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Morphological risk of the femur causing anterior cruciate ligament (ACL) injuries : Comparative 3-Dimensional Mean model analysis of ACL and non-injured patients

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Background & Purpose

- ***Anterior cruciate ligament (ACL)*** injuries commonly affect young, active individuals and increase the risk of osteoarthritis (OA).

- However, there is inconsistency in the 2D radiographic findings of ACL injuries reported in the literature.

- This study directly compared ***statistical shape modeling (SSM)*** and ***principal component analysis (PCA)*** of femoral models between patients with and without ACL injury, and additionally developed a ***machine learning model to predict ACL*** injury based on femoral morphology.

Methods

- ✓3D femoral shape simulations were retrospectively performed in **60 patients with ACL(male:30, female:30)** and **60 matched controls(male:30, female:30).**

- ✓The mean follow-up CT period: 3 days.

Variables	Normal	ACL
Age, yrs	37.417±12.310	36.717±13.088
Sex (male/female), n (%)	30 (50) / 30 (50)	30 (50) / 30 (50)
Height	168.275±8.353	167.045±8.224
Kg	69.203±15.947	67.992±13.565
Affected side (Right/left), n (%)	37 (61.67) / 23 (38.33)	35 (58.33) / 25 (41.67)

Methods

- ✓Clinical assessments were performed using **patient-reported outcomes(PROs).**

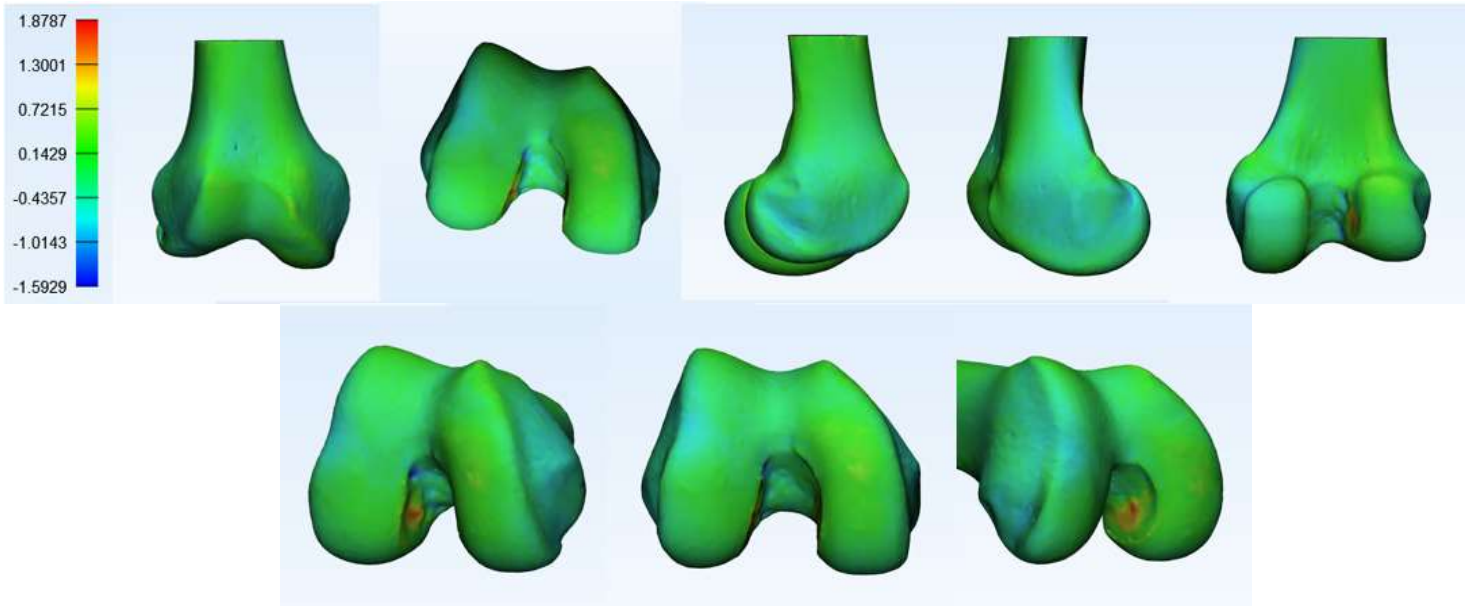
- ✓The 3D Visualize surface differences by distance map ***associated with patellar biomechanics*** were performed
  - ✓Population 60 ACL vs 60 Normal
  - ✓Male 30 ACL vs 30 Normal
  - ✓Female 30 ACL vs 30 Normal

- ✓A logistic regression analysis was performed to identify key features that distinguish ACL-injured from non-injured subjects, which were subsequently used to train a ***machine learning model for ACL classification***.

