

Sequential Wear Patterns of the Articular Cartilage of the Thumb Carpometacarpal Joint in Osteoarthritis

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Purpose: The thumb carpometacarpal (CMC) joint is a primary location for osteoarthritis (OA) in the body; however, articular cartilage thickness distribution during progression of OA in the joint has not been reported previously. Determining the cartilage wear patterns within the joint is important in understanding the etiology and treatment of thumb CMC joint OA. This study used cadaveric specimens to investigate the wear patterns of the articular surfaces of the trapezium and thumb metacarpal.

Methods: A total of 104 fresh-frozen thumb CMC joints were radiographed, disarticulated, and visually staged for OA. Cartilage thickness maps of the trapezium and metacarpal were determined for each joint by using stereophotogrammetry. Average cartilage thickness maps for the trapezium and metacarpal were generated from all specimens for each of 4 stages of OA, showing the progression of cartilage thickness changes with disease.

Results: In normal joints, the surface-wide mean thickness of the articular layers is 0.8 ± 0.2 mm for the trapezium and 0.7 ± 0.2 mm for the metacarpal. The average thickness maps were analyzed by anatomic quadrant (dorsal-radial, dorsal-ulnar, volar-radial, volar-ulnar) within the 4 stages of OA. Corresponding quadrants also were compared across the increasing stages of OA. Results show that cartilage degradation is initiated in the radial quadrants of the metacarpal and progresses to the volar quadrants of the articular surface, while significant wear is seen on the dorsal-radial quadrant of the trapezium and progresses to the volar quadrants in late-stage osteoarthritis.

Conclusions: These quantitative results on cartilage thinning agree with previous investigators' reports of high load bearing and low load bearing areas in the CMC joint during functional pinch and grasp positions. Understanding the progression of OA in the thumb CMC joint may aid in the surgical treatment of this disease. (*J Hand Surg* 2003;28A:597-604. Copyright © 2003 by the American Society for Surgery of the Hand.)

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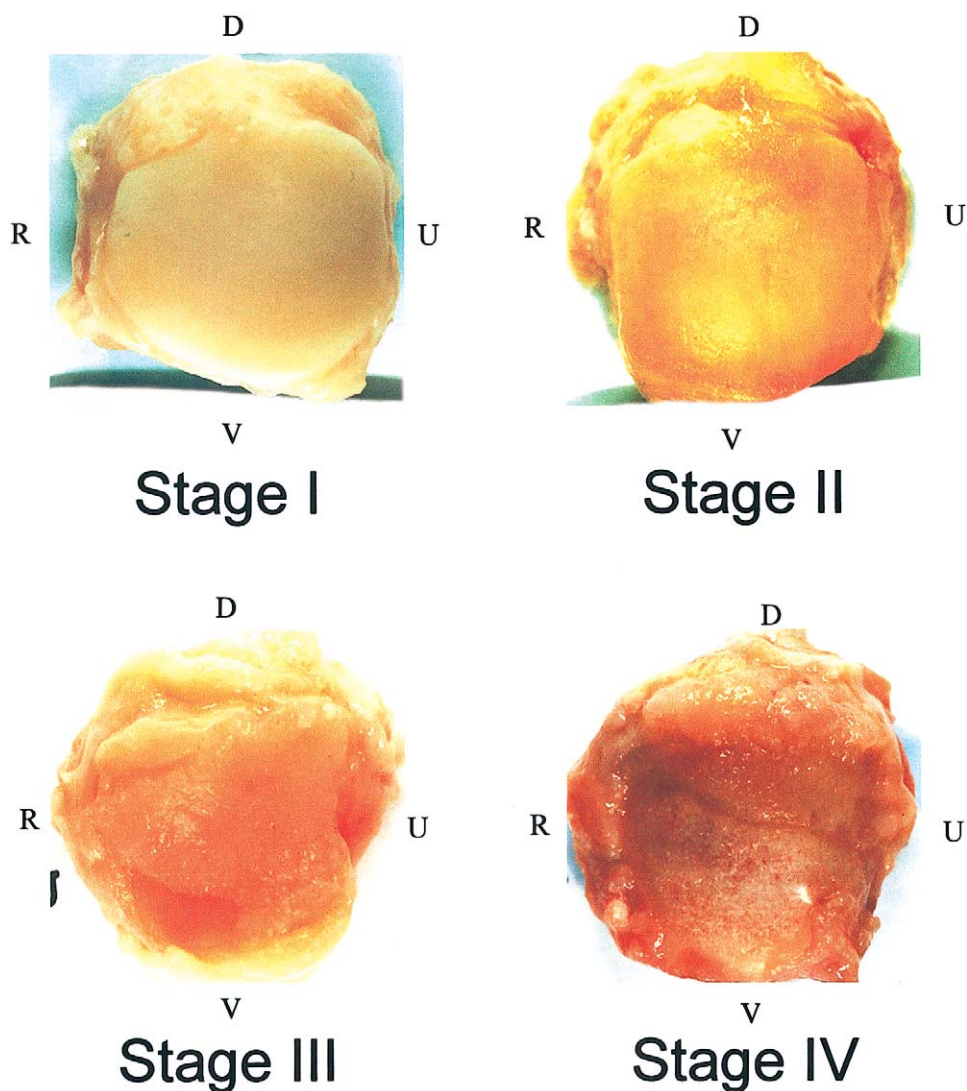


