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Indentation response of human patella with elastic modulus correlation to localized fractal dimension and bone mineral density

Jason R. Kerrigan[a,*], David Sanchez-Molina[b], Jan Neggers[c], Carlos Arregui-Dalmases[a,b], Juan Velazquez-Ameijide[b], Jeff R. Crandall[a]

[a]University of Virginia, Center for Applied Biomechanics, 4040 Lewis & Clark Drive, Charlottesville 22911, VA, USA
[b]Universitat Politècnica de Catalunya—Barcelona Tech, Comte d'Urgell 187, CP 08036 Barcelona, Spain
[c]Eindhoven University of Technology, Department of Mechanical Engineering, 5612 AZ Eindhoven, The Netherlands

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ABSTRACT

The goal of this study was to determine material properties for the anterior cortex and subcortical regions of human patellae and relate those properties to mineral density and fractal dimension of the bone. Ten human patellae were obtained from eight fresh frozen human cadavers and subjected to anteriorly-directed spherical indentation–relaxation experiments using two different sized indenters to two different indentation depths. Response data were fit to a three-mode viscoelastic model obtained through elastic–viscoelastic correspondence of the Hertzian contact relation for spherical indentation. A location-specific effective bone density measurement that more heavily weighted bone material close to the indentation site (by von Mises stress distribution) was determined from micro-computed tomography (38 μm resolution) data captured for each specimen. The same imagery data were used to compute location specific fractal dimension estimates for each indentation site. Individual and averaged patella material models verified the hypothesis that when the larger indenter and greater indentation depth is used to engage the surface and deeper (trabecular) bone, the bone exhibits a more compliant response than when only the surface (cortical) bone was engaged (instantaneous elastic modulus was 325 MPa vs. 207 MPa, $p<0.05$). Effective bone mineral density was shown to be a significant predictor of the elastic modulus for both small and large indentation types ($p<0.05$) despite relatively low correlations. Exponential regressions of fractal dimension on elastic modulus showed significant relationships with high correlation for both the small ($R^2=0.93$) and large ($R^2=0.97$) indentations.

1. Introduction

Approximately half of all lower limb injuries sustained by vehicle occupants in frontal crashes are to the knee–thigh–hip (KTH) complex (Kuppa et al., 2001; Kuppa and Fessahaie, 2003). In fact, KTH injuries account for 18% of all the moderate injuries and 23% of all the life-years lost to injury (LLI) to frontal crash-involved occupants based on the US crash data

*Corresponding author. Tel.: +1 434 296 7288x149; fax: +1 434 296 3453.
E-mail addresses: jrk3z@virginia.edu (J.R. Kerrigan), david.sanchez-molina@upc.edu (D. Sanchez-Molina), j.neggers@tue.nl (J. Neggers), carlos.arregui@upc.edu (C. Arregui-Dalmases), juan.velazquez@upc.edu (J. Velazquez-Ameijide), jrc2h@virginia.edu (J.R. Crandall).

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from 1993 to 2001. The total cost of KTH injuries in the United States has been estimated at over $4.7 billion (Blincoe et al., 2002; Kuppa and Fessahaie, 2003). KTH injuries typically occur as a result of knee-to-knee bolster loading in frontal crashes, and the individual structure that is injured has been shown using epidemiological, computational, and experimental studies to be sensitive to knee flexion angle, hip abduction angle and hip flexion angle (Ruan et al., 2008; Rupp et al., 2003). While the knee joint is typically loaded through the patella, variation in lower extremity joint angles results in a variation in the direction of load applied to the patella and the location on the patella where the load is applied. Attempts to mitigate KTH injuries, and generally all crash-induced occupant injuries, through the development of vehicle counter measures are now focused on the development and use of detailed computational (finite element) models of the human body largely due to improvements in computational technology and costs associated with experimental testing vs. computational simulation (cf. Li et al. (2010), Shin et al. (2012)). Thus, accurate computational models of the patella are necessary to determine how knee bolster loading is transferred to the femur and hip joint for accurate injury prediction.

Previous studies have described the complexity of the microstructure of the patella and how this structure affects the material properties (Raux et al., 1975; Townsend et al., 1977). Specifically, Townsend et al. (1975) measured elastic moduli of patella trabecular bone in compression tests and Raux et al. (1975) described how cortical and trabecular microstructure varied with patella region. While cortical bone material properties for other bones can be found in the literature (cf. Gomez and Nahum (2002)), no cortical bone material properties for the patella could be found in the literature. Additionally, pilot computed tomography scans of human patellae suggested that patella cortical bone had substantially lower density than that of other long bones (femur, tibia, clavicle, etc.) that are well characterized in the literature.

Thus, the current study was aimed at determining material properties for human patellae for use in computational simulations. Spherical indentation testing was chosen as the loading mode because it permitted determination of a localized measurement, without the need to modify (cut, machine, etc.) test specimens. A secondary goal of this study was to examine how bone density and fractal dimension affect elastic modulus in an effort to determine correlations that could be used to predict subject-specific material properties without the need to perform mechanical characterization testing. While the relationship between bone material properties and density, or mineral content, has been evaluated in numerous investigations (cf. Goldstein (1985)), the current study aims to examine the correlation between patella elastic modulus extracted from a single indentation test and density measurements that are specific to not only the specimen, but also the specific indentation location. Similarly, while fractal dimension has been correlated to bone material properties (Dougherty and Henebry, 2001; Haire et al., 1998; Sanchez-Molina et al., 2012), the current study investigates a test location-specific correlation.

2. Materials and methods

2.1. *Specimen preparation*

Eleven patellae were extracted from eight male fresh-frozen post-mortem human surrogates (PMHS) yielding three left and eight right patellae (Table 1). The PMHS were obtained and treated in accordance with the ethical guidelines established by the Human Usage Review Panel of the United States National Highway Traffic Safety Administration, and all testing and handling procedures were reviewed and approved by the Center for Applied Biomechanics Biological Protocol Committee and an independent Oversight Committee at the University of Virginia. All soft tissues, other than the posterior articular cartilage, were removed by scraping the surface of the bone.

To facilitate micro-computed tomography (micro-CT) scanning, each patella was clamped and cut by making a single transverse cut along the midline using a low-speed liquid-cooled (saline) diamond saw (IsoMet, Buehler, Lake Bluff, IL, USA) (Fig. 1). Each patella half was cast (R1 FastCast 891, Goldenwest Mfg. Co, Grass Valley, CA, USA) into a

Table 1 – Subject and specimen information. Length measured in the superior–inferior direction, width in the medial–lateral direction and thickness in the anterior–posterior direction.

Subject no.	Age (years)	Mass (kg)	Stature (m)	Length (mm)	Width (mm)	Thickness (mm)
215R	70	105	1.84	50.6	51.1	28.1
319R	52	77	1.79	42.7	48.2	26.9
320R	48	68	1.68	45.6	46.8	27.5
322R	49	58	1.78	47.7	49.7	30.0
323R	44	77	1.72	48.4	49.3	29.4
420R	59	95	1.80	46.4	50.7	27.5
420L	59	95	1.80	46.8	50.0	27.5
427R	79	79	1.84	47.6	51.6	29.4
427L	79	79	1.84	47.8	51.5	28.1
430R	74	47	1.73	51.7	48.0	25.0
430L	74	47	1.73	48.0	45.8	24.4
Average	62	75	1.78	47.6	49.3	27.6
Standard deviation	13	19	0.05	2.4	1.9	1.7