A three-dimensional analysis of osteoarthritic changes in the thumb carpometacarpal joint

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Abstract
The purpose of this study is to gain a better understanding of the changes due to osteoarthritis (OA) occurring in the thumb carpometacarpal (CMC) joint by comparing quantitative geometrical measurements in computed tomography scans of healthy and pathological joints in various stages of OA. The measurements were [1] the subluxation of the metacarpal on the trapezium, [2] distance from the scaphoid centre to the metacarpal base, and [3] distance from the metacarpal base to the articulating surface of the trapezium. The three-dimensional position of three characteristic points on the metacarpal, trapezium, and scaphoid were detected in each of the 90 wrists we scanned. The distances between the points were compared by statistical analysis. With high accuracy, we have been able to confirm and quantify that subluxation occurs in the dorso-radial direction. A significant difference in trapezium height and joint space width was found between the OA and control groups. The results indicate how to restore the centre of rotation in surgical treatment of OA with total joint arthroplasty, but the clinical relevance of these findings has to be tested in further clinical studies.

Keywords
Osteoarthritis, trapeziometacarpal joint, trapezium, carpal bones, CT

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Introduction
The prehensile biomechanical function of the hand is largely due to the complex saddle-shaped thumb carpometacarpal (CMC) or trapeziometacarpal (TM) joint,
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which enables tri-planar motion. Unfortunately, the unique motion of the thumb CMC joint renders it vulnerable to attrition of the articular surfaces leading to osteoarthritis (OA), especially in postmenopausal women, and to a lesser degree, in men (Bettinger et al., 2001; Eaton and Littler, 1969; 1973). Depending on the progression of the disease, symptoms range from discomfort to the complete inability to manipulate objects (Cerveri et al., 2010; Xu et al., 1998).

The exact etiology of thumb CMC joint OA is disputed, but articular cartilage degeneration has been attributed to the high loads transmitted across the joint and to specific articular surface topography and mechanics (Chao and An, 1978; Maxian et al., 1995). A common rationalization is that ligament laxity and incompetence lead to subluxation of the thumb metacarpal on the trapezium and areas of high contact stress occur. This results in cartilage erosion, further subluxation, and OA (Bettinger et al., 2001; Momose et al., 1999).

The osteoarthritic changes of the thumb CMC joint seen on radiographs are classified using the four stage Eaton–Glickel classification of 1987 by evaluation of osteophytes, joint space narrowing, osteosclerosis, subluxation, and cystic changes in the thumb CMC joint. In Eaton stage IV, there are similar destructive changes in the scaphotrapezial joint (Eaton and Glickel, 1987). Early joint degeneration (stage I) may be treated by conservative means such as immobilization or steroid injections. In the later stages (II, III, and IV) surgery may be required, and commonly used methods include trapezectomy, tendon interposition arthroplasty, and hemi and total joint replacement surgery (Gangopadhyay et al., 2012; Giddins, 2012; Johnston et al., 2011; Kaszap et al., 2012; Klahn et al., 2012; Maru et al., 2012; Poulter and Davis, 2011; Regnard, 2006; Ulrich-Vinther et al., 2008).

The osteoarthritic dataset of CT scans were obtained at Holstebro Regional Hospital and Herning Regional Hospital, Denmark. All subjects experienced thumb pain and dysfunction. They were all graded for thumb CMC OA by an experienced hand surgeon (T.B.H.) using the Eaton–Glickel classification based on standard radiographs (Hansen et al., 2012).

The control dataset of CT scans were obtained as part of standard patient care, to assess both the symptomatic and contralateral healthy wrist as a reference. These scans were collected over 2 years at the Academic Medical Center, The Netherlands. An experienced radiologist assessed all scans over this period and excluded all wrists showing pathological changes.

Image acquisition

The osteoarthritic dataset images were acquired using 3 CT scanners: LightSpeed VCT; LightSpeed16 scanner (GE Medical Systems, Milwaukee, Wisconsin, USA); and Brilliance 64 (Philips Medical Systems, Best, The Netherlands). Control dataset images were acquired using an Mx8000 Quad CT scanner (Philips Medical Systems).

The acquisition parameters for all scans were similar. Representative acquisition parameters were collimation 2 x 0.5 mm, tube voltage 120 kV, effective dose mAs 75, pitch 0.875, and slice thickness 0.6 mm; scans were made in ‘ultra high resolution’ mode (i.e., small focal spot size). Tomographic reconstructions were made with a high resolution kernel, field of view of 150 mm, slice increment of 0.3 mm, and matrix of 512 x 512 pixels.