Figure 1. Images depicting the progression of OA on the articular surface of the thumb metacarpal. Severity of OA shown by specimens range from stage I (minimally osteoarthritic) to stage IV (end-stage osteoarthritic). Anatomic directions: D, dorsal; V, palmar; R, radial; U, ulnar.

The saddle-shaped thumb carpometacarpal (CMC) joint is responsible for the prehensile ability of the human hand. A considerable amount of hand function can be lost with advanced osteoarthritis (OA) of the CMC joint.¹ Whereas a 6% prevalence has been reported in men aged 55 to 64 years old, Armstrong et al² found a 25% prevalence of CMC joint OA in postmenopausal women, with 28% to 55% of these individuals complaining of basal thumb pain. A greater understanding of the pathogenesis of CMC joint osteoarthritis may be clinically useful.

Determining the articular cartilage wear pattern of the thumb CMC joint is important in elucidating the etiology of OA. An example of OA progression on the thumb metacarpal articular surface is shown in Figure 1. Although the normal cartilage thickness

distribution in the thumb CMC joint has not been reported previously in the literature, the location of OA wear patterns and the etiology of articular cartilage degradation has been the subject of debate. Koebke³ suggested that incongruent joint contact caused by pronation of the metacarpal may lead to a localized stress peak on the volar-ulnar and dorsal-radial regions of the trapezium. A study by Eaton and Littler^{4,5} concluded that placement of the trapezium and metacarpal into an incongruous position during functional opposition and pinch positions concentrated joint contact stresses on the dorsal-radial facet of the trapezium, leading to initiation of cartilage thinning on this facet. Ateshian et al⁶ found similar results in their study of the CMC joint with contact occurring on the volar-ulnar and dorsal-radial regions

of the trapezium during lateral pinch in the presence of metacarpal pronation. Further studies by Pieron⁷ reported contact in the palmar compartment of the joint during flexion-adduction, whereas Pellegrini et al^{8,9} reported contact patterns and eburnation of articular surfaces in the volar regions of the joint during the functional position of lateral pinch.

The objective of this study was to determine the normal pattern of articular cartilage thickness of the trapezium and metacarpal across the spectrum of OA stages by using detailed quantitative analysis. Our goals were as follows: (1) to measure the cartilage thickness in the trapezium and metacarpal of specimens of varying degrees of OA; (2) to calculate average thickness maps for each stage of OA; (3) to determine regional differences in thickness within each surface at a given stage statistically; and (4) to determine differences across stages within a given anatomic region of the articular surfaces statistically.

Materials and Methods

Cadaver Specimen Procurement and Osteoarthritis Staging

A total of 104 fresh-frozen human cadaveric hand specimens (63 male, 41 female; age range, 18–97 y; average 52.3 ± 17.8 y [\pm SD]) were used in this experiment. Specimens were obtained from human tissue donor programs and randomly assigned to this study. All specimens were stored at -40°C before dissection and measurement. After thawing at room temperature for 6 hours radiographs of the thumb CMC joint were obtained and were staged by previously described methods⁵; the criteria used for radiographic staging is displayed in Table 1. The joints were dissected carefully to expose the articular surface of both the trapezium and metacarpal without damage to the cartilage. Each joint was staged visually for OA by using an anatomic grading method previously reported,¹⁰ which is based on a summary of previous classifications of articular cartilage in various diarthrodial joints reported in the literature. The staging protocol designated stage I as normal cartilage, stage II as cartilage with minor defects, stage III as progressively degenerated cartilage, and stage IV as articular surfaces with evidence of severe OA (Table 2). In addition to assessment of surface coverage of fibrillation, pitting, clefts, and osteophyte formation, a hand-held depth probe for estimating the depth of cartilage lesions, under a $2\times$ to $4\times$ magnification, was used to help assign OA stage. Each joint was then assigned an overall stage accord-

