The Human First Carpometacarpal Joint:

Osteoarthritic Degeneration and 3-Dimensional Modeling

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ABSTRACT: The purpose of this study was to gain insight into potential mechanical factors contributing to osteoarthritis of the human first carpometacarpal joint (CMC). This was accomplished by creating three-dimensional (3-D) computer models of the articular surfaces of CMC joints of older humans and by determining their locus of cartilage degeneration. The research questions of this study were: 1) What is the articular wear pattern of cartilage degeneration in CMC osteoarthritis?, (2) Are there significant topographic differences in joint area and contour between the joints of males and females?, and 3) Are there measurable bony joint recesses consistently found within the joint? The articular surfaces of 25 embalmed cadaveric joints (from 13 cadavers) were graded for degree of osteoarthritis, and the location of degeneration was mapped using a dissection microscope. The surfaces of 14 mildly degenerated joints were digitized and reconstructed as 3-D computer models using the Microscribe 3D-X Digitizer and the Rhinoceros 2.0 NURBS Modeling Software. This technology provided accurate and reproducible information on joint area and topography. The dorsoradial trapezial region was found to be significantly more degenerated than other quadrants in both males and females. Mean trapezial articular surface area was 197 mm^2 in males and 160 mm^2 in females; the respective mean areas for the metacarpal were 239 mm^2 in males and 184 mm^2 in females. Joints of females were found to be significantly more concave in radioulnar profile than those of males. Three bony joint recesses were consistently found, two in the radial and ulnar aspects of the trapezium and the third in the palmar surface of the metacarpal.

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INTRODUCTION

Normal hand function is dependent on the prehensile capacity of the thumb and specifically on its basal or first carpometacarpal joint. First carpometacarpal joint osteoarthritis (CMC-OA) can be disabling,[1] and the CMC itself is the most frequent operative focus in the osteoarthritic upper extremity.[2] Although it is known that basal joint arthritis preferentially affects women older than 45 years,[3–8] the factors responsible for the higher prevalence in this demographic group are controversial.

The two currently preeminent theories of CMC-OA etiology are the Ligamentous Laxity and the Joint Impingement theories. Proponents of the first theory[2,9–14] have observed that CMC-OA frequently coexists with degeneration of the palmar or beak ligament, and have proposed that ligamentous laxity at the CMC may result in abnormal shear stresses and degeneration in the anterior compartment of the joint. Other investigators,[15–19] however, have pointed to the dorsoradial aspect of the trapezium as the primary site of osteoarthritic degeneration. These authors have proposed that rotation of the thumb metacarpal on the trapezium during pinch and grip tasks results in reduced contact areas and localized increases in contact stress (i.e., joint impingement) that may predispose the CMC to early degenerative change. Because the observations of the two groups have been contradictory, determining the articular wear pattern in CMC-OA was a primary research question of the present study. We hypothesized that mechanical abrasion of the cartilage should result in differences in the degree of degeneration between the quadrants of the joint.

The higher prevalence of CMC-OA in females relative to that found in males has led to a search for relevant differences in topography between male and female joints.[17–23] At present, however, there is much controversy regarding which topographic

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features predispose the joint to pathology.[9,18–20,22–25] Thus, the second research question of this study was whether there are any significant topographic differences between male and female joints that might account for the demographic differences in CMC-OA susceptibility. We hypothesized that these might be manifested in differences in joint area or contour.

Additional controversy has surrounded details of CMC surface topography, including the presence and location of bony joint recesses.[2,9,26] These have been reported at the margins of the metacarpal and trapezial articular surfaces where the articular cartilage curls away, leaving small pockets between the joint capsule and the nonarticulating cartilage. The recesses may serve an important function by accommodating metacarpal translation during normal movement.[2,26] The third research question of this study was whether measurable bony joint recesses could be located consistently within the CMC. We hypothesized that these features could be visualized and their areas quantified using three-dimensional (3-D) digitization and computer modeling technology.

Thus, the purpose of this investigation was to create 3-D computer models of the normal human CMC using commercially available digitization and computer-aided design equipment. The CMC models could then be used in the determination of global and subtle anatomical features. In addition, the location of joint degeneration in this series of specimens could be determined to gain insight into potential mechanical factors in CMC-OA pathogenesis.

