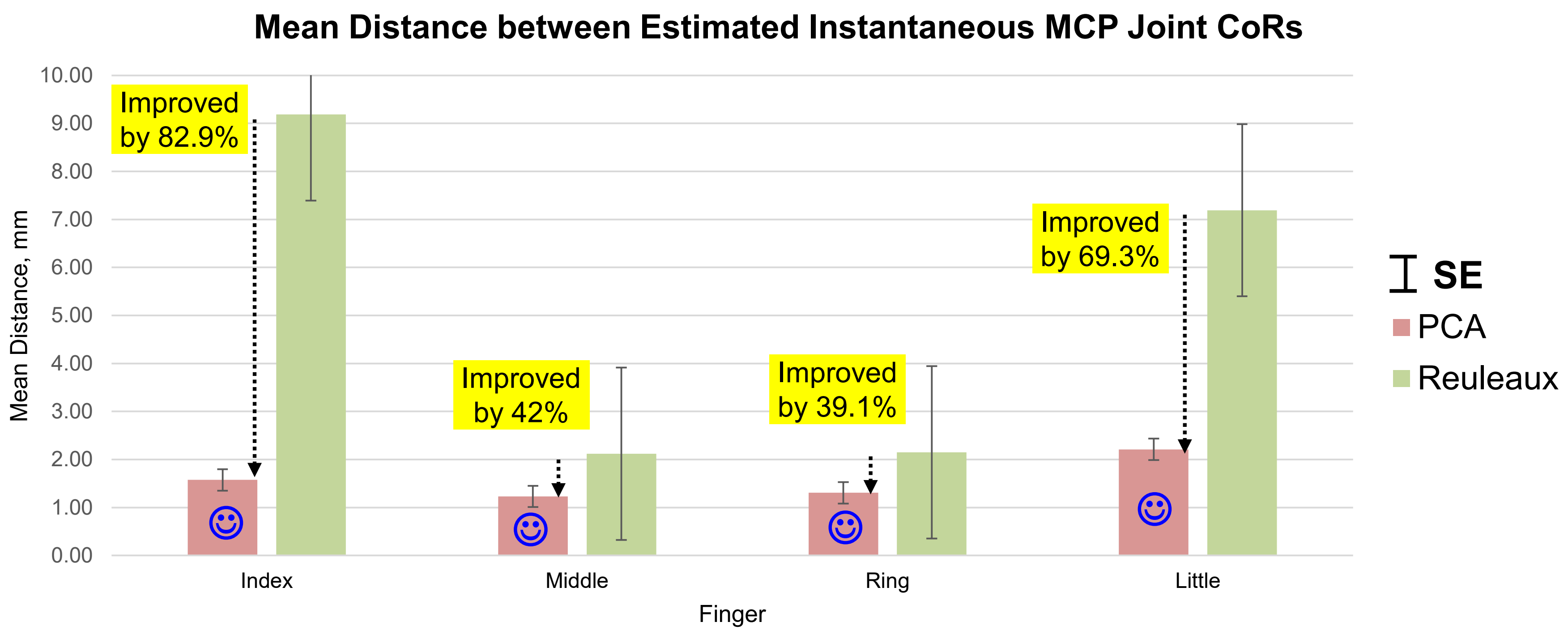
P9

Finger	P-Value of Paired T-test of PCA with Realeaux		
	MCP	PIP	DIP
Index	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Middle	$p = 0.003$	$p < 0.0005$	$p < 0.0005$
Ring	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$
Little	$p < 0.0005$	$p < 0.0005$	$p = 0.169$

Consistency of Instantaneous CoR: MCP Joint

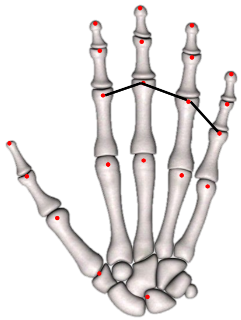
- PCA method provided more consistent and less variability results (MD = 1.57±0.52 for index, 1.23±0.84 for middle, 2.12±0.82 for ring, 2.21±1.18 mm for little fingers)