Table 1. Criteria Used to Assess Radiographic Stage of OA in the CMC Joint

Radiographic Stage	Description
I	Normal appearance of articular contours Slight widening of joint space
II	Slight joint space narrowing Small bone or calcified fragments <2 mm
III	Noticeable joint space narrowing Small bone or calcified fragments >2 mm
IV	Major subluxation present Very narrow joint space Cystic and sclerotic subchondral bone changes Osteophyte formation

ing to the highest level of degeneration observed at any site on the trapezium or metacarpal.

Cartilage Thickness Measurement

The 3-dimensional topography and cartilage thickness of the trapezium and metacarpal cartilage layers were quantified by using the optical noncontacting technique of stereophotogrammetry¹¹ ($25\ \mu\text{m}$ accuracy). Briefly the trapezium and thumb metacarpal were each affixed to a frame fitted with precision alignment targets by using cyanoacrylate cement, and each assembly was placed in a precision calibration frame. A fine mesh was projected on the articular surface (producing approximately 275 intersection points on the articular surface), and 2 large format photographs (8×10 in, Sinar Photography, Edison, NJ) were taken of the specimen, its alignment targets, and the calibration frame. Photos of the subchondral bone surface were taken after the cartilage surface was dissolved using a mild sodium hypochlorite solution. Using custom written software the 3-dimensional coordinates of the nodes of the projected mesh for the cartilage and subchondral bone surfaces for each bone were calculated based on camera parameters and the digitized positions of the node points on the photographs. For thickness calculation the articular surface and subchondral bone surface of each bone were realigned using the coordinates of the alignment targets common to both sets of photographs, and cartilage thickness was evaluated as the distance from the articular surface to the corresponding subchondral bone surface, to produce surface-wide thickness maps.¹¹ For statistical analysis, each trapezium and metacarpal surface was di-

Table 2. Staging Protocol to Describe Visual Degeneration of OA Articular Cartilage

Visual Stage	Cartilage State	Description
I	Normal	Smooth, shiny, intact surface
II	Early degeneration	Matted, dull surface
IIa	Localized fibrillation and/or localized pitting	<25% of total surface <25% of depth
IIb	Moderate fibrillation and/or localized pitting	<50% of total surface <25% of depth
IIc	Pervasive fibrillation and/or localized pitting	<50% of total surface area <25% of depth
III	Progressive degeneration	
	Pitting	>25% of depth
	With or without fibrillation	(localized, moderate, or pervasive)
	Fissures, clefts, blisters	
	Deep fissures, clefts to bone	
IV	End-stage degeneration	
	Bone eburnation	
	Osteophytes	

vided into 4 quadrants (dorsal-radial, dorsal-ulnar, volar-radial, and volar-ulnar) and the mean cartilage thickness within each quadrant was calculated. All surfaces also were aligned to a common anatomically based coordinate system.¹⁰ The origin of this coordinate system was located at the geometric center of each articular surface. At this origin, the directions of minimum and maximum surface curvature were calculated and were assigned as the x and y axes, respectively.¹² The z-axis, surface normal at the origin, was calculated as the cross-product of unit vectors along the x and y axes. All surfaces were scaled by the square root of articular surface area to minimize gender-specific and interspecimen variations in size. All left-hand surfaces were mirrored into right hands. An average cartilage topography and thickness map was calculated from the aligned surfaces for each of the trapezial and metacarpal surfaces of OA stages I, II, III, and IV.