Result Population ACL vs Non-ACL

3D Overview

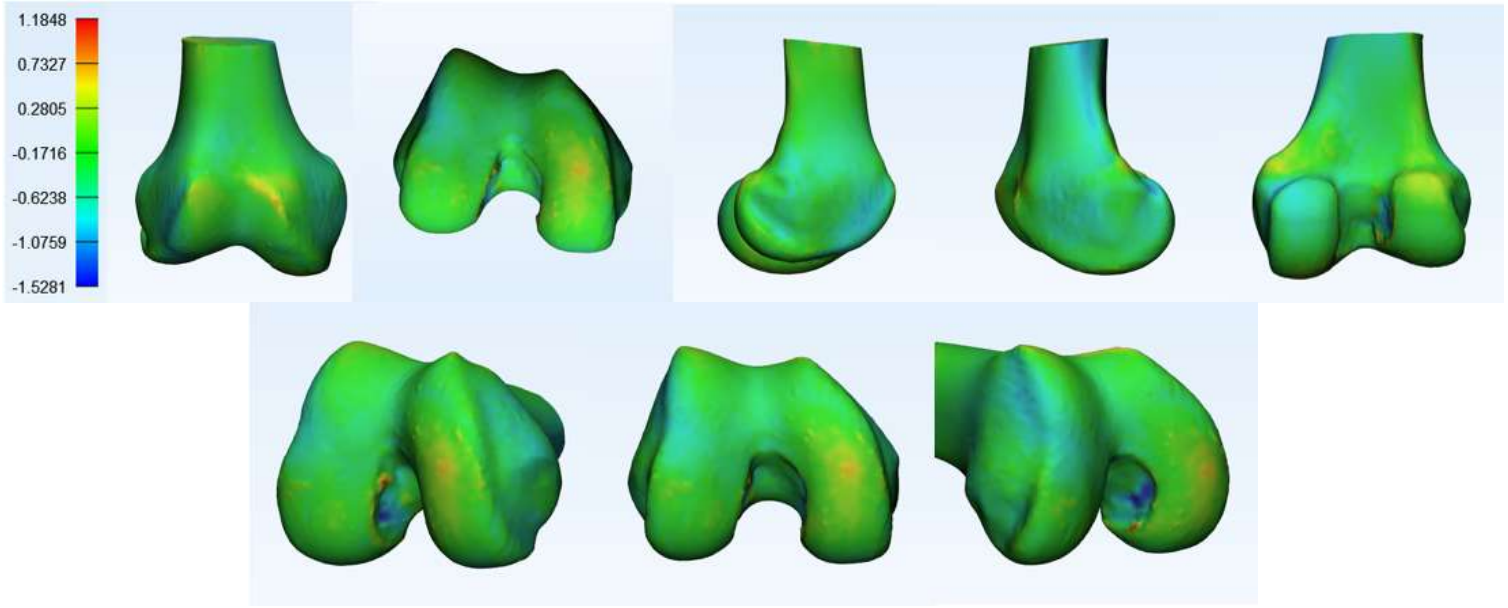
- Medial-lateral direction, both Intercondylar notch wall moved inward
- Anterior-posterior direction, trochlea anteriorized
- Proximal- distal direction, medial condyle distalized, lateral codyle proximalized



Result Male ACL vs Non-ACL

3D Overview

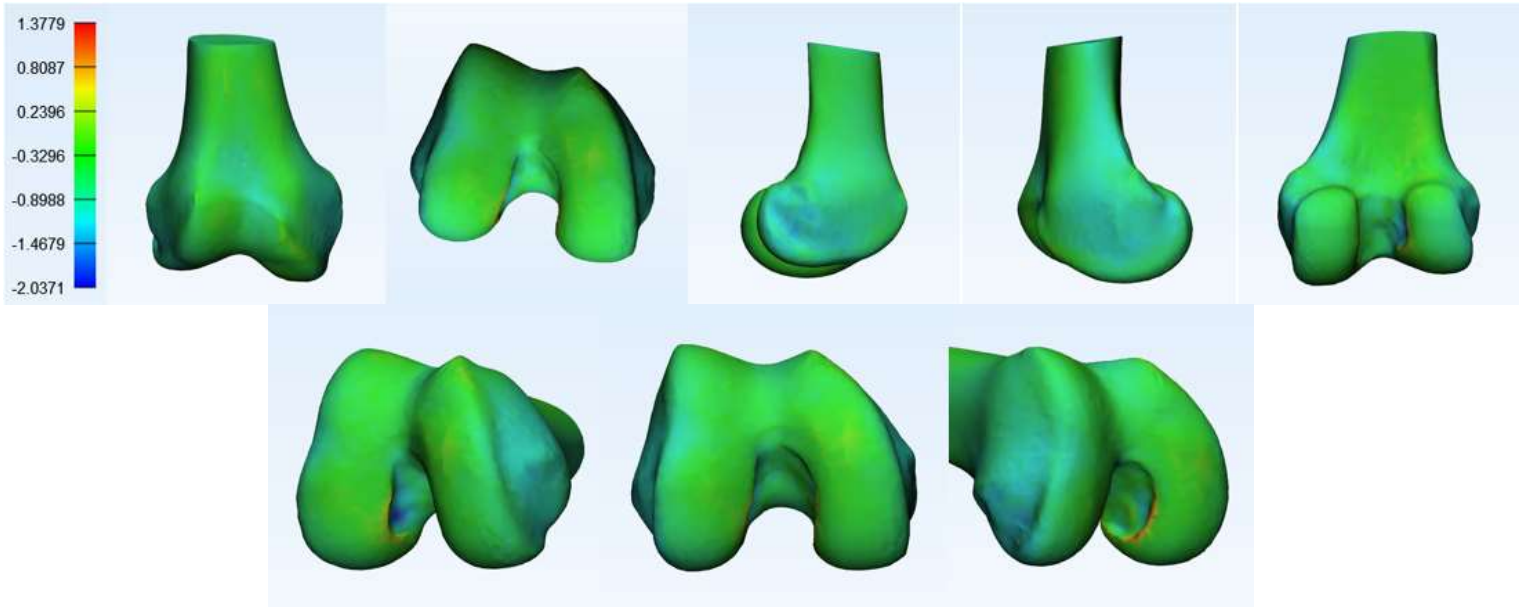
- Medial-lateral direction, both notch wall moved outward, femoral shaft lateralized
- Anterior-posterior direction, trochlea anteriorized
- Proximal- distal direction, Medial condyle distalized, lateral codyle proximalized



