

Biomechanical effect of isolated capitate shortening in Kienböck's disease: an anatomical study

The Journal of Hand Surgery
(European Volume)
38E(5) 500-507
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DOI: 10.1177/1753193412458996
jhs.sagepub.com



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Abstract

Multiple operations have been proposed to slow the progression of osteonecrosis and secondary carpal damage in Kienböck's disease. To assess the biomechanical changes after capitate shortening, we inserted pressure-testing devices into the carpal and radiocarpal joints in an anatomical study. Pressure sensors were placed into eight thawed non-fixated human cadaver arms to measure the forces transmitted in physiological loading. Longitudinal 9.8 N and 19.6 N forces were applied before and after capitate shortening. After capitate shortening, significant load reduction on the lunate was evident in all specimens. An average decrease of 49% was seen under a 9.8 N load and 56% under a 19.6 N load. The load was transferred to the radial and ulnar intercarpal joints. More relief of pressure on the lunate after isolated capitate shortening is achieved with a shallow angle between the scaphoid and capitate in the posteroanterior radiograph.

Keywords

Anatomical study, biomechanics, capitate shortening, Kienböck's disease, lunate necrosis

Date received: 6th March 2012; revised: 15th July 2012; accepted: 17th July 2012

Introduction

Kienböck's disease is defined as aseptic necrosis of the lunate. The advanced clinical and radiographic stages are characterized by carpal collapse, joint incongruity, and osteoarthritis. Vascular abnormalities and skeletal variations are suggested as predictive factors (Almquist, 1993; Schuind et al., 2008). The treatment depends on the severity of the damage to the lunate, carpal stability, and presence of degenerative changes. In general, operations can be divided into those that preserve



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or remove the lunate. Lunate-preserving procedures usually aim for relief of pressure on the lunate or improvement in vascularization. Partial or complete capitate shortening is believed to decrease force on the lunate by transferring the axial load onto the scaphoid, radius, and triquetrum (Almquist, 1993; Schuind et al., 2008).

Anatomical validation of changes in wrist biomechanics is difficult to obtain and has not yet been reported after isolated capitate shortening. To measure the biomechanical changes after isolated capitate shortening, we inserted pressure-testing devices into the carpal and radiocarpal joints in an anatomical study.

Methods

Pressure sensors were placed into eight thawed non-fixed human cadaver arms to measure the forces that are transmitted in an actual anatomical setting. Only specimens with type I lunates with only one midcarpal joint surface were included in the study. The frozen arms were defrosted in a water bath and a radiograph was taken. Arms were disarticulated at the elbow. The proximal third of the forearm was freed from soft tissue. The ulna and radius were cut transversely distal to the elbow joint and held upright in a rectangular bowl,

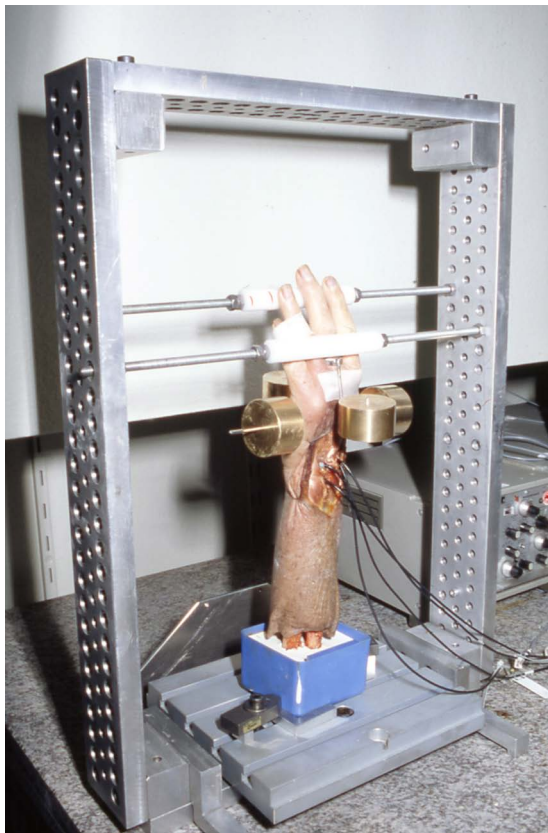


Figure 1. Experimental set-up.

