Towards Explainable and Unprecedented Accuracy in Matching Challenging Finger Crease Patterns

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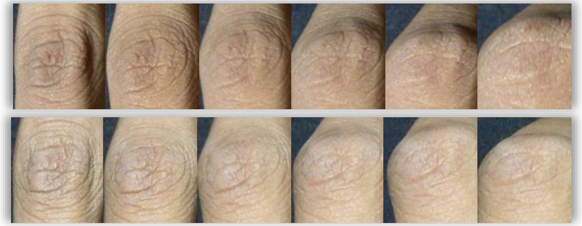
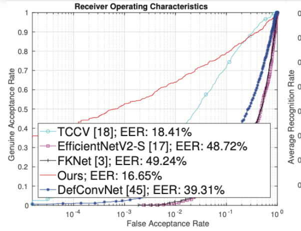
Department of Data Science and Artificial Intelligence, The Hong Kong Polytechnic University

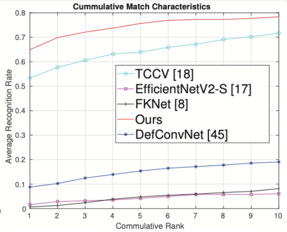
CVPR Nashville JUNE 11-15, 2025

Problems:

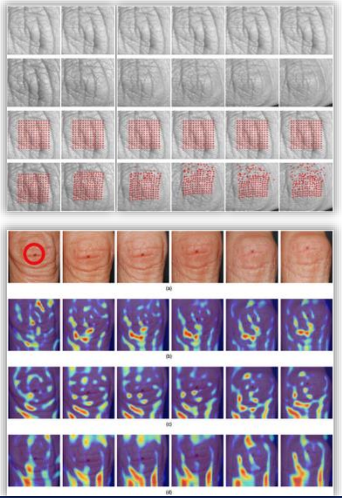
1). *Poor Cross-Pose Performance*





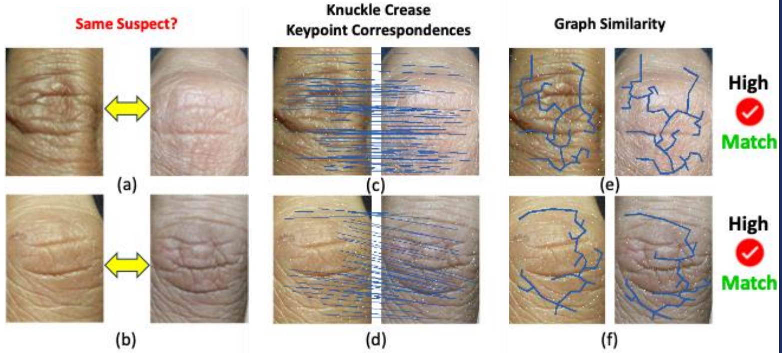


2). *Consolidate Match Evidence*



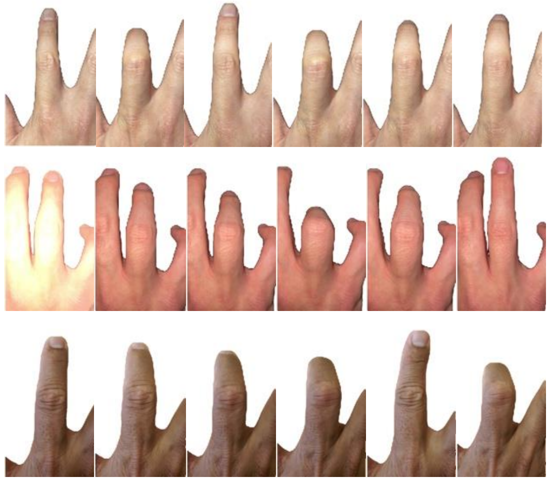
Solution:

Explainable and Unprecedented Accuracy

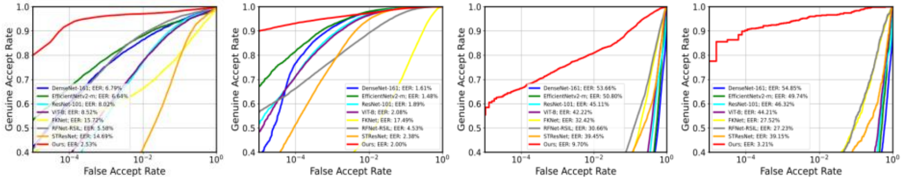


Contribution:

1). A Multi-Pose Finger Knuckle Dataset



Within-Database and Cross-Database Experiment



Estimation of Finger Knuckle Uniqueness Experiment

Δ_k	Δ_f	(m,n,w,α)	$\overline{p(T^p,T^g)}$	$\overline{\lambda}_\alpha$	$\overline{\text{FRC}}_\alpha$
6.750	0.726	(69,69,15,0.05)	2.980×10^{-4}	6.167	6.780×10^{-4}
6.750	0.726	(69,69,17,0.05)	2.980×10^{-4}	6.613	1.860×10^{-4}
6.750	0.726	(69,69,19,0.05)	2.980×10^{-4}	6.996	4.408×10^{-5}
6.750	0.726	(69,69,21,0.05)	2.980×10^{-4}	7.325	9.055×10^{-6}
3.750	0.726	(69,69,17,0.05)	1.031×10^{-4}	2.962	2.948×10^{-9}
5.250	0.726	(69,69,17,0.05)	1.914×10^{-4}	4.950	4.731×10^{-6}
8.250	0.726	(69,69,17,0.05)	4.119×10^{-4}	8.061	1.729×10^{-3}
9.750	0.726	(69,69,17,0.05)	5.273×10^{-4}	9.124	6.080×10^{-3}
6.750	0.626	(69,69,17,0.05)	6.210×10^{-6}	N/A	N/A
6.750	0.676	(69,69,17,0.05)	5.309×10^{-5}	1.367	1.546×10^{-14}
6.750	0.776	(69,69,17,0.05)	1.194×10^{-3}	12.476	8.305×10^{-2}
6.750	0.826	(69,69,17,0.05)	3.620×10^{-3}	14.893	2.421×10^{-1}