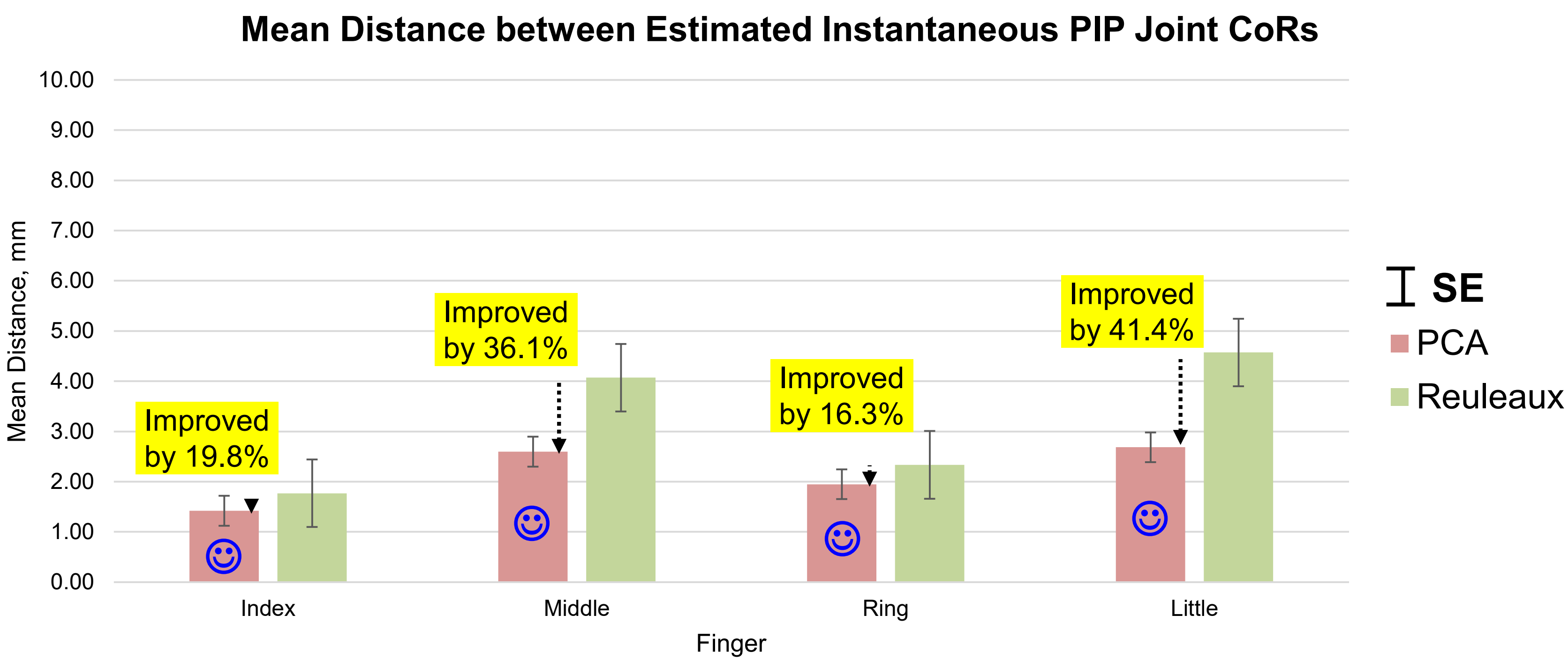




Consistency of Instantaneous CoR: PIP Joint

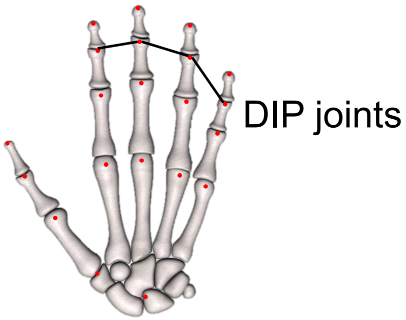
- PCA method provided more consistent and less variability results (MD = 1.42±0.85 for index, 2.60± 2.07 for middle, 1.95±1.26 for ring, 2.68±2.46 mm for little fingers)

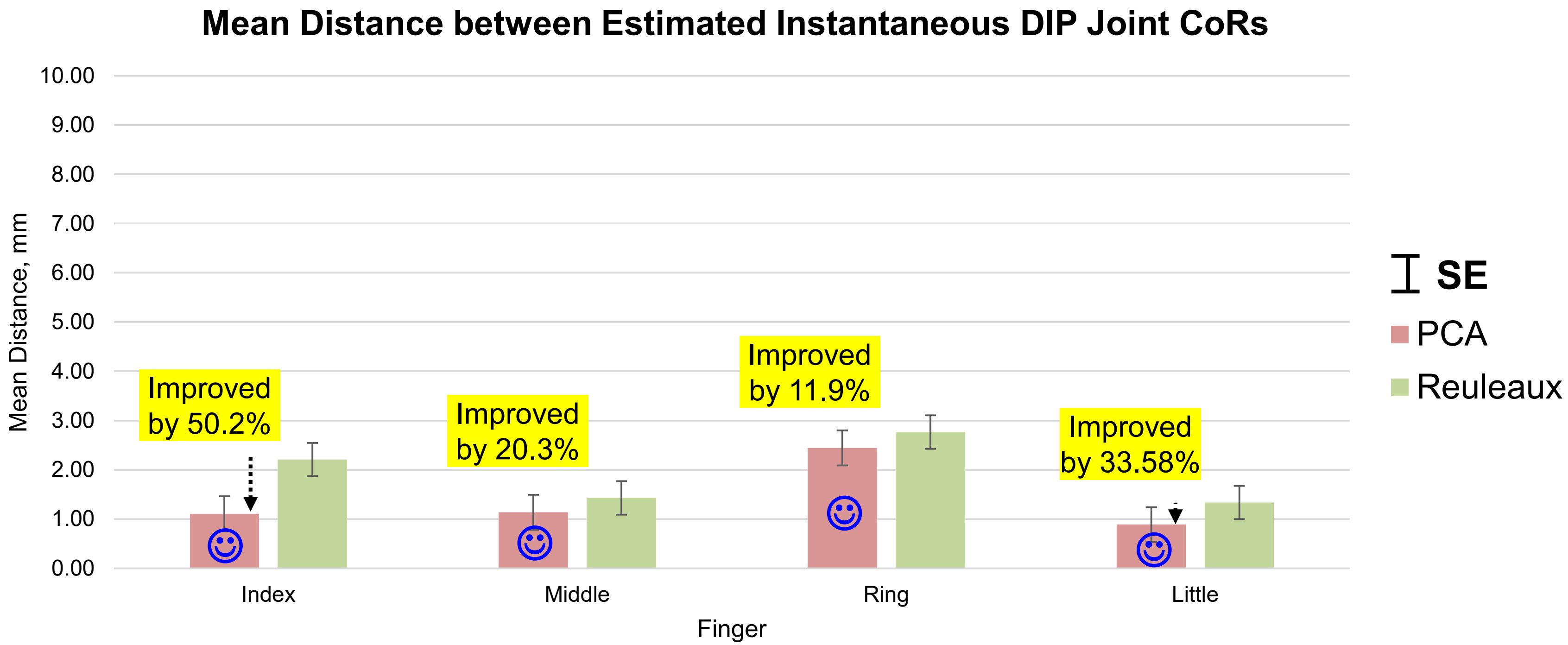




Consistency of Instantaneous CoR: DIP Joint

- PCA method provided more consistent and less variability results (MD = 1.10±0.53 for index, 1.14±0.51 for middle, 2.44±3.07 for ring, 0.89±0.51 mm for little fingers)