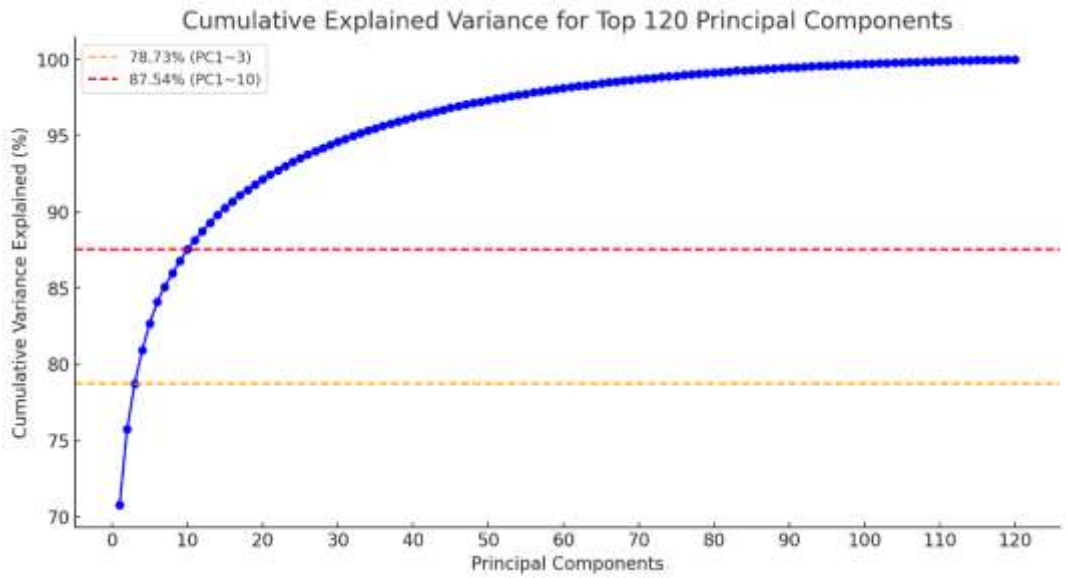
Result Female ACL vs Non-ACL

3D Overview

- Medial-lateral direction, both notch ridges moves inward, and epicondyle shrinked
- Anterior-posterior direction, patella surface shows decreased concavity
- Proximal- distal direction, medial condyle distalized, lateral condyle proximalized



Results – logistic regression analysis

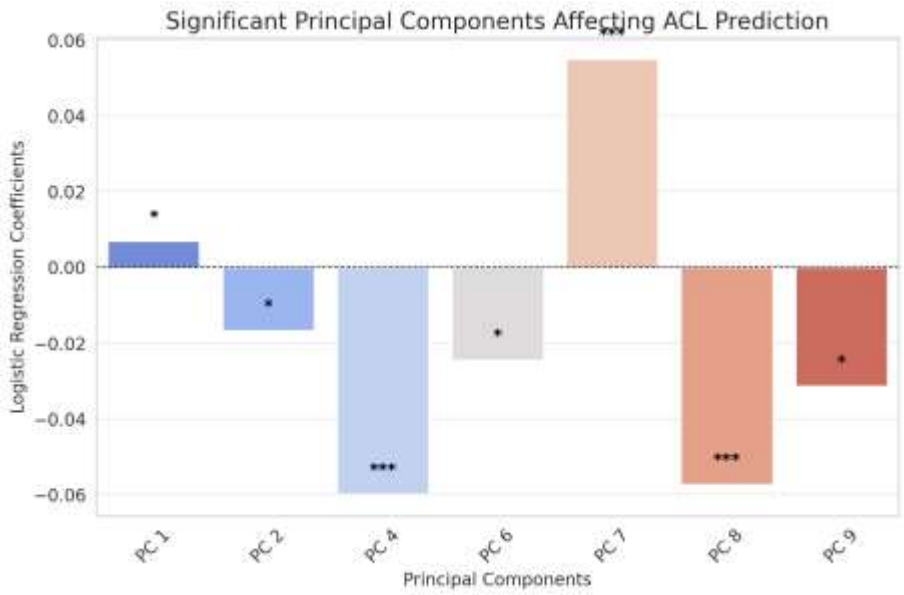


✓ **Cumulative explained variation**

- PC1~3 explained 78.73% , and PC1~10 accounted for 87.54% of population variance

