Sensitivity analyses on ligament material models and attachment sites

1. Get prestretch range for LCL, MCL, ACL and PCL and check Young's Moduli.

According to Orozco et al. (Orozco et al., 2018):

All Poisson's ratios = 0.4

Young's Modulus: ACL = 123
PCL = 168
MCL = 224
LCL = 280

Methods

For all ligaments try: Prestretch 0.8 to 1.05 in steps of 0.01
Young's modulus literature + and – 60:
ACL: 63 – 183 in steps of 20
PCL: 108 – 228 in steps of 20
MCL: 164 – 284 in steps of 20
LCL: 220 – 340 in steps of 20

Simulations: All ligaments: 0.5 rad flexion
ACL: AP in the anterior direction (tib relative to fem) 5 mm
PCL: AP in the posterior direction (tib relative to fem) 5 mm
MCL: VV into valgus (-VV) 3° (0.05235 rad)
LCL: VV into varus (+VV) 3° (0.05235 rad)

Per ligament 25 * 7 = 175 FE simulations & 175 AP or VV simulations

Results

Results presented in: *1_YoungsModulus&Prestretch.pptx*

Conclusion

ACL → Young's modulus: 123 Prestretch: 0.85 – 1.0
PCL → Young's modulus: 168 Prestretch: 0.88 – 1.04
MCL → Young's modulus: 224 Prestretch: 0.88 – 1.0
LCL → Young's modulus: 280 Prestretch: 0.89 – 1.0

- When multiple Young's moduli had similar behaviour, the literature value (Orozco 2018) was chosen.
- Prestretch value 1.0 is unstable when all other values are 1.0 as well and often doesn't run, this is probably due to no force acting on the models.

2. Check prestretch range for force driven simulations

In the calibrations we use force driven simulations, therefore we need to know the performance of the models in these simulations.

Methods

Investigate the ligament prestretch values in simulations of the following forces/moments:
ACL & PCL:

1. AP -50N,
2. AP +50N,
3. AP -100N,
4. AP +100N

MCL & LCL:

1. VV -500Nmm,
2. VV +500Nmm,
3. VV -1000 Nmm,
4. VV +1000 Nmm

ACL, PCL, MCL & LCL:

1. IE -500Nmm,
2. IE +500Nmm,
3. IE -1000 Nmm,
4. IE +1000 Nmm

Prestretch range 0.8 – 1.04 for each ligament, changing one ligament prestretch value at the time.

The following 8 python scripts starting the simulations were run:

1. ACL AP	-50, +50, -100, +100N	prestretch 0.8 – 1.04	Total runs = 100
2. PCL AP	-50, +50, -100, +100N	prestretch 0.8 – 1.04	Total runs = 100
3. MCL VV	-500, +500, -1000, +1000Nmm	prestretch 0.8 – 1.04	Total runs = 100
4. LCL VV	-500, +500, -1000, +1000Nmm	prestretch 0.8 – 1.04	Total runs = 100
5. ACL IE	-500, +500, -1000, +1000Nmm	prestretch 0.8 – 1.04	Total runs = 100
6. PCL IE	-500, +500, -1000, +1000Nmm	prestretch 0.8 – 1.04	Total runs = 100
7. MCL IE	-500, +500, -1000, +1000Nmm	prestretch 0.8 – 1.04	Total runs = 100
8. LCL IE	-500, +500, -1000, +1000Nmm	prestretch 0.8 – 1.04	Total runs = 100

Results

Full results in: *2_prestretch_test_force_driven.pptx*

Conclusion

Stable ranges of the prestretch values:
ACL: 0.88 – 1.04 (probably don’t want to go higher than 1.0)
PCL: 0.86 – 1.04

MCL: 0.89 – 1.04
LCL: 0.93 – 1.04 (probably don't want to go higher than 1.0)