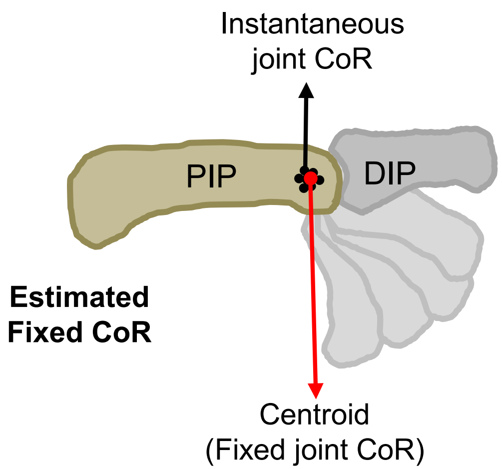




CT-Based
Fixed Joint CoR Estimation

Fixed Joint CoR Estimation: K-means Clustering

- **K-means clustering** method
  - Estimate a centroid from a group of estimated instantaneous joint CoRs as fixed CoR using K-means clustering technique (K = 1)



K-means technique:
Minimize the squared error function

$$J(V) = \sum_{i=1}^{k} \sum_{j=1}^{K_i} \left(\left\| X_i - V_j \right\| \right)^2$$

K_i = the number of data points in i^{th} case

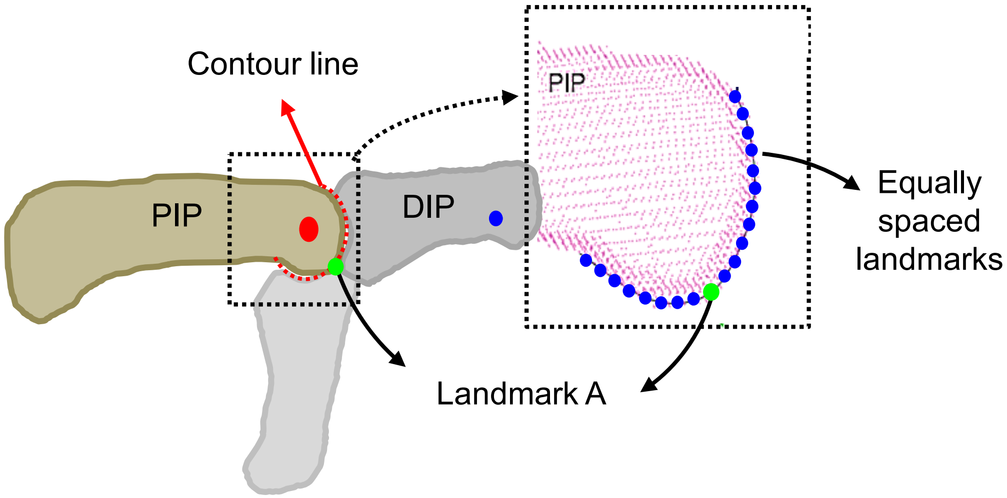
$k = 1$ which is the number of cluster centers

V_j = the centroid for cluster j

$\left\| X_i - V_j \right\|$ = the distance between 2 n-dimensional data points, X_i,V_j

Fixed Joint CoR Estimation: Bone Curvature (1/2)

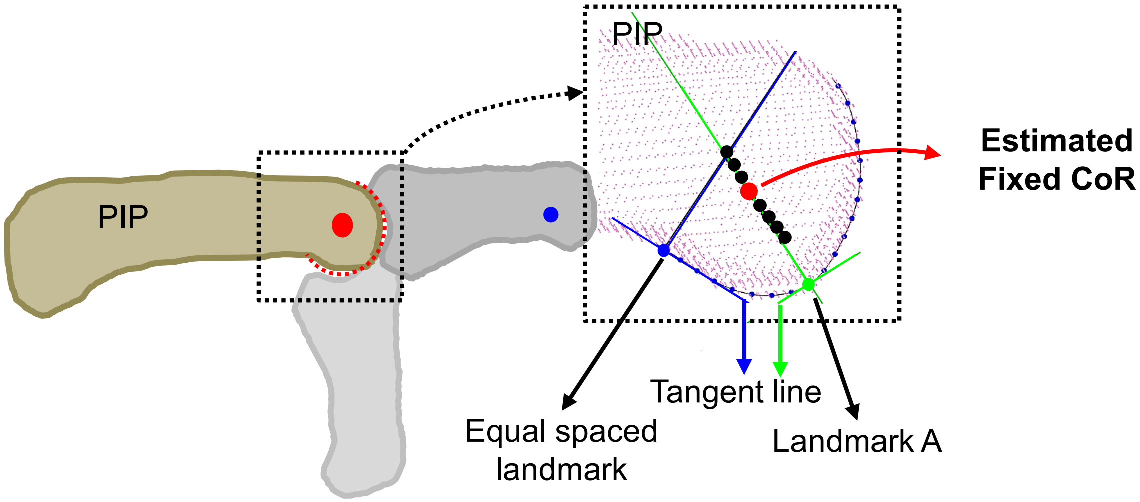
- **Bone curvature** method
  - Estimate the fixed joint CoR from the center of the curvature of bone head
  - Steps
    - S1. Define a contour line of the bone head, landmark A (point that has the highest curvature on the contour), equally spaced landmarks along the contour



N.K. Fowler, A. N. (2001). Method of determination of three dimensional index finger moment arms and tendon lines of action using high resolution MRI scans. Journal of Biomechanics, 34, 791-797.

