Impact of Ligament Stiffness Adjustment on Knee Joint Mechanics in Mechanically Aligned Posterior-Stabilized (PS) Total Knee Arthroplasty (TKA)

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Contents

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I Introduction

Introduction

Treatment Process for Knee Osteoarthritis[1,2]

Disease	Cause	Symptom
Osteoarthritis (Degeneration)	• Aging of joints • Obesity • Excessive and continuous joint use • Damage to cartilage and joint tissue • Accident • Heredity • Hormone • Shape of the joints	• Local pain in the joint • Stiffness of the joints • Friction sound during joint • Movement feeling of swelling 

1. Conservative
   - Daily habits / Exercise
   - Auxiliary device
   - Medicine treatment

2. Arthroscopic cure
   - Clean the inside of the joint
   - Remove synovium active film

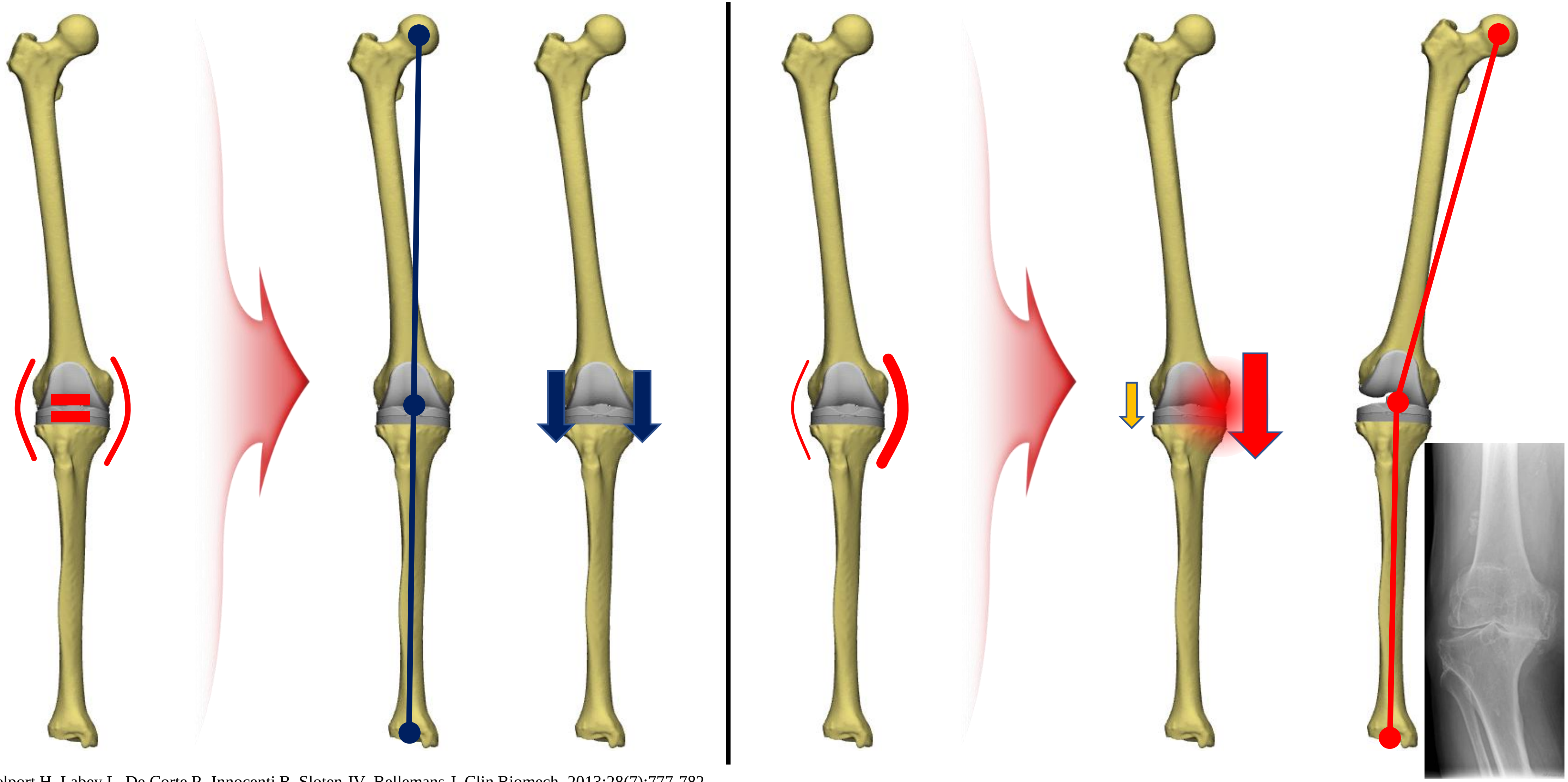
3. Total Knee Arthroplasty
   - Final treatment for arthritis
   - Implantation for damaged knee

4. Benefits of Total Knee Arthroplasty
   - Elimination the lesion and release pain
   - Restore the kinematic function of lower limb
   - Recover the varus/valgus knee to normal
   - Return to daily activities

[1] Yang et. al, History of Total Knee Replacement, 2010
[2] Vaienti et. al, Understanding the human knee and its relationship to total knee replacement, 2017

Introduction

Impacts of Soft Tissue Balance[3,4,5,6]



[3] Delport H, Labey L, De Corte R, Innocenti B, Sloten JV, Bellemans J. Clin Biomech. 2013;28(7):777-782.
[4] Sim J, Lee Y, Kwak J, Yang S, Kim K, Lee B. Clin Orthop Surg. 2013;5(4):287-291.
[5] Lee H, Kim S, Park Y. Arch Orthop Trauma Surg. 2020;140(10):1523-1531.
[6] ROSSI, Roberto, et al. International orthopaedics, 2019, 43.1: 151-158.

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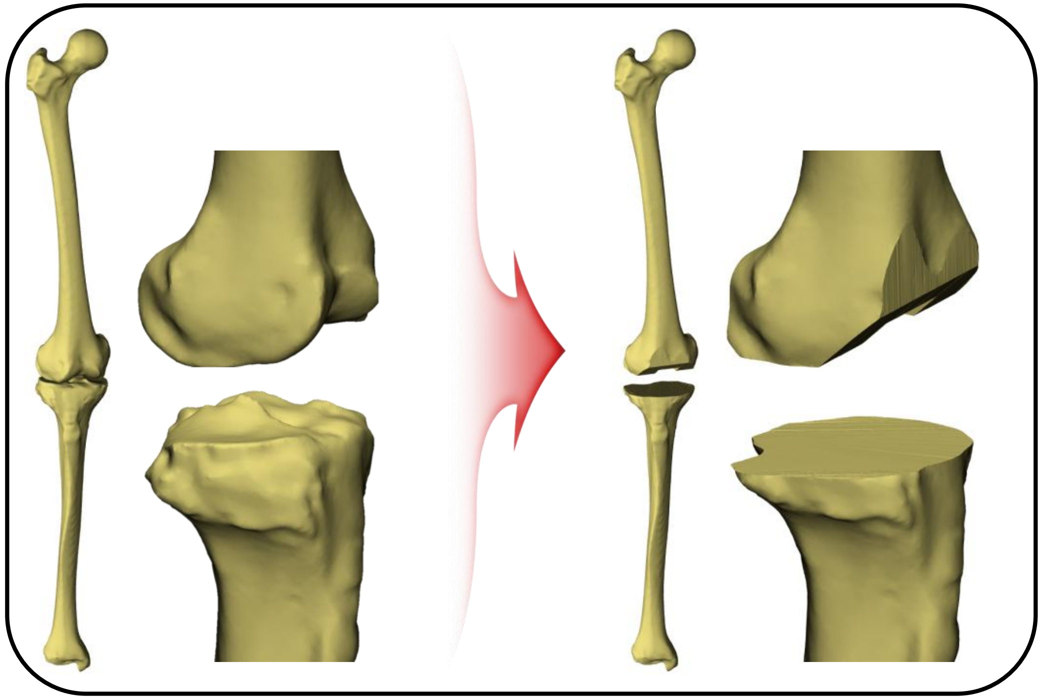
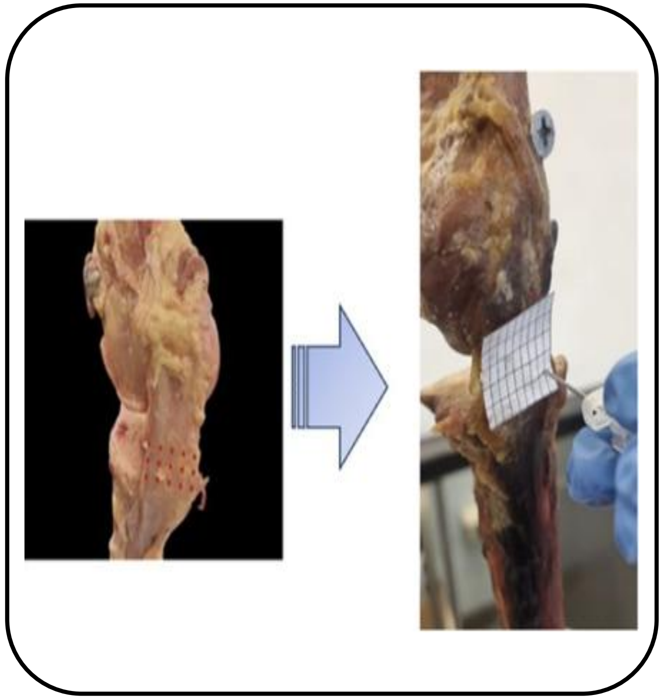
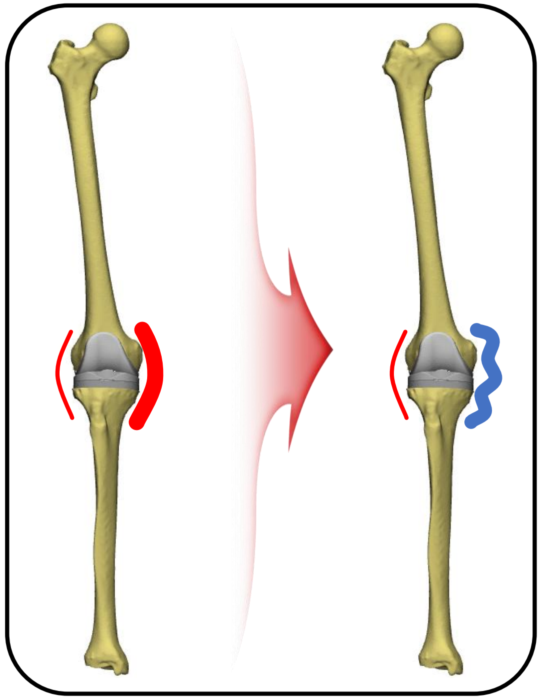
Methods to Improve Soft Tissue Balance