Results – logistic regression analysis

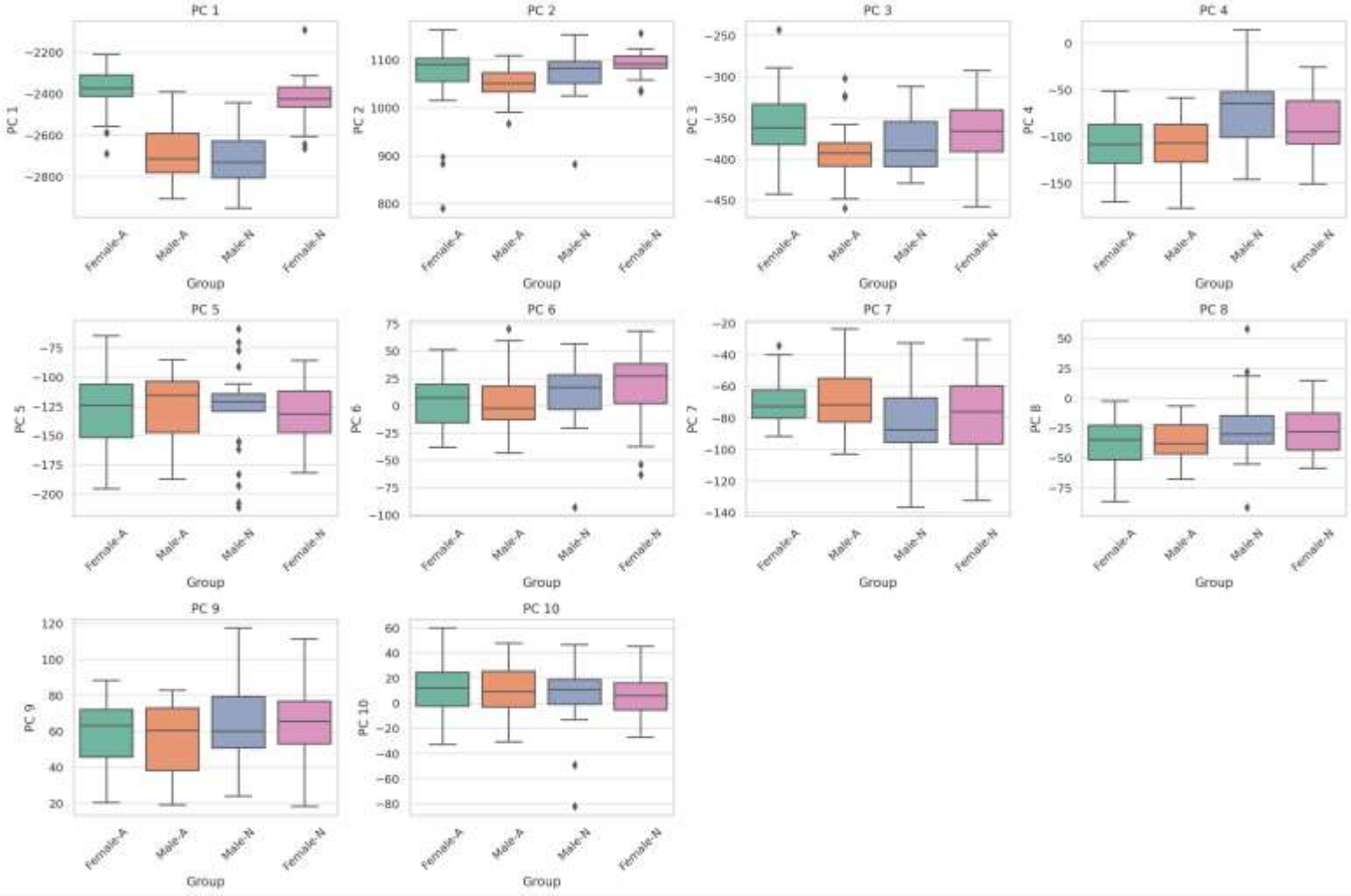
PC	RC	P-value	Adjusted RC	Adjusted P-value
PC1	-1.007	0.080	1.335	0.016
PC2	0.539	0.065	-0.861	0.024
PC3	1.335	0.016	0.403	0.305
PC4	-0.861	0.024	-2.049	0.000
PC5	0.403	0.305	0.130	0.641
PC6	-2.049	0.000	-0.672	0.036
PC7	0.130	0.641	1.267	0.001
PC8	-0.672	0.036	-1.240	0.000
PC9	1.267	0.001	-0.649	0.042
PC10	-1.240	0.000	0.605	0.072



✓ **Significance markers:*** (p < 0.001), ** (p < 0.01), * (p < 0.05)**

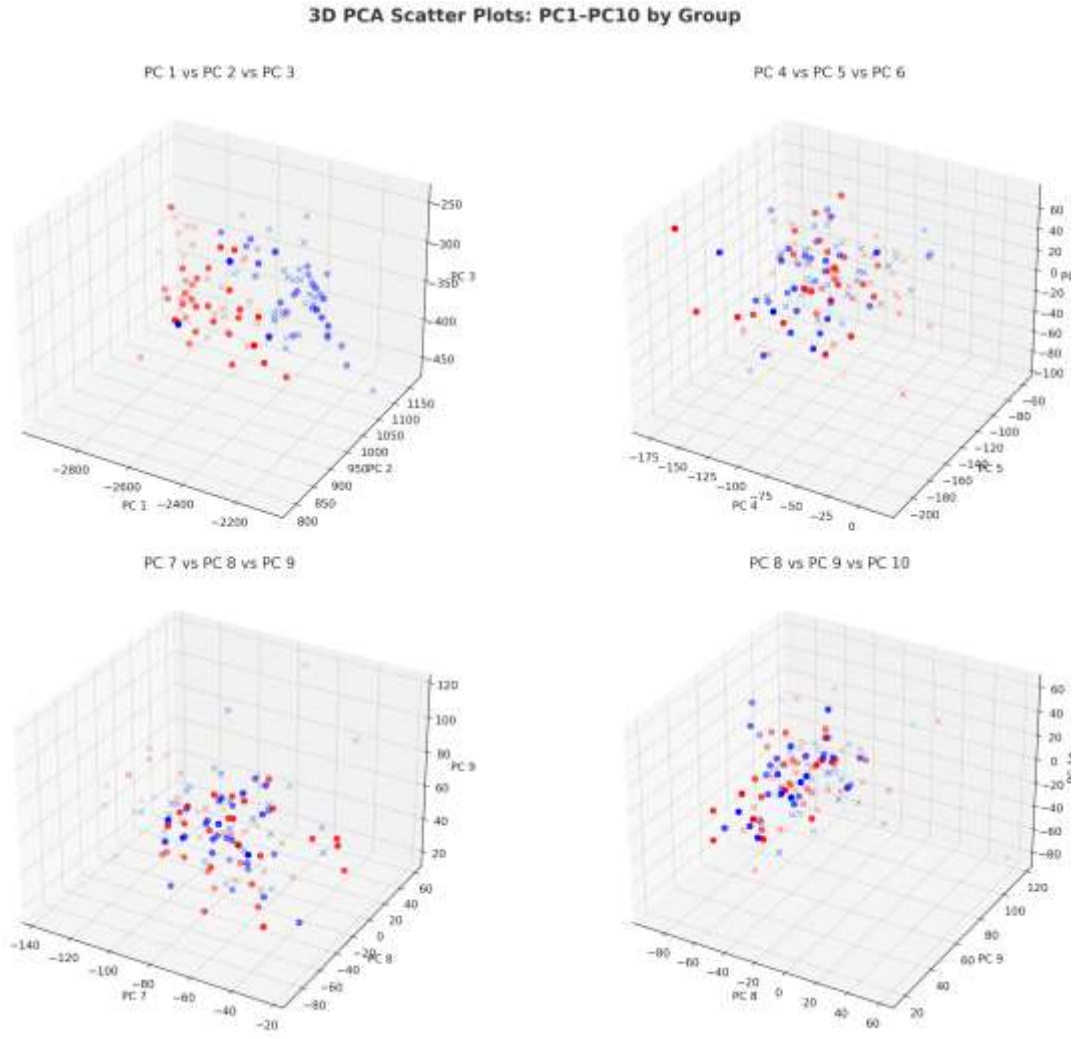
- PC7 contributes significantly to ACL risk, and PC4 PC8 strongly reduce ACL risk.
- Other PCs (PC1, PC2, PC6, and PC9) have moderate influences.