Fixed Joint CoR Estimation: Bone Curvature (2/2)

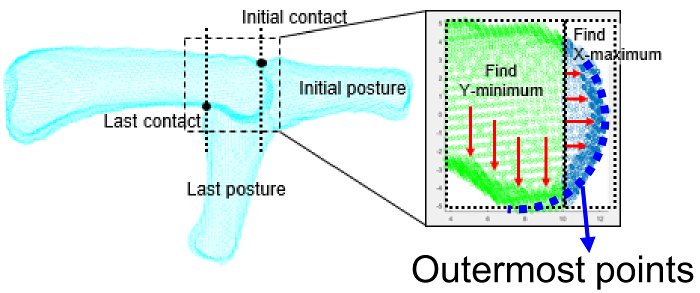
- Steps (cont.)
  - S2. Draw tangent lines that passing through the landmark A and an equal spaced landmark
  - S3. Draw the normal of the tangent lines
  - S4. Find an intersection point between the normal lines
  - S5. Compute a centroid as fixed CoR using K-means clustering (K = 1)



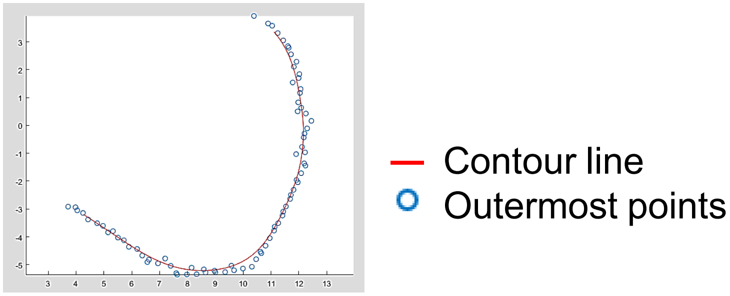
N.K. Fowler, A. N. (2001). Method of determination of three dimensional index finger moment arms and tendon lines of action using high resolution MRI scans. Journal of Biomechanics, 34, 791-797.

S1. Define Contour Line and Landmarks (3/3)

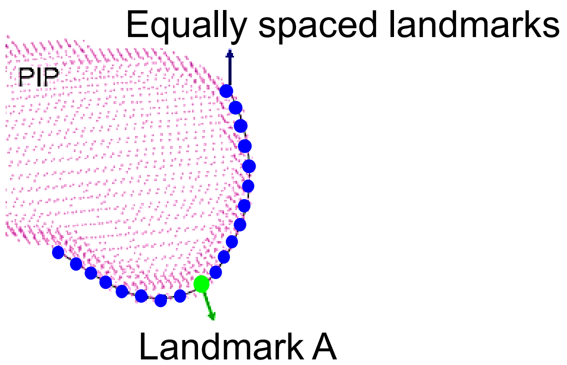
1. Find the outermost points around the bone head surface



2. Connect those points to form a contour line and smooth the contour line using Gaussian smoothing filter (smoothing window = 5~15)

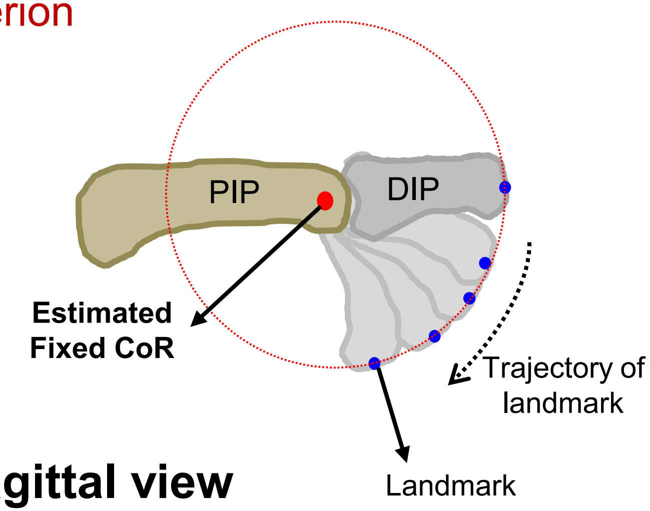


3. Determine the point with the highest curvature from the contour line as landmark A and other equally spaced landmarks



Fixed Joint CoR Estimation: D-K Method

- **D-K** method
  - Estimate a fixed joint CoR from the trajectory of a landmark
  - Steps
    - S1. Select a landmark from each posture at the same position of bone surface data
    - S2. Fit a circle to the trajectory of the landmark by minimizing the least square error criterion



Least square error criterion:

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

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

(x_i, y_i) = Marker locations
(A, B) = Calculated joint CoR
R = Radius of the fitted circle over the trajectory of marker motion

KASA. (1976). A Circle Fitting Procedure and Its Error Analysis. IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, 8-14.

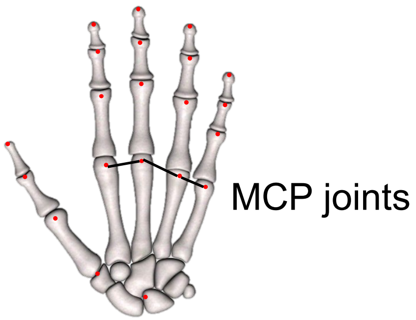
Consistency of Fixed CoR: Summary

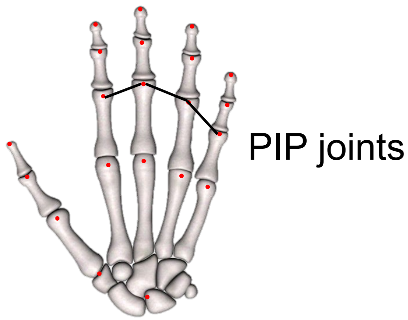
- Review of methods that provide the most consistent fixed joint CoR

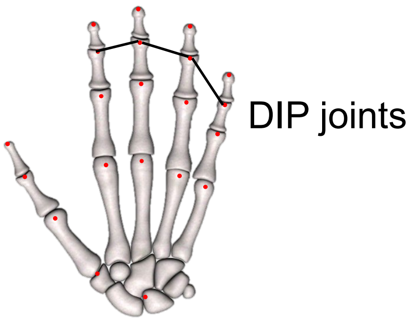
Unit: mm

	Index	Middle	Ring	Little
MCP	D-K (1.80±0.84)	Reuleaux (1.08 ± 0.25)	D-K (1.28±0.49)	PCA (1.37 ± 0.45)
PIP	D-K (0.41±0.20)	D-K (0.40±0.15)	Reuleaux (0.45 ± 0.23)	D-K (0.47±0.28)
DIP	D-K (0.52 ± 0.14)	Reuleaux (0.65 ± 0.21)	D-K (0.45 ± 0.23)	D-K (0.33 ± 0.11)