Osteotomy



Selective Needle Punturing[7]



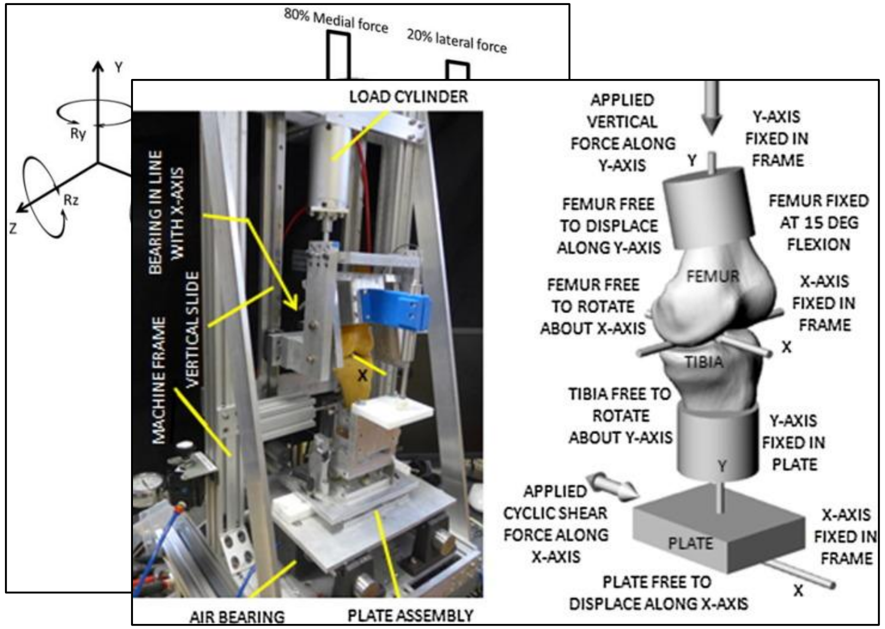
Selective Femoral Origin Release[8]

- Techniques such as medial epicondylar osteotomy and selective needle puncturing have shown promise for soft tissue balancing.
- However, further clinical trials and biomechanical studies are required to assess and validate these methods for patient outcomes

[7] REZAEI, Arash, et al. Precision soft tissue balancing: grid-assisted pie-crusting in total knee arthroplasty. *Frontiers in Surgery*, 2024, 11: 1331902.
[8] Lee S, Yang J, Lee Y, Yoon J. A novel medial soft tissue release method for varus deformity during total knee arthroplasty: femoral origin release of the medial collateral ligament. Knee Surg Relat Res. 2016;28(2):153–60.

Introduction

Literature Review



Previous studies have focused on **passive flexion scenarios**

➔Significant gap in understanding of how MCL tension affects functional knee biomechanics in **dynamic condition**

[9] Lee S, Yang J, Lee Y, Yoon J. A Novel Medial Soft Tissue Release Method for Varus Deformity during Total Knee Arthroplasty: Femoral Origin Release of the Medial Collateral Ligament. Knee Surg Relat Res. 2016;28(2):153-160.
[10] Müller J, Zakaria T, van der Merwe W, D'Angelo F. Computational Modelling of Mobile Bearing TKA Anterior-Posterior Dislocation. Comput Methods Biomech Biomed Engin. 2016;19(5):549-562.
[11] Reynolds R, Walker P, Buza J, Mechanisms of Anterior-Posterior Stability of the Knee Joint under Load Bearing. J. Biomech. 2017;57:39-45.
[12] Athwal K, Daou HE, Kittl C, Davies A, Deehan D, Amis A. The Superficial Medial Collateral Ligament is the Primary Medial Restraint to Knee Laxity after Cruciate-Retaining or Posterior-Stabilised Total Knee Arthroplasty: Effects of Implant Type and Partial Release. Knee Surg Sports Traumatol Arthrosc. 2016;24(8):2646-2655

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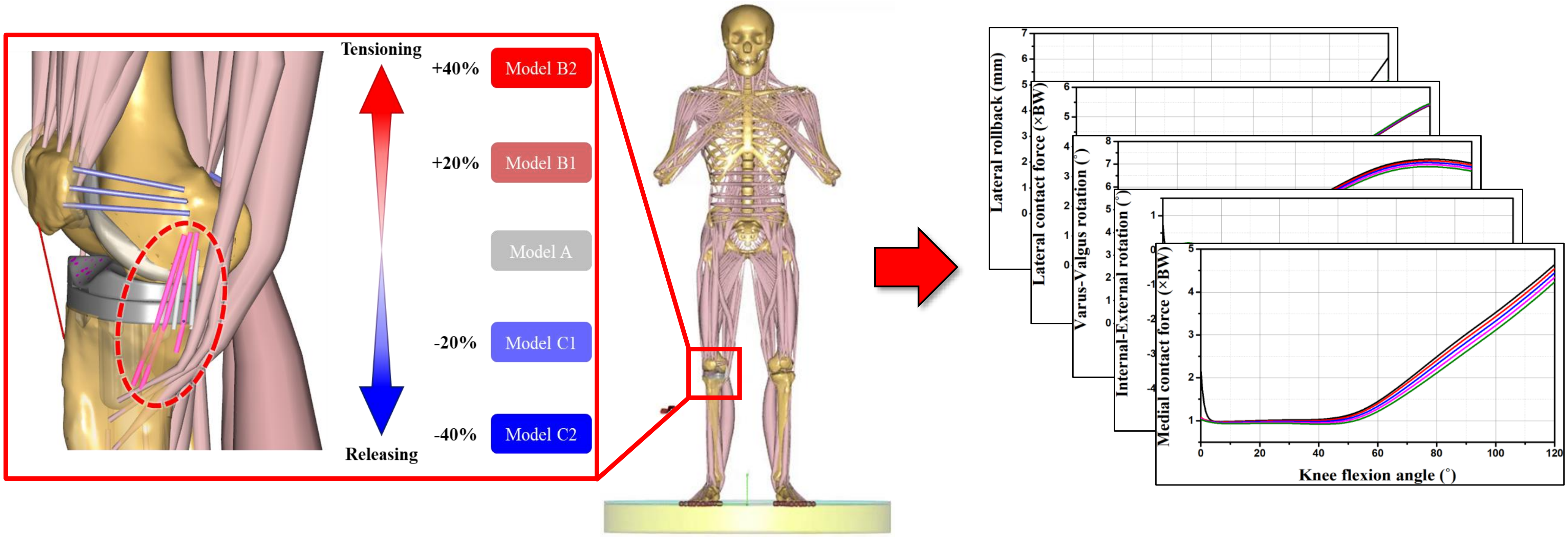
Introduction

Purpose

Purpose

To investigate Impact of MCL Stiffness Adjustment on Knee Joint Mechanics

in Mechanically Aligned PS TKA.