Statistical Analyses

A 2-factor repeated measures analysis of variance (ANOVA) with least squares means was performed to find the effects of stage and quadrant on trapezial and metacarpal cartilage thickness, with $\alpha = .05$. Significance was taken at $p \leq .05$. A Duncan Multiple Range Test of the means was used when statistical significance was achieved in the ANOVA test. Statistical analyses were performed using a statistical package (SAS Institute Inc., Cary, NC) on a personal computer. The distribution of joints across age ranges and the relationship between joint stage and age was examined. In addition a 2-tailed paired *t*-test

was performed to determine differences between visual and radiographic staging of the CMC joint.

Results

Cadaver Specimen Age Characterization

A summary of specimen age, gender, visual staging, and x-ray staging is displayed in Table 3. Thirty-two percent of the joints tested were between 60 and 79

Table 3. Age, Gender, and Stage Distribution of Specimens

Factor	Levels	Number in Group
Visual stage	I	9
	II	40
	III	40
	IV	15
Radiographic stage	I	44
	II	44
	III	6
	IV	4
Gender	Not graded	6
	Male	63
Age	Female	41
	20–39 y	19
	40–59 y	52
Visual stage for men	60–79 y	33
	I	5
	II	25
Visual stage for women	III	27
	IV	6
	I	4
	II	15
Visual stage for women	III	13
	IV	9

years of age, 50% were between 40 and 59 years, and 18% were 39 years old or less. One-way ANOVA indicated that age had a statistically significant effect on visual staging of OA ($p < .001$), with young specimens having an average visual staging of 1.68 ± 0.66 (\pm SD), middle-aged specimens having an average staging of 2.50 ± 0.64 , and older specimens having an average staging of 3.24 ± 0.66 .

Comparison of Radiographic and Visual Osteoarthritis Stages

Forty-four specimens were graded radiographically as stage I, 44 as stage II, 6 as stage III, and 4 as stage IV. Six specimens were not radiographed. Nine specimens were graded visually as stage I, 40 as stage II, 40 as stage III, and 15 as stage IV. Average radiographic stage of all specimens (1.69 ± 0.77) was significantly less than the overall visual stage (2.58 ± 0.84), $p < .001$.

Effect of Visual Osteoarthritis Stage on Surface-Wide Mean Cartilage Thickness

The results of the ANOVA analysis showed that the mean cartilage thickness of the trapezium in stage IV specimens (0.6 ± 0.3 mm) was significantly thinner ($p < .001$) than stage I (0.8 ± 0.2 mm), stage II (0.9 ± 0.2 mm), and stage III (0.8 ± 0.2 mm) specimens. The analysis also showed that the mean cartilage thickness of the metacarpal in stage IV specimens (0.6 ± 0.2 mm) was not significantly different ($p = .107$) than stage I (0.7 ± 0.2 mm), stage II (0.9 ± 0.02 mm), or stage III (0.7 ± 0.02 mm) specimens.

Effect of Visual Osteoarthritis Stage on Cartilage Thickness From Individual Quadrants

Average cartilage thickness maps for each stage are displayed in Figure 2. Figures 3 and 4 display the average cartilage thickness for each quadrant as a function of OA stage with statistical differences noted. On the trapezium, the dorsal-radial, volar-radial, and volar-ulnar quadrants of stage IV specimens were thinner than stages I, II, and III specimens ($p < .001$). A similar pattern was seen in the dorsal-ulnar quadrant but was not significant. On the metacarpal the volar-radial quadrant of stage IV metacarpal specimens was significantly thinner than stage II and III specimens, $p < .0001$ and $p = .001$ respectively, but it was not thinner than stage I specimens, $p = .26$. The volar-ulnar quadrant of stage IV meta-

carpal specimens also was significantly thinner than that in stages I, II, and III, $p < .001$. In addition on the metacarpal the cartilage thickness of the dorsal quadrants was not significantly different across the 4 stages.

Comparison of Cartilage Thickness of Quadrants Within Visual Stages of Osteoarthritis

Figures 5 and 6 display the average cartilage thickness for each OA stage as a function of the quadrants within the stage.

Trapezium. In stage I specimens the radial quadrants were significantly thinner than the dorsal-ulnar quadrant ($p = .03$), but not the volar-ulnar quadrant. In stage II specimens the volar quadrants tended to be thinner than the dorsal quadrants, although only significantly for the volar-radial quadrant, $p < .001$. In stage III specimens the thickness of the volar-ulnar, volar-radial, and dorsal-radial quadrants were similar and thinner than the dorsal-ulnar quadrant, $p < .001$, and the dorsal-radial quadrant had the thinnest cartilage. In stage IV specimens the volar quadrants were thinner than the dorsal quadrants but only significantly against the dorsal-ulnar quadrant ($p < .001$).