Estimated fixed joint CoR by Delonge-Kasa (D-K) is selected as reference CoR and used to validate motion-based joint CoR



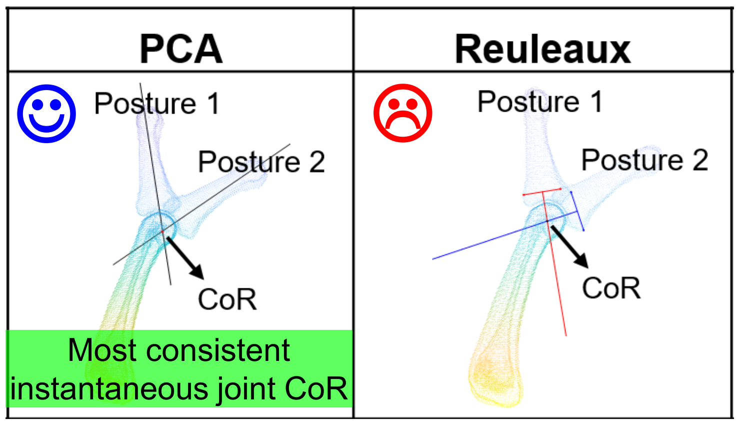




Discussion

CT-based Joint CoR Estimation (1/2)

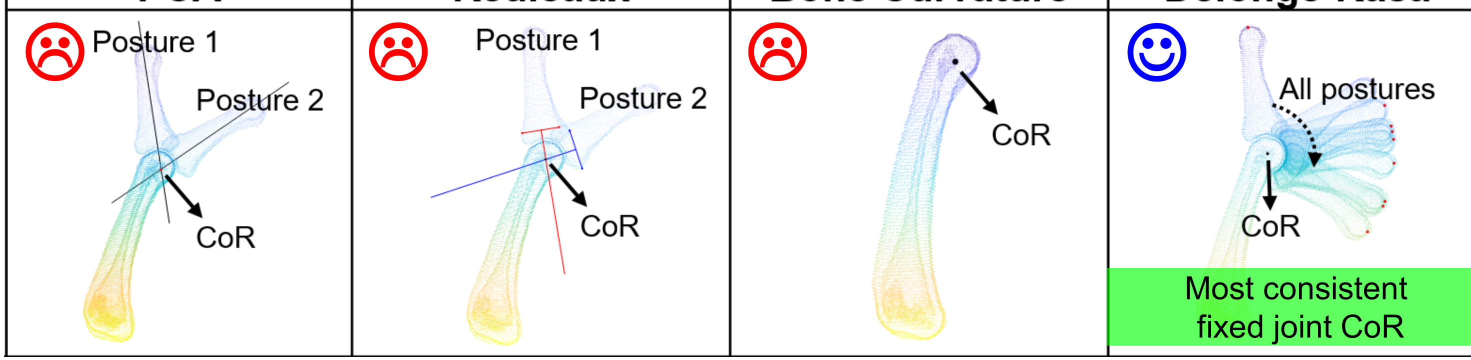
- Compared the instantaneous joint CoR estimation methods: PCA and Reuleaux
  - PCA (1.71±0.84) > Reuleaux (3.43±3.86) in terms of the mean consistency and variability of CoR
    - MCP: 58.3% higher (Variability: 82.4% lower)
    - PIP: 28.4% higher (Variability: 61.5% lower)
    - DIP: 29% higher (Variability: 30.0% lower)



CT-based Joint CoR Estimation (2/2)

- Compared the fixed joint CoR estimation methods: PCA, Reuleaux, D-K, and Bone curvature
  - D-K (0.77±0.3) > Reuleaux (0.82±0.32) > PCA (0.92±0.30) > Bone curvature (0.95±0.41) in terms of the mean consistency and variability of the CoR

PCA	Reuleaux	Bone Curvature	Delonge-Kasa	
(0.92±0.30)	(0.82±0.32)	(0.95±0.41)	(0.77 ± 0.3)	mm



Limitation & Future Study

- Limitation
  - The experiment is costly and lack of practicability
  - The evaluation of techniques is not include the thumb
- Future study
  - Extend the evaluation to thumb
  - Use hand anthropometric information (or motion capture data) to estimate finger joint CoR for practical application

Q & A

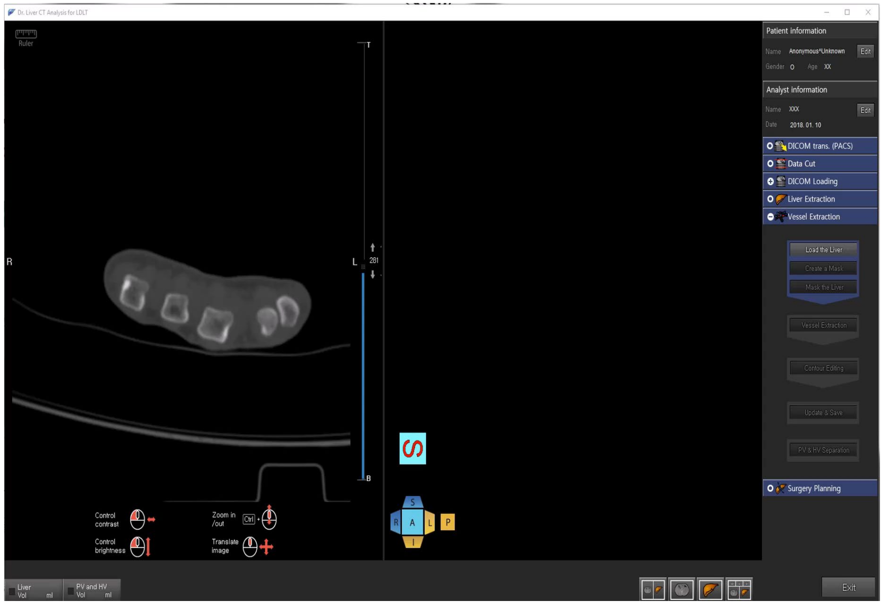
?