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II Materials & Methods

Materials & Methods

Musculoskeletal Model Construction

AnyBody Modeling System
(AMS) v7.4.2

Contact conditions[13]

Definition

- Tibiofemoral (Medial/Lateral) Contact
- Patellofemoral (Medial/Lateral) Contact

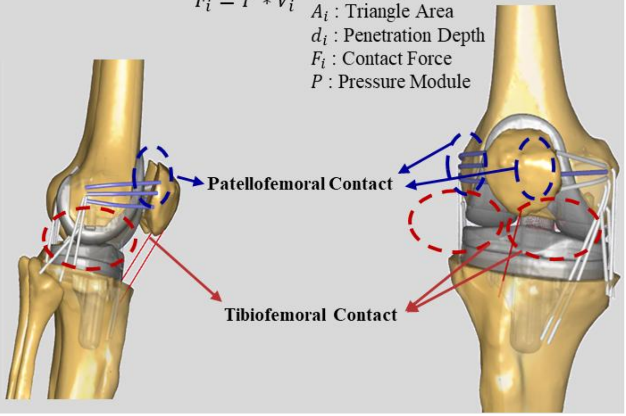
Properties and Contact Analysis

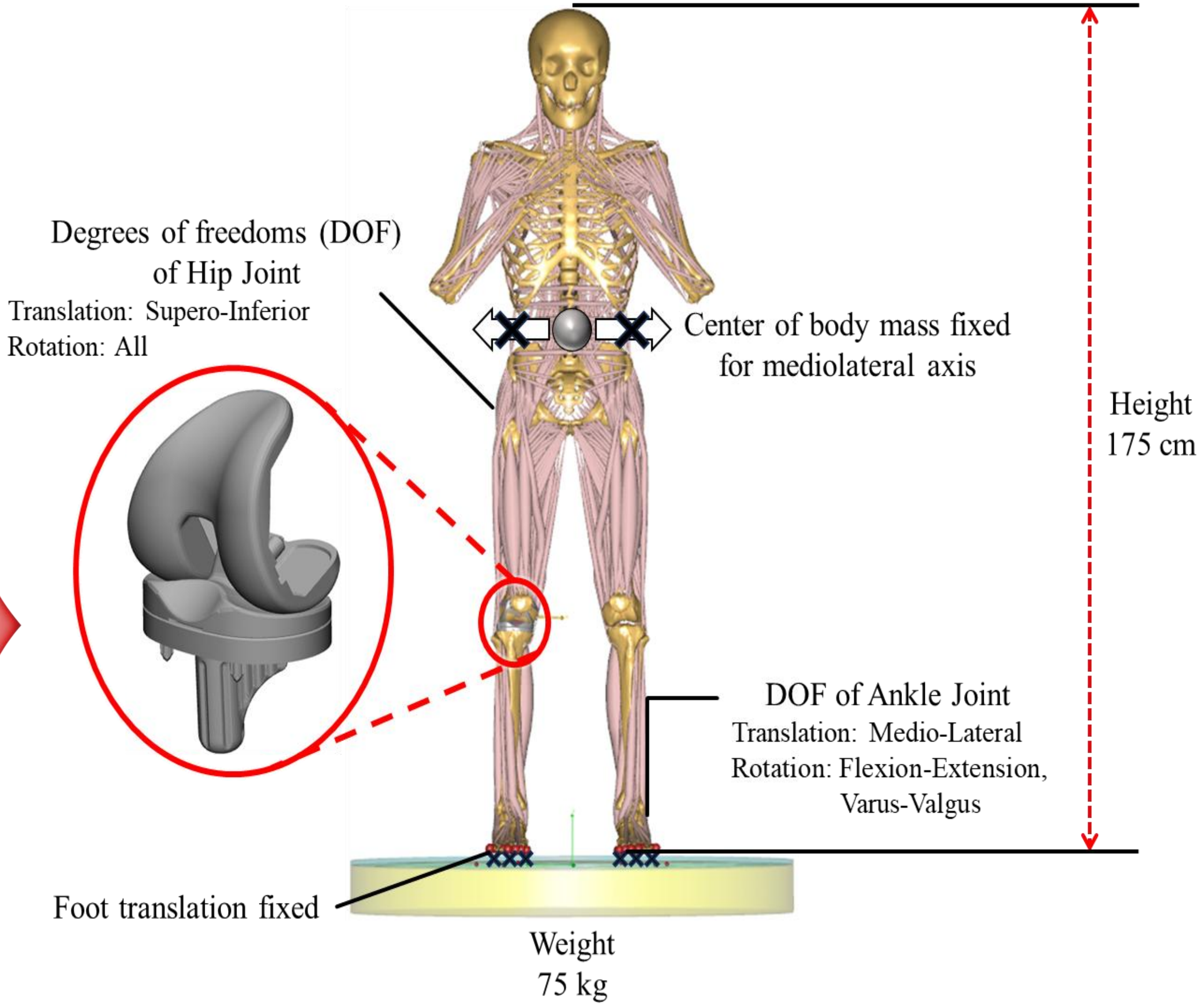
- Pressure Modulus : $9.3 \times \frac{10^9 N}{m^3}$

$$V_i = A_i * d_i$$

$$F_i = P * V_i$$

V_i : Volume
A_i : Triangle Area
d_i : Penetration Depth
F_i : Contact Force
P : Pressure Module