which was consecutively filled with Palacos® (Heraeus, Wehrheim, Germany) or Ureol® 5200 (Ciba-Geigy AG, Basel, Switzerland), a polyurethane potting cement. To reduce costs and increase weight, steel globes (1 cm in diameter) were put into the Palacos. The matrix body was cured within 30 minutes. The wrist and forearm were held in a neutral position. A special frame was constructed to hold the hand in a neutral upright position to allow axial weight loading (Figure 1). The Palacos base was fixed on a floor plate while the hand was held between two transverse plastic barrels, which were affixed to two adjustable poles on the frame.

Procedure

Pressure sensors (BMD-HL 02.03.01, Wazau Mess- und Prüfsysteme GmbH, Berlin, Germany) were placed using a dorsal approach. The device consists of a sensor with a diameter of 8 mm and a height of 5.2 mm. The centre of the sensor facing the joint contains a 1-mm round pressure transmitter (Figure 2). Pressure sensors, which were completely embedded in the bone, allowed assessment of the total force transmission from one bone to the other. The distribution on different parts of the joint surfaces was not measured.

After a longitudinal incision of 7–10 cm in the dorsal midline of the wrist, the extensor retinaculum was split between the third and fourth extensor compartments. The subsequent positions of the sensors were marked with cannulas under X-ray control. Sensors were always placed in the concave-bearing area to avoid projection of the barrel edges into the joint space. First, the dorsal radiocarpal joint was visualized using a longitudinal incision in the radiocarpal ligament. To prevent complete opening of the joint, and thus causing additional trauma to the



Figure 2. The pressure sensor placed in the intercarpal joints.

ligaments, a small channel was created in parallel alignment to the joint surface from a dorsal approach. Later, cables from the sensor were placed in this space, which was subsequently filled with Palacos. After marking the position of the sensor in the radius, space for the sensor was made using a chisel and electrical trepan. Care was taken to achieve an adequate depth for central placement of the pressure sensor. A thin metal plate with a short nail on the back was positioned on the opposite joint surface to create a stable contact area for the pressure transducer. The plate was adjusted to lie central and parallel to the pressure sensor. Both devices were completely embedded in the bone and cartilage. The correct position of the placeholder and metal plate was controlled under fluoroscopy in both planes. The same technique used to place a sensor into the radius was applied to the trapezoid, scaphoid, and triquetrum (Figure 3). Thus, force transmission could be measured between the scaphoid and trapezoid (ST), scaphoid and capitate (SC), triquetrum and hamate (TH), and radius and lunate (RL). At the end of the preparation, the pressure devices and metal

plates were affixed with Palacos or instant adhesive, respectively. Each sensor was placed in the same position in all eight cadavers. All divided ligaments were sutured. Final radiographs confirmed the proper position of all devices.

To secure an equal force transmission, a transverse 4.0 mm Rush pin was drilled into the index to small finger metacarpals while the thumb metacarpal was fixed to the index with a 2.0 mm Kirschner wire. A 9.8 N force was applied with two 500 g weights placed on either side of the Rush pin with care to ensure that they were both the same distance from the midline of the middle metacarpal to prevent radial or ulnar overload. To avoid bilateral bending of the transverse wires with the 19.6 N force, a brace was constructed with a central ring to be placed over the middle finger and two attached hooks perpendicular to the Rush pin that held the additional 500 g weights (Figure 1).

The arms were stored at 7°C overnight. Measurements were carried out the following day before and after capitate shortening.

Capitate shortening

Capitate shortening was done as described by Almquist (1993), but without capitolunate fusion. The capitate was exposed between the extensor tendons of the middle and ring finger. The proximal osteotomy was made with an oscillating saw perpendicular to the capitate axis. The second cut was placed 1.5 mm further distally, creating a 1.8–2 mm defect. Proximal and distal surfaces were fixed with two compression bone screws (Normed, Tuttlingen, Germany) confirmed by posteroanterior and lateral radiographs.