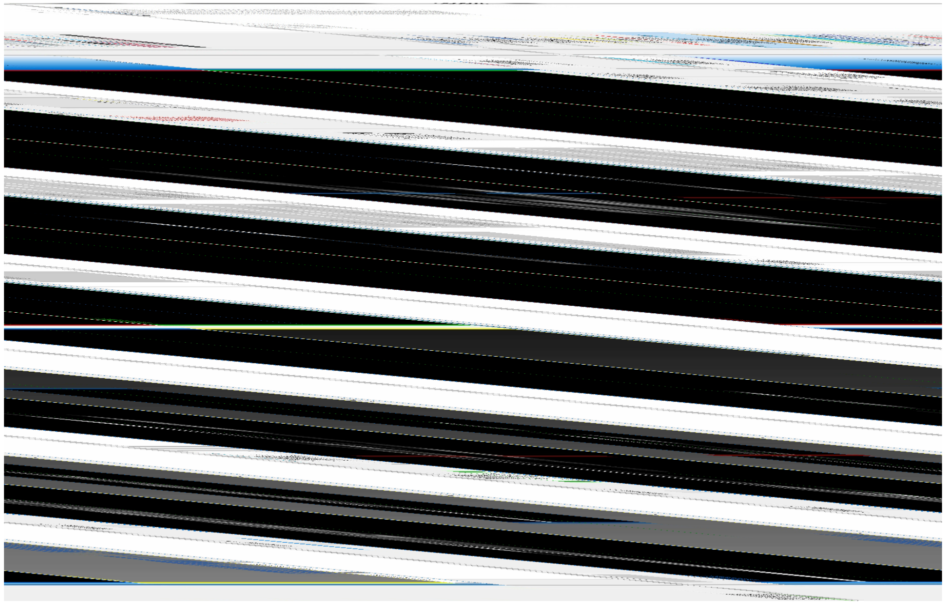
THANK YOU
FOR
YOUR
ATTENTION
ANY QUESTIONS?

