Published in final edited form as:
Conf Proc IEEE Eng Med Biol Soc. 2014 ; 2014: 4354–4357. doi:10.1109/EMBC.2014.6944588.

Thumb carpometacarpal joint congruence during functional tasks and thumb range-of-motion activities

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Abstract

Joint incongruity is often cited as a possible etiological factor for the high incidence of thumb carpometacarpal (CMC) joint osteoarthritis (OA) in older women. There is evidence suggesting that biomechanics plays a role in CMC OA progression, but little is known about how CMC joint congruence, specifically, differs among different cohorts. The purpose of this in vivo study was to determine if CMC joint congruence differs with sex, age, and early stage OA for different thumb positions. Using CT data from 155 subjects and a congruence metric that is based on both articular morphology and joint posture, we did not find any differences in CMC joint congruence with sex or age group, but found that patients in the early stages of OA exhibit lower congruence than healthy subjects of the same age group.

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I. INTRODUCTION

The opposability of the human thumb is owed to the saddle-shaped thumb carpometacarpal (CMC) joint, located at the base of the thumb (Fig. 1). This versatile joint, however, is often prone to osteoarthritis (OA). CMC OA, which can be highly debilitating due to the central role that the thumb plays in many tasks of daily living, is a disease of undetermined etiology. While there is evidence that systemic and genetic factors are implicated in its progression [1], [2], biomechanics is also believed to play an important role [3], [4]. Due to a mechanical disadvantage, the CMC joint experiences loads that are up to 12 times higher than the loads applied at the tip of the thumb [5]. Adequate distribution of contact stresses in the joint, which is necessary for healthy cartilage metabolism, is highly dependent on joint congruence [3]. Therefore, previous studies have hypothesized that women, who are more predisposed to CMC OA, may have inherently less congruent joints than men [6]–[8].

Previous studies of CMC joint congruence have been based on average principal curvatures of the articular geometry of older cadaveric specimens [7], [8]. These studies concluded that: 1) female joints are less congruent than male joints, 2) elderly joints are more congruent than middle-aged joints, and 3) severely arthritic joints are more congruent than minimally arthritic joints. These studies are limited in two ways. First, the use of older cadaveric specimens does not permit insight into baseline sex-related differences in articular morphology and congruence because aging and OA are confounding factors. Second, congruence depends on both articular geometry and physiological joint posture, which is guided by muscles and ligaments.

The aim of the current study was to assess thumb CMC joint congruence in vivo, across different thumb positions, as a function of sex, age, and early stage OA. We recruited healthy men and women of two age groups, as well as patients with early stage OA. We hypothesized that congruence would not be different between young healthy men and women, that it would not be different between age groups, and that it would be lower in the OA patients than in healthy subjects of the same age group.

II. METHODS

A. Data Acquisition

After receiving approval from our Institutional Review Board and obtaining informed consents, 68 asymptomatic subjects (16 young men, age = 24.7 ± 4.5 yr.; 17 young women, age = 24.7 ± 3.2 yr.; 16 older men, age = 53.8 ± 8.7 yr.; 19 older women, age = 55.8 ± 6.6 yr.) and 87 patients with Eaton Stage I/II CMC OA [9] (39 men, age = 60.2 ± 7.6 yr.; 48 women, age = 51.5 ± 10.5 yr.) were enrolled in the study. The dominant wrists and thumbs of the healthy subjects and the affected wrists and thumbs of the OA patients were CT-scanned at a resolution of approximately 0.3mm × 0.3mm × 0.625mm, in a neutral position, during three isometric functional tasks (key pinch, jar grasp, and jar open), and during four maximum thumb range-of-motion positions (extension, flexion, abduction, and adduction). Thumb postures were standardized with an adjustable brace for the neutral position and with custom-designed polycarbonate fixtures for the functional tasks and range-of-motion positions (Fig. 2a–h). During the functional tasks, the subjects were scanned while they applied 80% of their pre-recorded maximum effort for that particular task. A Labview program displaying feedback from a load cell that was mounted into the fixtures assisted them in maintaining the load during the 30–45 second scan.

B. Data Analysis

The bones in the CMC joint were segmented semi-automatically (Mimics, Leuven, Belgium) from the neutral CT volumes and exported as 3-D meshed surfaces. Joint postures across the different tasks were obtained by computing 3-D kinematics of the trapezium and first metacarpal from the neutral position to the remaining positions with a markerless bone registration algorithm [10]. The subchondral surfaces were manually delineated on both the trapezium and metacarpal by tracing the visible margin of cartilage (Fig. 3a). Fifth order polynomial surfaces were fit to the articular surface points and principal curvatures (k_{min} and k_{max}) were computed at points uniformly sampled on the fitted surfaces (Fig. 3b).