METHODS

Specimens and Method of Preparation

Twenty-five embalmed cadaveric hands (12 right and 13 left) were examined. Specimens were obtained from 12 cadavers bilaterally and from a single hand from one cadaver. All hands were obtained from the Division of Anatomy, Department of Surgery at the University of Toronto. There were 15 hands from males and ten from females. The mean age of the cadavers was 72.5 years (SD = 8.9 years). The thumb joints of the hands had not been disected previously. The principal investigator (M.K.) performed each dissection. The superficial tissues were removed to expose the articular surfaces of the trapezium and metacarpal.

System for Staging CMC-OA Degeneration

A primary goal of the present study was to develop an understanding of the normal surface topography of the CMC in older human hands. It was thus important to use a method of staging that differentiated mildly degenerated from moderately to severely degenerated joints, and allowed for both grading the degree of cartilage degeneration in the quadrants and rating the overall level of specimen degeneration. The joint cartilage was graded on the basis of two parameters: the location and degree of cartilage lesion.

The degree of cartilage lesion was graded on a five-point scale[27] that allowed for the coding of degree of cartilage damage based on the observations of specific common types of cartilage lesions.

The system used to grade the location of cartilage damage[23] divided the trapezium and metacarpal into a total of six anatomical areas (dorsoradial, voloradial, dorsoulnar, and voloulnar trapezial; volar and dorsal metacarpal). Each anatomical site on the trapezium and on the metacarpal was observed under magnification (2×–4×) and the presence of specific lesions noted. The assignment of osteoarthritis grade was performed on a single occasion by a single rater (M.K.), who assigned each region of interest a grade consistent with the presence of the characteristic features typical of that grade (Table 1). In addition, photographs of the sites were taken and drawings of the surface features were made to improve reliability of the staging process. An overall joint grade was assigned to each specimen on the basis of the highest site-specific grade for that joint. Data concerning the intrarater reliability of grade estimation based on this system[27] are not available.

In this study, joint surfaces in which overall degeneration was mild (grade 0–2) were considered representative of healthy joints and were subsequently selected for 3-D modeling. The mean age of the mildly degenerated sample was 68.7 years (SD = 8.4) whereas the mean age of the moderately to severely degenerated sample was 76.4 years (SD = 7.4).

TABLE 1. **Anatomical Osteoarthritis (OA) Grading Scheme**

Grade	*Characterization*	*Surface Characteristics*
0	Normal cartilage	No visible changes
1	Dubious if OA present	Slight unevenness Granularity of the surface Shallow furrows or streaking
2	Mild OA	Superficial fraying Superficial splitting Superficial pitting Small erosions
3	Moderate OA	Extensive ulceration Cartilage loss
4	Severe OA	Large areas of complete degeneration accompanied by exposure and eburnation of bone

Adapted from Byers PD, Contepomi A, Farkas DA. A postmortem study of the hip joint including the prevalence of the features of the right side. Ann Rheum Dis. 1970;29:15–30.

Computerized 3-D Modeling Equipment

Three-dimensional modeling equipment consisted of a personal computer, a high-resolution monitor, a 3-D digitizer with hand control, a standard digitizing stylus (Microscribe 3DX; Immersion Corporation, San Jose, CA), and a computer-aided design program (Rhinoceros 2.0 NURBS Modeling Software for Windows; Robert McNeal & Associates, Seattle, WA). Equipment for grading of joints affected by osteoarthritis included a digital camera (Nikon Coolpix 950) and a dissecting microscope.

Method of Digitization and Reconstruction of 3-D CMC Models

A method of reconstruction of 3-D computer models of metacarpal and trapezial surfaces was developed using a digitizer and computer-aided design program (Rhinoceros 2.0). Before digitization, the specimen was mounted in a vice at a constant location relative to the laboratory coordinate system. Axes of the latter were determined as part of the Rhinoceros 2.0 calibration process.

