Adverse mechanical differences during walking in knees with patellar instability

Annette Chang, Anthony Gatti, Shital N. Parikh, Seth L. Sherman, and Marissa Sinopoli

Intro: Anatomy influences patellar instability

- *Patellar instability:* tendency of the patella (kneecap) to shift out of place
- Patellar instability is influenced by an individual's joint anatomy

Aim

To determine how mean patellar **tilt,** patellar **shift**, and **lateral trochlear constraint force** during walking differ between knees with patellar instability and controls

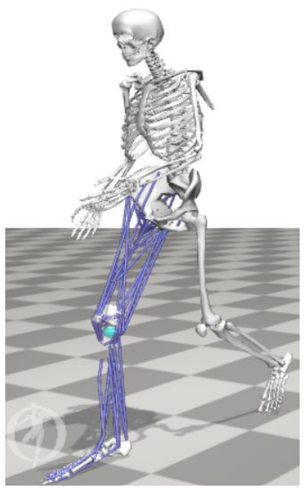
Methods: Musculoskeletal simulation pipeline

Simulations were conducted on
8 knees with patellar instability and
8 control knees segmented from MRIs

Generate subject-specific 3D knee meshes from MRIs



Integrate each knee into a generic 3D full-body musculoskeletal model [1,2]



Run gait simulations (COMAK) with the musculoskeletal models using a generic gait trial [3]

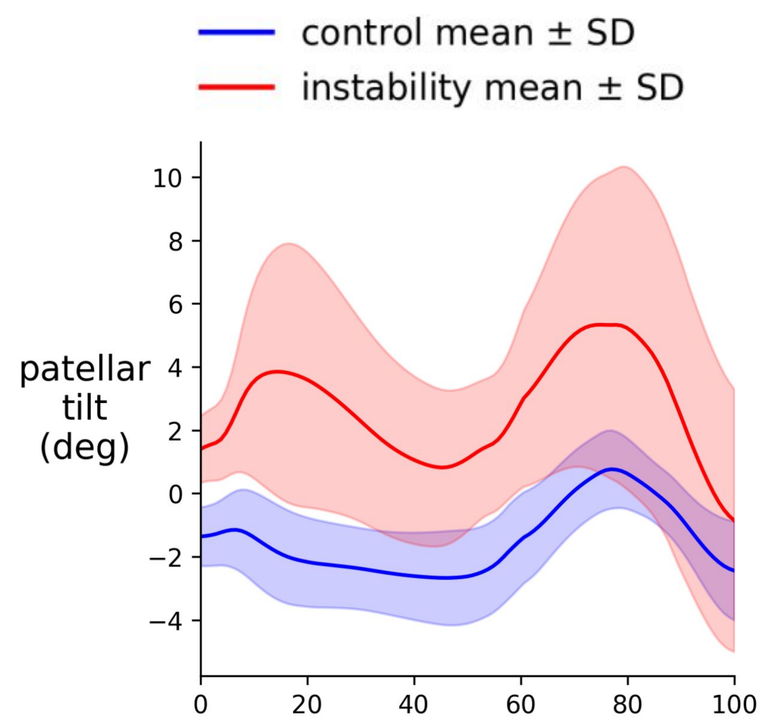


Knees with patellar instability undergo adverse mechanics

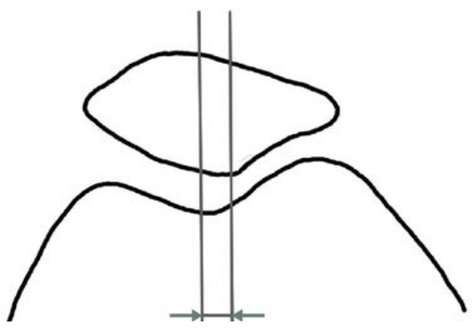
Subjects with patellar instability demonstrate **greater patellar tilt** during stance and early swing