Δ_k	Δ_f	(m,n,w,α)	$\overline{p(T^p,T^g)}$	$\overline{\lambda}_\alpha$	$\overline{\text{FRC}}_\alpha$
9.258	0.844	(69,69,2,0.05)	5.387×10^{-5}	0.316	4.161×10^{-3}
9.258	0.844	(69,69,4,0.05)	5.387×10^{-5}	0.478	1.400×10^{-4}
9.258	0.844	(69,69,6,0.05)	5.387×10^{-5}	0.601	3.328×10^{-6}
9.258	0.844	(69,69,8,0.05)	5.387×10^{-5}	0.694	5.497×10^{-8}
9.258	0.844	(69,69,17,0.05)	5.387×10^{-5}	0.880	1.515×10^{-17}
6.258	0.844	(69,69,4,0.05)	2.459×10^{-5}	0.230	4.385×10^{-6}
7.758	0.844	(69,69,4,0.05)	3.765×10^{-5}	0.341	2.915×10^{-5}
10.758	0.844	(69,69,4,0.05)	7.306×10^{-5}	0.624	4.709×10^{-4}
12.258	0.844	(69,69,4,0.05)	9.494×10^{-5}	0.784	1.290×10^{-3}
9.258	0.744	(69,69,4,0.05)	5.932×10^{-6}	N/A	8.678×10^{-9}
9.258	0.794	(69,69,4,0.05)	1.954×10^{-5}	0.194	1.968×10^{-6}
9.258	0.894	(69,69,4,0.05)	1.247×10^{-4}	0.954	2.999×10^{-3}
9.258	0.944	(69,69,4,0.05)	2.510×10^{-4}	1.551	2.106×10^{-2}

3). Uniqueness of 2D Finger Knuckle Patterns

- **Joint Mixture Gaussian Distribution**

$$f(\boldsymbol{k}, \boldsymbol{f} \mid \Omega) = \sum_{n=1}^{N} \epsilon_n f_n^K\left(\boldsymbol{k} \mid \boldsymbol{\mu}_n^{(1)}, \boldsymbol{\Sigma}_n^{(1)}\right) \cdot f_n^F\left(\boldsymbol{f} \mid \boldsymbol{\mu}_n^{(2)}, \boldsymbol{\Sigma}_n^{(2)}\right)$$

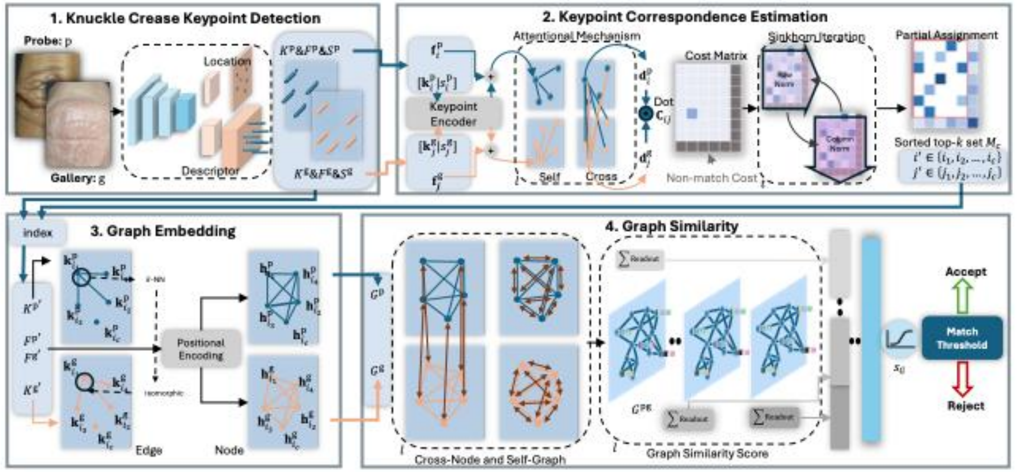
- **Calculate of $\overline{FRC}$ Index**

$$p(w; T^{\mathrm{p}}, T^{\mathrm{g}}) = \sum_{w}^{\infty} \frac{e^{-\lambda(T^{\mathrm{p}}, T^{\mathrm{g}})} \lambda(T^{\mathrm{p}}, T^{\mathrm{g}})^w}{w!}$$

$$p(T^{\mathrm{p}}, T^{\mathrm{g}}) = \int_{(\boldsymbol{k}^{\mathrm{p}}, \boldsymbol{f}^{\mathrm{p}}) \in B(\boldsymbol{k}^{\mathrm{g}}, \boldsymbol{f}^{\mathrm{g}})} f_{T^{\mathrm{p}}}\left((\boldsymbol{k}^{\mathrm{p}}, \boldsymbol{f}^{\mathrm{p}})\right) f_{T^{\mathrm{g}}}\left((\boldsymbol{k}^{\mathrm{g}}, \boldsymbol{f}^{\mathrm{g}})\right) d\boldsymbol{k}^{\mathrm{p}} d\boldsymbol{f}^{\mathrm{p}} d\boldsymbol{k}^{\mathrm{g}} d\boldsymbol{f}^{\mathrm{g}}$$

$$\overline{FRC} = \frac{2}{z(z-1)} \sum_{T^{\mathrm{p}} \neq T^{\mathrm{g}}} p(w; T^{\mathrm{p}}, T^{\mathrm{g}})$$