For all scans, in both the OA and control datasets, the voxel (three-dimensional pixel) sizes differed, but all deviated < 10% from a size of 0.3 x 0.3 x 0.3 mm³. All scans were resampled to isotropic voxels of 0.3 mm using linear interpolation to simplify post-processing. All analyses and measurements were performed using MATLAB R2010a (MathWorks, Inc., Natick, Massachusetts, USA).

Semi-automatic segmentation

An initial, rough segmentation of the carpal bones was obtained using simple thresholding and confirmed project. Permission from the data protection agency was obtained (Jr. Nr. 1-16-02-67-12).

Patient characteristics

We reviewed CT scans of patients with thumb CMC joint OA and those with normal thumb CMC joints.

All subjects underwent investigation including a CT scan as part of routine clinical assessment. Thus, no extra investigations were performed over and above our norm, and so no consent was required. In accordance with local ethical guidelines, no ethical approval was required for this study because it was a medical database research...
with manual identification of each bone in MATLAB R2010a (MathWorks, Inc.). Where thresholding did not separate the bones, a manual correction was applied to the thresholding result by manually annotating the bone surface. This initial segmentation was obtained and refined using a level set segmentation method (Caselles et al., 1997; Sethian, 1999). Subsequently, a marching cubes method was used to extract a triangulated bone surface from the segmentation results (Lorensen and Cline, 1987). This method was previously found to be reproducible with a precision in the order of a tenth of the voxel size for different CT scans of the same carpal bones, while the accuracy was judged visually to be in the order of the voxel size (van de Giessen et al., 2009). An example of a fully segmented wrist can be seen in Figure 1.

Orientation and registration

Several of the measurements described in the following sections are orientation dependent. Therefore, all wrists were mirrored to resemble a left wrist. Furthermore, all scaphoids, trapezia, and metacarpals were aligned to a reference using a point cloud registration method (Myronenko and Song, 2010). This resulted in the scaphoids and trapezia of all the wrists being aligned and scaled in order to remove the effect of the difference in wrist size between subjects. This ensures that the difference in the metacarpal position between all subjects can be compared quantitatively.

Measurements

In order to perform the analyses, it was necessary to find the joint space of the thumb CMC joint and three anatomical landmark points for each wrist. The thumb CMC joint space was found first and then used to derive the intercondylar point on the metacarpal and reference point on the trapezium. A third reference point for the scaphoid was automatically determined, as described below.

**Thumb CMC joint space identification**

For each wrist, the joint space was defined by finding the joint surface between the trapezium and metacarpal using a method described by van de Giessen et al. (2009). The detection of the joint surface is restricted by two conditions: (1) the angle between the normal vectors of the adjacent bone surfaces should deviate less than a predetermined angle and (2) the maximum distance between adjacent bone surfaces should be less than a predetermined distance. The first condition ensures that the surface is only found between bone surfaces facing each other; the second condition prevents false detections of oppositely oriented, but non-adjacent surfaces. These settings only affected the outer edge of the surface and were experimentally determined to produce consistent joint space surfaces for all included wrists (van de Giessen et al., 2009).

**Reference points**

Three reference points were identified in each wrist: the intercondylar point on the metacarpal, a reference point on the trapezium, and a reference point for the scaphoid (Figure 2).

The intercondylar point was defined as the point between the rounded protuberances at the base of the metacarpal. Using the previously detected surface between the metacarpal and trapezium, reference points can be approximated by projecting the centre of gravity of the thumb CMC joint surface onto the metacarpal and trapezium, thus obtaining the intercondylar point on the metacarpal and reference point on the trapezium. The centre of gravity of each scaphoid was calculated and used as the final reference point for the scaphoid. Using these reference points, the following three measurements were made: subluxation of the metacarpal with respect to the trapezium; scaphoid-metacarpal height; and joint space width.

**Subluxation**

Subluxation of the metacarpal was measured using the location of the intercondylar point on the metacarpal in the three dimensional space of the aligned wrists. Using the OA and control groups as two
separate classes, a linear discriminant analysis (LDA) was performed to obtain the optimal axis along which to measure the subluxation (Fisher, 1936). In this study, LDA was used to find an axis along which the difference in metacarpal position between the two groups could be measured. This difference measured along the axis is the subluxation of the metacarpal with respect to the trapezium. Furthermore, the direction of the calculated axis indicates the direction of subluxation.

The data were split randomly using 20% of the intercondylar metacarpal points for each group to calculate the direction of the axis. The remaining 80% of the two groups was used to quantify the accuracy of the calculated direction. To verify that the axis was calculated consistently, this procedure was repeated 100 times with the complete dataset.

**Scaphoid-metacarpal height**

The scaphoid-metacarpal height is defined as the distance between the scaphoid reference point and the metacarpal intercondylar point (Figure 2). This height represents a new measure to quantify the change in the joint and we believe this may be correlated to joint laxity.