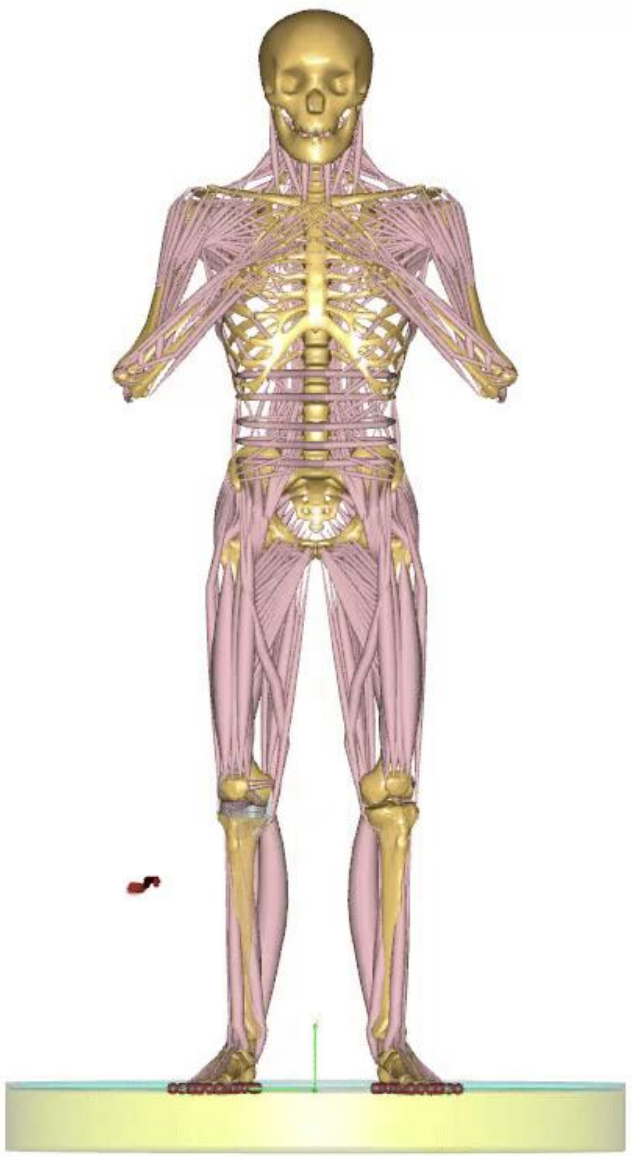




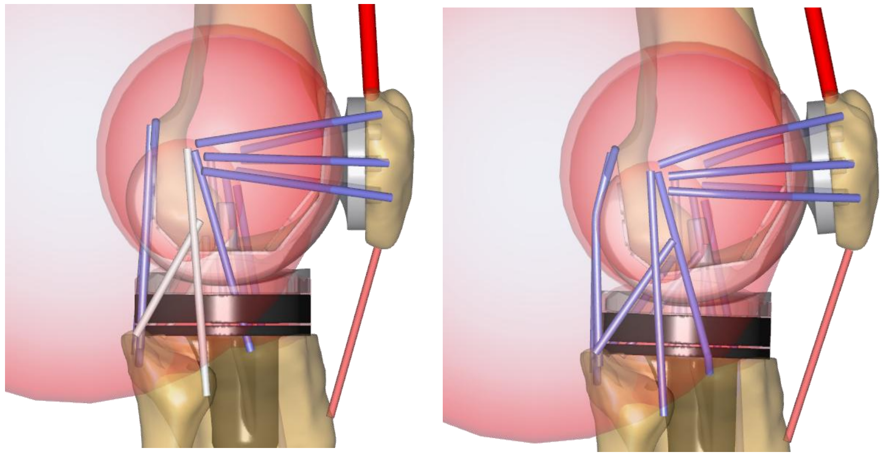
[13] FREGLY, Benjamin J.; BEI, Yanhong; SYLVESTER, Mark E. Experimental evaluation of an elastic foundation model to predict contact pressures in knee replacements. Journal of biomechanics, 2003, 36.11: 1659-1668.D'LIMA, Darryl D., et al. In vivo knee moments and shear after total knee arthroplasty. Journal of biomechanics, 2007, 40: S11-S17.

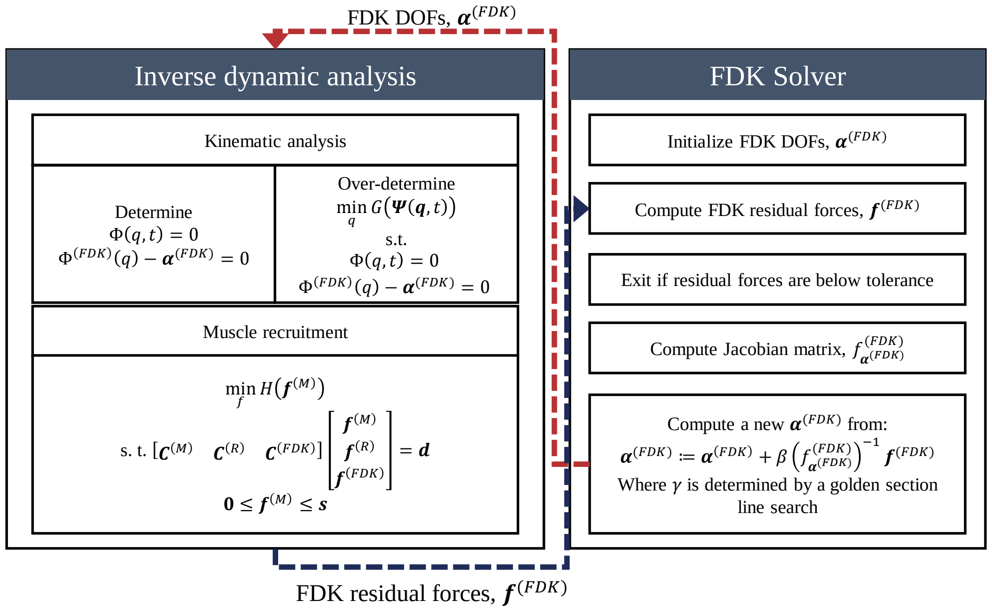
Materials & Methods

Musculoskeletal Model Construction



Ligament Wrapping Surface



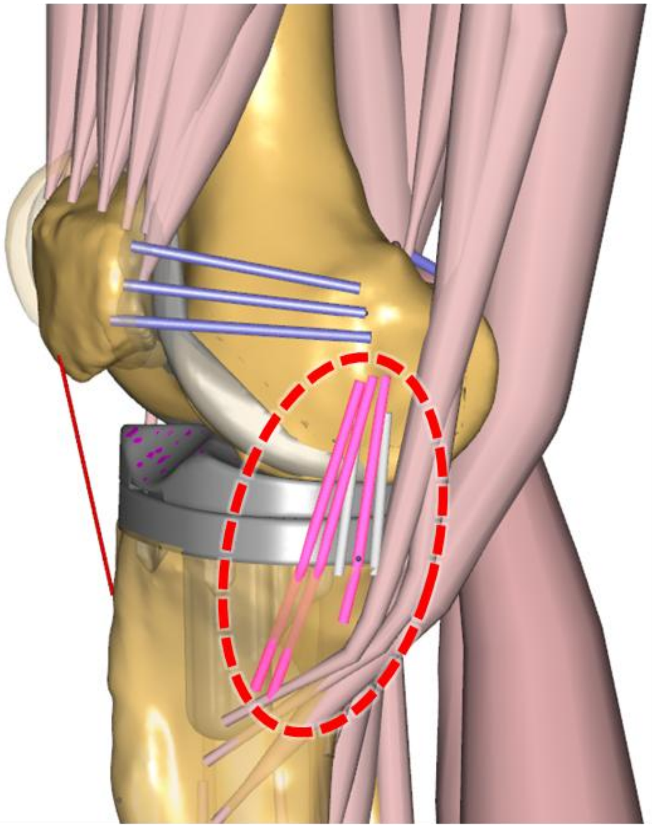


Materials & Methods

Ligament Stiffness Adjustment

Ligament Properties[14]

Ligament	Stiffness (N)	Reference strain
LCL	4000	0.06
aMCL	2500	-0.02
cMCL	3000	0.04
pMCL	2500	0.05
PFL	4000	0.06
OPL	2000	0.07
mCAP	2500	0.08
lCAP	2500	0.06
ALS	2000	0.06
aCM	2000	-0.27
pCM	4500	-0.06
sMPFL	2000	0.1
mMPFL	2000	0.1
iMPFL	2000	0.1
sLPFL	1000	0.15
mLPFL	1000	0.15
iLPFL	1000	0.15

Ligament configuration		Model variations	Detailed values
 Tensioning	+40%	Model B2	aMCL: 3500 N/m cMCL: 4200 N/m pMCL: 3500 N/m
	+20%	Model B1	aMCL: 3000 N/m cMCL: 3600 N/m pMCL: 3000 N/m
		Model A	aMCL: 2500 N/m cMCL: 3000 N/m pMCL: 2500 N/m
	-20%	Model C1	aMCL: 2000 N/m cMCL: 2400 N/m pMCL: 2000 N/m
Releasing	-40%	Model C2	aMCL: 1500 N/m cMCL: 1800 N/m pMCL: 1500 N/m

[14] MARRA, Marco A., et al. A subject-specific musculoskeletal modeling framework to predict in vivo mechanics of total knee arthroplasty. Journal of biomechanical engineering, 2015, 137.2: 020904.