2). Our Framework to Match Cross-Pose Images



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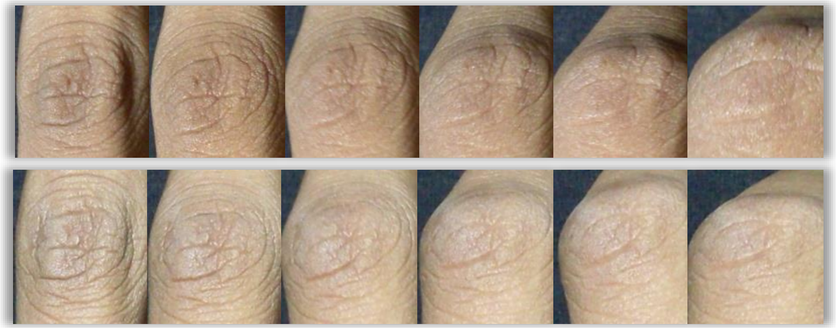

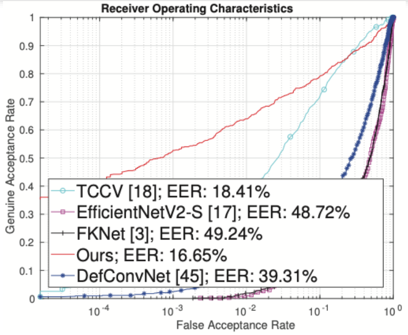

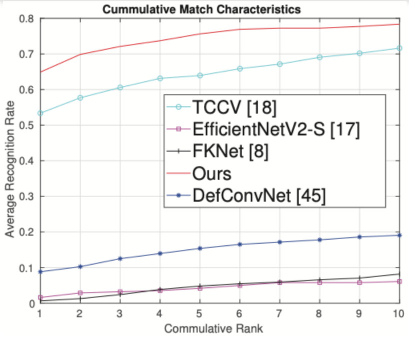

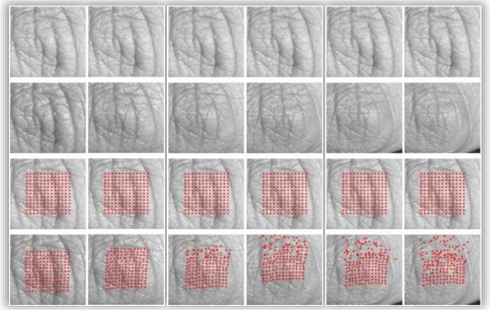

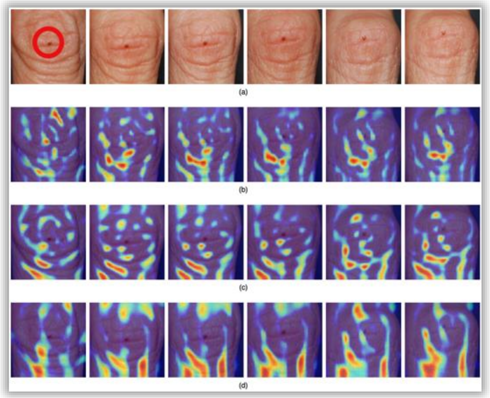

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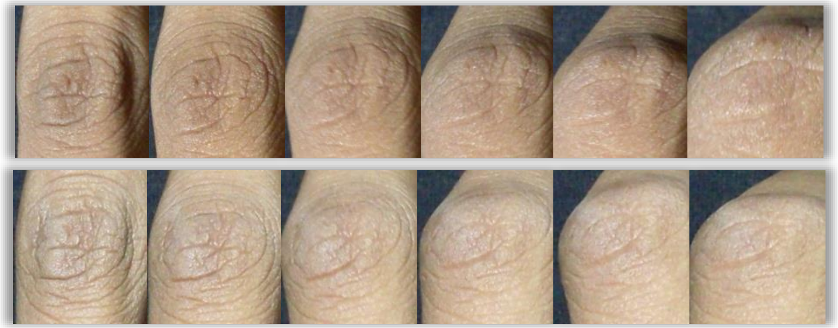
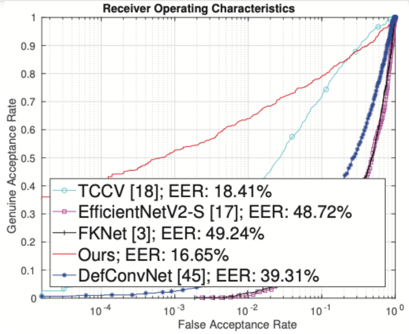
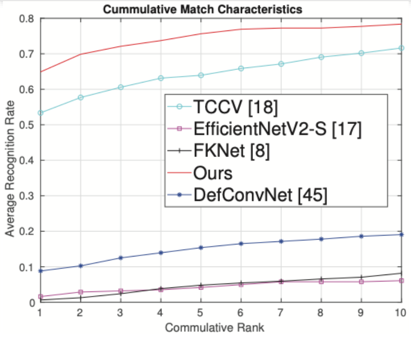
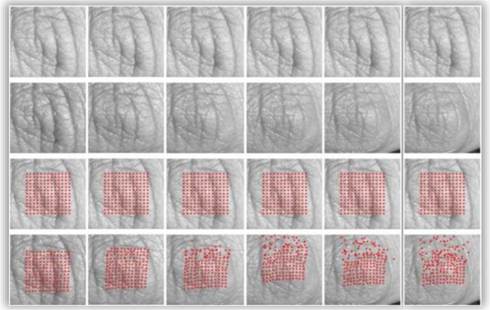
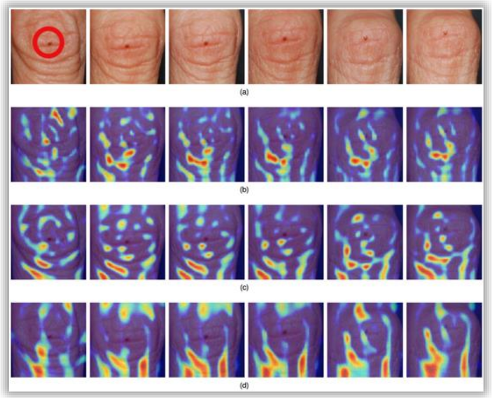