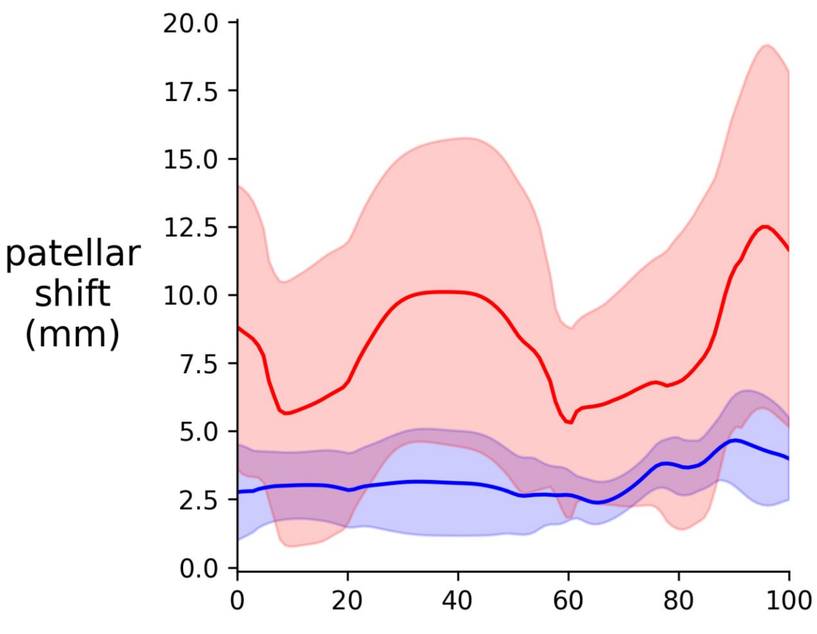
Adapted from Ji et al. 2015



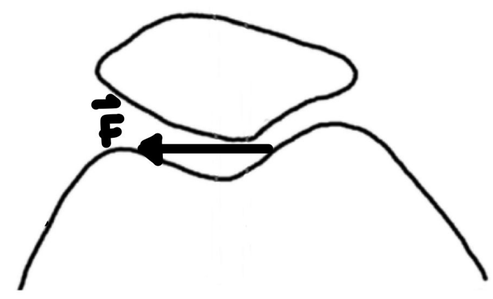
Subjects with patellar instability demonstrate **greater patellar shift** across the gait cycle



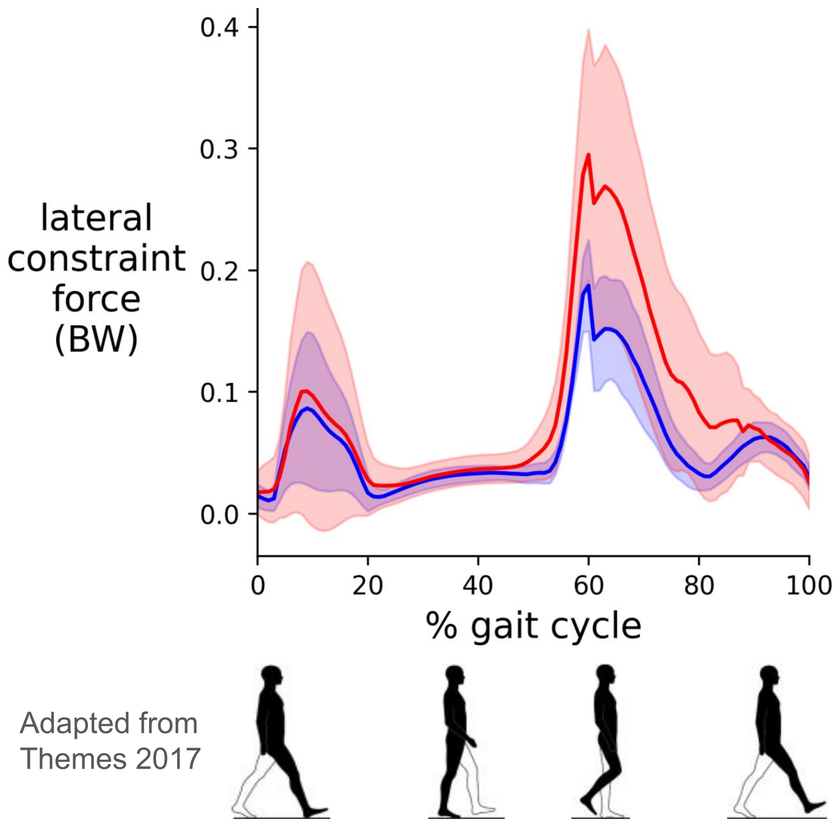
Adapted from Ji et al. 2015



Subjects with patellar instability demonstrate **greater lateral constraint force** during swing



Adapted from Ji et al. 2015



Adapted from Themes 2017

Conclusion: A better understanding of variations in patellar mechanics

- **Anatomical differences** between the patellar instability and control groups led to **differences in patellar mechanics**
- Simulation has the potential to inform **personalized treatment plans** for patients with patellar instability
- Future work may explore patellar mechanics in movements such as **jumping, pivoting**, and **single limb** forward motion

Acknowledgments

Thanks to Sara Wexler for project assistance. This work was generously supported by Harvey Mudd College.

