PHYSIOLOGICAL MECHANICAL PROPERTIES OF HEALTHY CARTILAGE ACROSS THE DISTAL FEMUR

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INTRODUCTION

Knee osteoarthritis (OA) debilitates 10% of the world's population [1]. Since knee articular cartilage (AC) lesions associated with OA manifest in common regional patterns [2, 3], accurate characterization of AC mechanical properties across the joint surface could reveal important insight into the disease process. A previous study by our group determined that tibial plateau AC exhibits significant regional heterogeneity [4]. The extent of AC mechanical heterogeneity across the distal femur, the other major articulating surface of the knee joint, is not well known. Data gathered at physiologically-relevant strain rates is particularly sparse. Thus the purposes of this study were: 1) to measure the compressive elastic modulus of AC from across the distal femur using a physiologically-relevant strain rate, and 2) to determine whether any mechanical variability of the AC assumes a common regional pattern.

METHODS

Full-thickness cylindrical AC samples (4-mm diam.) were taken from eight non-osteoarthritic fresh-frozen female Caucasian cadaveric knees (age: 41-54, BMI < 26). India ink was used to identify areas of AC fibrillation [4]. No samples were taken from fibrillated areas. Samples were extracted from 29 consistent sites on the trochlea (9) and femoral condyles (20) of each knee (Figure 1).

Mechanical testing and data analysis were performed using previously published techniques [4]. Briefly, a custom-built high-speed compression device was used to perform unconfined compression at 100% strain/sec on each specimen. This strain rate was selected because it is consistent with the *in vivo* strain rate of cartilage during walking [5]. A black ink speckle pattern was applied along the length of each specimen prior to testing to allow for optical tracking of local tissue deformation. Three experimental trials were conducted in which the specimen was compressed from 0% strain to 20% strain and immediately released back to 0% strain. Simultaneous force and video data were recorded at 125 Hz. Five minutes was allowed between each trial for the specimen to re-equilibrate with the solution.

The average axial nominal strain was computed from the local tissue deformations using commercial digital image correlation software (VIC-2D 2009, Correlated Solution, SC). Nominal stress-strain curves were computed for each trial. The tangent modulus at 10% strain ($E_{10\%}$) was extracted from each curve and averaged across trials.

For statistical analysis, the trochlea and condyles were divided into regions according to mediolateral location and joint contact frequency. Contact frequency was defined as weightbearing (WB), or the region that articulated with the opposing surface during 0° - 30° knee flexion, and less weightbearing (LWB), or the region that articulated beyond 30° knee flexion [6] (Figure 1). This regional division was selected because walking mechanics may factor predominantly in OA development [7] and knee flexion during walking rarely exceeds 30°.

Mean $E_{10\%}$ was computed for each region and the values were submitted to repeated-measures ANOVA to test for the main effects of mediolateral location, contact frequency, and their interaction. Separate tests were conducted for the trochlea and condyles. Bonferroni-corrected pairwise comparisons were undertaken in the case of statistically significant main effects. Significance was set at 0.05 for all tests.

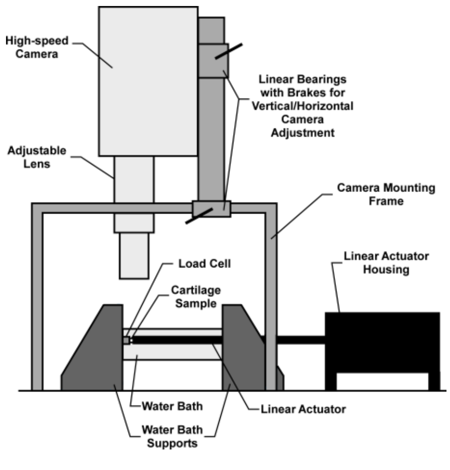

Figure 1: Schematic of mechanical testing device used to perform unconfined compression on cylindrical AC explants at 100% strain/sec [4].

RESULTS AND DISCUSSION

Large variability in $E_{10\%}$ was evident across the distal femur (Figure 1). The stiffest test sites were found to have moduli nearly 400% larger than the most compliant sites.

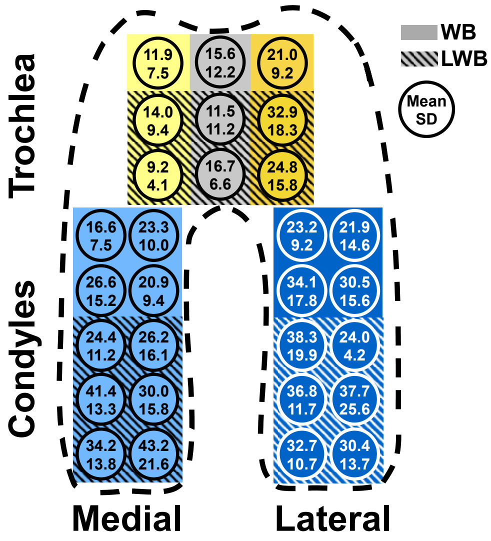

Figure 1: Mean and standard deviation (SD) $E_{10\%}$ (MPa) at 29 test sites on the distal femur. Circles denote test sites. Colors represent the mediolateral regional divisions and shading represents the weightbearing (WB) and less weightbearing (LWB) regions. $E_{10\%}$ varied substantially across the surface.