Metacarpal. In stage I specimens the volar-ulnar, volar-radial, and dorsal-radial quadrants were thinner than the dorsal-ulnar quadrant ($p < .001$). In stage II specimens only the volar-radial quadrant was thinner than the dorsal quadrants, $p = .003$, and had the thinnest cartilage in the stage. In stage III specimens cartilage thickness in all 4 quadrants was significantly different, with the volar quadrants thinner than the dorsal quadrants ($p < .001$). In stage IV specimens the cartilage thickness of the dorsal quadrants were similar ($p = .37$), as was the cartilage thickness of the volar quadrants ($p = .53$). The volar quadrants were significantly thinner than the dorsal quadrants ($p < .001$).

Discussion

In this study average cartilage thickness data were presented for the trapezium and metacarpal, by stage and quadrant, for specimens of varying stages of OA. Quantitative methodologies were used to create average CMC joint articular cartilage thickness maps for specimens of varying stages of OA and to partition the articular surfaces into quadrants to elucidate region-specific thickness patterns.

An anatomic visual staging system previously de-

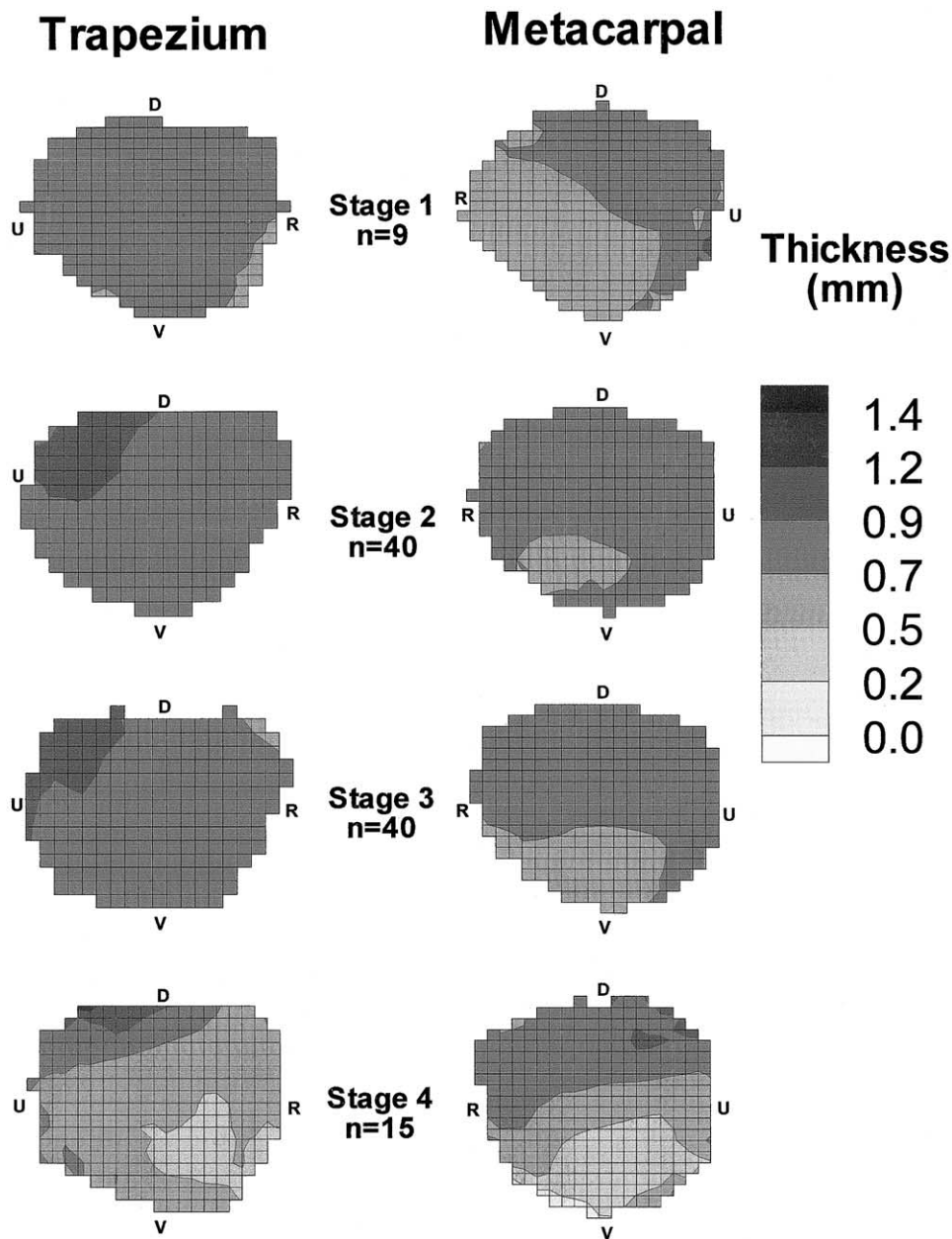


Figure 2. Average cartilage thickness maps of the trapezium and metacarpal, by visual stage of OA. r, radial; u, ulnar; d, dorsal; v, palmar.

veloped in our laboratory was used in this study. Although there are several different classification systems for the description of articular cartilage degeneration,¹³⁻¹⁷ this visual staging system was used because it has greater local sensitivity to degenerative changes than radiographic staging.¹⁰ This sensitivity has been shown when making correlations between anatomic OA stage and changes in cartilage mechanical properties and biochemical composition.¹⁸

Each articular surface was partitioned into quadrants