3. Find influence of Prestretch and ACL attachment sites on force – displacement behaviour

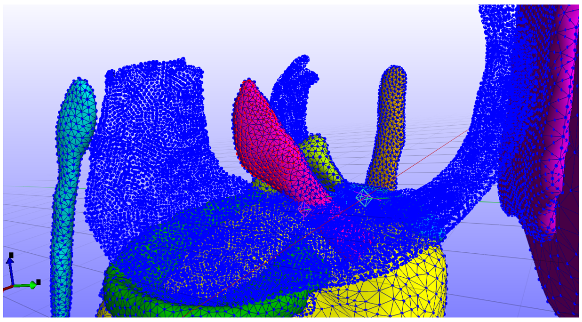
We want to obtain the force, displacement behaviour for different prestretch and different attachment sites of the ACL.

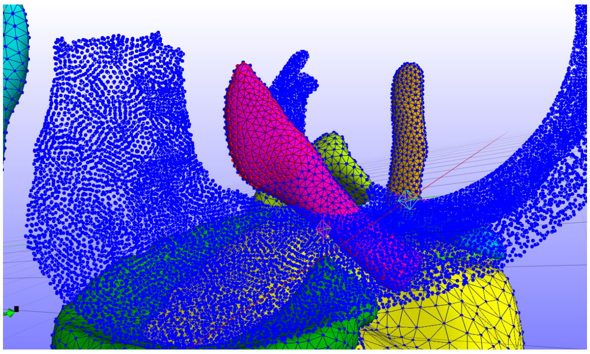
Methods

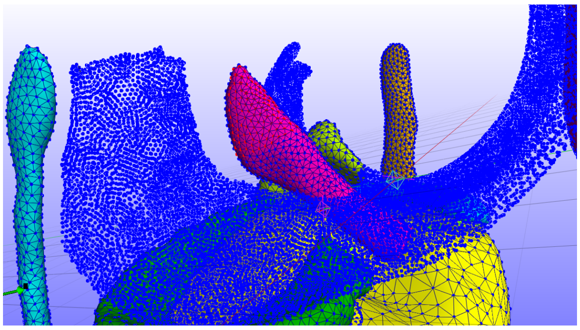
Test with Young's modulus fixed at:
- ACL: 123
- PCL: 168
- MCL: 224
- LCL: 280

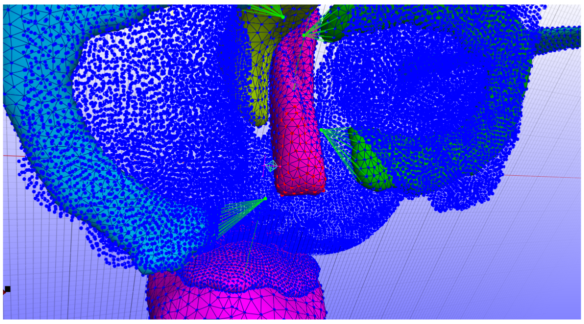
Test prestretch ranges:
- ACL: 0.8 – 1.04

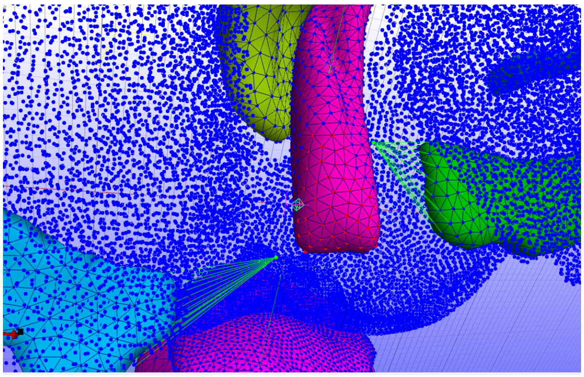
3 femur ACL attachment nodesets
3 tibia ACL attachment nodesets