**Joint space width**

The joint space width refers to the joint gap between the articulating surfaces of the metacarpal and trapezium.

**Data analysis**

For each measurement three statistical analyses were performed. The first analysis compared the control and OA groups. The second analysis compared women to men within the OA group. The final analysis compared OA stage II against stage III. Stages I and IV were excluded due to insufficient numbers.

The resulting measurement data were tested for normality using the Shapiro–Wilk test in addition to skewness and kurtosis tests. Normally distributed data with equal variances were tested with a t-test (two-group mean-comparison test). Equality of variances were tested with an F-test (two-group variance-comparison test). Non-normal data were tested with the non-parametric Wilcoxon rank-sum test. The 95% confidence intervals for non-normal data were estimated using bias-corrected and accelerated bootstrapping from 4000 replicates. Significance levels were set at $p < 0.05$.

**Results**

The OA group consisted of 45 CT scans of patients (11 males, 34 females) with a mean age of 58 (40−72) years. The control group consisted of 45 CT scans of patients with a mean age of 38 (18−62) years. In the OA group, there were one stage I, 18 stage II, 25 stage III, and one stage IV on the Eaton–Glickel classification. All distances were measured in the coordinate system of the reference subject.

**Subluxation**

The difference in the osteoarthritic group thumb metacarpal subluxation was found to be a mean of 2.45 mm (95% CI 2.06−2.77, $p \leq 0.001$) compared with control (Figure 3). There was a significantly higher mean difference of 0.74 mm (95% CI 0.18−1.31, $p = 0.011$) for men compared with women (Figure 4). When stage II and III cases were compared, there was a non-significant tendency to increased subluxation in stage III of 0.37 mm (95% CI −0.10 to 0.84, $p = 0.123$). The direction of subluxation determined by LDA was radial-dorsal, as illustrated in Figure 5.

**Scaphoid-metacarpal height**

A decrease in scaphoid-metacarpal height of 1.65 mm (95% CI 1.20−2.10, $p \leq 0.001$) was measured in the osteoarthritic group compared with the control.
No statistically significant difference in scaphoid-metacarpal height was found between men and women. The mean decrease in scaphoid-metacarpal height was 0.41 mm (95% CI −0.13 to 0.86, $p = 0.065$) more in stage III cases compared with stage II, which might be clinically relevant, but was not statistically significant.

**Joint space width**

A decrease in joint space width of 0.53 mm (95% CI 0.41–0.65, $p \leq 0.001$) was measured in the
ostearthritic groups compared with the control group (Figure 7). No statistically significant difference was found between men and women. No significant difference was found between stages II and III. A complete summary of the results are presented in Table 1.

<table>
<thead>
<tr>
<th>Group</th>
<th>Control</th>
<th>OA</th>
<th>Mean difference (SD), mm</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subluxation</td>
<td>−1.90 to 2.31</td>
<td>−1.23 to 2.15</td>
<td>2.45 (0.18)</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Scaphoid-metacarpal height</td>
<td>24.92 to 27.32</td>
<td>23.27 to 26.00</td>
<td>1.65 (0.23)</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Joint space width</td>
<td>0.54 to 1.64</td>
<td>0.46 to 1.44</td>
<td>0.53 (0.06)</td>
<td>&lt; 0.001*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sex</th>
<th>Male</th>
<th>Female</th>
<th>Mean difference (SD), mm</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subluxation</td>
<td>−2.59 to −0.60</td>
<td>−0.74 (0.28)</td>
<td>&lt; 0.001*</td>
<td></td>
</tr>
<tr>
<td>Scaphoid-metacarpal height</td>
<td>20.87 to 24.36</td>
<td>21.51 to 26.00</td>
<td>0.08 (0.34)</td>
<td>0.862</td>
</tr>
<tr>
<td>Joint space width</td>
<td>0.14 to 1.27</td>
<td>0.01 to 1.44</td>
<td>−0.13 (0.10)</td>
<td>0.086</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OA stage</th>
<th>Stage II</th>
<th>Stage III</th>
<th>Mean difference (SD), mm</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subluxation</td>
<td>−2.73 to 0.83</td>
<td>−2.55 to −0.11</td>
<td>0.37 (0.23)</td>
<td>0.123</td>
</tr>
<tr>
<td>Scaphoid-metacarpal height</td>
<td>21.51 to 24.65</td>
<td>21.66 to 24.30</td>
<td>0.41 (0.25)</td>
<td>0.065</td>
</tr>
<tr>
<td>Joint space width</td>
<td>0.09 to 1.44</td>
<td>0.01 to 1.27</td>
<td>0.10 (0.09)</td>
<td>0.14</td>
</tr>
</tbody>
</table>

*Statistically significant difference.

