Steeper Tibial Posterior Slope is a Risk Factor in ACL Injury - Gait Simulation by a Lower Extremity Model

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Disclosures: **H. Marouane:** None. **A. Shirazi-Adl:** None. **M. Adouni:** None. **J. Hashemi:** None.

Introduction: The anterior cruciate ligament (ACL) rupture is a common human knee joint injury with higher prevalence in female athletes compared to their male counterparts [1]. An improved understanding of the joint functional biomechanics is required to delineate the existing sex-based disparity in ACL injuries and to develop effective strategies for the prevention and treatment of associated disorders regardless of sex. The posterior tibial slope (PTS) has been identified as a parameter affecting the tibial anterior translation and ACL rupture under large compression forces [2, 3]. Comparison of medical images of patients with non-contact ACL ruptures versus control subjects has indicated PTS as a risk factor [4, 5]. Larger PTS in females than males has been argued as a factor in higher prevalence of ACL rupture in the former group [5, 6]. In vitro cadaver investigations simulating steeper PTS via anterior osteotomy have however either been inconclusive [7] or even refuted such association [8, 9]. Anterior wedge opening osteotomies nevertheless alter the entire joint articular configuration and ACL orientation/length when pivoting the tibial epiphysis about a posterior location to produce 5-10 mm anterior opening. In addition, very small compression forces were considered in these in vitro studies. Computational modeling has the advantage to circumvent such shortcomings and in altering PTS without undue changes in remaining joint structures. In the current study we use a lower extremity musculoskeletal model including a detailed finite element (FE) model of the knee joint [10] to compute the effect of changes in medial and/or lateral PTSs by ±5 deg on the knee joint biomechanics in general and ACL force in particular throughout the stance phase of gait.

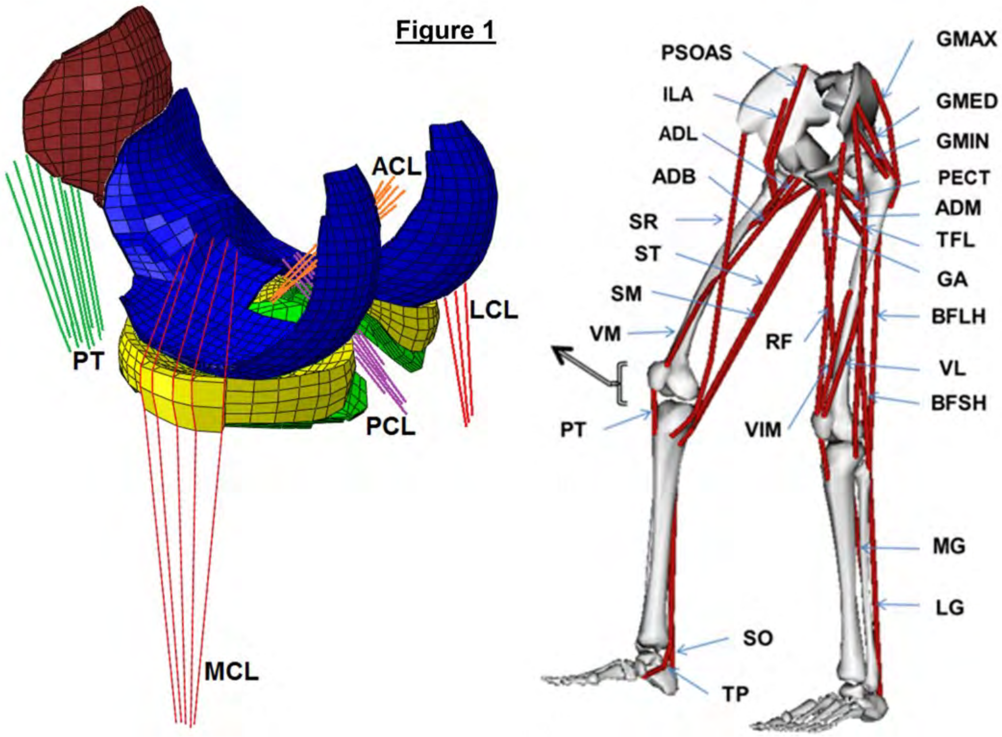
Methods: A validated FE model of the entire knee joint (Fig. 1) that consists of bony structures (tibia, femur and patella) and their compliant cartilage layers as well as menisci, major tibiofemoral (TF) (ACL, PCL, LCL, MCL) and patellofemoral (MPFL, LPFL) ligaments, patellar tendon (PT) and detailed musculature is employed [10]. The articular cartilage layers and menisci are simulated as non-homogeneous nonlinear depth dependent composites of collagen fibrils and incompressible matrices. Cartilage layers are reinforced by fibril networks parallel to the articular surface in the superficial zone, randomly oriented in the middle zone and vertical in the deep zone. Ligaments are simulated by a number of nonlinear axial elements with initial pre-strains. This detailed knee model is introduced in a musculoskeletal model of the lower extremity including hip and ankle joints as well as uni- and bi-articular muscles to simulate the stance phase of gait under in vivo kinematics/kinetics reported for normal subjects [11]. Muscle forces are evaluated iteratively and applied as additional external forces along with the ground reaction forces and in vivo joint rotations/moments [11] to investigate the knee joint biomechanics at stance phase of gait. In each period of gait (0, 5, 25, 50, 75 and 100%) and in order to evaluate the effect of changes in PTS, the initial medial and/or lateral PTSs are altered by ±5 deg by rigidly rotating tibial plateaus around local lateral-medial axes with minimal changes in tibial proximal surface geometry while leaving the ligaments and muscles footprints unchanged. These changes alter hence only the PTS with no effect on articular soft tissues and ligaments.