Measurements

Measurements were taken in a neutral position before and after capitate shortening. Load changes were assessed after applying forces of 9.8 N and 19.6 N. All sensors were connected to a KWS 3073 high-frequency amplifier (Hottinger Baldwin Messtechnik, Darmstadt, Germany) in all tests.

Two and four 500 g weights were applied, respectively, with force transduction being recorded after 1, 2, 3, and 4 minutes to minimize errors in measurement. The average value was used for further evaluation. The actual force was calculated as the difference between the values with applied weights and mean initial force without load. The sequence of release and weight application was repeated eight times for 9.8 N and six times for 19.6 N. We started 19.6 N testing with hand number 2. In hands 6 and 8, measurements were also restricted to 9.8 N due to considerable delay



Figure 3. Position of the pressure transmitters seen in the posteroanterior radiograph. Two K-wires were placed to equally distribute load across all metacarpal bones.

during preparation stemming from difficulties in placing the probes. Overall, 9.8 N was applied to eight hands and 19.6 N to five hands.

The anatomical axis of the scaphoid in relation to the capitate was measured on pre-test posterior-anterior radiographs and assessed for correlation to force reduction on the lunate under axial workload (Figure 4). Angles were measured on the printed radiograph using a goniometer with a measuring inaccuracy of 1°.

Statistical analysis

Pre-operative forces were compared with their corresponding post-operative results. For this purpose, the mean load of each single specimen and respective sensor was determined (both pre- and post-test). The presence or absence of significant differences was analyzed using the Wilcoxon signed-rank test as a non-parametric test used for paired samples. Differences between measurements were considered to be significant for a two-sided $p < 0.05$.

Correlation coefficients (r) between the angulation of the lunate and scaphoid, and the decrease in forces transmitted to the lunate, were determined. The linear regression line and the corresponding functional description were calculated.



Figure 4. Angle between longitudinal axes of the capitate and scaphoid in a posteroanterior view.

Results

Data processing was done after completion of all experiments. Figure 5A and B illustrate the arithmetic mean of force measurement of the specified articulations before and after capitate shortening as a percentage of the overall load after 9.8 N and 19.6 N, respectively. Mean values were compared with those after capitate shortening, and percentage of load augmentation was calculated as shown in Table 1.

On average, in the intact carpus, 3.99 (SD 0.67) N of the 9.8 N loads were transferred across the radiolunate (RL) joint. Regarding the carpal bones as three columns (i.e., radial, central, and ulnar), the ulnar column with the hamotriquetral (HT) joint absorbed 1.33 (SD 0.29) N and the radial column, with the scaphotrapezoidal (ST) and scaphocapitate (SC) joints, absorbed 1.40 (SD 0.41) N and 1.67 (SD 1.04) N, respectively. For the 19.6 N load pre-shortening, 7.81 (SD 2.44) N was transferred to the RL, 2.54 (SD 0.92) N on the HT, and 2.09 (SD 0.68) N and 3.89 (SD 1.59) N on the ST and SC, respectively.

After capitate shortening, significant load reduction on the lunate was evident in all specimens. An average decrease of 49% (range 18–68%) was seen under a 9.8 N load ($p < 0.001$) and 56% (range 27–76%) under a 19.6 N load ($p < 0.02$). The load was distributed onto the radial and ulnar intercarpal joints as shown in Table 1.

Relevance of angulation between the scaphoid and capitate

There was a significant negative correlation in the angle between the longitudinal axis of the capitate and scaphoid in a posteroanterior view (Figure 4) and decrease in load on the lunate ($r = -0.94$ under a 9.8 N load; $r = -0.95$ under a 19.6 N load) (Figure 6). Based on these findings, the following relationship was established: the larger the angle between the capitate and scaphoid, the lower the forces between the lunate and radius after capitate shortening.

Based on these correlations, it was possible to determine mathematical functions for the decrease in forces transmitted to the lunate in relation to the angle between the capitate and scaphoid, with the 9.8 N ($y = -1.27x - 12.85$) and 19.6 N ($y = -1.83x + 1.59$) loads.