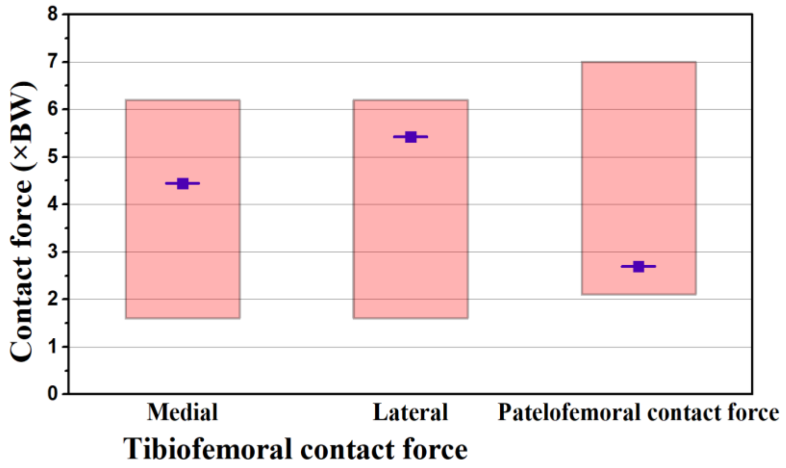
Materials & Methods

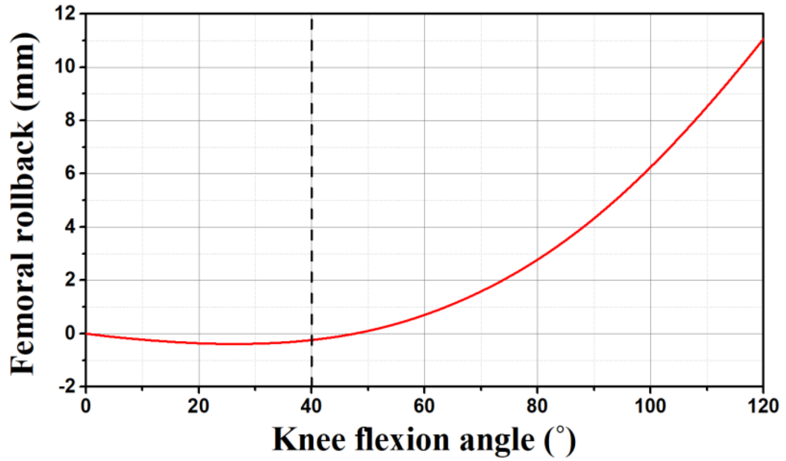
Validation of Musculoskeletal Model

Literature Review

Author	Title
D'Lima et. al [15]	In vivo knee moments and shear after total knee arthroplasty
Nagura et. al [16]	Tibiofemoral joint contact force in deep knee flexion and its consideration in knee osteoarthritis and joint replacement
Escamilla et. al [17]	The Effects of Technique Variations on Knee Biomechanics During the Squat and Leg Press
Mason et. al [18]	Patellofemoral joint forces
Kim et. al [19]	Different intraoperative kinematics with comparable clinical outcomes of ultracongruent and posterior stabilized mobile-bearing total knee arthroplasty

Musculoskeletal Model





[15] D'Lima et. al, In vivo knee moments and shear after total knee arthroplasty. 2007
[16] Nagura et. al, Tibiofemoral joint contact force in deep knee flexion and its consideration in knee osteoarthritis and joint replacement. 2006
[17] Escamillaet. al, Effects of technique variations on knee biomechanics during the squat and leg press. 2001
[18] Masonet. al, Patellofemoral joint forces. 2008 [26] Kim et. al, Different intraoperative kinematics with comparable clinical outcomes of ultracongruent and posterior stabilized mobile-bearing total knee arthroplasty. 2016
[19] Kim et. al, Different intraoperative kinematics with comparable clinical outcomes of ultracongruent and posterior stabilized mobile-bearing total knee arthroplasty. 2016

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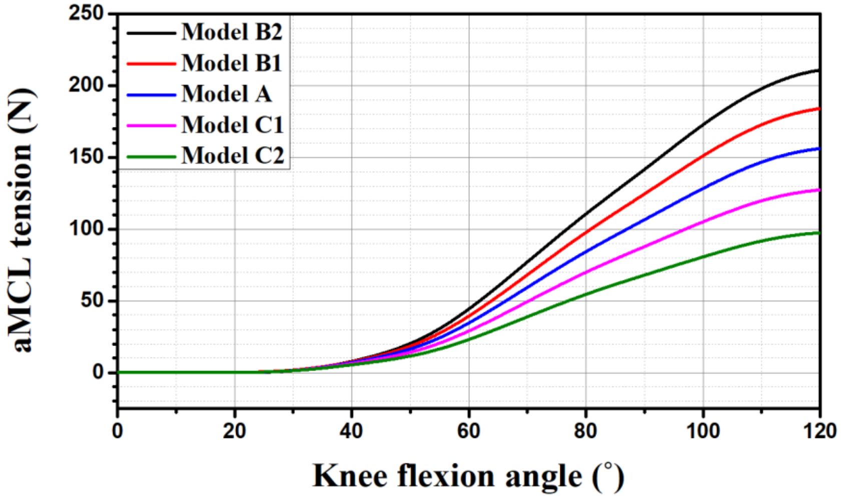
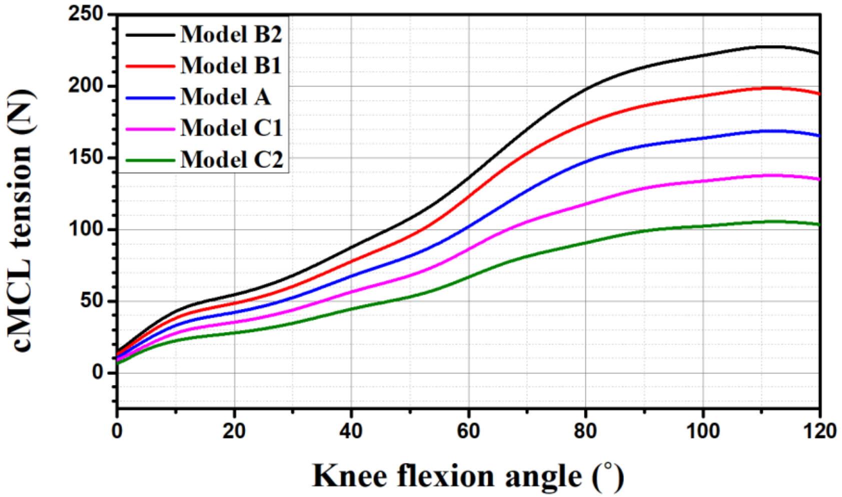
III Results