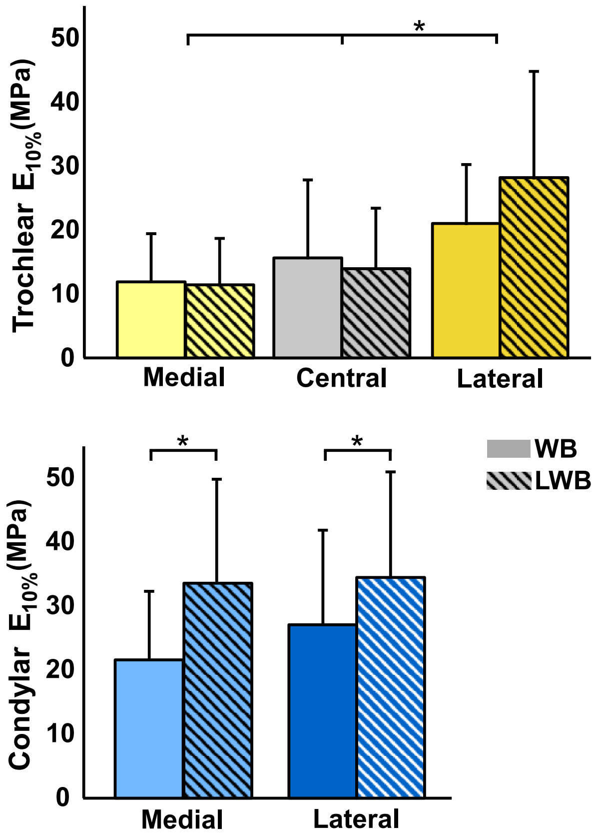

Figure 2: Mean $E_{10\%}$ (MPa) by region for the trochlea (upper) and condyles (lower). Bars represent 1 SD. Asterisk denotes $p < .05$. Colors represent the mediolateral regional divisions and shading represents the weightbearing (WB) and less weightbearing (LWB) regions. In the trochlea, the medial and central regions had significantly lower moduli compared to the lateral region. In the condyles, the weightbearing regions were significantly less stiff than the less weightbearing regions.

Across the trochlea, the lateral region had significantly higher $E_{10\%}$ (26.06 ± 14.90 MPa) compared to the medial (11.57 ± 7.18 MPa) and central (14.46 ± 10.13 MPa) regions ($p < .01$, .05, respectively, Figure 2). No significant difference was evident between the medial and central regions ($p = .93$). Mean $E_{10\%}$ for WB (15.46 ± 9.96 MPa) was approximately equal to mean $E_{10\%}$ for LWB (17.10 ± 13.18 MPa) $p = .63$. There was no significant interaction of side and contact frequency ($p = .37$).

The condyles displayed a pattern of regional dependence that was directly opposite to the trochlear pattern (Figure 2). Mean $E_{10\%}$ of the medial condyle (29.09 ± 15.46 MPa) was approximately equal to mean $E_{10\%}$ of the lateral condyle (31.18 ± 16.03 MPa), $p = .15$. However, mean $E_{10\%}$ was lower in WB (24.47 ± 13.14 MPa) compared to LWB (34.01 ± 16.24 MPa), $p < .01$. No significant interaction of side and contact frequency was detected ($p = .48$).

CONCLUSIONS

This study represents the first detailed topographical mapping of healthy human distal femoral AC mechanics elicited under a physiologically-relevant loading rate. We determined that healthy human femoral AC exhibits significant variability in its compressive elastic modulus and that variability followed common patterns across individuals. Specifically, the lateral aspect of the trochlea was nearly twice as stiff as the medial and central regions, and the LWB regions of the condyles were approximately 1.4 times stiffer than the WB regions. These data provide critical information for investigating the contribution of joint loading to knee OA development. On the trochlea, an abnormal shift in joint contact from the stiff lateral facet to the relatively soft center, as seen in OA patients [8], may explain why OA lesions originate centrally [2]. On the condyles, lesions commonly develop in the medial WB and the lateral LWB [2], which we determined to be the softest and stiffest regions of the condyles, respectively. The large disparity in $E_{10\%}$ between these two regions suggests that cartilage mechanics alone cannot predict condylar OA. This suggests separate mechanisms for each condyle or a kinematic abnormality, such as increased external tibial rotation, that could simultaneously alter loading on both regions. Future work should investigate these hypotheses and extend these analyses to other subject demographics.

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