References

[1] Delp et al. 2007, 10.1109/tbme.2007.901024
[2] Seth et al. 2018, 10.1371/journal.pcbi.1006223
[3] Smith et al. 2018, 10.1080/21681163.2016.1172346

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Adverse biomechanics during walking in knees with patellar instability

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Patellar instability is marked by the tendency of the patella to shift out of place and is influenced by an individual's anatomy. Understanding the biomechanical consequences of anatomical differences is critical to informing interventions and treatments for patellar instability. The goal of this research is to estimate how patellar kinematics and constraint forces during walking differ between 8 knees with patellar instability and 8 controls. This study included segmented knees from magnetic resonance images provided by Cincinnati Children's Hospital Medical Center. We integrated each knee into a generic musculoskeletal model and performed musculoskeletal simulations using generic walking gait data. We performed these simulations using OpenSim, an open source musculoskeletal simulation software, and COMAK, an open source optimization algorithm that enables cartilage contact force estimation in a six degree of freedom patellofemoral joint. For each knee, we compared simulated patellofemoral patellar tilt, patellar shift, and trochlear constraint force on the patella over a walking gait cycle. Mean patellar tilt, patellar shift, and lateral trochlear constraint force were each greater in the patellar instability knees than in the control knees. These findings demonstrate that anatomical differences influence patellar mechanics and show the value of musculoskeletal simulation in understanding patellar instability. Extensions of this work may support the exploration of the mechanisms behind patellar mechanics and development of personalized treatment plans for patients with patellar instability.

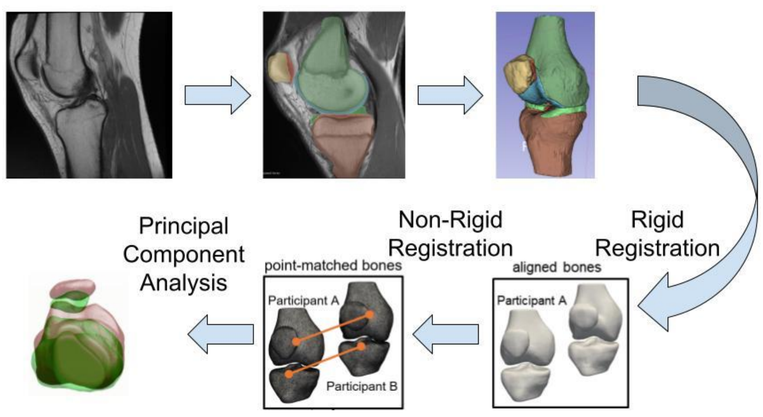
A Generalizable Statistical Shape Model Capturing Knee Joint Anatomical Variation for Patellar Instability Insights

Kangjia Huang, Ethan Sandoval, Amy Enayati,
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Patellar Instability

