The Impact of Tibial Slope on Knee Stiffness in an Advanced Knee Simulator Model

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INTRODUCTION: Total knee arthroplasty (TKA) is a widely performed surgical procedure aimed at relieving pain and restoring function in individuals who have severe knee joint damage and osteoarthritis. Among the critical factors influencing TKA success are the posterior tibial slope (PTS) and the tibial insert thickness[1]. Appropriate PTS and insert selection facilitate balanced flexion and extension gaps, facilitating the appropriate tensioning of the posterior cruciate ligament (PCL) and other soft tissues. Variations in these factors can affect knee kinematics, influencing factors such as ligament tension and knee stability[2]. Simulated tibial slope conditions were assessed in a knee simulator model with varying insert thicknesses to understand the effects of tibial slope on knee laxity using the pendulum knee drop (PKD) test with inertia measurement units (IMU).

METHODS: An advanced knee simulator model (AKS) was designed using a 3-dimensional (3D) computed tomographic scan of a patient undergoing a left TKA with varus deformity and moderate osteophytes, and 3D printed[3]. The proximal femur and distal tibia were designed as modular end caps representative of the native femur and tibia, enabling replacement after each robotic-assisted total knee arthroplasty (RATKA). The native anatomy exhibited 11.6 degrees of medial posterior slope and 9.3 degrees of lateral posterior slope. There were two surgeons who independently planned and executed their own surgical plans, where component size and tibial slope were standardized based on size 4 components and 3° PTS. Modular tibial end caps were created to simulate a +5° change for each surgical plan, resulting in 8° PTS. For the two distinct surgical plans, the PKD test was performed for the default slope and the +5° PTS with six different insert thicknesses ranging from nine mm to 14 mm by one mm increments. A two-sensor IMU system was used to measure knee range-of-motion (ROM) where the leg was allowed to swing passively from full extension until rest. There were three trials conducted for each variation, where the logarithmic decrement ratio was estimated to quantify knee laxity between slope conditions, and knee excursion frequency was recorded. The data was normally distributed, and an analyses of variance (ANOVA) tests with Tukey *post hoc* tests were used to assess significance between tibial slope conditions and insert thicknesses.

RESULTS: The increased PTS condition resulted in greater laxity with every insert for S2 and inserts greater than 10 mm for S1, as demonstrated by lower logarithmic decrement (LD) values and increased oscillations. The LD values ranged from 0.176 to 1.244 as seen in Figure 1. For both surgeons, the LDs for the default and increased PTS plans demonstrated exponential growth in relation to greater insert thicknesses, with the +5° PTS plans resulting in an exponential decrease in laxities (Figure 1). The average oscillations ranged from 4.00 to 8.67 across insert thicknesses, with the greatest excursions observed for nine mm inserts in both slope conditions for S1. The fewest oscillations corresponded with the S1 default plan and a 14 mm insert. A positive correlation was observed between insert thickness and the percent difference in LD scores between slope configurations for each surgeon. The correlation indicates that PTS increasingly impacts laxity based on inter-observations. On average, both surgeons demonstrated greater laxity with the increased PTS, where the S1 plan was stiffer than the S2 plan for both slope conditions.

DISCUSSION: In this study, we evaluated the impact of varying tibial slopes on knee joint laxity using the PKD test, with the LD and excursion frequency as the quantifying metrics among two surgical plans. Our findings indicate that increased posterior slope results in lower LD values, indicating greater laxity. The effects of the PTS on the laxity values become increasingly apparent with increasing insert thickness. Increased PTS demonstrated greater observable laxity, where a 12 mm insert in the increased PTS case would be needed to restore comparable laxities to the default surgical plan. This substantial difference between slope conditions emphasizes the impact of tibial slope on knee laxity and the ability to impact soft-tissue balance. This study highlights the effectiveness of the PKD test in detecting laxity changes associated with varying tibial slopes across surgical plans. The ability of the PKD to detect subtle biomechanical changes further underscores its potential as an objective tool for assessing joint mechanics in TKA and highlights the importance of precise surgical planning in total knee arthroplasty.

SIGNIFICANCE/CLINICAL RELEVANCE: This study highlights the effectiveness of the PKD test in detecting laxity changes associated with varying tibial slope and inserts across surgical plans. The ability of the PKD to detect subtle biomechanical changes further underscores its potential as an objective tool for assessing joint mechanics in TKA.

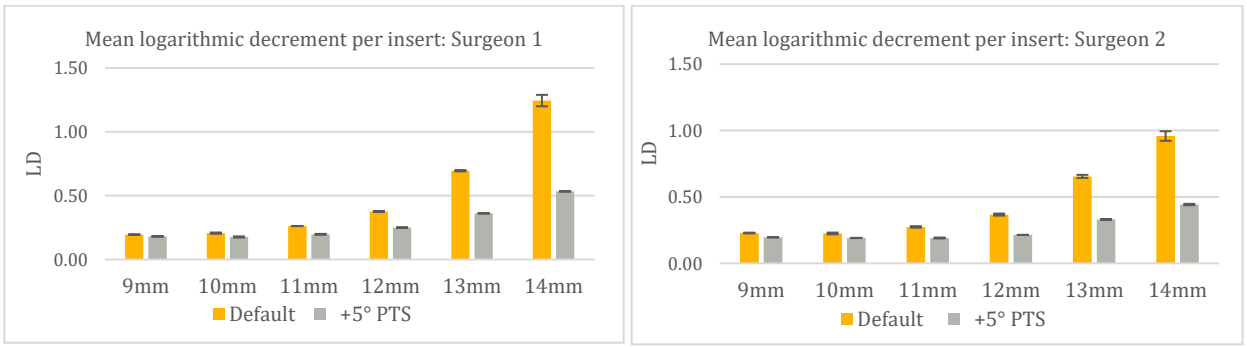

Figure 1: Log decrement values for default and increased PTS conditions by insert thickness for Surgeon 1 (a) and Surgeon 2 (b).