Joint congruence was evaluated using polar histograms of curvature (H) of the mating articular surfaces—essentially 3D histograms, with the physical polar coordinates (r, θ) being the first two dimensions and curvature being the third. (Fig. 3c) [11]. The polar coordinate system was registered to each articular surface by defining the saddle point as the origin and the dorsal-volar principal direction of curvature as the polar axis. The advantage of using polar histograms as shape descriptors is that they preserve spatial information. Polar histograms of k_{max} curvature were computed for the trapezial surfaces and polar histograms of k_{min} curvature were computed for the metacarpal surfaces, since the principal directions of curvature are offset by 90º between the trapezial and metacarpal surfaces. Congruence was conceptualized as a measure of the dissimilarity between the histograms, H_1 and H_2, of mating surfaces in the same joint and was computed using a modified Bhattacharyya distance [12]. As previously mentioned, the congruence of a joint depends on both articular bone geometry and joint position. To ensure that positional information was incorporated in the congruence measure, both the trapezial and the metacarpal polar histograms of curvature were computed in terms of one coordinate system—the trapezial coordinate system. Across positions, the histogram of the trapezial articular surface, H_1, was kept unchanged, whereas the histogram of the metacarpal articular surface, dH_2, was recomputed, as the relative position of the metacarpal with respect to the trapezium changed. The dissimilarity between H_1 and dH_2, or position-dependent congruence measure (pJC), was then computed at each position as follows:

$$pJC(H_1, dH_2) = -ln\left(\sum_{x=1}^{b^3} \sqrt{H_1(x) * dH_2(x)} * w_x\right). \quad (1)$$

The number of bins, b, for each of the dimensions of the histograms was 7. A weighing factor that is inversely proportional to the bone-to-bone distance was implemented to ensure that the areas on the mating articular surfaces that were in closer proximity had a higher weight on the final congruence metric:

$$w_x = \frac{b^2}{h_x * \sum_{y=1:b^2} \frac{1}{hy}}, \qquad (2)$$

where h is the average bone-to-bone distance for a given physical bin, or a sector in the polar coordinate system.

C. Statistical Analysis

Repeated measures analyses of variance (ANOVAs) were used to determine if joint congruence changed significantly across the different joint positions in healthy subjects and OA patients. Pairwise multiple comparisons of the congruence measure in the neutral position versus all the other positions were carried out using Dunnett’s method. Multivariate ANOVAs of the congruence metric across the different joint postures were used to determine the effect of sex in the young healthy subjects, the effect of age group in both healthy men and healthy women, and the effect of early OA in OA patients and age-matched healthy controls.

III. RESULTS

Joint congruence in the neutral position was significantly different from congruence in the other positions, both in healthy subjects and in OA patients ($p<0.001$). Congruence in the healthy young subjects was not significantly differenct between sex groups ($p<0.05$ across all of the scanned positions; Fig. 4a). Age also did not have a significant effect on the congruence of either men or women ($p<0.05$ across all of the positions; Fig. 4b). Patients with early OA had significantly higher *pJC*, which corresponds to lower congruence, across all the positions (Neutral $p < 0.0001$; Pinch $p = 0.0006$; Pinch Load $p = 0.0042$; Jar Open $p = 0.0076$; Jar Open Load $p = 0.0047$; Jar Twist $p = 0.0004$; Jar Twist Load $p = 0.0027$; Flexion $p = 0.0027$; Extension $p = 0.0053$; Abduction $p = 0.0021$; Adduction $p = 0.0066$; Fig. 4c).

IV. DISCUSSION AND CONCLUSION

The purpose of this study was to determine if the congruence of the CMC joint differs with sex, age, or early stage OA. Using in vivo data from 155 subjects and a congruence measure that accounts for both articular shape and joint position, we did not find sex and age group to affect CMC joint congruence. We found that subjects in the early stages of OA have lower congruence than healthy subjects of the same age group.

When interpreting the results presented here, it is important to acknowledge the following limitations and characteristics of the study. First, our analysis was performed on subchondral bone surfaces because joint contact cannot be determined directly from CT volume images. To account for the lack of contact information, we employed a weighing factor in the congruence measure, which assigns higher weight to the areas that are in closer proximity. Second, this is a cross-sectional study, therefore the effects of aging and OA cannot be determined with certainty, but in the absence of longitudinal data, the results presented here provide valuable insight. Lastly, it should be noted that the congruence measure utilized here is a measure of articular conformity, independent of joint size. Larger joints, with the same shape and congruence as smaller joints, have larger contact areas, and therefore allow for a better distribution of contact stresses, which when not optimally distributed, contribute to chondrocyte derangement and cartilage degradation.