Briefly, articular surface reconstruction with this method requires both 3-D coordinates representing the surface and a perimeter delimiting the joint facet margins. To digitize surface points, the operator first must specify a base digitizing plane at the radial end of the joint to be digitized and an axis normal to the plane running in an ulnar direction. The software then divides the space occupied by the sample into multiple equidistant digitizing planes parallel to the base plane, the given distance having been specified by the operator. Points were sampled at a frequency of 1,000 Hz each time the digitizer stylus tip passed through one of the digitizing planes. The digitizer was able to differentiate points a minimum distance of 0.23 mm apart. When the digitization of the surface was complete, a visual inspection of the finished product on the computer monitor revealed a representation of a surface composed of serial profiles in each section plane. These serial profiles were composed of 3-D coordinate points previously sampled. The latter then served as input data for a 3-D surface-fitting procedure by the Rhinoceros 2.0 system, finally yielding a manipulable computer representation of the joint surface.

Methods of Analysis of CMC Area and Topography

Analysis of the reconstructed 3-D computer models was facilitated by the automatic calculation by Rhinoceros 2.0 of joint surface curvatures. These are intrinsic geometric properties that are well suited for characterizing the topography of any arbitrary anatomical surface.[28] By assigning different colors to different surface curvature values and superimposing the colors onto the topographical model, color-coded topographical maps of the joint surfaces were created as described by Ateshian et al.,[20] from which subtle anatomical features could be discerned (e.g., sellar versus ovoid geometries).

In addition, two-dimensional midline profiles were assessed to yield information regarding surface contour in the radioulnar and dorsovolar anatomical directions. The depth of concavity of each reconstructed surface was determined by examining its midline profile in the direction of maximum concavity with the Rhinocerus 2.0 software. The end points of the profile curve were connected creating a closed figure that was then viewed using the software from a location in the model space that was orthogonal to it. A normal curve was then constructed from the top of the figure to the nadir of the profile curve. This length was taken to represent the depth of the concavity of the surface. The depth of concavity was divided by the length of the top of the figure and multiplied by 100 to yield an index of concavity. An index of the height of the convexity of the surface was created in an analogous way by examining the midline profile of the surface in the direction of maximum convexity.

The Rhinoceros 2.0 software computed the areas of each 3-D computer model of trapezial or metacarpal main facet or bony recess.

Accuracy and Reliability of 3-D Digitization and Surface Reconstruction

To test the accuracy of the 3-D digitization and reconstruction system, one facet of a steel gauge block was digitized 20 times. A gauge block is a size standard used to check the accuracy of measuring instruments and whose measurements are known to within 0.001 mm. The area of the facet was calculated from its length and width as measured by digital caliper 20 times. A sample *t*-test determined that there was no statistically significant difference between the area as measured by digitizer and the mean area measured by digital caliper (i.e., $p > 0.05$).

To measure the precision of the digitization and reconstruction method, the standard error of the mean (SEM) was calculated using the data for the steel gauge block. The SEM was 0.19 mm^2, and the method was deemed precise.

Data Analysis

Descriptive Quantitative Analysis

The median and range of osteoarthritis grades for regions of interest in the CMCs of mildly degenerated, moderately to severely degenerated, and overall specimens were calculated.

The means and standard deviations for the areas of the main facets and bony joint recesses of the

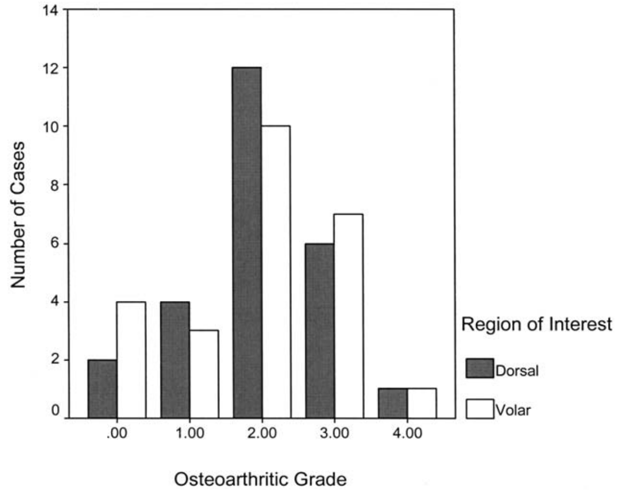

FIGURE 1. The number of cases in each osteoarthritis-grade category subcategorized by metacarpal region of interest. No significant difference was found between dorsal and volar regions of interest (Wilcoxon signed ranks test).

trapezial and metacarpal surfaces were calculated, as well as for the indices of convexity and of concavity for each main facet.

