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FLEXION ANGLE DEPENDENT DIFFERENCES IN JOINT KINEMATICS AND ACL FORCE IN RESPONSE TO APPLIED LOADS ARE CONSERVED THROUGHOUT SKELETAL GROWTH IN THE PORCINE STIFLE JOINT

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INTRODUCTION

The incidence of anterior cruciate ligament (ACL) injuries has been increasing significantly in skeletally immature populations over the past decade [1]. ACL injuries are most commonly treated through surgical reconstruction procedures which are designed to restore function and stability to the knee joint under both translational and rotational loading conditions. Interestingly, in the mature knee joint, less translation (~3-5 mm) and axial plane rotation (~5-7°) occurs under applied tibial loads when the joint is extended compared to when the joint is flexed [2,3]. Joint flexion has implications in surgery. For example, the flexion angle of the knee can influence the force carried in the native ACL [3]. Likewise, flexion angle at the time of ACL graft fixation can have a substantial effect on the force carried by the reconstruction graft [3]. Additionally, joint laxity, which varies by knee flexion, can be used as an intraoperative measure of ACL graft function [2]. These flexion-dependent behaviors of different tissues under anterior tibial translation at full extension versus flexed positions depend on tissue engagement. Previous work in our lab has shown that the resulting kinematics from applied tibial loads is age-dependent with greater normalized translation in younger joints [4,5]. It is important to determine if the impact of flexion angle on joint laxity and ACL function is conserved throughout skeletal growth, potentially helping to inform optimal joint flexion during ACL reconstruction of pediatric patients. Here, we hypothesized that joint laxity under applied anterior-posterior and varus-valgus loads would be decreased and the percentage of applied anterior tibial force carried by the ACL would be decreased at full extension (40° in the pig) versus 60° of flexion across juvenile and adolescent stages in the porcine knee model.

METHODS

Hind limbs were collected from female Yorkshire cross-breed pigs representing four age groups ranging from juvenile to late adolescent stages (3-18 months, n=22 total). All soft tissue was dissected away from the femur and tibia in order to expose the surface of the bones, and a fiberglass epoxy was fixed to the bones inside of molds that were designed to fit custom-built clamps. Joints were mechanically tested using a 6 degree-of-freedom universal force sensing robotic system (KUKA/SimVitro) which is capable of operating under both kinematic and kinetic control.

The following biomechanical tests were performed using the robotic system. A passive path was established for each limb by moving the tibia from full extension (40° in the pig) to 90° of flexion and finding the kinematic positions with minimized loads in the remaining 5 degrees of freedom. The kinematics for passive path positions at 40° and 60° of flexion were recorded. Scaled anterior-posterior tibial loads and varus-valgus moments were applied to the joints at both 40° and 60° of flexion while loads in the remaining degrees of freedom were minimized. The kinematic paths were recorded and repeated in intact, AM bundle deficient, and ACL deficient (AM and PL) bundle deficient) states and the resulting loads were recorded. The kinematic paths were exported for further processing. Parameters of interest included anterior-posterior tibial translation (APTT) and varus-valgus rotation (VVR) under applied loads. The principle of superposition was applied to determine the *in situ* forces carried by the ACL and its bundles at maximum anterior translation and varus and valgus rotation [5]. Normality of data sets was confirmed. Statistical analysis consisted of repeated measures ANOVA testing with Tukey's post hoc analysis where age and flexion angle were the main effects, and flexion angle as a repeated measure ($p<0.05$).

RESULTS

Under the application of anterior-posterior tibial loads, APTT of the joint varied significantly as an effect of flexion angle ($p<0.05$) with no significant effect due to age ($p>0.05$) or the interaction of age and angle ($p>0.05$). Specifically, increasing knee flexion resulted in mean APTT increases from extension (40° of flexion) to 60° of flexion of 1.6 mm at 4.5 months (19%), 1.4 mm at 6 months (21%), and 1.3 mm at 18 months (18%) (Fig. 1). These increases were statistically significant in all but the 3 month age group.

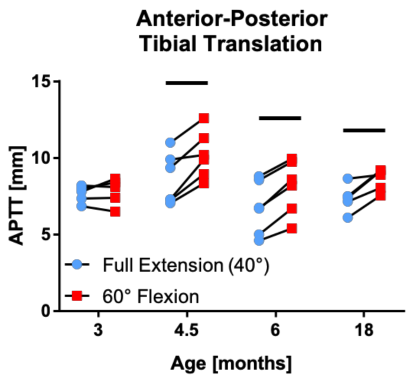

Figure 1: Anterior-posterior tibial translation (APTT) is greater at 60° of flexion relative to full extension during growth. Connected points show data from individual specimens, bar shows p<0.05 between angles.