to facilitate the analysis of regional variations in cartilage thickness as well as sequential patterns with increasing OA, which are less well defined when performing surface-wide cartilage thickness analyses. (Indeed in the case of the metacarpal the surface-wide mean thickness at stage IV was not statistically different from that of stages I, II, and III; however, statistical differences were found at stage IV in the volar-radial and volar-ulnar quadrants.) This approach also allows the description of articular wear patterns in a manner consistent with CMC joint literature.

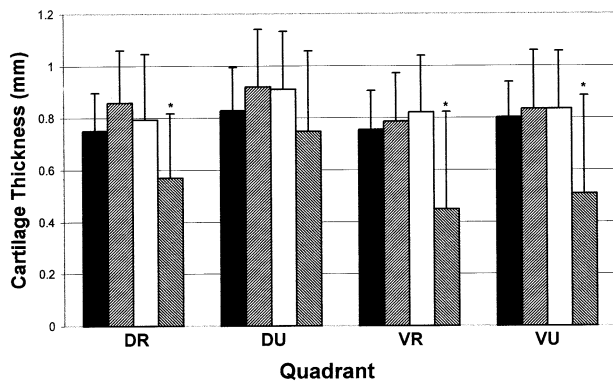


Figure 3. Trapezium cartilage thickness versus quadrant (mean ± SD). *Indicates stage IV is significantly thinner than stages I, II, and III. □, stage I; ▨, stage II; ■, stage III; ▩, stage IV. * $p < .05$.

It was found that the visual staging of the joint was almost one full grade higher than the radiographic staging of the joint. Previous investigators have found similar results of poor correlation of radiographic staging and visual staging¹⁹ and radiographic staging with symptoms of OA.²⁰ This finding confirms that radiographic staging is more likely to detect advanced stages of OA and is not sensitive to early disease progression.

In general as expected it was observed that as the visual staging of the specimen increased, the amount of cartilage across the trapezium and metacarpal surfaces decreased markedly. Trends found on the metacarpal show that degradation of the cartilage surface originates in the radial quadrants of the articular surface and quickly progresses to the volar quadrants in stages II, III, and IV. In early OA stages on the trapezium cartilage thinning is seen on the radial and volar quadrants in stages I and II, progresses to the

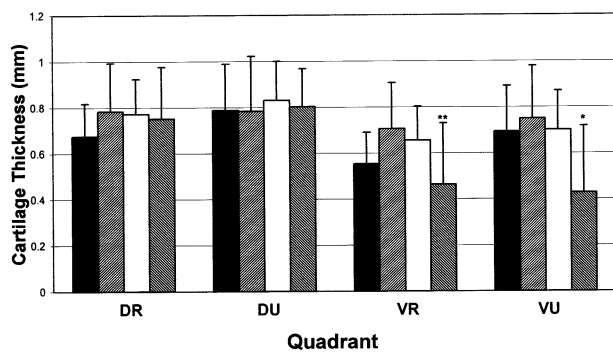


Figure 4. Metacarpal cartilage thickness versus quadrant (mean ± SD). *Indicates stage IV is significantly thinner than stages I, II, and III. **Indicates stage IV is significantly thinner than stages II and III only. □, stage I; ▨, stage II; ■, stage III; ▩, stage IV. *, ** $p < .05$.