Results

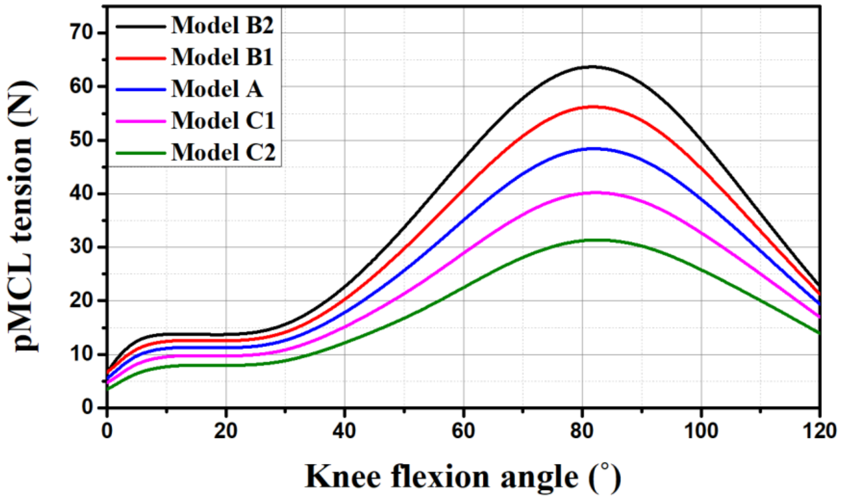
MCL Tension



Anterior MCL (aMCL) tension



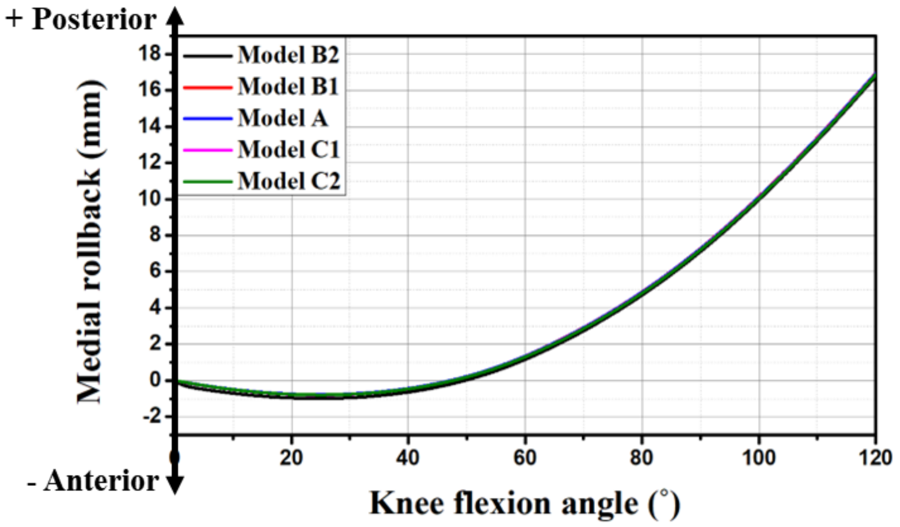
Central MCL (cMCL) tension



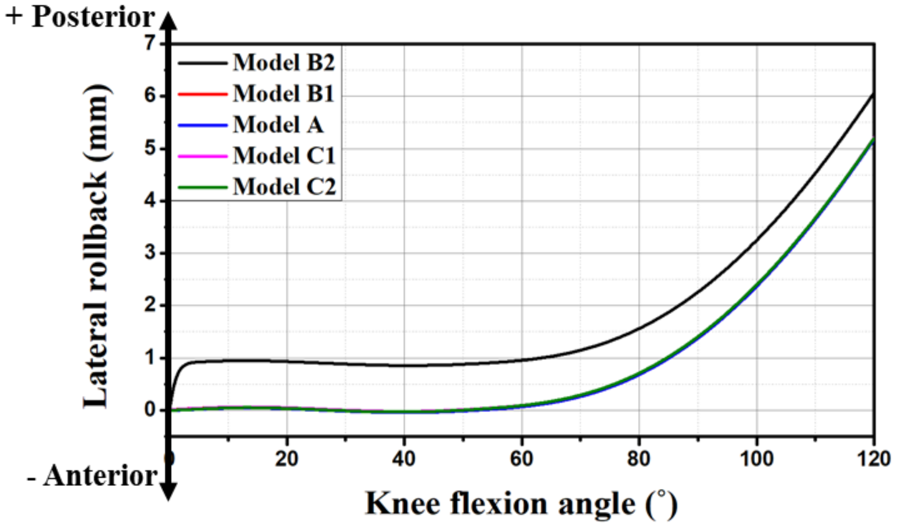
Posterior MCL (pMCL) tension

Results

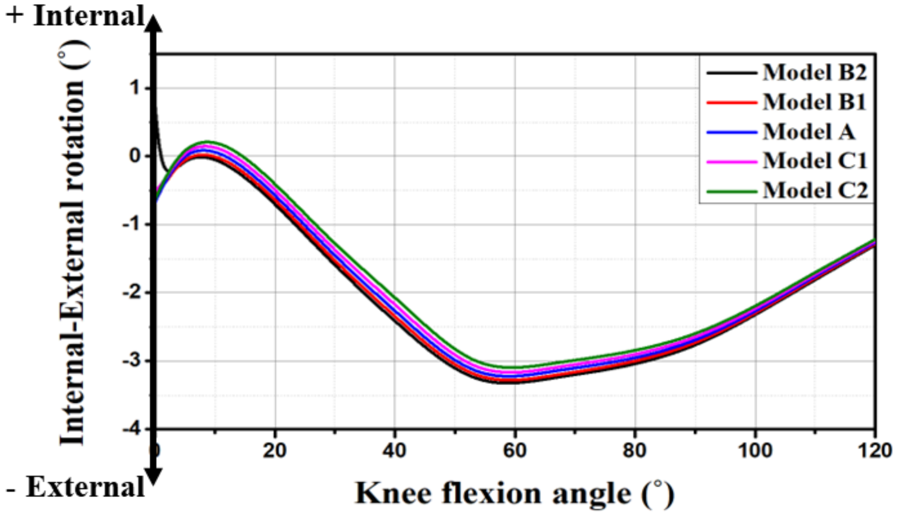
Kinematic Properties



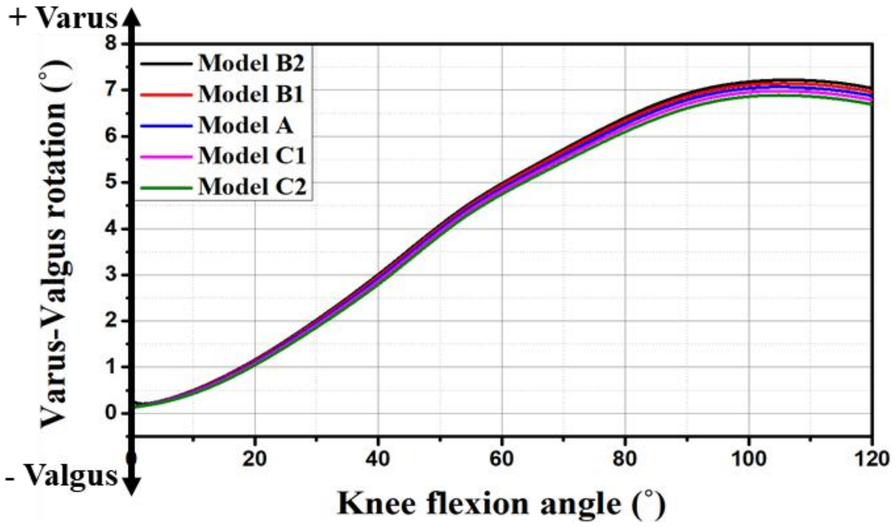
Medial rollback



Lateral rollback



Internal-External rotation



Varus-Valgus rotation

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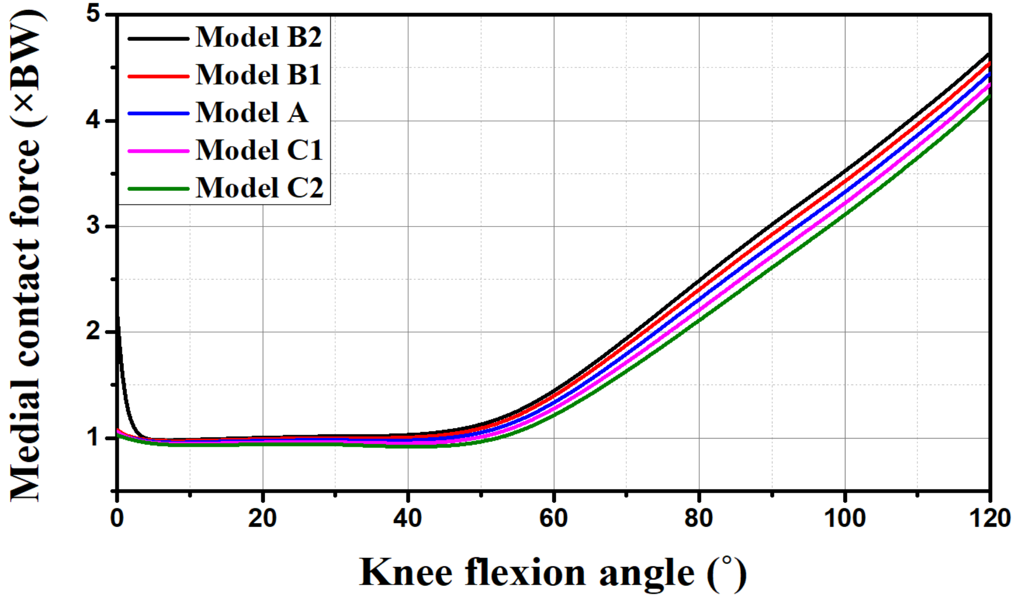
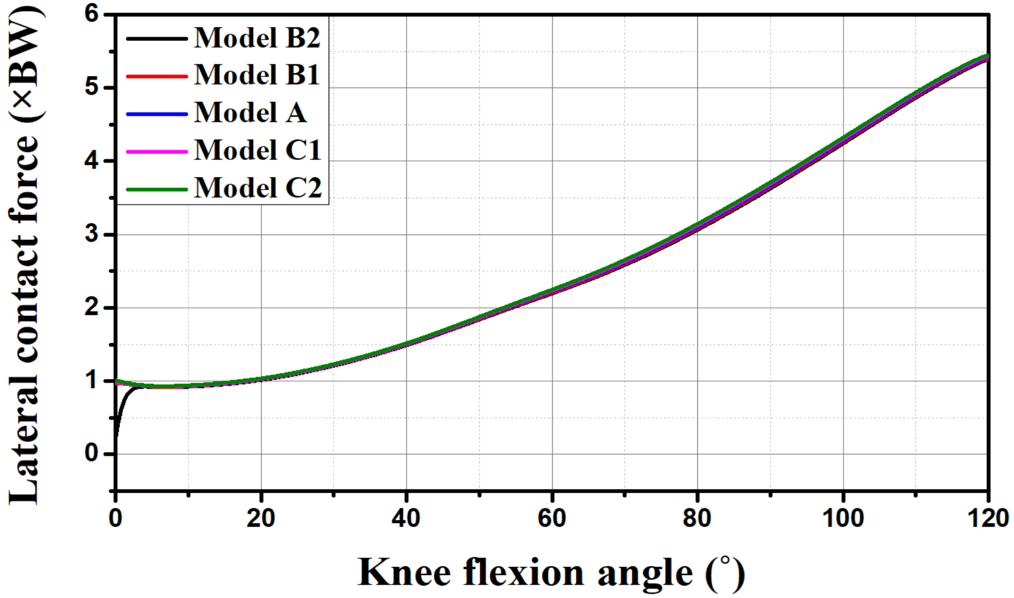
Results

