Validation of Cartilage Thickness Calculations Using Indentation Analysis

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Introduction. Osteoarthritis (OA) is a degenerative disease of articular cartilage. Radiography is commonly used to determine the grade of OA within a joint [1], but only provides an indirect measure of cartilage thickness. Magnetic resonance imaging (MRI) is a non-invasive method for quantifying cartilage distribution within a joint [2]. Three dimensional (3D) spoiled gradient-recalled echo (SPGR) images are commonly used to calculate cartilage thickness and volume [3,4]; however, a limited number of cartilage thickness validation studies have been performed (e.g. [5-8]). While these studies have acquired histological [6-8], computed tomography arthrography [5] or ultrasound [9] data for cartilage thickness validation, these methods have relied on interpolated data points or regional maxima for statistical analyses and have not used a matching point-to-point criteria for statistical comparison. Validation of indirect cartilage thickness measurements from an MR image dataset is strengthened by a direct cartilage thickness measurement at the same anatomical locations. The goal of this study was to perform a matching point-to-point validation of indirect cartilage thickness calculations using a 3D SPGR image dataset with direct cartilage thickness measurements using biomechanical indentation testing at the same anatomical locations.

Materials and Methods. Adult bovine knees were acquired from a local abattoir. The knees were carefully disarticulated and the distal femur was cut in half in the sagittal plane to separate the condyles. Next, a custom designed L-shaped phantom with a hollow core was rigidly attached to each condyle and filled with a diluted gadolinium solution (Fig. 1). The condyle was then submerged in oil and positioned within the MR scanner. Using a fat-suppressed pulse sequence provides high contrast between the articular surface and the surrounding oil. Image Acquisition: Imaging was performed using a 3T clinical MRI system and an 8-channel phased array knee coil. A 3D T1-weighted fat-suppressed SPGR sequence was used to generate a volumetric dataset for cartilage segmentation and thickness quantification. Imaging parameters were: TR:13.2ms, TE:2.7ms, FOV:13cm, flip angle:10°, slice thickness:0.7mm, matrix:512x512, receiver bandwidth: ±62.5kHz, NEX:3. These parameters displayed the articular cartilage as hyper-intense voxels. Indentation Measurements: Immediately following imaging, the condyle was mounted to an EnduraTEC material testing system (ELF 3200, Bose Corp., MN USA) with the articular surface oriented perpendicular to an indentation needle (∅=0.6mm, length=7mm). A 3D digitizing stylus with a needle tipped probe (Microscribe G2x, Immersion Corp, CA USA) (accuracy: 0.23mm) was used to determine the orientation of the condyle relative to the indenter in the laboratory coordinate system (LCS) using points etched on the surface of the phantom. Indentation of the cartilage was performed at a constant displacement rate of 0.05 mm/s. A small increase in measured force denoted initial contact with the cartilage surface, followed by a rapid increase in force when contact with underlying bone occurred. The differences in displacement between the two phenomena denoted the cartilage thickness. The accuracy of the indentation system is 2-5% of actual thickness. The point of indentation was marked with ink and its 3D location was digitized relative to the phantom in the LCS before orienting the specimen to another test location. Indentation testing was repeated for points across the articular surface, which were within the working volume of the indentation device. The indented points were separated by approximately 3mm. Image Analysis: Custom written software (GE Healthcare, Waukesha, WI USA) was used for semi-automated segmentation of the image datasets. First, the hyper-intense voxels of the gadolinium contrast fluid within the phantom were identified, segmented and used to create an image-space coordinate system (ISCS). Next, the cartilage of the condyle was segmented and the deep and superficial surfaces of the cartilage were defined. An iterative closest point calculation method was used to define cartilage thickness. Finally, the locations from the indentation testing were transformed to the ISCS by aligning the coordinates of the phantom in the LCS with coordinates of the phantom in the ICS. This alignment enabled a one-to-one pairing of cartilage thickness calculations/measurements from the LCS and ISCS. Statistical Analysis: A regression and correlation analysis was performed between MR thickness data with corresponding indentation thickness data. In addition, a Bland-Altman analysis was performed [10]. The Bland-Altman plot displays the average thickness of a point calculated by MRI and indentation on the ordinate and the difference of the measurements on the abscissa. Repeatability of the thickness measurements was calculated as 1.96•st.dev. of the average thickness difference.

Results. A total of 69 paired MRI-indentation thickness data points have been analyzed from 4 bovine condyles. The results of the regression analysis are shown in Figure 2. The Pearson correlation coefficient (r) was 0.9. The Bland-Altman analysis found differences of 0.047±0.218 mm (mean ± st.dev.), with the MR measurements being slightly thinner than the corresponding indentation measurements (Fig. 3). The repeatability of the measurements was 0.43 mm.

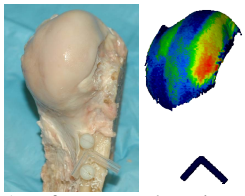

Figure 1. Left – Prepared specimen with rigid fixation of L-shaped phantom. Right – The cartilage thickness map from the same specimen. The segmented phantom is also shown.

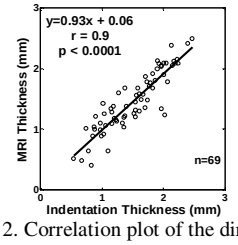

Figure 2. Correlation plot of the direct indentation cartilage thickness measurement versus the indirect MRI cartilage thickness calculation.

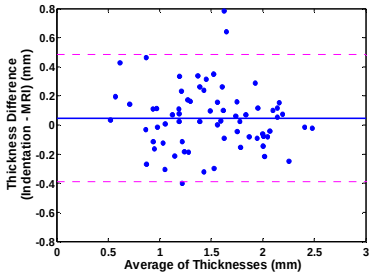

Figure 3. Bland-Altman plot of paired indentation and MRI cartilage thickness data points. The mean difference is shown as a solid line and the limits of agreement are shown as dashed lines.

Discussion. The present study used a custom designed L-shaped phantom to register the indirect MRI cartilage thickness calculations with direct indentation cartilage thickness measurements. The one-to-one analysis of the data is a benefit over previous studies which have validated MRI cartilage thickness measurements by using interpolated or regional thickness measurements. The correlation found in this study is similar to a previous report of MR and direct cartilage thickness measurements [8]. In addition, the mean difference of the current measurements is 40% smaller than another validation study [7] and only 2.9% of the current thickness differences were greater than 0.5mm [6]. A strength of the current study was the ability to align the biomechanical and imaging datasets. Furthermore, the 3D indentation measurements and 3D cartilage thickness calculations allowed for out of plane curvature of the articular surface, which may have an effect when attempting to validate cartilage thickness measurements [11]. This study will aid in validating a tool for clinical evaluation of in-vivo cartilage thickness.

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