Our finding that patients with early stage OA have less congruent CMC joints than healthy subjects of similar age contradicts findings from a previous study that reported improved joint congruence with OA progression [8]. Xu et al. obtained these results by utilizing a congruence measure that is based solely on the average principal curvatures of the joint [8]. Joint congruence, however, is heavily dependent on joint position. The differences with joint position that we found here underscore the importance of a congruence measure that takes physiological position into account. Also, unlike bone remodeling due to aging, which reportedly occurs in a predictable manner, i.e., flattening of the joint [13], morphological changes due to CMC OA have been documented as irregular [14], making average curvature measures less informative than shape descriptors that preserve spatial information. Our congruence measure incorporates spatial information on the curvature of articular surfaces. As mentioned above, it cannot be determined if congruence is lower in arthritis-prone joints or if it co-develops with other arthritic progressions. We have found that joint kinematics are not different between healthy subjects and patients with early stage OA [15], [16], but the shape of the articular joint surfaces [17] and cartilage thicknesses [18], [19] are different. It remains to be determined whether the difference in congruence, as measured here, is a result of altered morphology, decreased cartilage thickness, or a shift in joint contact that results in altered conformity.

Our inability to detect differences with sex and age groups is also in disagreement with previous findings [7], [8]. Again, the previously reported differences are based on a measure of the similarity between the average principal curvatures of the mating articular surfaces, without accounting for joint posture. Such a measure yields higher congruence for larger joints, even if the joint shape is identical, and higher congruence for flatter joints, even if joint contact is the same. Since the trapezial and metacarpal saddles are non-conforming, their flattening may result in better geometrical similarity, which may lead to altered, but not greater, contact during physiological joint positions. Xu et al. reported that, although the CMC joint flattens with aging, resulting in an increase in the congruence measure that is based on average principal curvatures, joint contact does not increase [8].

CMC OA affects two-thirds of women over the age of 55 years [20]. Current treatment options are limited to injections or surgical procedures that reduce pain, without restoring thumb mobility. Advances in treatment options, including implants, could significantly improve quality of life in CMC OA patients, if restoration of thumb mobility is achieved. A crucial first steps in developing and implementing new procedures is understanding the biomechanics of this joint, in health and disease. Our findings suggest that joint congruence is not a primary etiological factor in CMC OA, but larger bones may result in greater joint contact and better distribution of stresses. A study of joint space will shed further light into the findings reported here.

Acknowledgments

The authors thank A Garcia and D Kenny for subject recruitment, JC Tarrant for assisting in subject scanning and data processing, JB Schwartz for assisting in subject scanning, B Berg for his software engineering support, Dr. M Conconi for conversations on joint congruence, Dr. CJ Got for lending his clinical expertise, and Dr. BJ Wilcox for designing the Labview program used during CT scanning.

This work was supported by the National Institutes of Health Grant number AR059185 and the American Society for Surgery of the Hand.

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Figure 1.

a) Three-dimensional rendering of a CT scan of a right hand, with the thumb CMC joint highlighted

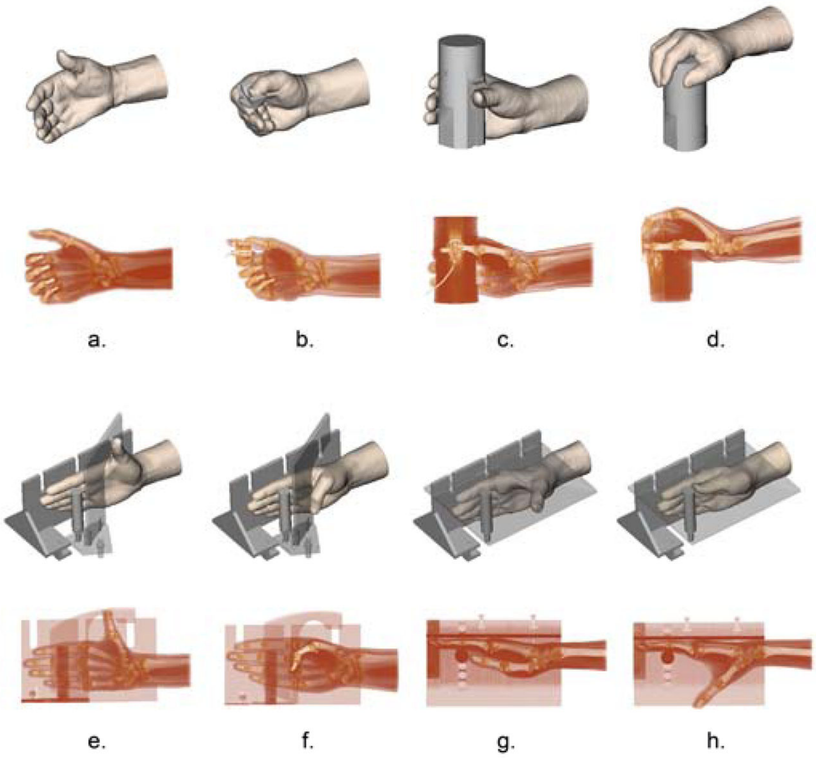

Figure 2.