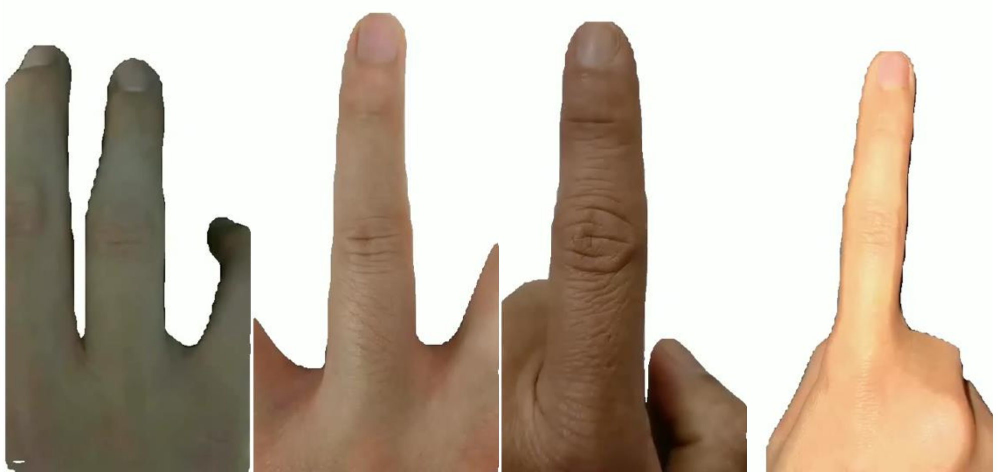






Problem Definition:

- **How to *accurately* match the cross-pose finger crease pattern?**
- **How to *efficiently* give the match evidences?**



Samples from our collected the large-scale multi-pose finger knuckle dataset.

Multi-Pose Dataset

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Matching Framework: Explainable and Unprecedented Accuracy