Appendices

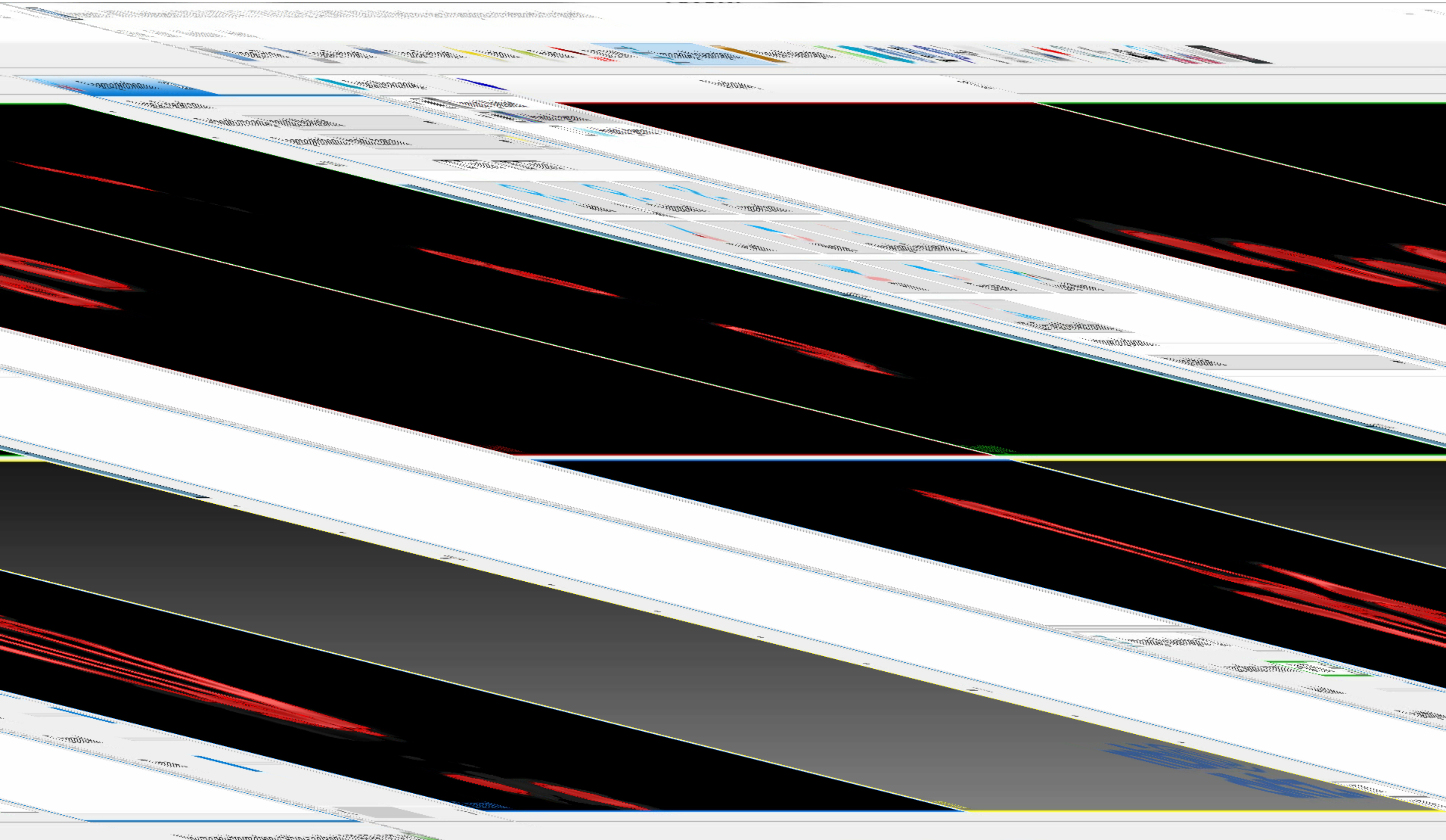
Demo: Segmented Bone Model

- Step 1: Masking method
- Step 2: Threshold based method

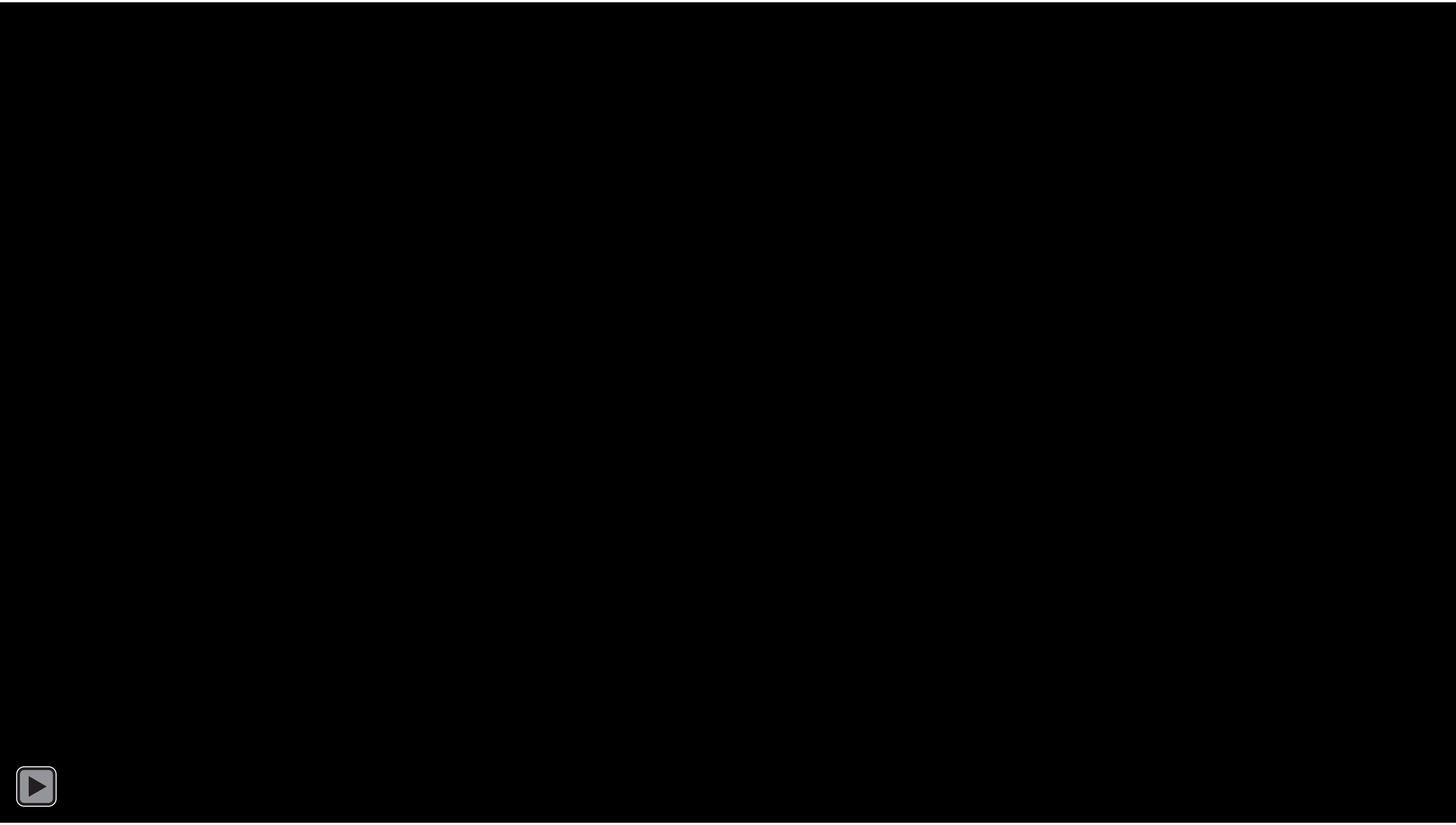




Demo: Separation of Bone Segments

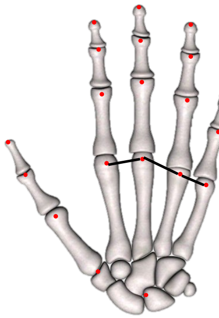


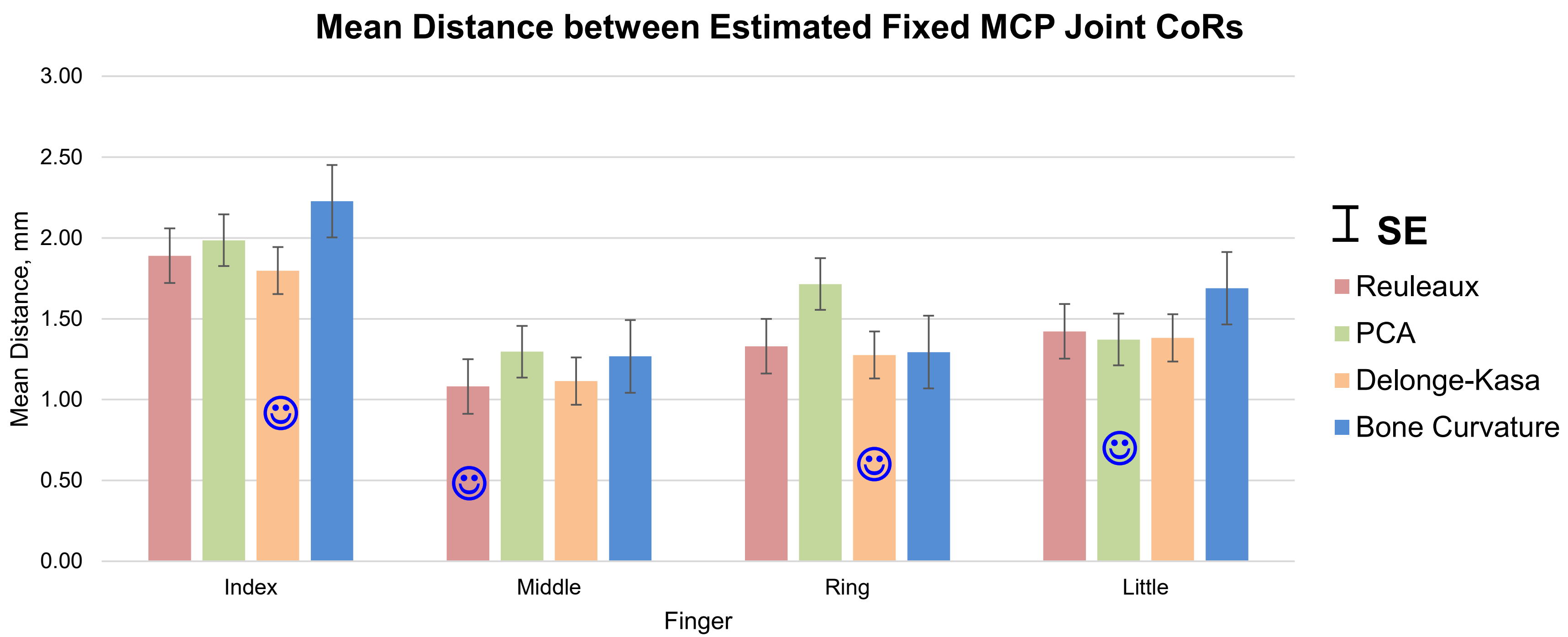
Demo: Registration of Each Bone Segments