In order to calculate a line from both series of measurements, an equation of the line was calculated from all points in Figure 6. The regression line is defined by the following function: $y = -1.44x - 9.09$. Variable y represents the post-operative reduction in force on the lunate as a percentage of the pre-load. Variable x describes the angle between the longitudinal axes of the capitate and scaphoid.

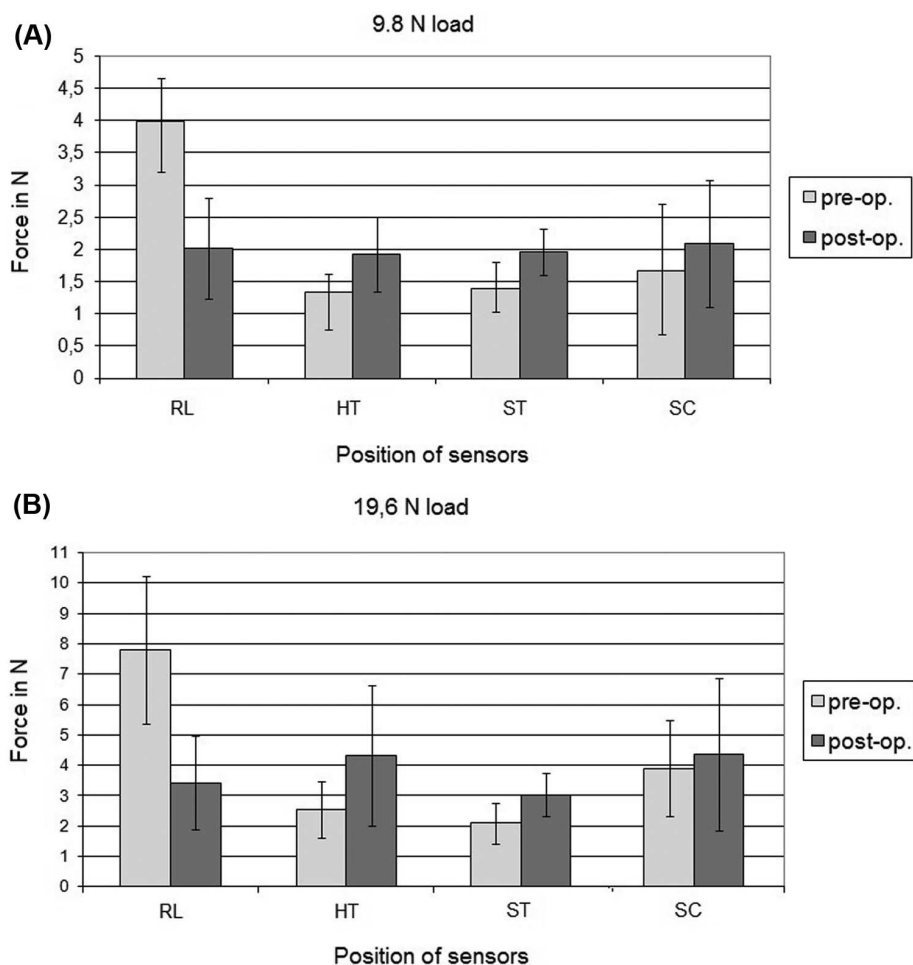


Figure 5. Load distributions on the specified joints under forces of 9.8 N (A) and 19.6 N (B). Whiskers indicate standard deviations.

Table 1. Percentage changes in force transmission over the specified intracarpal and radiocarpal joints after capitate shortening

	Radius-lunate, %	Hamate-triquetrum, %	Scaphoid-trapezoid, %	Scaphoid-capitate, %	Radius-scaphoid, %
9.8 N	-49 ($p < 0.001$)	47 ($p < 0.02$)	52 ($p < 0.02$)	66 ns	-
19.6 N	-56 ($p < 0.02$)	69 ($p < 0.05$)	59 ns	32 ns	-
Horii et al. (1990)	-66	149	69	-52	26
Viola et al. (1998)	-24	-	-	-	20

- = not measured; ns = not significant

Discussion

Kienböck's disease is relatively uncommon; published studies are mostly small and heterogeneous (Lichtman et al., 2010). As a result, treatment of