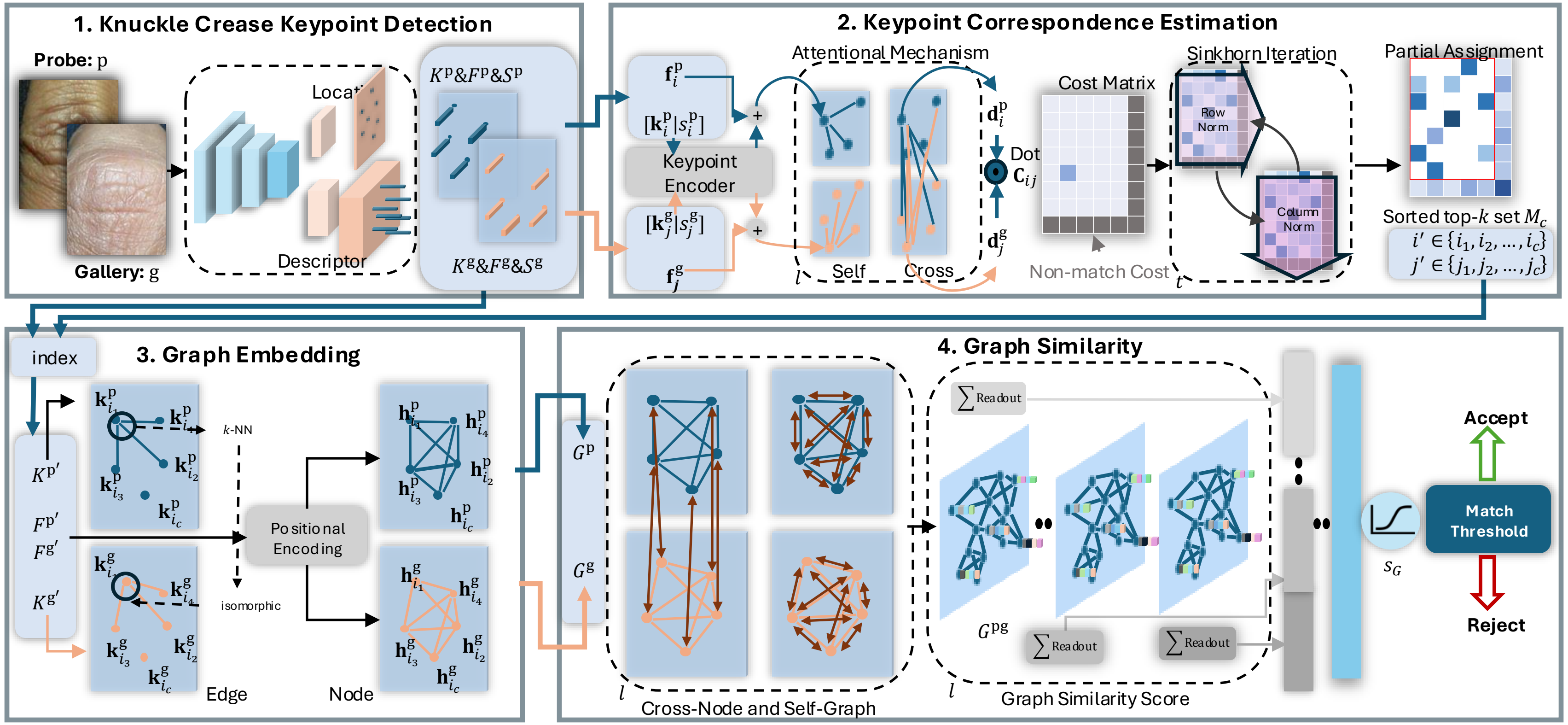
Genuine **Imposter**

0). Input Image Pairs

1). Keypoint Detection

2). Correspondence Estimation

3). Graph Embedding & Matching



Ajay Kumar and Zhenyu Zhou. A method and device for biometric identification using finger images. U.S. Patent No.63/774,168, 2025.

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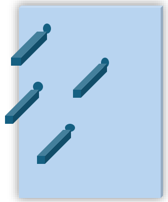
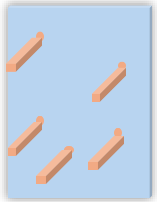
Theoretical Explainability: Uniqueness of Contactless 2D Finger Knuckle Patterns

1). Detected a pair of template T^{p} and T^{g} :

$$F^{\mathrm{p}} = \{\boldsymbol{f}_i^{\mathrm{p}} \mid i \in \{1,2,\ldots,n\}\} \qquad F^{\mathrm{g}} = \{\boldsymbol{f}_i^{\mathrm{g}} \mid i \in \{1,2,\ldots,\mathrm{m}\}\}$$

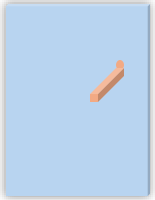
$$K^{\mathrm{p}} = \{\boldsymbol{k}_i^{\mathrm{p}} \mid i \in \{1,2,\ldots,n\}\} \qquad K^{\mathrm{g}} = \{\boldsymbol{k}_i^{\mathrm{g}} \mid i \in \{1,2,\ldots,\mathrm{m}\}\}$$





where, $\boldsymbol{k} = (x, y) \in K$ and $\boldsymbol{f} = (f_1, f_2, \ldots, f_d) \in F$

3). $p(T^{\mathrm{p}}, T^{\mathrm{g}})$:



2). Joint Mixture Gaussian Distribution

$$f(\boldsymbol{k}, \boldsymbol{f} \mid \Omega) = \sum_{n=1}^{N} \epsilon_n f_n^K\left(\boldsymbol{k} \mid \boldsymbol{\mu}_n^{(1)}, \boldsymbol{\Sigma}_n^{(1)}\right) \cdot f_n^F\left(\boldsymbol{f} \mid \boldsymbol{\mu}_n^{(2)}, \boldsymbol{\Sigma}_n^{(2)}\right)$$

4). Calculate of $\overline{FRC}$ Index

$$p(T^{\mathrm{p}}, T^{\mathrm{g}}) = \int_{(\boldsymbol{k}^{\mathrm{p}}, \boldsymbol{f}^{\mathrm{p}}) \in B(\boldsymbol{k}^{\mathrm{g}}, \boldsymbol{f}^{\mathrm{g}})} f_{T^{\mathrm{p}}}\big((\boldsymbol{k}^{\mathrm{p}}, \boldsymbol{f}^{\mathrm{p}})\big) f_{T^{\mathrm{g}}}\big((\boldsymbol{k}^{\mathrm{g}}, \boldsymbol{f}^{\mathrm{g}})\big) d\boldsymbol{k}^{\mathrm{p}} d\boldsymbol{f}^{\mathrm{p}} d\boldsymbol{k}^{\mathrm{g}} d\boldsymbol{f}^{\mathrm{g}}$$

$$\lambda(T^{\mathrm{p}}, T^{\mathrm{g}}) = \mathrm{m} * n * p(T^{\mathrm{p}}, T^{\mathrm{g}})$$

$$p(w; T^{\mathrm{p}}, T^{\mathrm{g}}) = \sum_{w}^{\infty} \frac{e^{-\lambda(T^{\mathrm{p}}, T^{\mathrm{g}})} \lambda(T^{\mathrm{p}}, T^{\mathrm{g}})^w}{w!}$$

$$\overline{FRC} = \frac{2}{z(z-1)} \sum_{T^{\mathrm{p}} \neq T^{\mathrm{g}}} p(w; T^{\mathrm{p}}, T^{\mathrm{g}})$$