Consistency of Fixed CoR: MCP Joint

- Methods that provide the most consistent results
  - Index and ring: **D-K** (Index = 1.80±0.84; Ring = 1.28±0.49)
  - Middle: **Reuleaux** (1.08 ± 0.25)
  - Little: **PCA** (1.37 ± 0.45)





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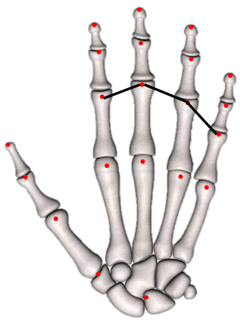
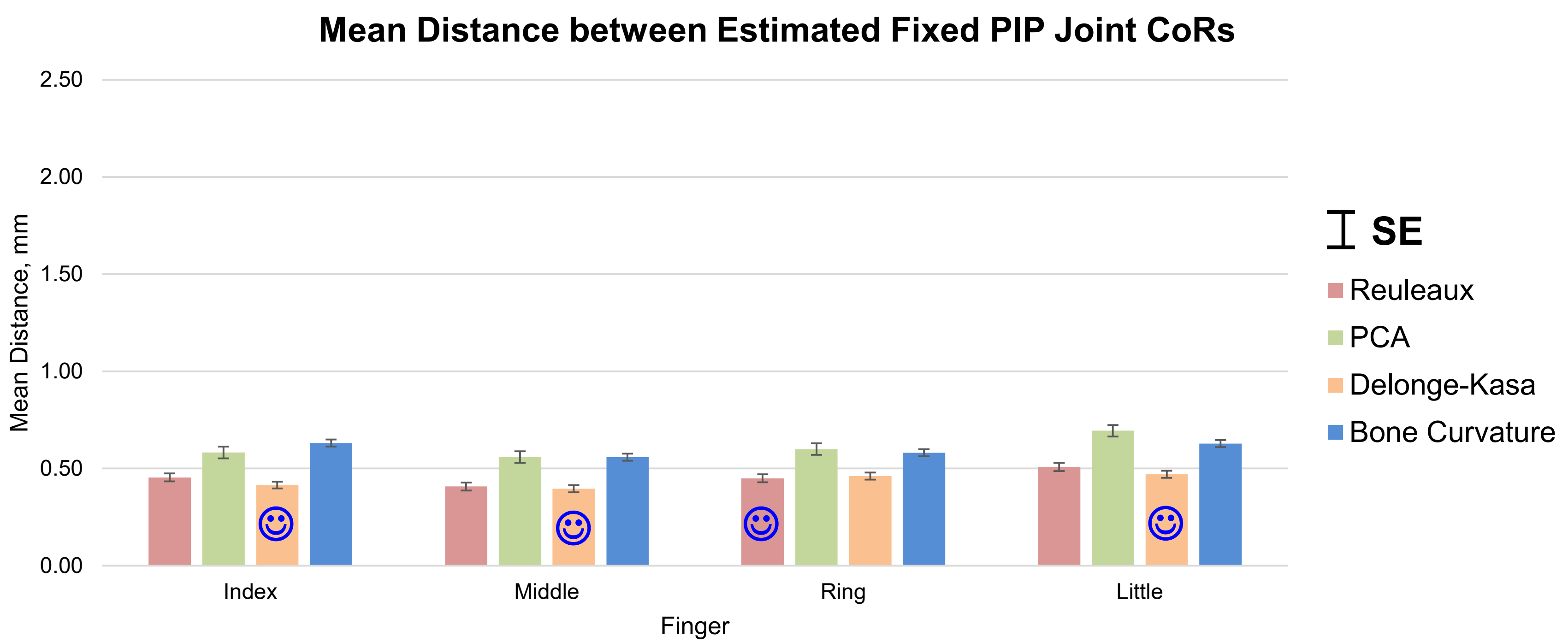
Consistency of Fixed CoR: PIP Joint

- Method that provides the most consistent results
  - Index, Middle, and Little finger : **D-K**

    (Index = 0.41±0.20; Middle = 0.40±0.15; Little = 0.47±0.28)
  - Ring finger : **Reuleaux** (0.45 ± 0.23)





Consistency of Fixed CoR: DIP Joint

- Method that provides the most consistent results
  - Index, Ring, and Little finger : **D-K**

    (Index = 0.52 ± 0.14; Ring = 0.45 ± 0.23; Little = 0.33 ± 0.11)
  - Middle finger : **Reuleaux** (0.65 ± 0.21)