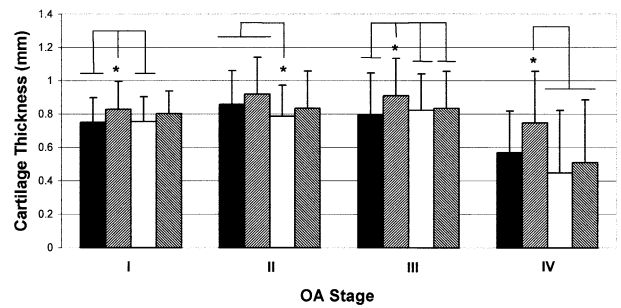


Figure 5. Trapezium quadrant cartilage thickness versus OA stage. (DR, dorsal-radial; DU, dorsal-ulnar; VR, volar-radial; VU, volar-ulnar.) *Indicates the statistical differences present as noted in the text. ■, DR; ▨, DU; □, VR; ▩, VU. * $p < .05$.

dorsal-radial quadrant in stage III, and becomes thinner in the volar portions of the cartilage surface in stage IV.

The CMC joint OA wear patterns shown in this study correlate directly with the sites of focal lesions observed by others in clinical and anatomic studies.^{5-7,21} The focal lesions of the articular cartilage showed in this study support the hypothesis that articular contact of the thumb metacarpal and trapezium shifts and splits to the dorsal-radial and volar-ulnar regions of the surfaces during normal activities of daily living.^{5,8,20,22} Ateshian et al⁶ showed that the contact areas of the CMC joint are located at the dorsal-radial and volar-ulnar regions of the CMC joint during lateral pinch, secondary to increased metacarpal pronation angle. These investigators also found that cartilage wear occurred on both the volar-ulnar and dorsal-radial quadrants of the CMC joint during pronation of the metacarpal.

This study showed considerable wear on articular surface regions identified as high load bearing in

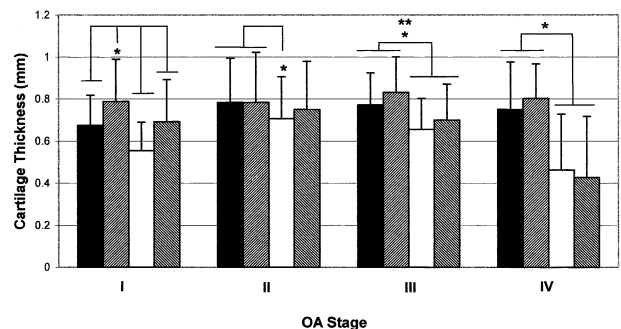


Figure 6. Metacarpal quadrant cartilage thickness versus OA stage. (DR, dorsal-radial; DU, dorsal-ulnar; VR, volar-radial; VU, volar-ulnar.) *Indicates significant differences present as noted in the text. **Indicates significant differences in cartilage thickness among all quadrants. ■, DR; ▨, DU; □, VR; ▩, VU. *, ** $p < .05$.

previous contact area studies,^{8,23} providing supporting evidence to the theory that abnormally high stresses may initiate or exacerbate OA progression in articular cartilage. Similarly the thickest cartilage was found in low load bearing sites (dorsal-ulnar trapezium and dorsal metacarpal). The resulting split in contact reduces the contact area between the metacarpal and trapezium and creates abnormally high cartilage contact stresses and may lead to the progression of CMC OA.

Clinical measures for treatment of CMC joint OA might be developed by knowing the articular cartilage thickness and the sequential wear patterns associated with CMC joint OA. The goal of these treatments may be to alter the contact between the trapezium and thumb metacarpal during activities of daily living in which load transmission is transferred from degenerated cartilage to healthier cartilage within the joint. These treatments may be as simple as specific thumb muscle strengthening exercises, or may require more complex surgical procedures to alter the overall biomechanics of the joint. Despite of the complexity of treatment, the clinician may be able to alter the time course of OA progression in the CMC joint.

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