Descriptive Qualitative Analysis

Color-coded topographical maps that were generated automatically by Rhinoceros 2.0 software using surface curvatures were scrutinized for distinct topographical features such as sellar (i.e., saddle shaped) or ovoid (i.e. convex) geometries. The presence and location of bony joint recesses were recorded.

Inferential Analysis

In terms of the cartilage grading, the null hypothesis was that the distribution of osteoarthritis grades was equal within each region of interest (i.e., that they each had about the same median osteoarthritis grade). Comparisons were made using the Wilcoxon signed rank test, and the Bonferroni adjustment to the alpha level was made because of the multiple comparisons used (i.e., the alpha level was 0.05/7, where 7 was the number of comparisons made).

In terms of the topographical analyses, the null hypotheses were that there would be no statistically significant differences between specimens from males and females with respect to the mean values of a number of parameters. These parameters were 1) area of the main facet of trapezium, 2) area of the main metacarpal facet, 3) index of concavity for trapezium, 4) index of convexity for trapezium, 5) index of concavity for metacarpal, and 6) index of convexity for metacarpal. The Student's t-test was applied to determine the difference between parameters.

Study Limitations

Approximately 60% of the specimens from females examined in this study were either moderately or severely degenerated. Thus, a limitation of this study was the small number of female specimens available for topographic analysis.

RESULTS

Descriptive Quantitative Analysis

Analysis of cartilage grading patterns revealed that there was no statistically significant difference in median-osteoarthritis level between the volar and dorsal regions of the metacarpal (Figure 1). However in the trapezium the dorsoradial aspect of the joint showed consistently higher levels of osteoarthritic degeneration (Figure 2). This result was significant for the pooled sample (i.e., consisting of both the mildly as well as the moderately/severely degenerated specimens).

The mean area of the trapezial articular surface for males (197.30 mm^2) was significantly larger than that for females (160.50 mm^2). Likewise, the mean area of the metacarpal articular surface for males (239.66 mm^2) was larger than that for females (184.51 mm^2) (Table 2). The convexity of the trapezium was more pronounced than its concavity; the same was true of the surface of the metacarpal. Comparisons of the articular profiles of joints from males and females revealed that the trapezium of the male was significantly less concave in the radioulnar profile than that of the female (concavity index for males was 8.7% of radioulnar width compared with 11.6% for the joints of females) (Table 3).

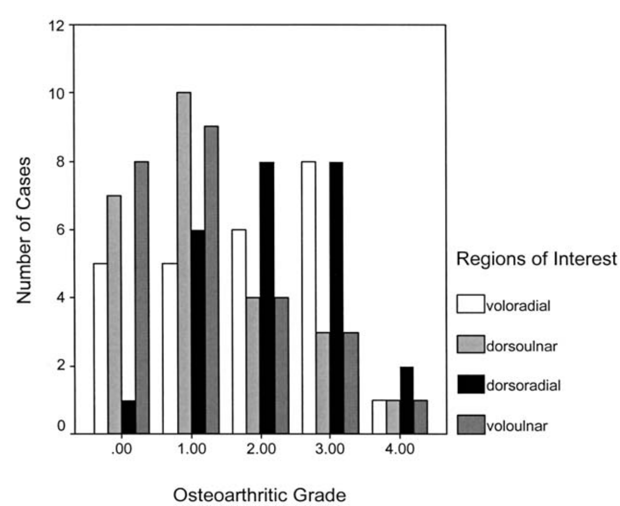

FIGURE 2. The number of cases in each osteoarthritis-grade category subcategorized by trapezial region of interest. A significant difference ($p < 0.007$) between the dorsoradial region and both the voloulnar and dorsoulnar regions of interest was found (Wilcoxon signed ranks test).

TABLE 2. **Areas of Trapezial and Metacarpal Facets and Bony Joint Recesses**

	Areas of Trapezial Facets and Recesses (mm^2) (mean ± SD) n = 14			*Areas of Metacarpal Facets and Recesses (mm^2) (mean ± SD) n = 14*	
	Main Facet	*Radial Recess*	*Ulnar Recess*	*Main Facet*	*Volar Recess*
Male hands (*n* = 10)*	197.30 ± 14.56†	24.76 ± 7.16	23.77 ± 9.11	239.66 ± 26.03‡	32.12 ± 10.43
Female hands (*n* = 4)*	160.50 ± 13.36†	20.84 ± 3.72	13.68 ± 2.76	184.51 ± 19.28‡	21.52 ± 12.10

For each joint feature the mean area for males was compared with that for females.
*Note: Of the total number of hands dissected (25), a total of 14 hands (10 from males, 4 from females) were of osteoarthritis grade 0–2 (i.e., mild degeneration). It was these hands only from which three-dimensional computer models were reconstructed and for which area measures are available.
†$p < 0.005$.
‡$p < 0.005$.

