

Impact of Sagittal Slope Reducing High Tibial Osteotomy and Lateral Extraarticular Tenodesis on Tibiofemoral Contact Mechanics and Meniscal Loading in Knees with Increased Posterior Tibial Slope: A Computational Study

Isabella Gomez Hjerthen¹, Reza Pourmodheji¹, Mark Amirtharaj¹, Thomas Wickiewicz¹, Andrew Pearle¹, Matthieu Olivier², Danyal Nawabi¹, Carl Imhauser¹

¹Hospital for Special Surgery, New York, NY

²Department of Orthopedics and Traumatology, Aix-Marseille University, Marseille, France

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INTRODUCTION: Increased posterior-inferior directed slope of the lateral tibial plateau, or tibial slope, is associated with elevated risk of post-operative anterior cruciate ligament (ACL) graft failure [1]. Slope-reducing high tibial osteotomy (SRO) [2] and lateral extraarticular tenodesis (LET) [3], are two adjunctive procedures to ACL reconstruction (ACLR) that are increasingly used to reduce the risk of ACL graft failure in patients with increased tibial slope [4]. Prior in vitro biomechanical studies indicate that these two procedures protect the graft through distinct mechanisms. SRO reduces graft force by decreasing anterior tibial translation (ATT) under compressive loading [5, 6] while LET decreases graft force by limiting internal tibial rotation [7, 8]. These different mechanisms suggest that the procedures might have different effects on both tibiofemoral articular contact mechanics and loading of the menisci. However, their impact on articular and meniscus contact mechanics remains poorly understood despite the implications for long-term cartilage and meniscus health. Therefore, we sought to quantify the biomechanical impact of SRO and LET on knees with increased tibial slope, both in isolation and in combination, on 1) contact point translations, 2) tibiofemoral cartilage contact forces, and 3) meniscus loads.

METHODS: Using a previously published workflow, computational models of ten cadaveric tibiofemoral joints were developed (five male, five female, age: 33±7 years) [6]. First, the 3D geometries of each subject’s bones, cartilage, and menisci were reconstructed from MRI and CT scans (Materialise Mimics, Inc.). Second, two virtual slope-changing procedures were performed on each of the ten 3D-reconstructed tibias: 1) an anterior opening-wedge osteotomy to achieve knees with tibial slope of 15°, generating a tibia with high slope; and 2) a closing-wedge SRO to achieve knees with tibial slope of 5°, which is a common clinical target in SRO procedures. Third, the geometries of the bones, cartilage, and menisci, and the coordinates of the origins and insertions of the cruciate, collateral, and capsular ligaments, as well as the peripheral and root attachments of the menisci, were imported into a multi-body dynamics software (Adams, Hexagon, Inc.). Fourth, ligament slack lengths and stiffnesses, as well as the contact parameters between femoral cartilage, tibial cartilage and menisci, were standardized [9]. Fifth, modified Lemaire LET was simulated by using three nonlinear spring elements inserted at Gerdy’s tubercle distally and proximal and posterior to the lateral collateral ligament insertion proximally [10], and tensioned at 60° of flexion [7]. Four conditions were modelled for each knee: 1) 15° tibial slope (“high slope”); 2) 5° tibial slope (“SRO”); 3) 15° tibial slope and LET (“LET”); and 4) 5° tibial slope and LET (“SRO+LET”). Lastly, with the femur rigidly fixed, each of the knees was flexed to 15°, and the tibia was left free to move in all directions except flexion. Two load conditions were applied to the tibia to differentiate biomechanical response of SRO and LET: 1) 100 N of axial compression; and 2) loads applied during a clinical pivot shift exam, consisting of 100 N axial compression, 8 Nm valgus torque, 4 Nm internal rotation moment and a 30 N anterior force. On the medial and lateral tibial compartments, net anterior-posterior and medial-lateral translations of the contact points between the femoral and tibial cartilages were calculated from unloaded passive flexion to the peak applied loads. At the peak applied loads, the magnitude of the intersegmental contact forces between the femoral and tibial cartilage and between the femoral cartilage and the menisci were calculated. Comparisons between the outcomes for each of the four knee conditions were performed using a nonparametric Friedman test with Least Significant Difference (LSD) post-hoc correction for multiple comparisons ($\alpha = 0.05$).

RESULTS: Under compressive loads, SRO and SRO+LET decreased posterior translation of the contact point and increased cartilage contact force on the medial tibial compartment, and decreased loading of the medial meniscus (Table 1). Under the simulated pivot shift loads, LET and SRO+LET decreased the posterior translation of the contact point and increased the cartilage contact force on the lateral compartment, and increased loading of the lateral meniscus. In contrast, cartilage contact force decreased in the medial compartment, as did medial meniscus load (Table 2).

DISCUSSION: The effect of SRO, LET, and combined SRO and LET on tibiofemoral contact mechanics depends on the applied loads. SRO mainly affects the contact mechanics of the medial compartment of the knee under compressive loads. Specifically, SRO limits the posterior translation of the contact point on the medial tibial cartilage, offloading the medial meniscus but increasing the cartilage loading. Our results suggest an improvement in the congruency between the surfaces of the femoral and tibial cartilage, resulting in a more perpendicular contact force, reduced anterior translation of the medial tibial compartment, and less reliance on the medial meniscus for stabilization. These findings corroborate previous studies reporting decreased anterior tibial translation, and therefore reduced ACL loading, with decreasing tibial slope [5, 6]. In contrast, LET affected contact mechanics only under the loads simulating a clinical pivot shift exam, where lateral compartment contact forces and lateral meniscus load both increased. These results suggest a constraint in the mobility of the lateral compartment of the tibia, and likely stem from the ability of the LET to act as a checkrein in resisting the applied internal rotation moment [7, 8]. Combined SRO and LET magnified the kinematic correction of SRO under compression, while dampening both the force increases and kinematic correction of LET under pivoting loads.

SIGNIFICANCE/CLINICAL RELEVANCE: Both SRO and LET can increase articular contact forces. The impact of this finding on long-term cartilage health requires further investigation to inform clinical utilization guidelines for these adjunctive procedures, considering their short-term benefit of offloading the ACL and any potential long-term risks to cartilage health.

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Table 1: Effect of SRO, LET and combined SRO and LET on tibiofemoral contact mechanics under 100 N of axial compression

Procedure	Medial Compartment			Lateral Compartment
	Contact point posterior translation	Cartilage contact force	Meniscus contact force	Meniscus contact force
SRO	-57% (p < 0.01)	+28% (p < 0.05)	-50% (p < 0.001)	-52% (p < 0.01)
LET	---	---	---	---
SRO+LET	-93% (p < 0.01)	+19% (p < 0.05)	-48% (p < 0.01)	-11% (p < 0.01)

Table 2: Effect of SRO, LET and combined SRO and LET on tibiofemoral contact mechanics under full pivoting loads (100 N axial compression, 8 Nm valgus torque, 4 Nm internal rotation moment, 30 N anterior force).

Procedure	Medial Compartment		Lateral Compartment			
	Cartilage contact force	Meniscus contact force	Contact point lateral translation	Contact point posterior translation	Cartilage contact force	Meniscus contact force
SRO	---	-61% (p < 0.01)	---	---	---	---
LET	-58% (p < 0.01)	-50% (p < 0.05)	+105% (p < 0.01)	-27% (p < 0.05)	+14% (p < 0.05)	+20% (p < 0.05)
SRO+LET	-58% (p < 0.001)	-96% (p < 0.001)	+34% (p < 0.05)	-14% (p < 0.05)	+33% (p < 0.01)	---