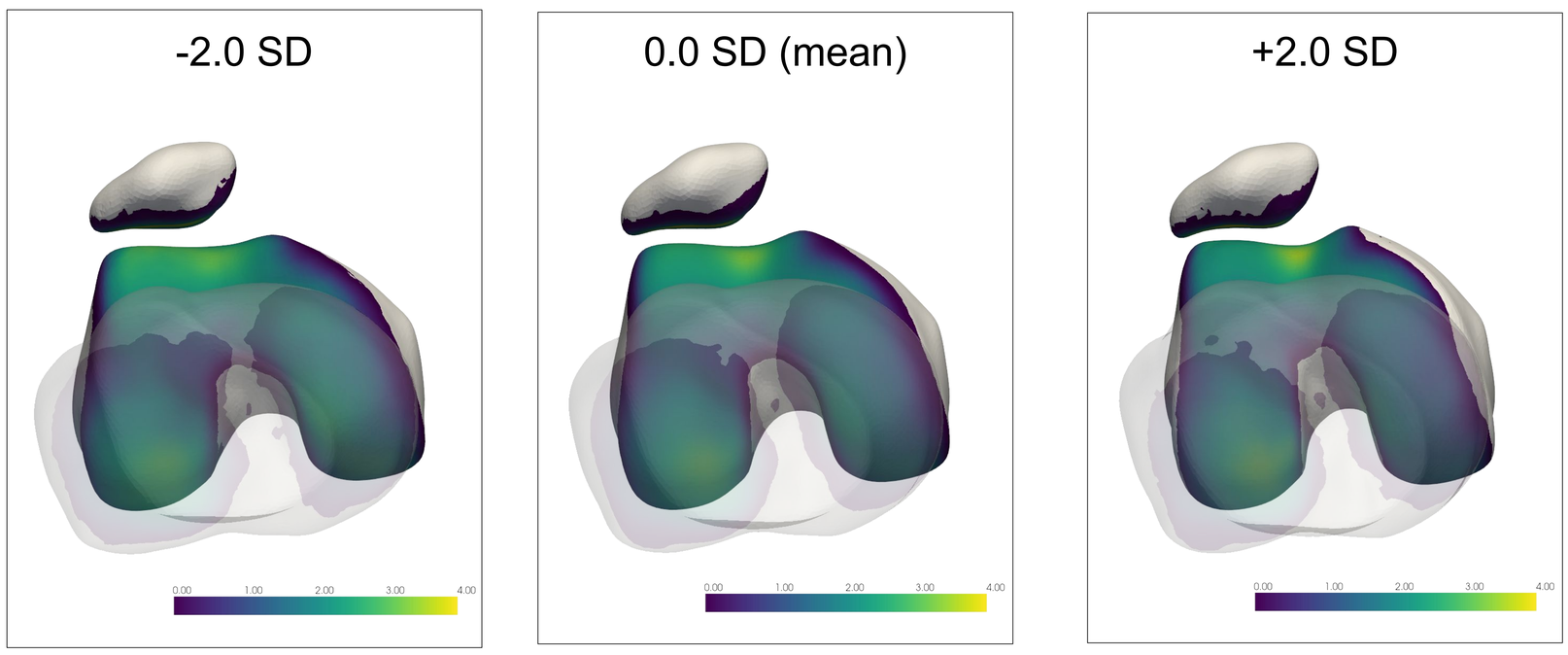
- Patellar instability (PI): dislocation of the kneecap, associated with pain and osteoarthritis
- Current methods for PI treatment decisions are limited (metrics measured from 2D patient scans[1], [2], [4]); full knee anatomy is not considered[2]
- Statistical shape models (SSMs) explain variation in 3D shapes[3]
- **Aim:** Leverage SSMs to analyze 3D knee anatomical variation in patients with and without PI to gain further insight into diagnosis and treatment

SSM Development

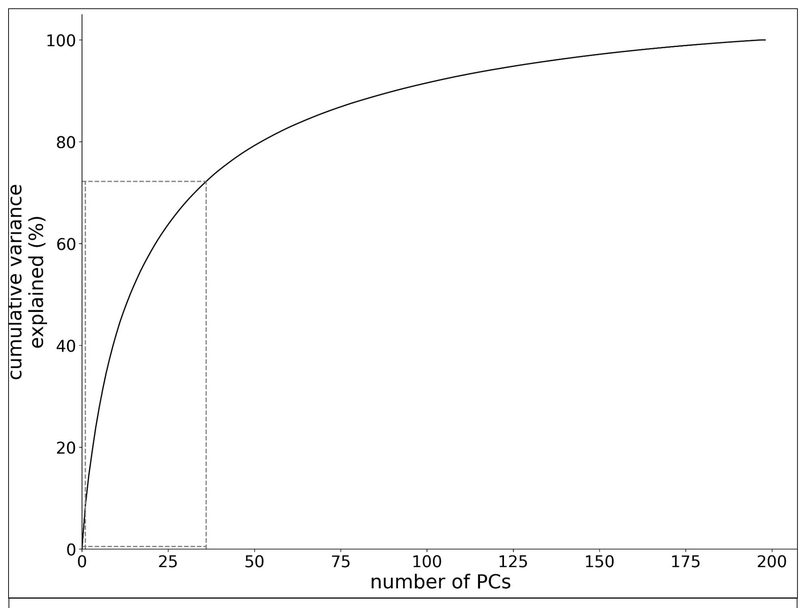


- Sagittal proton density-weighted magnetic resonance images (MRIs) of patient knees were segmented to identify bone (femur, patella, tibia) and cartilage regions:
  - **19** controls without PI
  - **179** patients with PI
  - Separate test set: **40** patients with and without PI for measuring model performance.
- SSM trained, visualized, and evaluated for performance:[3]
  - **Compactness**: amount of variance in training data that the model explains
  - **Generalizability**: ability to reconstruct unseen test knees, quantified by average symmetric surface distance