Joint rotation under applied varus-valgus moments were also measured. We found a significant effect due to age, flexion angle, and the interaction term ($p<0.05$). Unlike APTT, we found that increasing flexion angle resulted in greater VVR in the 3, 4.5, and 6 month age groups ($p<0.05$), but not in the 18 month age group ($p>0.05$). The increase in flexion angle resulted in mean increases of 1.8° (3 months), 2.8° (4.5 months), and 2.2° (6 months) in the separate age groups. These effects due to flexion angle were coupled with an overall decrease with age of ~11° from 16.9° (full extension) and 18.7° (60° of flexion) in the 3 month group to 6.2° (full extension) and 7.4° (60° of flexion) at 18 months. Significant decreases occurred between 3 months and all older groups, and from 4.5 months to the remaining older groups ($p<0.05$) (Fig. 2).

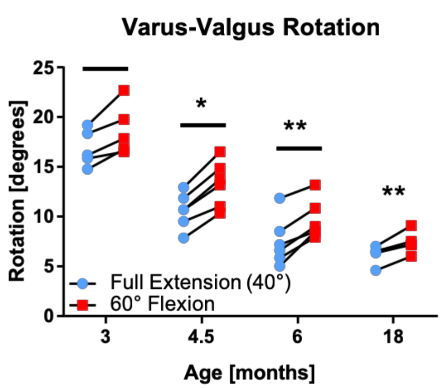

Figure 2: Varus-valgus rotation (VVR) decreased with increasing age in growth, and increased with joint flexion. Connected points show individual specimens, bar indicates p<0.05 between angles, *p<0.05 vs. 3 months, **p<0.05 vs. 3 and 4.5 months.

In addition to changes in joint kinematics, knee flexion had a significant effect on the forces carried in the soft tissues ($p<0.05$) while there was no significant effect due to age or the interaction term ($p>0.05$). Specifically, the ACL carried an average of 72% of the total applied anterior force in the joint at full extension which was significantly less than the mean 87% carried at 60° of flexion ($p<0.05$, Fig. 3). Furthermore, flexion angle had a significant effect ($p<0.05$) on the relative contributions of the AM and PL bundles of the ACL to resisting anterior force. The AM bundle of the ACL carried significantly more force at 60° of flexion compared to 40° of flexion ($p<0.05$, data not shown).

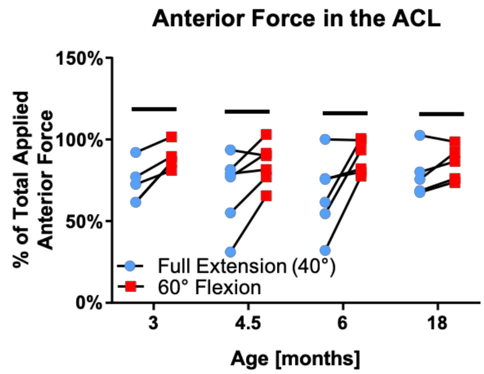

Figure 3: The ACL carried significantly less of the applied anterior tibial load (p<0.05) at full extension compared to 60° of flexion. Connected points show data from individual specimens, bar shows p<0.05 between angles.

DISCUSSION

In this study, we report significant increases in both translational and rotational joint laxity as a result of increasing knee flexion in skeletally immature pigs. Interestingly, these results were statistically significant in early through late adolescent groups for APTT while they were statistically significant in juvenile through mid-adolescent groups for VVR. Both translational and rotational laxity decreased as an effect of increasing age. Additionally, we found that the ACL carried a greater portion of applied anterior forces in flexed positions across juvenile and early adolescent porcine groups. These results are similar to previous studies focusing on the kinematic [2,3] and kinetic [6] properties of mature joints, while expanding our knowledge of the biomechanics of skeletally immature knees. While this study focused on a female model, future work will focus on expanding the data set to include male specimens and a greater range of ages. Additionally, the information gathered here may be used to motivate a non-invasive human study in pediatric and adolescent populations to investigate knee laxity at different flexion angles. Given that flexion angle is an important consideration for ACL graft function in adults, these findings may be important in developing age-specific clinical practices for a rapidly growing population of young patients with ACL injuries.

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