Kienböck's disease is still empirical. The slow progress of the disease with indistinct stages, frequent absence of significant symptoms, and unclear pathogenesis make sound scientific approaches difficult

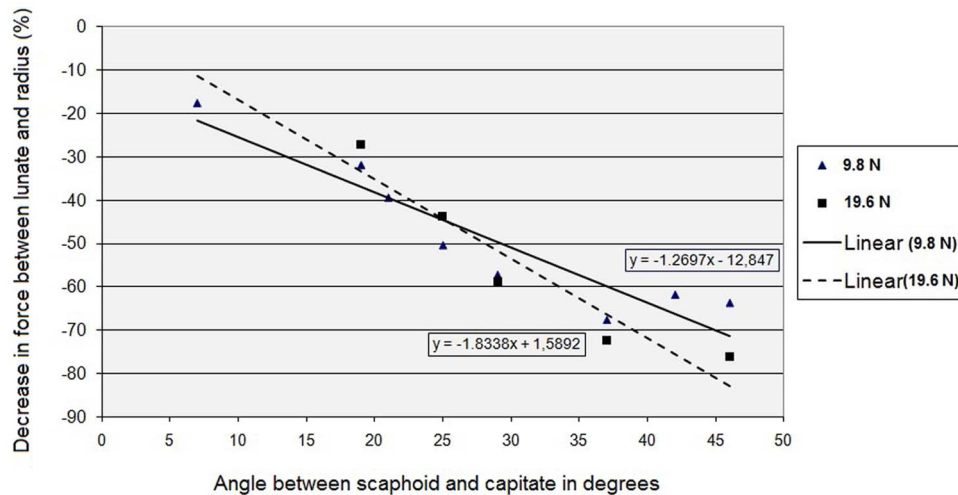


Figure 6. There was a significant negative correlation between the angle between the capitate and scaphoid, and decrease in pressure on the lunate bone. The chart displays the corresponding regression lines with the 9.8 N and 19.6 N loads.

(Lichtman et al., 2010; Schuind et al., 2008). So far, there have been few studies of the biomechanical basis for operative procedures (Horii et al., 1990; Viola et al., 1998). Histologically, Kienböck's disease is an osteonecrosis of the lunate. However, its precise aetiology is unknown, and different possible aetiologies have been discussed (Schuind et al., 2008). Jensen (1993) and Schiltenswolf et al. (1996) have measured high intraosseous pressures in the lunate in patients with Kienböck's disease.

Pressure overload on the lunate may affect the mechanical consequences of Kienböck's disease, and several operative procedures aim to reduce pressure on the lunate. As long as the lunate is not entirely collapsed with fixed scaphoid rotation and the bearing areas are still relatively congruent with only minor cartilage damage, disease progression and carpal misalignment might benefit from relief of load on the lunate. In those cases with the frequent ulna minus variance, radial shortening has been advocated to reduce loading on the radius by increasing the load on the ulnar aspect of the wrist (Watanabe et al., 2008; Zenzai et al., 2005). With ulna-plus or neutral variance, capitate shortening with or without capitoamate fusion has been reported to have promising results (Gay et al., 2009). Although the basic principle of this procedure seems rational, there are only limited data about the actual reduction in force on the lunate or possible overloading of the adjacent carpal joints that might lead to degenerative changes, instability, and further aggravate the patient's complaints.

Limited wrist arthrodesis or changes in bone configuration and shape inevitably lead to changes in the load vectors on the carpal bones. Little has been

published about force reduction after capitate shortening with capitoamate fusion. Two studies, one by Horii et al. (1990) that used a computer-simulated "rigid body spring" 2D model, and one by Viola et al. (1998) that used pressure-sensitive films, reported pressure decreases of 66% or 25% on the lunate, respectively. Horii et al. shortened the capitate by 4 mm, whereas Viola et al. shortened it by 2.9 mm. In our study, the capitate was shortened by 2 mm. There have been no previous studies of isolated capitate shortening without capitoamate fusion. Recently, Gíslason et al. (2012) presented a mechanical model that used a finite element model to predict changes after surgical interventions. This method provides another opportunity to assess load changes in the carpus.