TibioFemoral Joint Contact Forces



Medial contact force

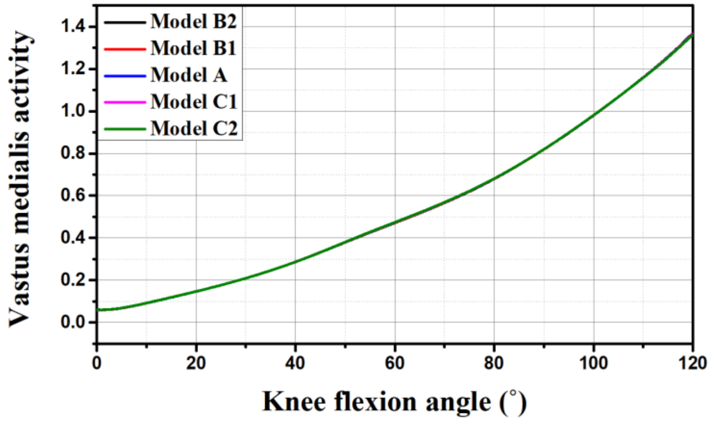


Lateral contact force

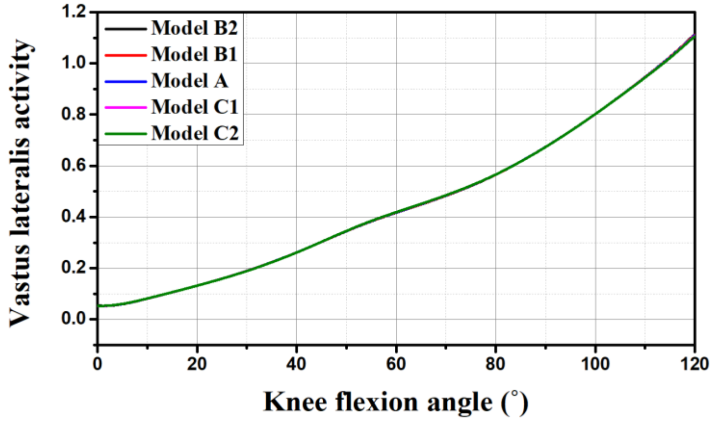
Results

Muscle Activities

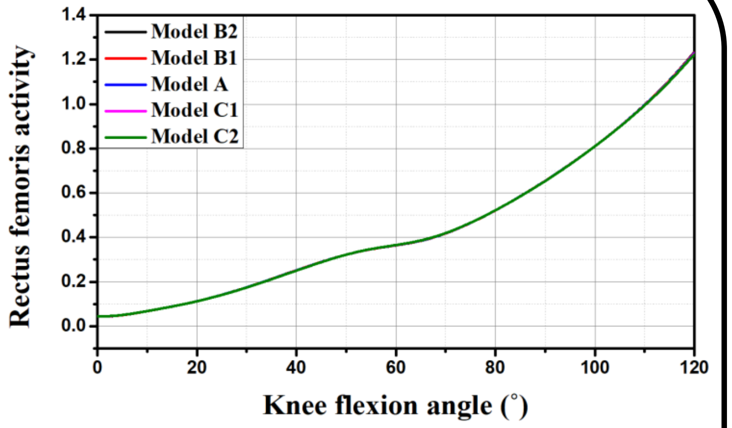
Quadriceps muscles



Vastus medialis activity

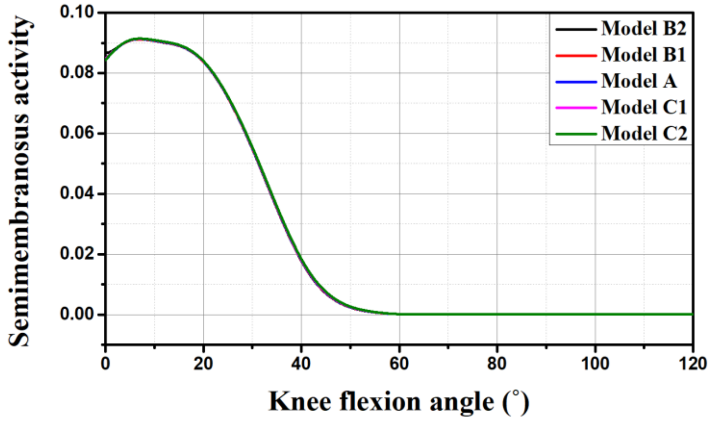


Vastus lateralis activity

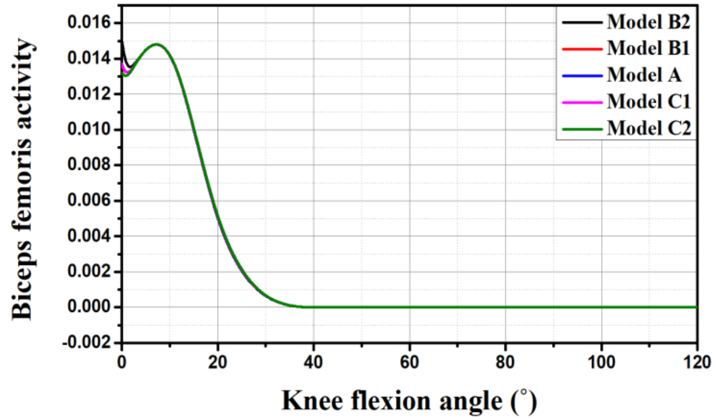


Rectus femoris activity

Hamstring muscles



Semimembranosus activity



Biceps femoris activity

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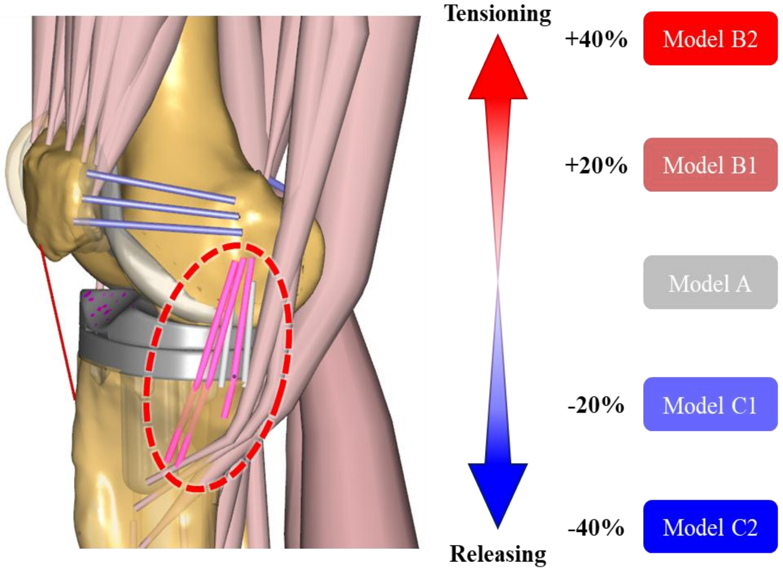
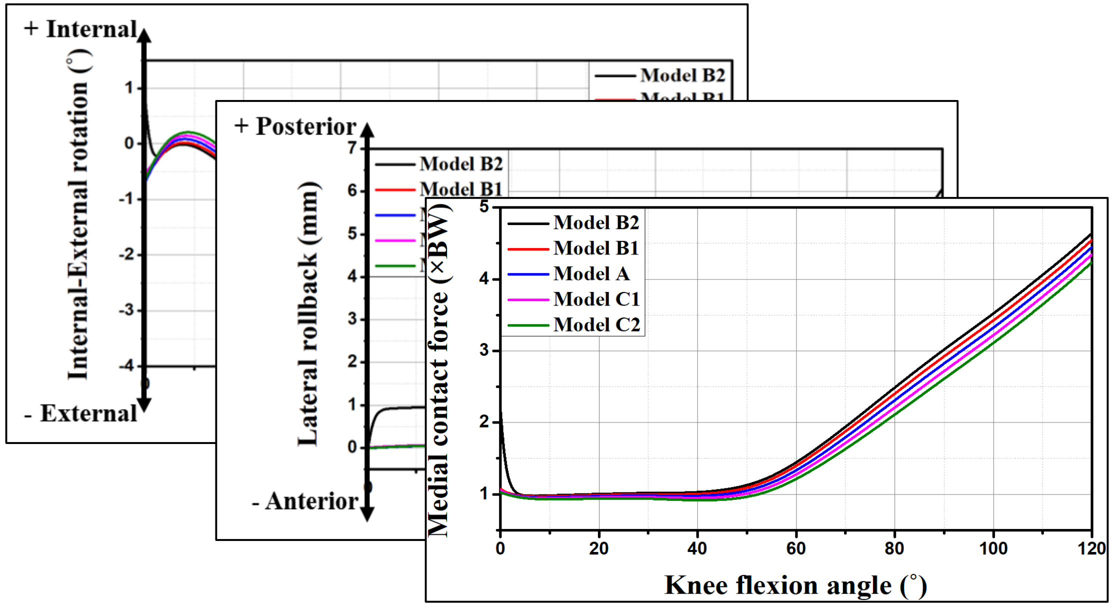
IV Discussion & Conclusion

