Changes in Tibial Plateau Geometry with Skeletal Maturation in a Porcine Model

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INTRODUCTION: The articulation of the femoral condyles and tibial plateaus is a key contributor to knee kinematics, affecting joint stability, range of motion, load distribution, and biomechanics.[1] Bony morphologic parameters like notch width have been associated with increased risk of anterior cruciate ligament (ACL) injury[1,2] and have been investigated throughout maturation using porcine models given the anatomical similarities to the human ACL.[3,4,5] Additional important features such as posterior tibial slope and tibial plateau curvature directly influence the articulation with the femoral condyles which is a crucial mechanism to ensure normal knee function.[6] Inconsistent evidence exists regarding changes in posterior tibial slope with age in humans, where slope has been found to remain constant or decrease with age.[7,8] Therefore, the objectives were to quantify posterior tibial slope, coronal plane curvature, and sagittal plane curvature of the medial and lateral tibial plateaus in Yorkshire crossbreed pigs and determine their associations with age. It was hypothesized that porcine posterior tibial slope would not change with age, medial plateaus would be concave, and lateral plateaus would be convex, similar to human anatomy.

METHODS: MRI datasets obtained for 6 stifle (knee) joints were analyzed from male Yorkshire pigs at 1.5, 4.5, and 18 months of age (n = 2 per group) representing three levels of skeletal maturity: 1) early youth, 2) pre-adolescent, and 3) skeletally mature, respectively. 3D geometric models of the tibia were created by segmenting bone from the MRI images obtained from a 3T Siemens MAGNETOM Skyra MRI system using MIMICS (v23). Outcome parameters quantified using the 3D geometries included posterior tibial slope, coronal plane curvature, and sagittal plane curvature of the medial and lateral tibial plateaus. Posterior tibial slope of the medial and lateral plateaus was measured on the porcine models similarly to clinical practice in human subjects.[2] Slopes were quantified at the sagittal plane midpoint of each plateau relative to a plane perpendicular the proximal tibial shaft axis. Plateau curvature was quantified at the sagittal and coronal plane midpoints, where a second order polynomial was fit to the subchondral bone of the respective plateau. The second derivative of the second order polynomial was utilized to determine if the plateau in each plane was convex or concave (negative=convex, positive=concave) and the magnitude of curvature. One observer reconstructed all geometric models, and all geometries were quantified using a custom written MATLAB code (v2023b). Spearman's correlations were utilized to determine the associations between age, posterior slope, and plateau curvature. Significance was set at $p<0.05$.

RESULTS: Medial and lateral porcine posterior tibial slopes ranged from 23.4-53.1° and 27.6-49.5°, respectively (Figure 1). Slope of the medial plateau was associated with age, where the slope decreased with increasing age ($p<0.05$, $r^2=0.91$). Sagittal plane curvature for the medial (-0.03 ± 0.02 mm^{-1}) and lateral (-0.04 ± 0.02 mm^{-1}) plateaus were negative, indicating convexity of the articular surface in that plane, which was consistent across ages (Table 1). While remaining convex, the curvature of the medial plateau in the sagittal plane decreased with age ($p<0.05$, $r^2=0.82$). The magnitude of coronal plane curvature of the medial (-0.01 ± 0.04 mm^{-1}) and lateral (-0.01 ± 0.02 mm^{-1}) plateaus approached zero, reflecting a nearly flat surface. The coronal plane curvature of both plateaus was observed to change with age; plateaus of 1.5-month specimens were convex while 4.5-month and 18-month-old specimens were concave. Age accounted for 83% and 72% of the variation in the medial and lateral plateau coronal plane curvature, respectively, throughout development.

DISCUSSION: The main findings of the study were that the porcine posterior slope of the medial plateau decreases with age and the coronal plane direction of curvature changes with age – refuting our hypothesis. The slope of the medial and lateral porcine plateaus was also found to be greater than that in humans.[9] The increased porcine slope compared to humans may help explain why stifle joints do not allow for full extension. In a porcine model, increased joint stiffness and decreased anterior tibial translation were associated with increased age.[10] These findings could result from a decrease in porcine posterior tibial slope as the tibia will be less anteriorly positioned with respect to the femur and allow more surface area for articulation. Throughout development, the porcine tibial plateaus were also observed to change from convex to concave in the coronal plane and remained minimally convex in the sagittal plane. Decreased porcine posterior tibial slopes and changes in plateau curvature from convex towards more concave may be a mechanism to improve joint stability through increased congruency and result in reduced anterior translation of the tibia. The association between medial plateau posterior tibial slope was adequately powered (power = 0.87) and the association between medial plateau sagittal plane curvature and age was inadequately powered (power = 0.69). Thus, future studies will include more specimens to increase the power of the study and investigate relationships between bony morphological parameters of the femoral condyles and age. As posterior slope was demonstrated to decrease with age in humans[8], a porcine model could be used to study how changes in bony morphology affect knee function and injury risk with age.

SIGNIFICANCE/CLINICAL RELEVANCE: Decreased posterior tibial slope and changes in the plateau curvature towards more concave morphologies may explain decreased anterior translations and increased joint stiffness previously observed with age in a porcine model.

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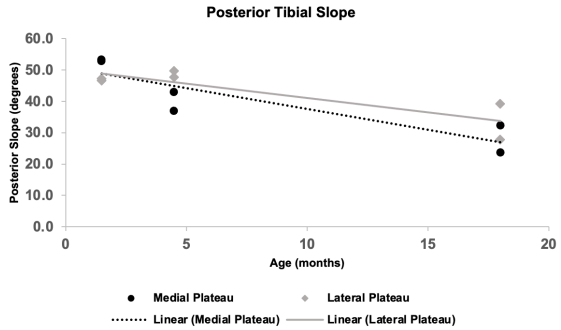

Figure 1. The association between posterior tibial slope in Yorkshire pigs throughout development.

Table 1. Age and bony morphological parameters quantified using 3D reconstructed geometries from MRI images of porcine stifle joints. Negative (convex) and positive (concave). Units of curvature: mm^{-1}.

	Sagittal Plane Curvature		Coronal Plane Curvature	
Age (months)	Medial	Lateral	Medial	Lateral
1.5	-0.05	-0.06	-0.07	-0.04
1.5	-0.05	-0.06	-0.04	-0.03
4.5	-0.02	-0.02	0.01	0.01
4.5	-0.02	-0.02	0.00	0.01
18	-0.01	-0.02	0.01	0.01
18	-0.02	-0.03	0.02	0.01