Results – MANOVA



- ✓ **Group Differences in ACL and Sex by MANOVA**
  - PC1 captures morphological features associated with ACL injury in males.
  - PC2 also demonstrated noticeable differences between sexes,
  - PC3 through PC10, no substantial differences were observed among the four groups

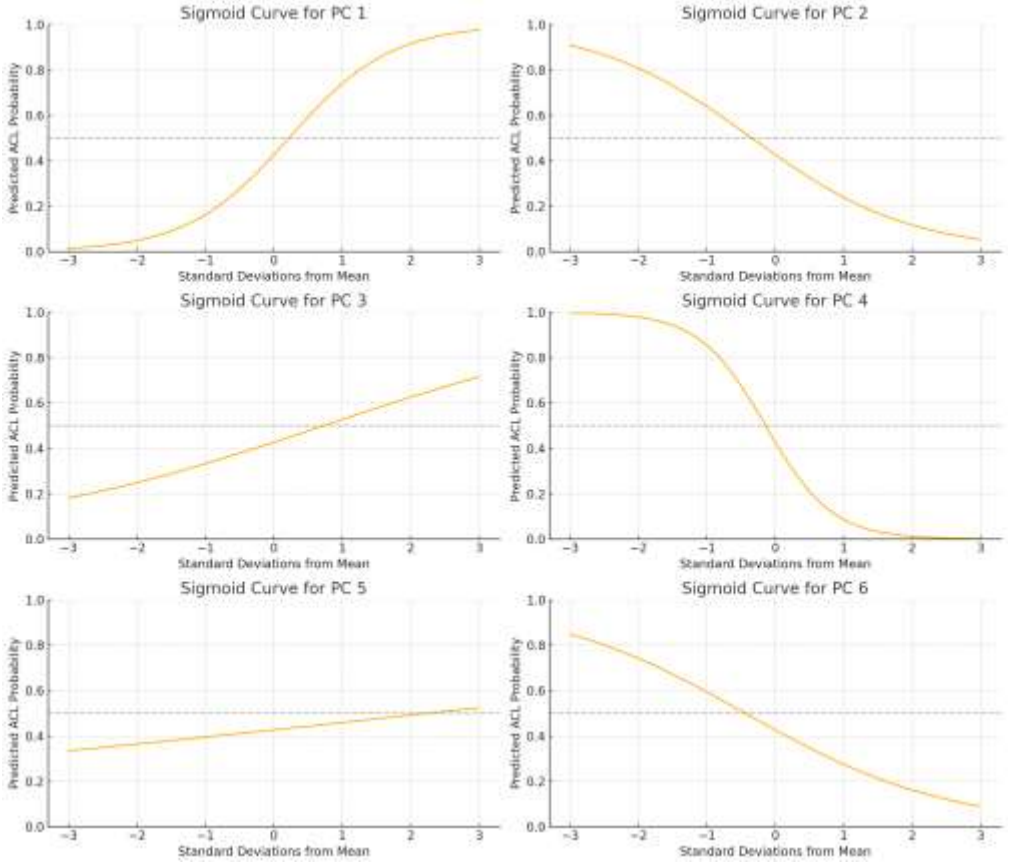
Results – 3D PC scatter

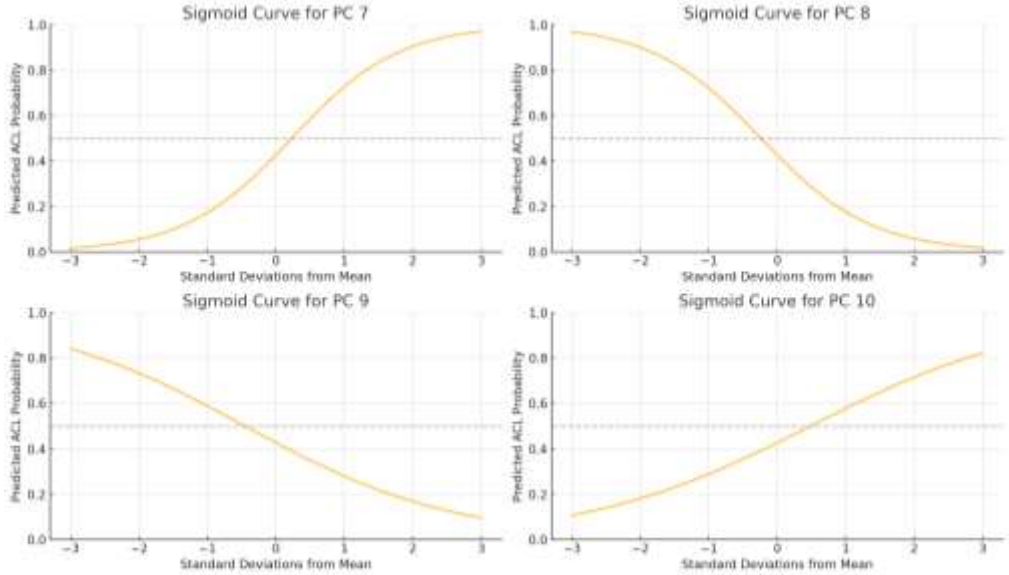


- ✓ **Group Differences in ACL and Sex by MANOVA**
  - **PC1** Clearly separates ACL-injured and non-injured groups, especially in males
  - **PC2** Distinguishes between sexes regardless of ACL status.
  - **PC3** Shows minor separation, contributing only when combined with PC1.