Three-dimensional renderings of the hand of one subject in the standardized thumb positions: **a)** neutral, **b)** key pinch, **c)** jar grasp, **d)** jar open, **e)** extension, **f)** flexion, **g)** abduction, and **h)** adduction

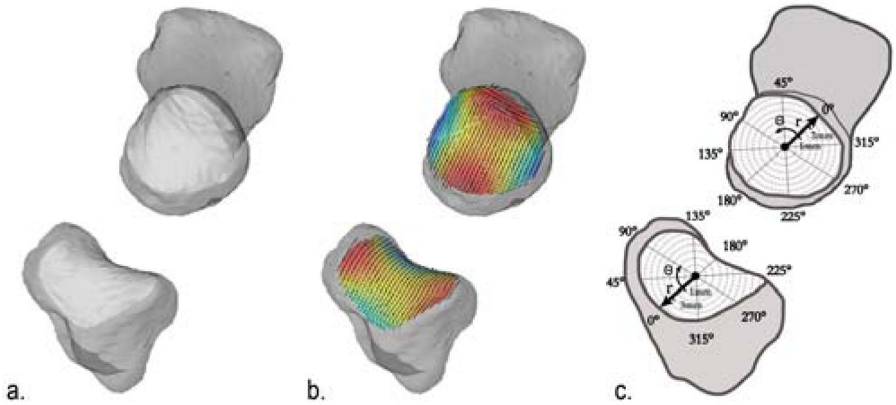

Figure 3.

a) The trapezium and metacarpal bones with the manually selected subchondral surfaces; **b)** fifth order polynomial surfaces fitted to the subchondralsurfaces, colored by elevation from the local inflection point, with the k_{max} vector field on the trapezium and the k_{min} vector field on the metacarpal; **c)** polar coordinate systems on the articular surfaces of a joint, illustrating two of the dimensions of the 3D histograms: **r** is the radial coordinate, or the distance from the origin (in mm), and θ is the angular coordinate, or the angle from the polar axis (in degrees)

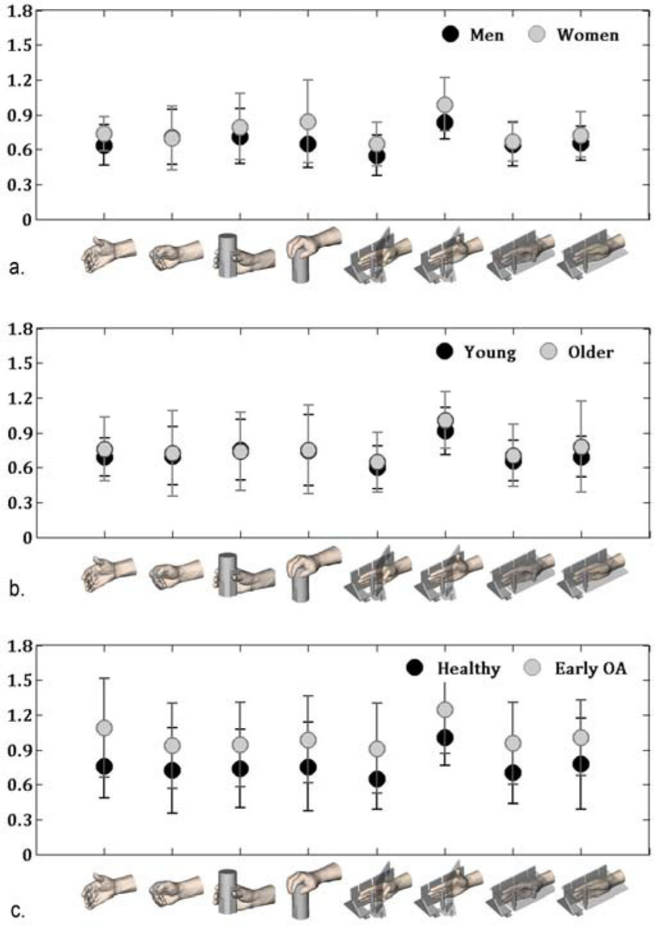

Figure 4.

Joint congruence (*pJC*), where a higher value corresponds to higher dissimilarity and therefore lower congruence, across the scanned positions **a)** was not significantly different between young healthy men and young healthy women **b)** was not significantly different between young healthy subjects and older healthy subjects **c)** was significantly higher in older healthy subjects than in patients with early stage OA, across all of the scanned positions