An inadequate decrease or excessive relief of load can, respectively, lead to progression of lunate necrosis or accelerate osteoarthritis in adjacent joints. To determine the biomechanical changes after isolated capitate shortening, we measured carpal force transmission in a cadaver model under different loads. To measure the total force transmission from one bone to the other, we chose to embed single-point pressure sensors in the carpal bones instead of using pressure-sensitive film sensors, as published by Viola et al. (1998). Our technique is more likely to alter the normal movements in the joints. We cannot come to a firm conclusion about differences in the actual force transmissions in different wrist positions. It is possible that higher peak forces might occur with wrist movement. A further limitation of this study is that the human cadaver does not completely represent

physiological conditions in the living human. Sensor placement as well as ligamentous tears and repair might also influence measurements.

Isolated capitate shortening resulted in a decrease in pressure on the lunate, as expected, and an increase in the load across the HT joint (Table 1). These results demonstrate that longitudinal forces can be diverted over the ulnar pillar of the carpus without capitoamate (CH) arthrodesis. However, the HT load increase was less pronounced than reported by Horii et al. (1990) with CH arthrodesis. In contrast, Viola et al. (1998) did not find this change in forces on the ulnocarpal joint and concluded that capitate shortening with CH fusion changed the load path primarily to the scaphoid. The rationale behind the capitoamate fusion is to prevent secondary proximal migration of the capitate. However, capitoamate instability does not play a role in carpal collapse and CH fusion alone does not reduce load transmission through the lunate (Trumble et al., 1986). Our results show that an additional CH fusion is not needed. Two studies have shown the biomechanical inefficiency of capitoamate fusion on reducing constraints on the lunate (An, 1993; Werner and Palmer, 1993). Furthermore, force vectors were equally distributed over both the radial and ulnar columns, preventing the overload of specific intercarpal joints. Some intra-carpal fusions (e.g., scaphotrapezotrapezoid or scaphocapitate) also reduce the radiolunate load. Their effect on unloading is proven, but the resulting loss of wrist range of motion makes them more useful for later stage (IIIB) Kienböck's disease (Allan et al., 2001; Allieu et al., 1991).

Capitate shortening can also be combined with pedicled or free-vascularized bone graft to improve lunate vascularization and may provide better results than either alone (Arora et al., 2010; Shin and Bishop, 2001; Waitayawinyu et al., 2008).

The anatomy of the carpus also plays a role in the amount of post-operative decrease in force. This particularly concerns the scaphocapitate angle in the posteroanterior radiograph. The mean scaphocapitate angle was reported to be 25° (SD 11°) in the posteroanterior radiograph in 80 healthy patients (Feipel et al., 1998). We found a mean angle of 28° (SD 12°, range 7–46°), and there was a significant negative correlation between the scaphocapitate angle and decrease in force on the lunate. The larger the angle between the capitate and scaphoid, the greater was the decrease in pressure. We believe that the shape of the capitate can explain this relationship. The capitate resembles a proximally narrowing cone sitting radially on the scaphoid. This requires that the scaphoid not be angulated too steeply so that the capitate does

not slip off toward the lunate. In other words, the more horizontal the scaphoid, the more force can be transmitted from the capitate to the scaphoid, lessening the risk that the capitate migrates proximally and, thus, increases pressure on the lunate. The regression line defined by $y = -1.44x - 9.09$ provides a way to determine the potential postoperative decrease in pressure on the lunate by measurement of the patient's pre-operative radiograph.

Conflict of interests

None declared.

Funding

This work was supported by BMW FIZ Germany (supply of the technical equipment). S.W. was supported by a project grant of the Graduate School of Information Science in Health and TUM Graduate School. No other grant from any other funding agency in the public, commercial, or not-for-profit sectors was received.

Acknowledgements

We are grateful to Mrs. Miriam Hanusch for her help in writing the methods and results sections, to BMW FIZ Germany for supplying the technical equipment, and to Mr. di Frangia for editing the English text.

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