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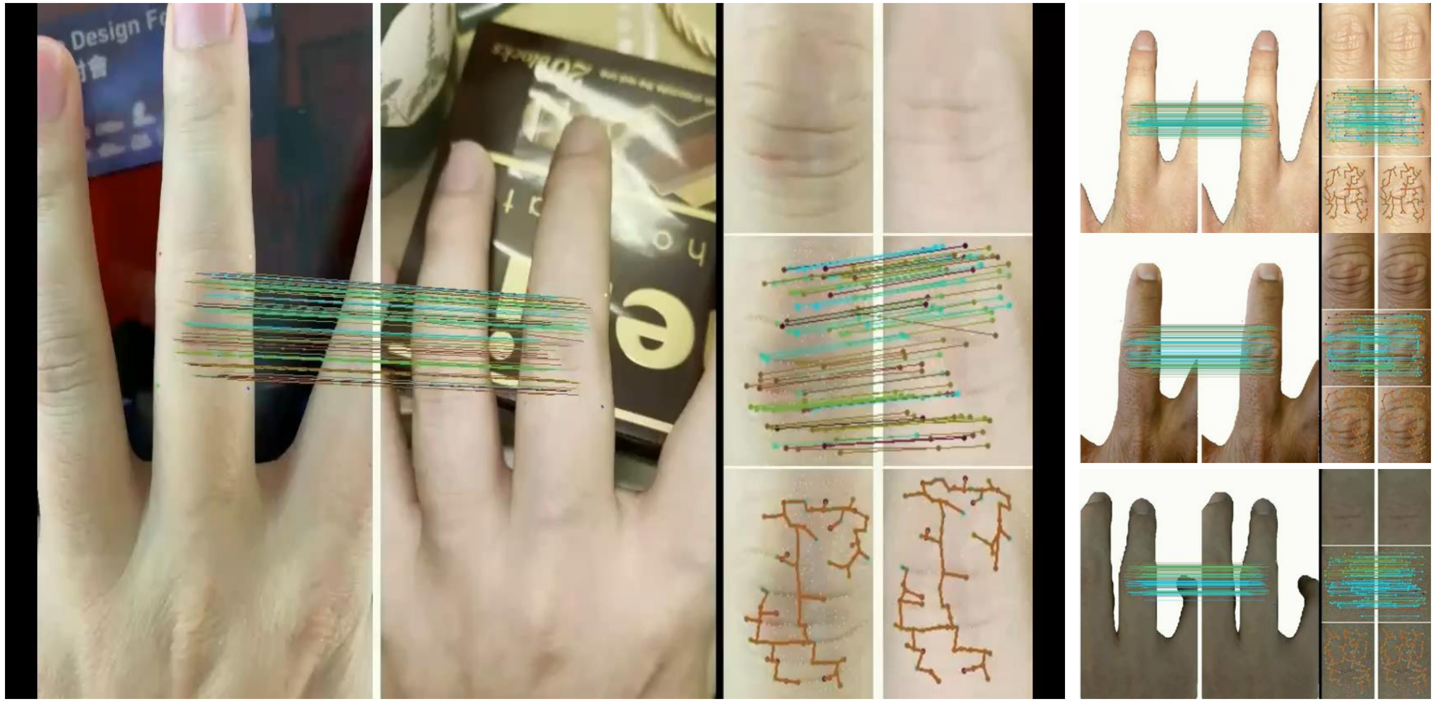
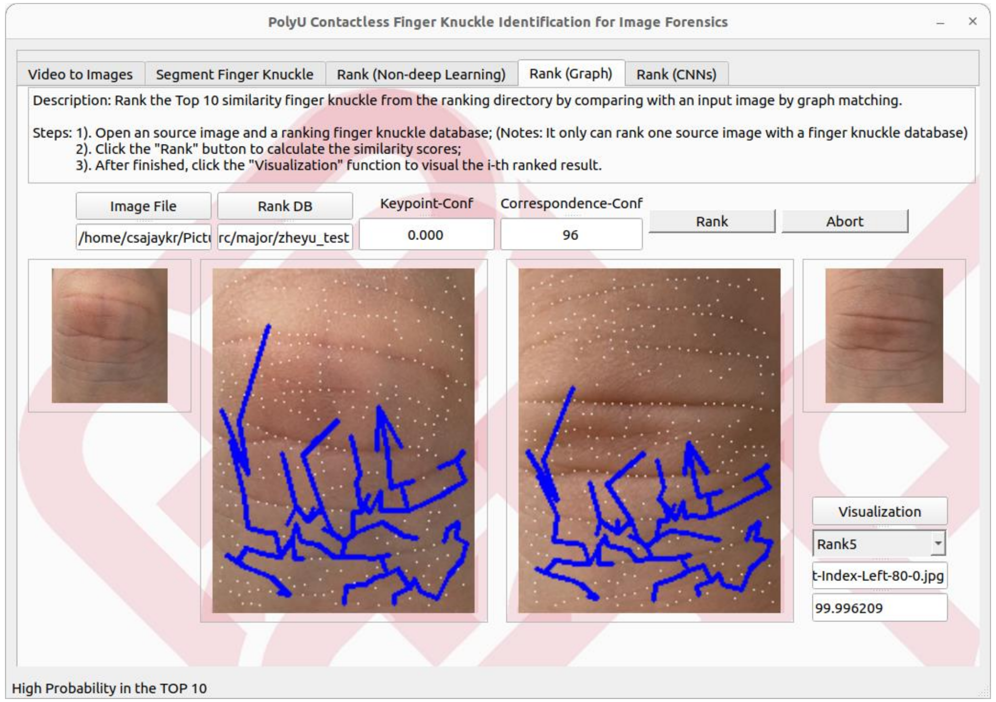
Experiments: Explainable Visual Graphs