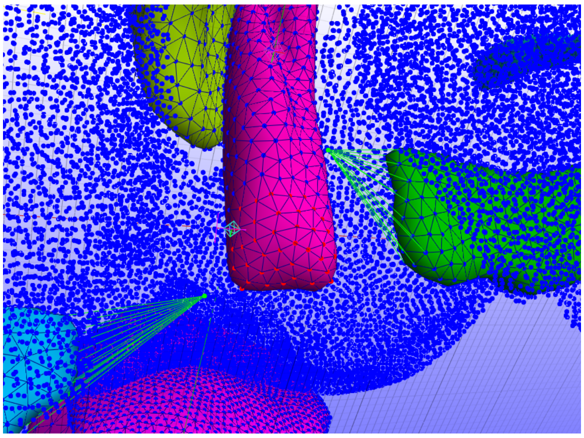

Femur 1


Femur 2


Femur 3


Tibia 1


Tibia 2


Tibia 3

AP simulation: -50, +50, -100, +100N

Results

Full results available in: *3_Results_AP_simulation.pptx* (13 simulation means femur attachment #1 and tibia attachment #2)

Conclusion

Influence of contact nodes is not as large as expected on AP. We do see more of an influence on IE angle, but this is not a large influence.

4. Find influence of Prestretch and ACL attachment sites on FE simulation.

Methods

The same methods used as in Sensitivity analysis 3, but now with a flexion rotation of 0.5 radians applied instead of AP forces.

Results

Results are available in: *4_results_FE_rotation.pptx*

Conclusion

No substantial differences found by changing the nodes involved in the contacts of the ACL ligament.

5. Find the influence of combinations of ACL, PCL prestretch and Young's modulus changes on kinematics

- Changing the prestretch values by 0.01
- Use NeoHookean material models for ligaments
- Not changing attachment sites.
- Check how far off the angles and positions are from the robot data.
- All simulations: 0 - 0.2 seconds prestretch application

Methods Simulations 1

- Only prestretch application (0-0.2 seconds) → changing one ligament at the time in the range of 0.8 to 1.4.
- Look at resulting kinematics

Results 1

Full results can be found in: *5 influence prestretch on kinematics.pptx*

- Found that ACL and PCL work oppositely on the AP position. But the robot data values are not reached yet.

Methods Simulations 2

- Run all combinations of ACL and PCL to see if we can get to the robot AP kinematic data.
  0.8 – 1.04 ACL
  0.8 – 1.04 PCL
- Total: 25 x 25 = 625 simulations.

Results 2

Full results can be found in: *5 prestretch ACL and PCL combinations.pptx*

- Only with the lowest ACL prestretch and the highest PCL prestretch we can get close to the robot values.
- Maybe we need to go back to also changing the Young's moduli to see if we can get to the AP positions in the robot data.

Methods Simulations 3

- ACL prestretch:	0.8 – 0.95	16 values	
PCL prestretch:	0.95 – 1.04	10 values	
ACL YM:	123 143 163	3 values	Stiffer than initial value
PCL YM:	128 168 208	3 values	Less and more stiff

Split in 10 runs (one per PCL value)

Results 3

Full results can be found in: *5 YM ACL PCL 095 to 110.pptx*

- It looks like to get to the robot AP position, the ACL and PCL prestretch should be in a balance. The Young's modulus does not have a large influence on AP position.
- Need to check the other kinematic values (check how far we are off). Only checked for VV and AP. VV slightly off but can probably be fixed with LCL and MCL prestretch.

Methods Simulation 4

To check now how far up the PCL prestretch will go until it gets unstable.

- Add PCL 1.11 – 1.20 prestretch values to simulations in simulation 3.

Results 4

Full results can be found in: *5 YM ACL PCL 111 to 120.pptx*

- With PCL prestretch value > 1.18 in combination with part of the ACL prestretch values, the model becomes unstable.

Conclusion

Different combinations of prestretch values have a different effect on the kinematic model outcomes. The Young's modulus was found to not have a large influence, however the tested ranges were small.

References

Orozco, G. A., Tanska, P., Mononen, M. E., Halonen, K. S., & Korhonen, R. K. (2018). The effect of constitutive representations and structural constituents of ligaments on knee joint mechanics. Scientific reports, 8(1), 1-15.