Figure 5. All intercondylar points shown together with the trapezium and reference axis. Arrow indicates the observed subluxation in the radial-dorsal direction.

Discussion

We investigated the mechanical and anatomical changes in the OA thumb CMC joint using CT scans. In this study, we confirm that subluxation occurs in the radial-dorsal direction and can be quantified using the described technique.

We believe that subluxation may be an important factor during joint replacement surgery. A common implant design used for TM joint replacements is based on a ball-and-socket joint. However, this replacement and similar designs approximate the thumb CMC joint kinematics poorly because the original saddle joint has a variable centre of rotation (Giddins, 2012; Johnston et al., 2011; Kaszap et al., 2012; Klahn et al., 2012; Maru et al., 2012). The normal TM joint axis of rotation for flexion-extension is located in the trapezium, while the axis of rotation for abduction-adduction is located in the metacarpal (Cerveri et al., 2010; Hollister et al., 1992; Imaeda et al., 1996; Santos and Valero-Cuevas, 2006; Valero-Cuevas et al., 2003). As these axes do not intersect, it is not possible to replace them with a single centre of rotation without changing the thumb CMC kinematics. Furthermore, the design of ball-and-socket
Joints leads to an extra horizontal stress on the trapezium component.

These changes may contribute to the high failure rates of ball-and-socket implants (Alnot and Saint Laurent, 1985; Giddins, 2012; Hansen and Snerum, 2008; Hansen and Vainorius, 2008; Hernandez-Cortes et al., 2012; Johnston et al., 2011; Kaszap et al., 2012; Klahn et al., 2012; Maru et al., 2012; Pérez-Ubeda et al., 2003; van Cappelle et al., 1999; Wachtl et al., 1998). Therefore, it appears important that subluxation is recognized and that the centre of rotation is restored as far as possible during prosthetic surgery.

Figure 6. Height from the scaphoid reference point to the intercondylar point on the metacarpal I. A decrease in height is seen for the OA group.

Figure 7. Joint space width between the trapezium and metacarpal I. The width decrease represents the joint space narrowing characteristic of OA.
Failure to correct the subluxation may lead to reduced joint motion and increased horizontal forces at the radial-dorsal rim of the cup and bone implant interfaces. This further aggravates the shortcomings of the ball-and-socket design and ultimately leads to an increased risk of implant failure. The results of this study may help improve the design of thumb CMC joint arthroplasties.

An important finding was that no significant difference in subluxation was found between stages II and III. This shows that subluxation is probably not a good criterion to differentiate between stages II and III. In addition, the degree of subluxation is not included in the Eaton–Glickel classification as originally described and often, when considering subluxation, stage II and III are seen as one group (Hansen et al., 2012). Problems with intra-rater reliability with the Eaton–Glickel classification may also bias this analysis. Due to problems with the inter-rater reliability of the Eaton–Glickel classification [Dela Rosa et al., 2004; Kubik and Lubahn, 2002], we chose to have assessments of the radiographs performed by a single experienced hand surgeon (T.B.H.).

In this study all wrists were scaled in order to remove the effect of wrist size. This is especially important because of the differences between male and female wrists. Despite the scaling performed, a statistically significant difference was found in subluxation between females and males. The results show that males experience a greater degree of subluxation for a similar stage of OA compared with females. A plausible explanation may be that males experience larger subluxation due to the difference in wrist size.

The study also confirms what is widely known: that a decrease in trapezium-metacarpal joint space width occurs with OA due to both a reduction in cartilage thickness and loss of bone stock. The reduction in joint space width increased with progressing OA. Similarly, we found that the scaphoid-metacarpal height was significantly decreased in the OA group. We suspect that a decrease in the scaphoid-metacarpal height is due to a combination of subluxation, ligament laxity, and loss of cartilage and even trapezium bone.

In advanced OA, the method to detect the bone edges failed to separate adjacent bones because the joint space was extremely narrow or missing (bone-on-bone contact). This is a limitation of the method, but was remedied by applying a manual correction to the initial labelling.

Possible future research includes developing methods to perform measurements directly on CT images without the need for segmenting the bone contours. This would limit the processing time and allow for real-time use in a clinical setting. This could be implemented using active shape models, as described by (Cootes et al., 1994). The resulting model may further improve our understanding of changes in the joint in patients with OA. In the future it would also be interesting to develop a method to measure the degree of restoration of joint rotation after total joint replacement and relate this to implant success and failure.

In conclusion, this study helps the understanding of the changes in joint anatomy in TM osteoarthritis and may be useful for the design of total joint prosthesis and refinement of surgical technique.

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Conflict of interests
None declared.

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