Results: Changes in PTS on medial and/or lateral plateaus had relatively small effects on estimated muscle forces; <50 N compared to the reference case, and hence on TF and PF contact forces and contact centers. On the other hand, steeper PTS markedly increased tibial anterior translation at all periods of gait while reverse trends were found with flatter PTS (Fig. 2, L and M indicate that PTS was altered only at one plateau). As a result and throughout stance, ACL force (mainly resisted by the posterolateral bundle) significantly increased with steeper PTS but decreased with reduced PTS (Fig. 3). The effect was much more pronounced at the mid-stance (50% period) with the changes verified to be primarily due to the alterations at the medial PTS than at the lateral PTS (Fig. 3). At this mid-stance, the contact centers on individual medial and lateral plateaus shifted slightly anteriorly as PTS altered. The contact center of the entire TF joint was located at the mid-medial plateau and moved slightly antero-laterally as PTS varied.

Discussion: The aim of this study was set to determine how changes in PTS at one or both plateaus, despite identical joint rotations/moments and ground reaction forces reported in gait of normal subjects, affect joint response and ACL forces during the stance phase. Computed results confirm that alterations in PTS affect joint biomechanics; the steeper PTS substantially increases the anterior tibial translation and ACL force while reverse trends are found with flatter PTS. Alterations in PTS separately in each plateau at a time demonstrated that the joint response was influenced primarily by changes in the plateau supporting a larger compression force; in the lateral plateau at 5% and in the medial plateau at 50% (Figs 2 and 3). During early stance at 0% and 5% periods, the lateral plateau supported larger contact forces whereas thereafter at 25-100% periods, it was the medial plateau that carried the major portion of contact forces. The increases in the anterior tibial translation and ACL force in steeper PTS in gait under large compression forces corroborate earlier in vitro [2, 3] and clinical imaging [4-6] studies. Contradictory findings of some previous in vitro investigations [7-9] are questionable due to very small compression forces employed, recording of strain in the anteromedial bundle rather than the posterolateral one and the perturbations in the joint articulation and ligament footprints caused during anterior wedge opening osteotomy.