Descriptive Qualitative Analysis

The metacarpal was predominantly saddle (or sellar) shaped (Figures 3A and 3C). The sellar topography extended along a central band from the radial to the ulnar aspect of the joint and spanning about two-thirds the width of the surface along the dorsovolar direction (Figure 3C). The dorsal and volar aspects of the metacarpal were ovoid (i.e., convex). The dorsal ovoid region usually consisted of one or sometimes two prominences, whereas the volar ovoid region usually had one. The trapezium was also generally saddle shaped over most of its surface (Figures 3B and 3D), with narrow ovoid regions appearing around the radial and ulnar periphery (Figure 3D). In each specimen, prominent bony joint recesses were found at the radial and the ulnar aspect of each trapezium (Figure 1B) and on the volar metacarpal surface (Figure 3A).

DISCUSSION

Quantitative Findings: Location of Osteoarthritic Degeneration

The primary research question addressed by this study was the location of cartilage degeneration in CMC-OA. We hypothesized that mechanical abrasion of cartilage should result in differences in the degree of degeneration between the regions of interest within the joint. A common articular wear pattern was observed, with the dorsoradial quadrant of the trapezium being significantly more degenerated, a finding suggested by the joint impingement model of CMC-OA pathogenesis.[15–19] Anterior degeneration, as explained by the Ligamentous Laxity model,[2,9–14] was not found in this sample. The joint impingement model was not completely supported by the findings of our study, in that we observed a lack of significant degeneration of the cartilage in the voloulnar surface of the trapezium.

A number of previous investigations have been conducted examining the articular wear pattern within the human CMC.[2,11,13,14,29,30] The results of Shi et al.[30] and of Momose[29] were in general agreement with those of the present study in that the radial aspect of the joint was reported to be the most degenerated region. In contrast, Pellegrini et al.[2,11,13,14] reported that eburnation appeared consistently in the palmar area of the CMC. However the samples examined by Pellegrini et al.[2,11,13,14] were significantly more degenerated than those examined in the present study, being radiographic stage III or IV or being harvested from patients undergoing total joint arthroplasty.

It may be that degeneration affects different parts of the trapezium in different stages of the disease, with the radial region being affected early on, and the volar region being affected later. The shift in osteoarthritic focus may be due to alteration of joint biomechanics resulting from changes in joint shape, changes in the mechanical properties of articular cartilage, or as a result of concomitant degeneration of other functionally important joint structures such

TABLE 3. **Measures of Joint Contour (i.e., Convexity and Concavity) for the Trapezium and the Metacarpal**

	Trapezium		*Metacarpal*	
	Convexity (mean ± SD)	*Concavity (mean ± SD)*	*Convexity (mean ± SD)*	*Concavity (mean ± SD)*
Male hands (*n* = 10)*	36.3 ± 8.2	8.7 ± 2.0†	23.9 ± 3.51	11.5 ± 3.3
Female hands (*n* = 4)*	34.6 ± 5.5	11.6 ± 1.7†	27.1 ± 3.9	9.6 ± 2.2

Indexes of concavity or convexity reported as percentages of greatest depth of concavity or convexity * 100/(width of surface). Mean indexes of concavity or convexity of males were compared with those of females.
*Note: Of the total number of hands dissected (25), a total of 14 hands (10 from males, 4 from females) were of osteoarthritis grade 0–2 (i.e., mild degeneration). It was these hands only from which three-dimensional computer models were reconstructed.
†$p < 0.05$.