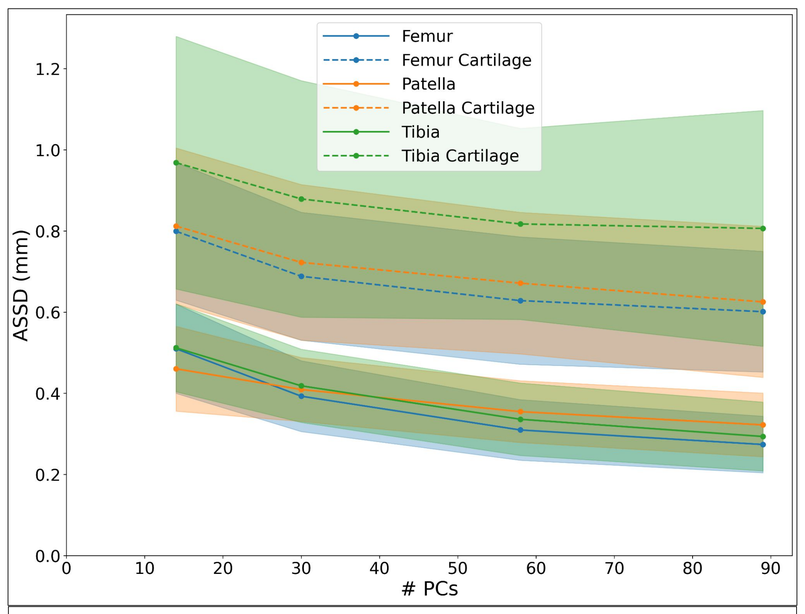
Shape Model Data and Performance



The **first principal component** (PC) reflects variation in trochlear depth and cartilage distribution.



Compactness: The model explains ~75% of training data variance with ~30 PCs.



Generalizability: Average symmetric surface distance (ASSD) ≤1.0mm indicates strong generalizability (scans had 1.00mm slice thickness).

Good Performance with Room for Improvement

- Our model demonstrates **respectable compactness and generalizability** metrics that indicate it produces values **meaningfully reflective of knee anatomy**
- Primary shape features are **related to known PI risk factors** (e.g., trochlear depth)[1], [2]
- Next steps: Model refinement and evaluation of model **specificity** — the model's ability to synthesize realistic knees.

Acknowledgments

Thanks to **George Skaff**, **Emily Bersin**, and other HUMBLE members for contributions to the patient data segmentation. Computational work in this project was supported by the **SoCal Research Computing Alliance** under NSF award #2232917, and this project was also generously supported by **Harvey Mudd College.**

References

- [1]Askenberger et al., 2016
- [2]Brenner et al., 2025
- [3]Brunton et al., 2014
- [4]Wierer et al., 2022

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A Generalizable Statistical Shape Model Capturing Knee Joint Anatomical Variation for Patellar Instability Insights

Kangjia Huang, Ethan Sandoval, Amy Enayati, Anthony Gatti, the JUPITER Group, Seth L. Sherman, and Marissa Sinopoli

Patellar instability is a condition of the kneecap, common among young athletes and associated with abnormal anatomy. Clinical assessments today largely utilize single-image measurements to evaluate anatomical risk factors, which may ignore information from 3D knee shape. Statistical Shape Models (SSMs) describe variation within populations of 3D geometries. This project aims to develop an SSM to describe detailed knee anatomy variation and provide quantitative metrics of patellar instability anatomy. Magnetic resonance images of 198 knees (19 controls, 179 patellar instability) were segmented to extract femur, patella, and tibia bones alongside associated cartilage. These segmentations were then used to produce 3D models of patient knees, which in turn were used to train the SSM. We measured the generalizability of the SSM by evaluating the average symmetric surface distance (ASSD), a measure of reconstruction similarity, associated with each of 41 test scans across a range of numbers of principal components. The SSM captured variation relating to known patellar instability metrics like trochlear depth and sulcus angle. 14 principal components were determined to be statistically significant through parallel analysis. These PCs achieved an average ASSD of 0.7 mm on the test set. Given the original scan parameters (1.0 mm slice spacing with 0.3 mm pixels), these metrics indicate sufficient shape model generalizability. These results suggest our shape model effectively captures anatomical detail. Future work will use this model to develop insights regarding patellar instability mechanisms and patient diagnosis, treatment, and quality of life.