Significance: Results of the present study suggest that at all periods of gait stance, from heel strike to toe off, an increase in the tibial PTS slope, either at both plateaus together or at the one carrying larger contact force (i.e., lateral at 0% and 5% periods whereas medial at 25-100% periods), significantly increases the tibial anterior translation and ACL force (resisted mainly by its posterolateral bundle). Steeper PTS is hence a major risk factor, especially in female subjects and under activities with large compression forces, in markedly increasing ACL force and its vulnerability to injury.

Figure 1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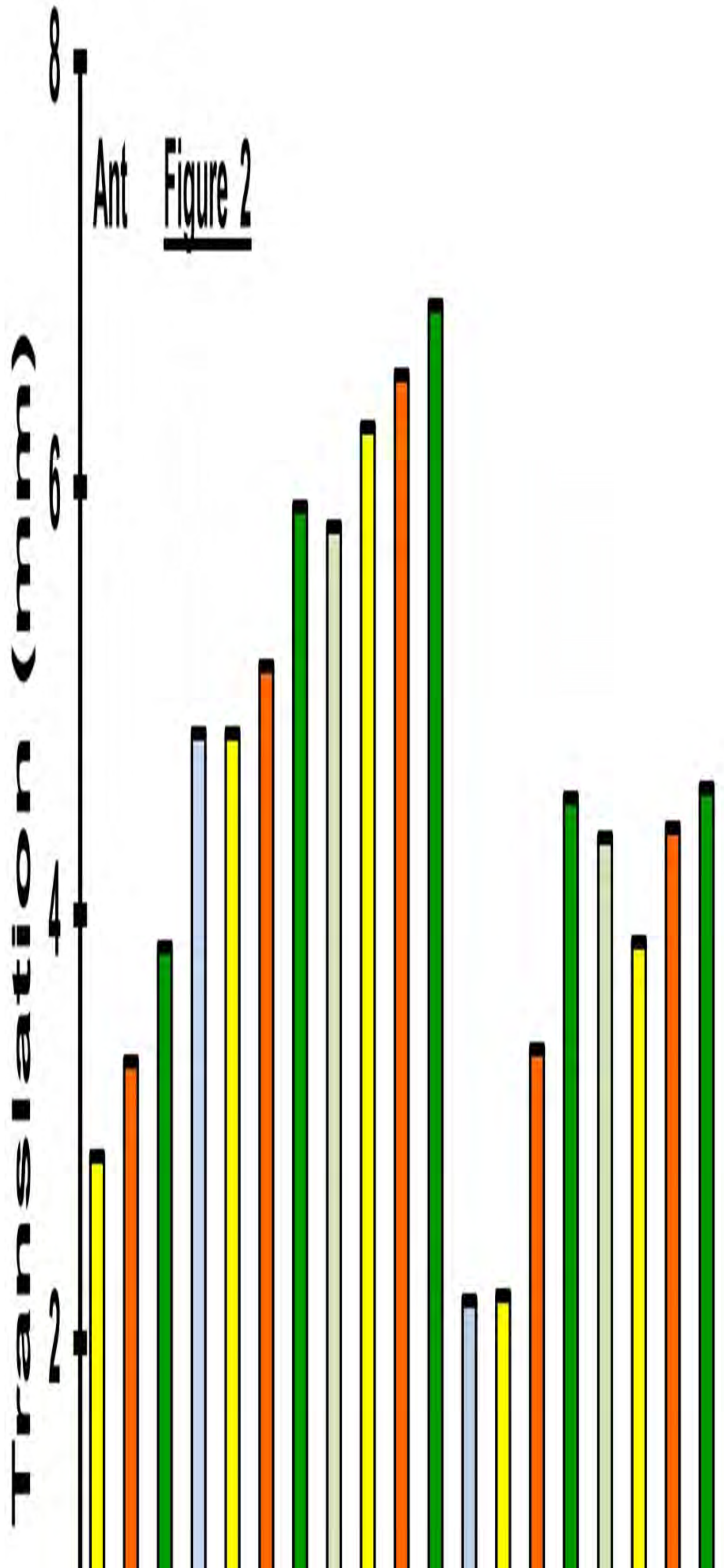
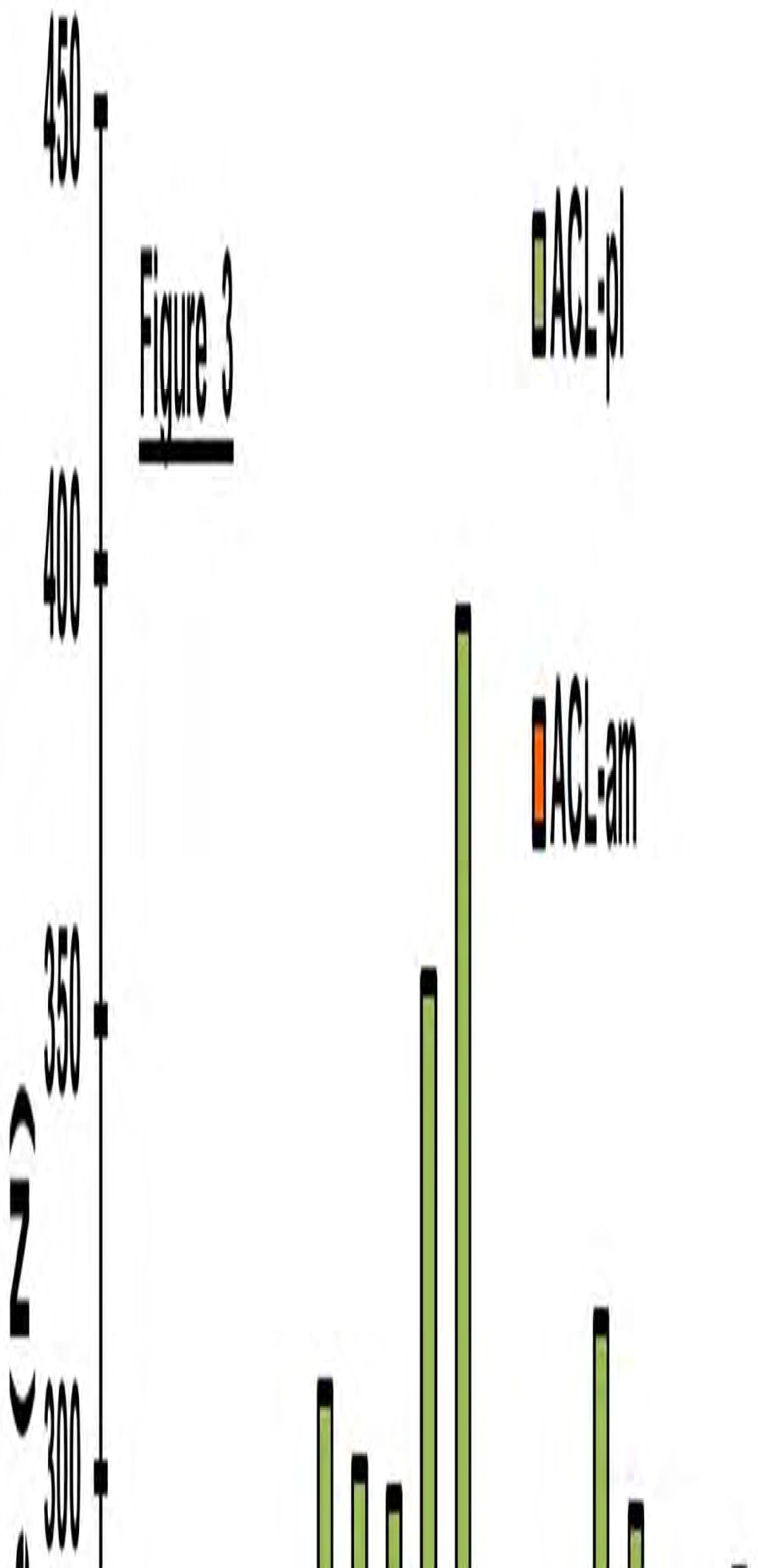


Figure 2

Figure 3



ORS 2015 Annual Meeting

Poster No: 1681