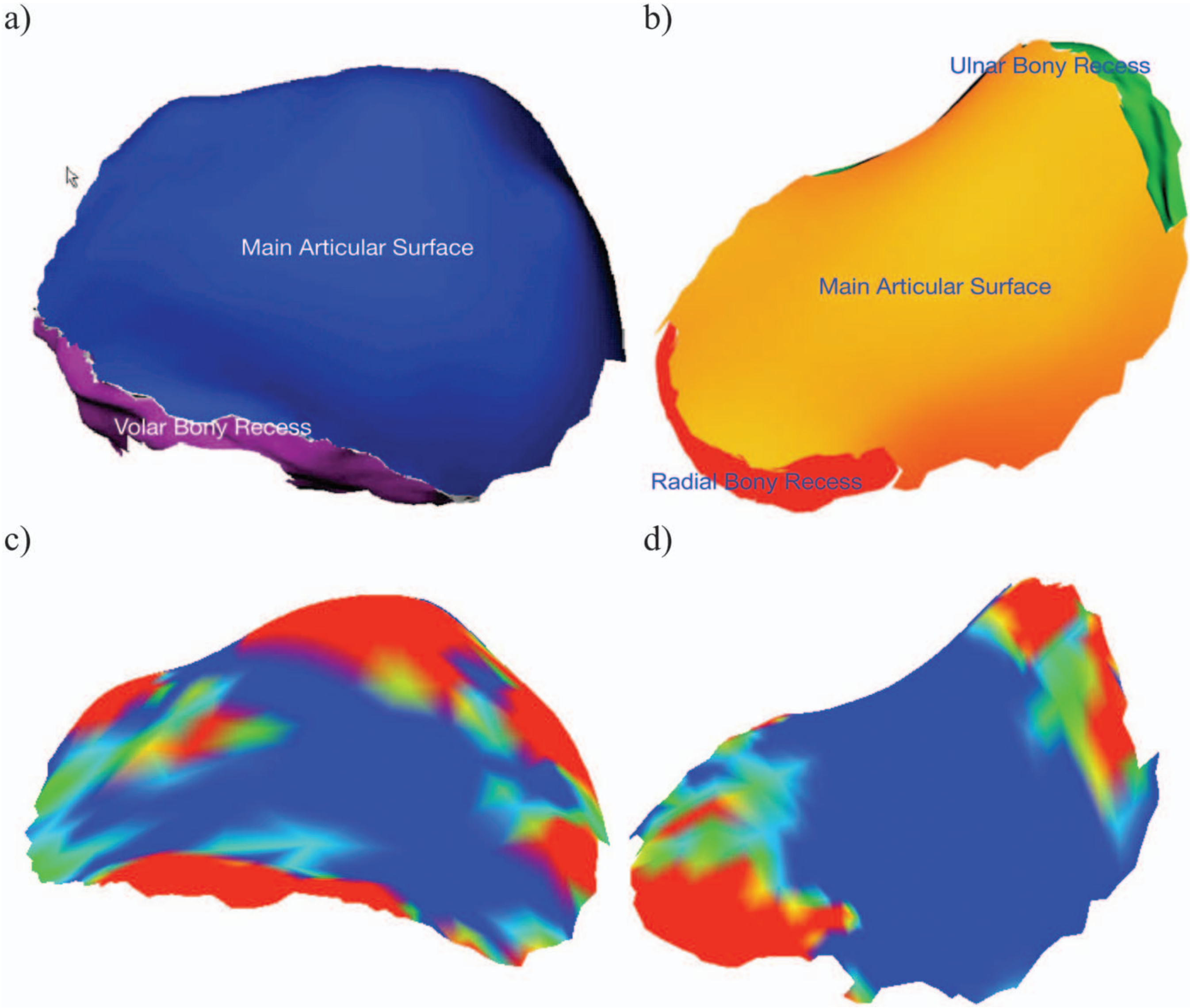

*FIGURE 3. Rendered images of voloinferior view (**a**) and dorsosuperior view of the right trapezium (**b**). In the metacarpal, the blue surface is the main articulating area whereas the purple area represents the volar bony recess. In the trapezium, the main articular area is shown in gold while the radial and ulnar bony recesses are shown in red and green, respectively. Surface curvature analysis of the main articular facets of the metacarpal (**c**) and the trapezium (**d**). Ovoid (i.e., convex) areas are shown in red, saddle-shaped areas in blue, and flat areas in green.*

as the palmar beak ligament. Wear pattern differences between mildly and severely degenerated specimens were recently reported by Koff et al.[31]

Quantitative Findings: Male/female Differences in Area and Joint Contour

The second research question of this study was whether there were any significant topographic differences between joints from males and females that might account for the known demographic differences in CMC-OA susceptibility. When the area and contour of the articular specimens were gauged, the joints from females were found to be both smaller and more concave in radioulnar profile than those from males.