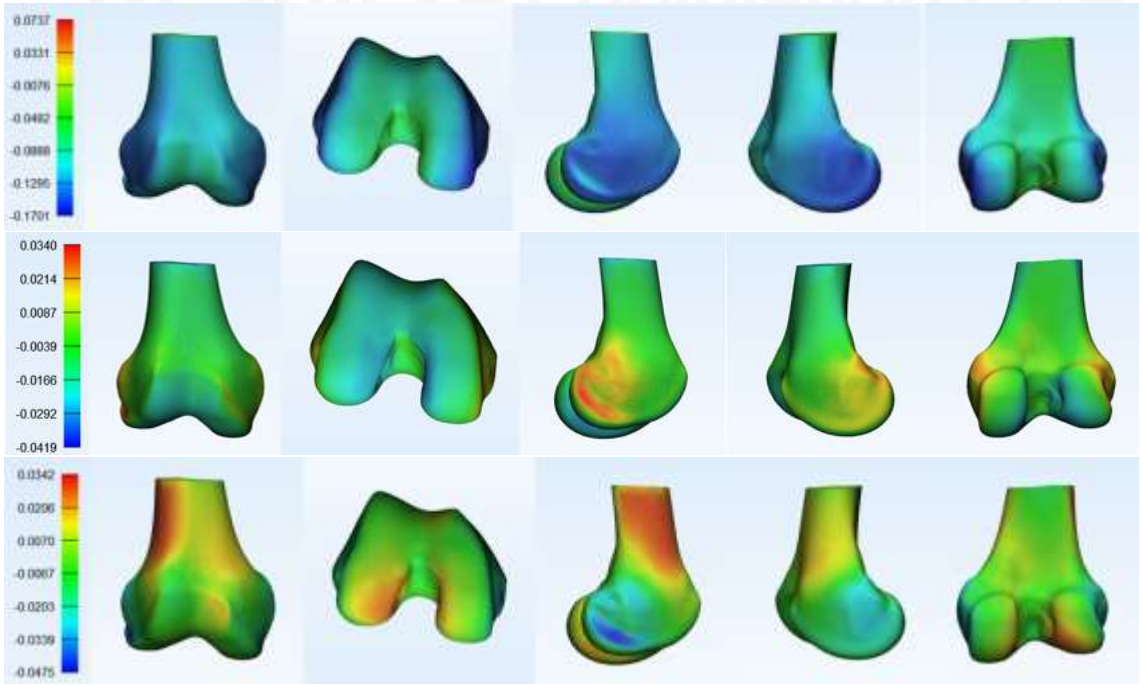
Predictable ACL probabilty

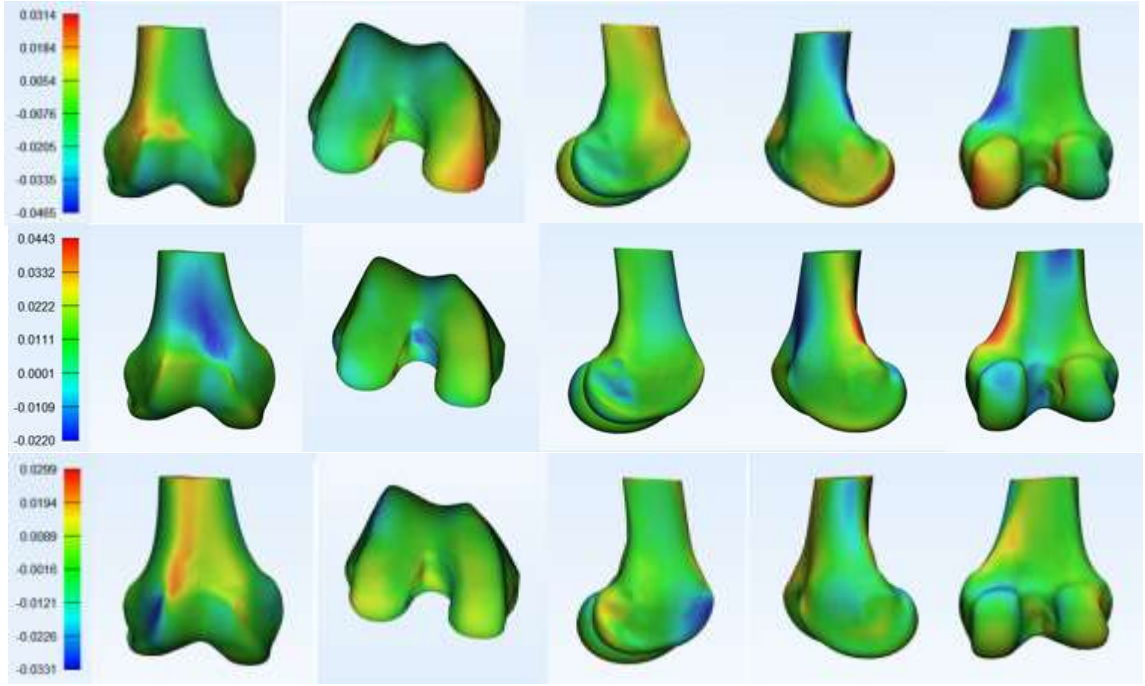
- Sigmoid curve for PCs





Results – Poplulation PCA

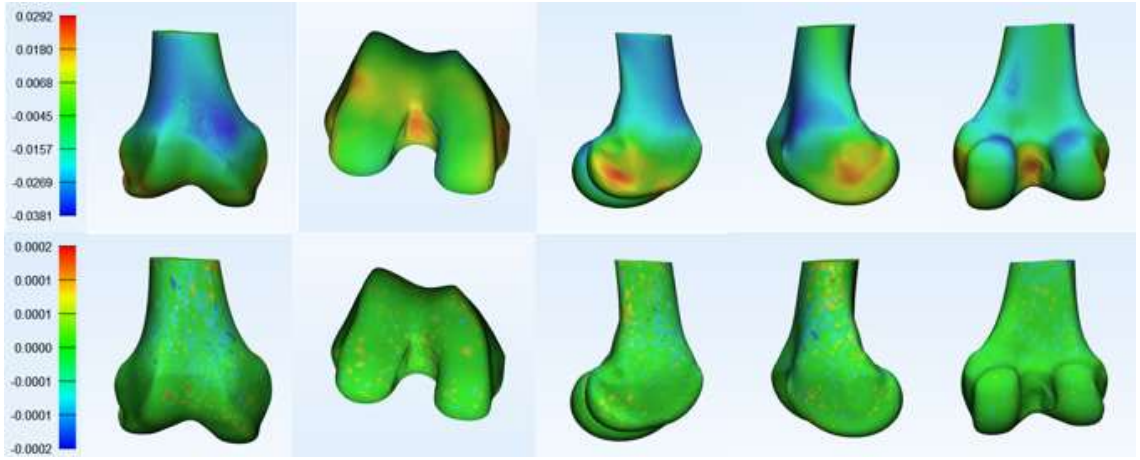


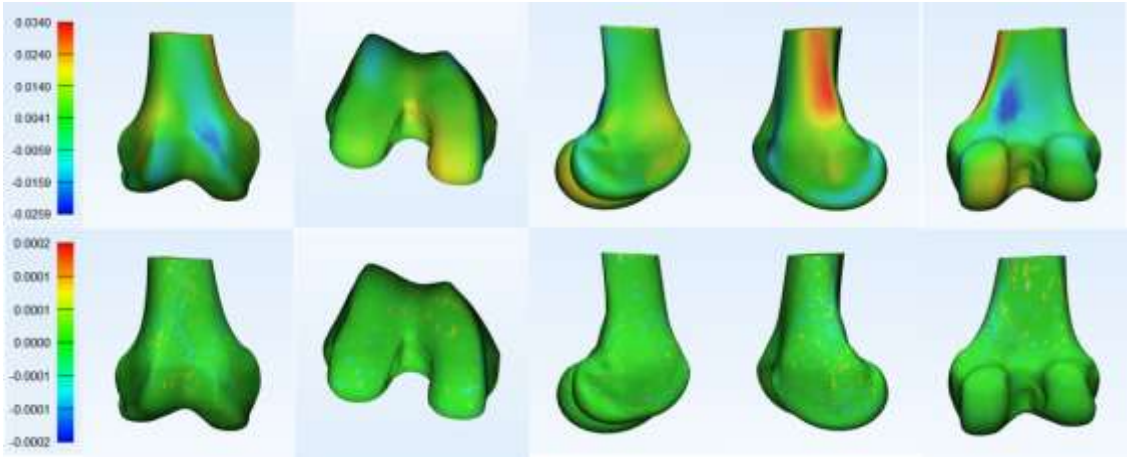


✓ **PC1-3, PC6, PC7,PC9 are related to ACL**

- **PC1 Associated with ACL-related structural variation , showing intercondylar notch narrowing, especially in ACL-injured males.**
- **PC2 Reflects sex-based differences, , characterized by epicondylar shrinking**
- **PC3 Captures rotational geometry and secondary geometric ACL risk factors to PC1.**