Discussion & Conclusion

Discussion

- This study provides **quantitative data** on the changes in femoral rollback and rotation when **MCL stiffness is adjusted**, offering **practical guidance** for surgeons during intraoperative decision-making.
- Adjusting MCL stiffness had measurable effects on femoral rollback, femoral rotation, and joint contact force, with the changes **most pronounced in Model B2**.
- In Model B2, a **significant movement** was observed in the initial phase of knee flexion (0°–2°).
- Excessive movements in the early phases of knee flexion, as seen in Model B2, could **result in uneven load distribution** across the knee, potentially **accelerating wear of the polyethylene insert** and **leading to premature prosthesis failure**.





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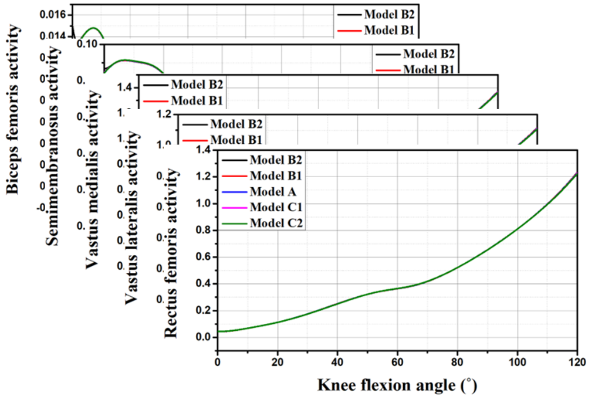
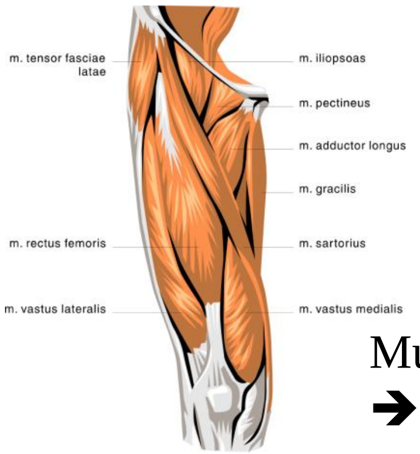
Discussion & Conclusion

Discussion

- Despite the significant effects of MCL stiffness on knee kinematics, the study showed **minimal changes in muscle activity** across the different models.
- In multi-body dynamics simulations, it is essential to achieve **equilibrium between internal forces** (e.g., ligament and muscle forces) **and external forces** (e.g., ground reaction forces or applied loads) for the model to converge and produce valid results.
- Ligament structures, especially the MCL, which **absorbed most of the force changes** resulting from stiffness adjustments, **reducing the need for compensatory muscle activity**.
- Previous research supports this finding, suggesting that in mechanically aligned TKA, **passive structures like ligaments play a more prominent role in maintaining stability compared to active muscle forces** [20,21].



Ligaments
➔ Passive stabilizer



Muscles
➔ Active stabilizer

[20] KERNOZEK, Thomas W.; RAGAN, Robert J. Estimation of anterior cruciate ligament tension from inverse dynamics data and electromyography in females during drop landing. Clinical biomechanics, 2008, 23.10: 1279-1286
[21] DELP, Scott Lee. Surgery simulation: a computer graphics system to analyze and design musculoskeletal reconstructions of the lower limb. Stanford University, 1990.

Discussion & Conclusion

Conclusion

- Increasing MCL tension may enhance stability, it also raises the **risk of excessive joint loading** and **accelerated prosthetic wear**.
- Based on these findings, **maintaining MCL stiffness within 20% of the normal range** is advisable to ensure joint stability while avoiding undue mechanical stress on the implant.

Limitation

- The study was conducted using a specific implant type, which may **limit the generalizability of the findings to other TKA designs**.
- Dynamic motion conditions, such as high-speed activities or pivoting movements, were not considered in this study, which may have revealed **different interactions between ligament stiffness and muscle activity**.
- The study did not account for variations in **patient-specific factors**, such as differences in muscle strength or ligament laxity, which could influence the results.

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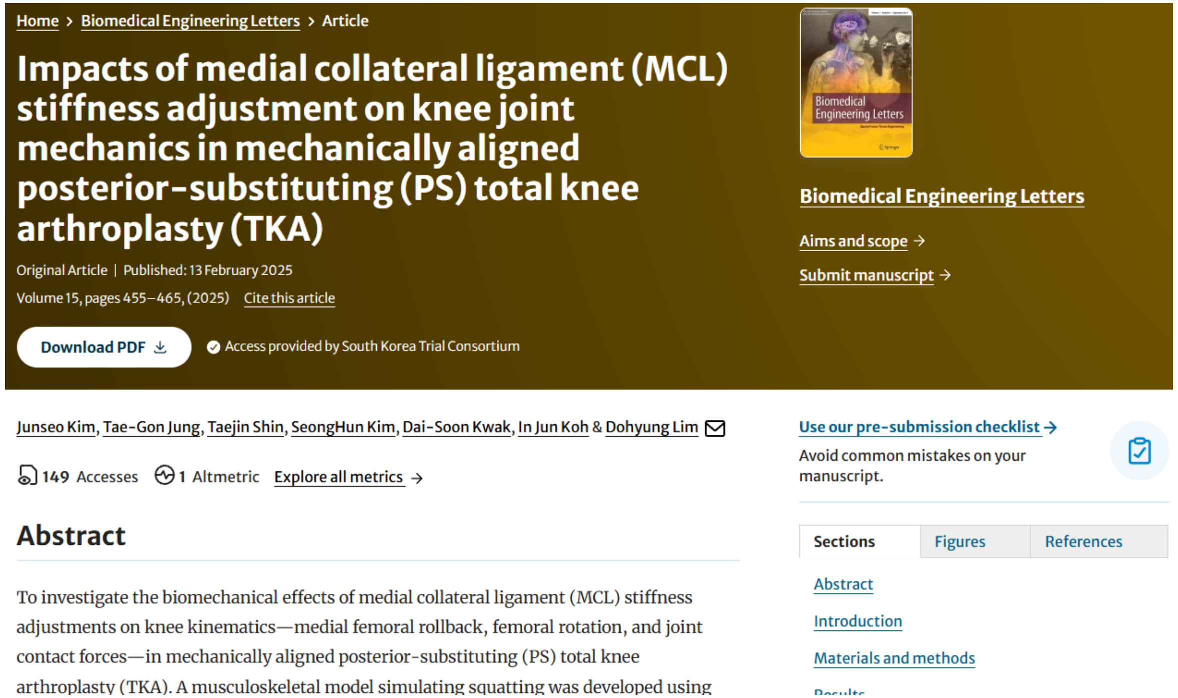
Thank You



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Impacts of medial collateral ligament (MCL) stiffness adjustment on knee joint mechanics in mechanically aligned posterior-substituting (PS) total knee arthroplasty (TKA)

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Abstract

Introduction

Materials and methods

Abstract

To investigate the biomechanical effects of medial collateral ligament (MCL) stiffness adjustments on knee kinematics—medial femoral rollback, femoral rotation, and joint contact forces—in mechanically aligned posterior-substituting (PS) total knee arthroplasty (TKA). A musculoskeletal model simulating squatting was developed using

Kim, J., Jung, TG., Shin, T. *et al*. Impacts of medial collateral ligament (MCL) stiffness adjustment on knee joint mechanics in mechanically aligned posterior-substituting (PS) total knee arthroplasty (TKA). *Biomed. Eng. Lett.* 15, 455–465 (2025). https://doi.org/10.1007/s13534-025-00463-x

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