The present investigation is only the second to report such precise measurements of CMC facet areas. Although conducted on a smaller sample of more degenerated specimens, Ateshian et al.[20] agreed that the joint surfaces of males and females differ in size. Also, it has been previously reported[32,33] that lateral key grip may put as much as 24 times the amount of force through the trapezial surface as exerted at the tip of the distal phalanx. Because the articular surfaces of joints from females are significantly smaller than those from males, an identical amount of force may result in greater physical stress through the female joint and thus pose a higher risk of cartilage damage.[23]

With respect to the parameter of joint contour, it is significant that the radioulnar profile of the trapezium bones from males was less concave (i.e., flatter) than that of female bones. The flatter radioulnar profile of male joints might function to protect against impingement of surfaces in CMC rotation (opposition) and contribute to less mechanical wear, and thus carry a lower risk of CMC-OA. Two previous studies of joint contour in the CMC[22,25] came to mutually contradictory conclusions regarding between-gender differences in joint contour, but neither used equipment of comparable precision to that used in the present investigation.

Qualitative Findings: Topography and Joint Recesses

The third research question of this study was whether bony joint recesses could be consistently found within the CMC joint. Our study confirms qualitative observations of CMC articular topography found in previous studies[20,24,34,35] as well as resolves previously conflicting reports pertaining to the presence and location of bony joint recesses. Our observations are consistent with the findings of Pellegrini[2] and Doerschuk et al.[9] with respect to the presence of an ulnar trapezial, radial trapezial, and volar metacarpal bony joint recess in each specimen examined.

A quantitative investigation by Ateshian et al.[20] reported that the trapezium, though generally saddle shaped, has a narrow ovoid region around the radial joint periphery, a finding confirmed by the present investigation. Zancolli[19] speculated that whereas the saddle-shaped topography is adapted for the angular movements of flexion/extension and abduction/adduction, the ''spheroidal facet'' is responsible for rotary movements of opposition/reposition. Increased wear of the dorsoradial facet of the trapezium was suggested to result from shear stresses at this area during the transition phase between thumb opposition and reposition, when there may be reduced contact between the dorsoradial region of the trapezium and the metacarpal crest.

Clinical Significance

What emerges from the present investigation is that CMC-OA is likely to be promoted by joint impingement resulting from thumb pronation. For this reason, splinting of the symptomatic thumb should emphasize neutral or slightly adducted and supinated positioning to offload the dorsalradial trapezial region. Because other investigations[2,9–14] have reported predominantly anterior damage in the presence of ligamentous hypermobility, anterior offloading may be given higher priority in such cases by splinting the thumb metacarpophalangeal joint into flexion.[36]

The efficacy of these recommendations should be assessed by future clinical studies. The outcome of such work will not only be helpful to patients with CMC-OA, but may also contribute to our understanding of the etiopathogenesis of this disorder.

CONCLUSION

The articular wear pattern of dorsalradial trapezial cartilage degeneration found in this study is in keeping with the joint impingement model of CMC-OA etiology. In this model, joint damage is caused by impingement of the joint surfaces during motions of the thumb requiring excessive rotation of the metacarpal base on the trapezium. The ligamentous laxity model, which predicts predominantly anterior joint degeneration, was not supported by the data in the sample examined. Recommendations for joint splinting of the symptomatic CMC were made on the basis of these findings. Future clinical studies need to be done to assess the efficacy of these recommendations.

Detailed measurements of 3-D computer models of the CMC joint surfaces revealed that female joints are smaller and more concave in radioulnar profile than those of their male counterparts. The topography of the female trapezium may increase the likelihood of joint surface impingement in functional tasks requiring pronation of the thumb and contribute to the observation of increased susceptibility among females to CMC-OA.

This study used commercially available 3-D digitization and reconstruction methods to visualize and quantitatively analyze the human CMC joint both globally and in its subtle topographical features, such as bony joint recesses. Two trapezial (i.e., radial and ulnar) and a volar metacarpal bony joint recesses were found. Reproducible and accurate 3-D geometric models of the cartilage surfaces of the trapezium and first metacarpal were generated using this technique.

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