Knuckle Crease Keypoint Correspondence Estimation



High Security and Law Enforcement Online System

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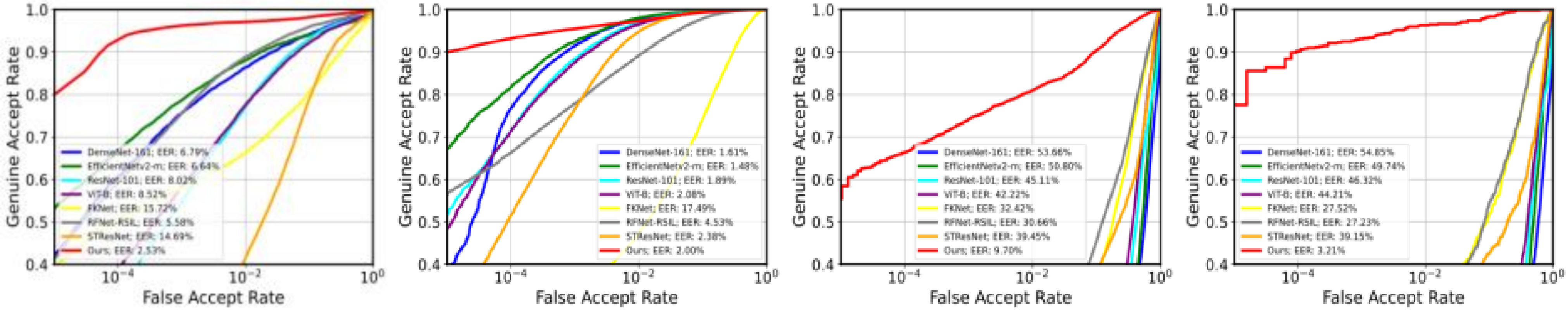
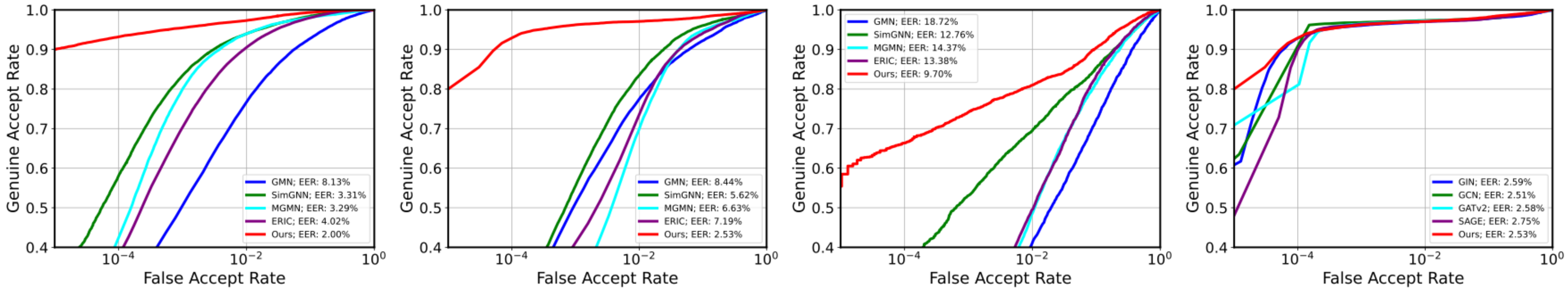
Experiments: Within-Database and Cross-Database

- Compare with CNN or attention-based methods



- Compare with graph-based methods



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Experiments: Estimation of 2D Finger Knuckle Uniqueness

Estimated Resolution for This Dataset: ~ 200 dpi

Δ_k	Δ_f	(m, n, w, α)	$\overline{p(T^p, T^g)}$	$\overline{\lambda}_\alpha$	$\overline{FRC}_\alpha$
6.750	0.726	(69,69,15,0.05)	2.980×10^{-4}	6.167	6.780×10^{-4}
6.750	0.726	(69,69,17,0.05)	2.980×10^{-4}	6.613	1.860×10^{-4}
6.750	0.726	(69,69,19,0.05)	2.980×10^{-4}	6.996	4.408×10^{-5}
6.750	0.726	(69,69,21,0.05)	2.980×10^{-4}	7.325	9.055×10^{-6}
3.750	0.726	(69,69,17,0.05)	1.031×10^{-4}	2.962	2.948×10^{-9}
5.250	0.726	(69,69,17,0.05)	1.914×10^{-4}	4.950	4.731×10^{-6}
8.250	0.726	(69,69,17,0.05)	4.119×10^{-4}	8.061	1.729×10^{-3}
9.750	0.726	(69,69,17,0.05)	5.273×10^{-4}	9.124	6.080×10^{-3}
6.750	0.626	(69,69,17,0.05)	6.210×10^{-6}	N/A	N/A
6.750	0.676	(69,69,17,0.05)	5.309×10^{-5}	1.367	1.546×10^{-14}
6.750	0.776	(69,69,17,0.05)	1.194×10^{-3}	12.476	8.305×10^{-2}
6.750	0.826	(69,69,17,0.05)	3.620×10^{-3}	14.893	2.421×10^{-1}