Results – Poplulation PCA

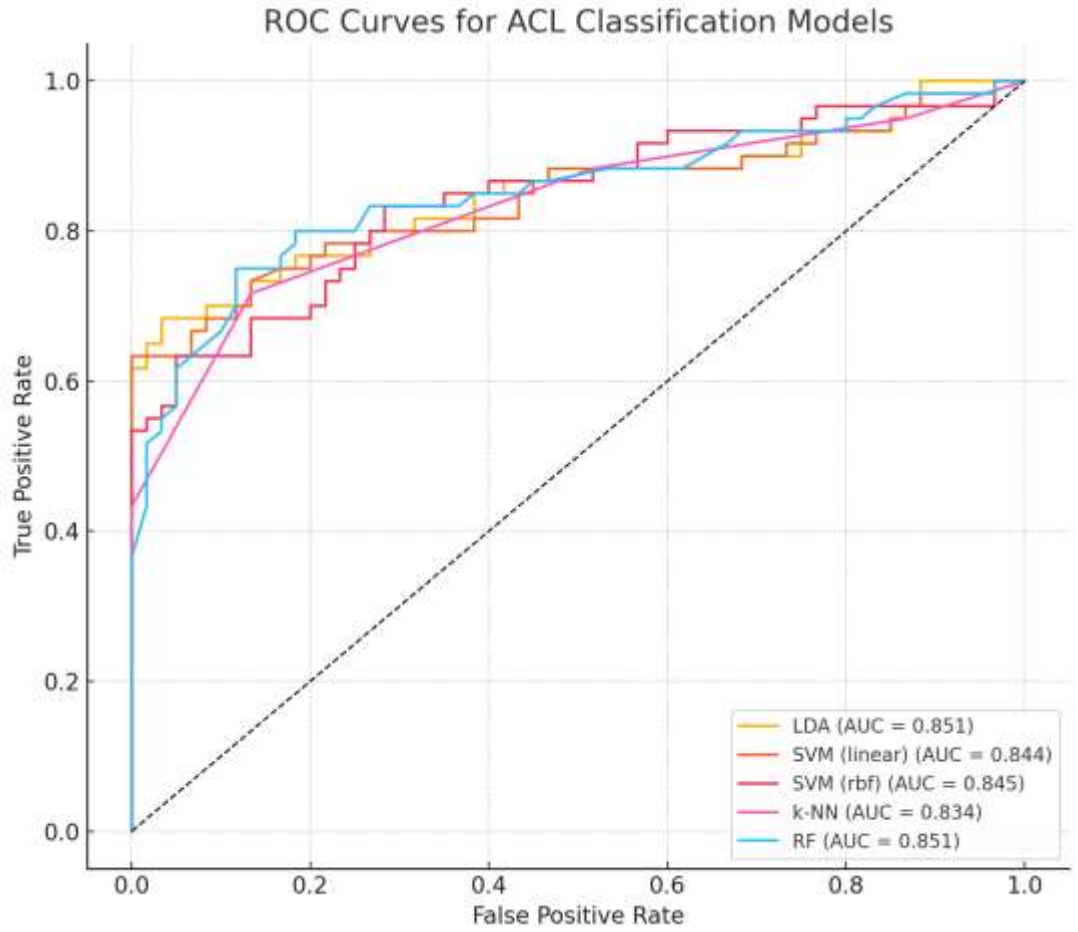


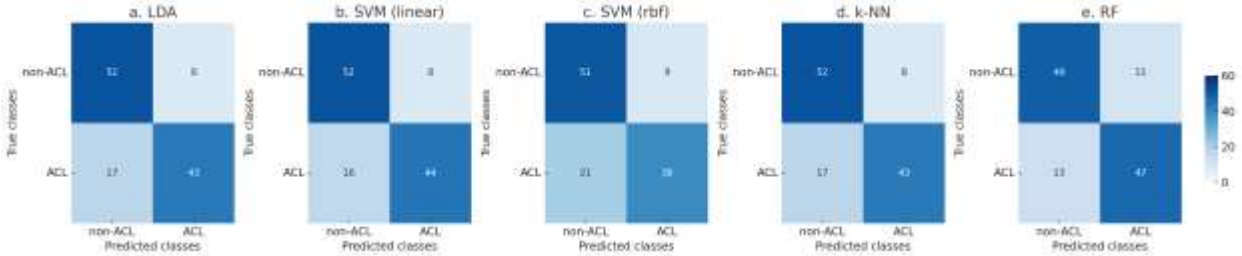


- ✓ **PC4, PC8 are related to non-ACL**
  - **close to the normal shape, their directions were statistically reversed to align with ACL-associated shape patterns**
  - **There was no appreciable difference in numerical values between the adjusted and mean models.**

ML-based prediction model for ACL

- Receiver Operating Characteristic(ROC) Curve





Classifier	Accuracy	Sensitivity	Specificity	AUC
LDA	0.792	0.717	0.867	0.851
SVM(with linear)	0.8	0.733	0.867	0.844
SVM(with rbf)	0.75	0.65	0.85	0.845
K-NN	0.792	0.717	0.867	0.834
Random Forest	0.8	0.783	0.817	0.851

Limitations & Future Directions

- **Limitations:**
  - Small sample size

- **Future Research:**
  - Long-bone
  - tibia

Conclusion

- **Regardless of sex**, femoral morphology characterized by **condylar asymmetry**, shaft anteriorization/lateralization, and notch narrowing may lead to **rotational misalignment**, increasing the risk of ACL injury

- **In males,** ACL injury is associated with **intercondylar notch narrowing*, epicondylar shrinking***, which may reflect a tighter bony geometry and internally rotated femoral alignment, increasing anterior ligament strain.

- **In females,** ACL injury risk is linked to **patellar anteriorization** and **adductor tubercle elevation**, features that may correspond to a more **externally rotated femoral alignment** and **altered patellofemoral tracking**, contributing to ligament overload.

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