Estimated Resolution for This Dataset: ~ 760 dpi

Δ_k	Δ_f	(m, n, w, α)	$\overline{p(T^p, T^g)}$	$\overline{\lambda}_\alpha$	$\overline{FRC}_\alpha$
9.258	0.844	(69,69,2,0.05)	5.387×10^{-5}	0.316	4.161×10^{-3}
9.258	0.844	(69,69,4,0.05)	5.387×10^{-5}	0.478	1.400×10^{-4}
9.258	0.844	(69,69,6,0.05)	5.387×10^{-5}	0.601	3.328×10^{-6}
9.258	0.844	(69,69,8,0.05)	5.387×10^{-5}	0.694	5.497×10^{-8}
9.258	0.844	(69,69,17,0.05)	5.387×10^{-5}	0.880	1.515×10^{-17}
6.258	0.844	(69,69,4,0.05)	2.459×10^{-5}	0.230	4.385×10^{-6}
7.758	0.844	(69,69,4,0.05)	3.765×10^{-5}	0.341	2.915×10^{-5}
10.758	0.844	(69,69,4,0.05)	7.306×10^{-5}	0.624	4.709×10^{-4}
12.258	0.844	(69,69,4,0.05)	9.494×10^{-5}	0.784	1.290×10^{-3}
9.258	0.744	(69,69,4,0.05)	5.932×10^{-6}	N/A	8.678×10^{-9}
9.258	0.794	(69,69,4,0.05)	1.954×10^{-5}	0.194	1.968×10^{-6}
9.258	0.894	(69,69,4,0.05)	1.247×10^{-4}	0.954	2.999×10^{-3}
9.258	0.944	(69,69,4,0.05)	2.510×10^{-4}	1.551	2.106×10^{-2}

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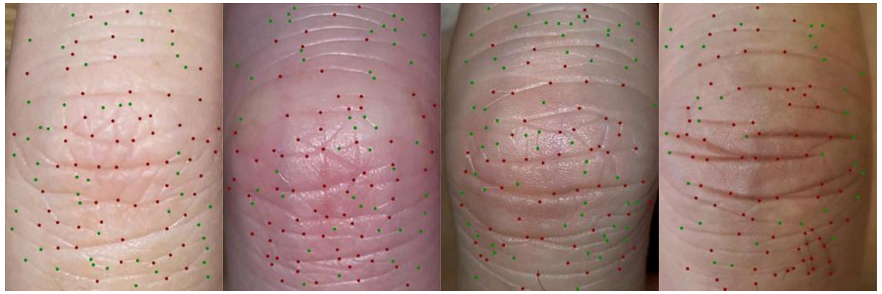
Experiments: Estimation Uniqueness using Knuckle Crease Bifurcations and Endings

Knuckle crease
***bifurcations* & *endings*:**



Dataset	Δ_k	Δ_f	(m,n,w,α) Bifurcation	(m,n,w,α) Ending	$\overline{p(T^p,T^g)}$ Bifurcation	$\overline{p(T^p,T^g)}$ Ending	$\overline{\text{FRC}}_\alpha$ Bifurcation	$\overline{\text{FRC}}_\alpha$ Ending
Hand Dorsal [30]	6.750	0.726	(55,55,11,0.05)	(14,14,2,0.05)	3.929×10^{-4}	4.300×10^{-4}	1.233×10^{-3}	5.843×10^{-4}
	6.750	0.726	(55,55,13,0.05)	(14,14,4,0.05)	3.929×10^{-4}	4.300×10^{-4}	2.807×10^{-4}	6.523×10^{-6}
	6.750	0.726	(55,55,15,0.05)	(14,14,6,0.05)	3.929×10^{-4}	4.300×10^{-4}	5.292×10^{-5}	4.640×10^{-8}
	5.250	0.726	(55,55,11,0.05)	(14,14,2,0.05)	2.541×10^{-4}	2.661×10^{-4}	7.947×10^{-5}	1.454×10^{-4}
	8.250	0.726	(55,55,11,0.05)	(14,14,2,0.05)	5.445×10^{-4}	6.267×10^{-4}	6.028×10^{-3}	1.642×10^{-3}
	6.750	0.676	(55,55,11,0.05)	(14,14,2,0.05)	7.376×10^{-5}	1.357×10^{-4}	5.252×10^{-10}	1.903×10^{-5}
	6.750	0.776	(55,55,11,0.05)	(14,14,2,0.05)	1.508×10^{-3}	1.106×10^{-3}	1.021×10^{-1}	6.641×10^{-3}
Ours	9.258	0.844	(61,61,3,0.05)	(8,8,1,0.05)	5.646×10^{-5}	2.068×10^{-4}	3.220×10^{-4}	9.609×10^{-5}
	9.258	0.844	(61,61,5,0.05)	(8,8,3,0.05)	5.646×10^{-5}	2.068×10^{-4}	5.419×10^{-6}	2.174×10^{-8}
	9.258	0.844	(61,61,7,0.05)	(8,8,5,0.05)	5.646×10^{-5}	2.068×10^{-4}	6.383×10^{-8}	3.146×10^{-12}
	7.758	0.844	(61,61,3,0.05)	(8,8,1,0.05)	4.006×10^{-5}	1.467×10^{-4}	9.134×10^{-5}	4.670×10^{-5}
	10.758	0.844	(61,61,3,0.05)	(8,8,1,0.05)	7.548×10^{-5}	2.781×10^{-4}	9.101×10^{-4}	1.779×10^{-4}
	9.258	0.794	(61,61,3,0.05)	(8,8,1,0.05)	2.103×10^{-5}	9.755×10^{-5}	9.293×10^{-6}	2.078×10^{-5}
	9.258	0.894	(61,61,3,0.05)	(8,8,1,0.05)	1.303×10^{-4}	3.858×10^{-4}	4.425×10^{-3}	3.373×10^{-4}