

Clinical and biomechanical investigation of an increased articular cavity depth after distal radius fractures: effect on range of motion, osteoarthritis and loading patterns

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Abstract

Introduction After fracture, distal radius malunion with dissociation of the volar and dorsal ulnar fracture fragments can lead to an increased articular cavity.

Patients and Methods To investigate its clinical impact we retrospectively analyzed the outcome of 81 patients and simulated this form of malunion in a biomechanical experiment with six cadaver specimens in a dynamic loading set-up.

Results In clinics, a higher arthritis stage was significantly correlated with an increased articular cavity depth and an increased anteroposterior distance. In cadaver specimens, a significantly decreased range of motion and significantly altered intraarticular contact characteristics were recognized for an increased cavity.

Conclusion Alterations in contact biomechanics could be one reason for the higher incidence of posttraumatic osteoarthritis when a deeper central impaction of the distal radius is present. From a clinical and experimental point of view, restoration of the normal shape of the distal radius is considered to minimize the risk for posttraumatic radiocarpal osteoarthritis.

Keywords Distal radius fracture · Radiocarpal osteoarthritis · Biomechanics · Radiographic evaluation

Introduction

Wrist arthritis is a common sequel following wrist trauma and is usually associated with impairment of function.

Either posttraumatic carpal instability or articular incongruity is known to cause joint degeneration [1, 2]. Intrinsic ligament tears as well as the combination of intrinsic and extrinsic ligamentous trauma alter carpal bone motion, which lead to changes in force distribution [3–5].

Articular incongruity like step-off or an increased dorsal tilt cause an increased pressure and alterations in pressure distribution, which lead to cartilage overload and osteoarthritis during long-term follow-up [6–8]. Wang et al. [9] demonstrated that a dorsal tilt which exceeds -10° is associated with joint degeneration at the dorsal rim of the distal radius. For several years an intraarticular step-off has been claimed to be a precondition for osteoarthritis, which is associated with clinical impairment [10–12].

During recent years another form of intraarticular malunion has been described—the increased articular cavity. This malunion is the sequel of an intraarticular crush fracture with a palmar ulnar, a dorsal ulnar and radial fragment as well as impaction of the central part of the articular surface. Radiographically, this residual deformity of the distal radius articular surface can be described by the teardrop angle and the anteroposterior distance. A considerable impression together with a dissociation of the volar and dorsal ulnar fracture fragments can lead to an increased articular cavity without gap or step-off [13–15].

To investigate the impact of an increased articular surface cavity at the distal radius, we evaluated clinical and radiological outcome of patients with an altered shape after intraarticular fracture. Furthermore, we simulated the described form of malunion in a biomechanical experiment and investigated intraarticular contact biomechanics as well as range of motion. The presented data is a combination of previously published papers and merges clinical and biomechanical results.

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Patients and methods

To investigate the effect of a deepened articular cavity and its biomechanical effects we combined data from two previously performed studies [16, 17]. For clinical evaluation 81 patients with an intraarticular distal radius fracture were followed up after a mean time of 9 years. We included 57 male and 24 female patients with a mean age of 37.8 years (17–60) which presented with an unstable fracture pattern and underwent ORIF in our department. Inclusion criteria were unstable dorsal dislocated intraarticular fractures, which were unstable following closed reduction and cast fixation. All patients displayed either a loss of palmar tilt $>5^\circ$, radial shortening of more than 3 mm or an articular step-off >2 mm. All fractures were intraarticular. According to the AO classification system there were 10 patients with a type C1 fracture, 46 with a C2 fracture and 25 patients displaying a C3 fracture. Preoperatively, a tomography or CT scan was performed. Surgery consisted of palmar *t*-plate fixation (distal radius plate, Stryker, Germany) and support of the metaphyseal comminution zone by a corticocancellous iliac crest graft which was inserted dorsally. Fragment reduction was performed indirectly and checked by fluoroscopy. No capsulotomy was performed during the reduction maneuver. Postoperatively, the wrist joint was immobilized by a plaster cast for 4 weeks.

Radiographic evaluation was performed on standard anteroposterior (ap) and 10° true lateral projections of both wrist joints. Palmar tilt, radial inclination, ulnar variance, ap distance and articular cavity depth (Fig. 1) were measured and compared to the uninjured side. Ap distance was defined as the distance measured from the dorsal to the volar rim of the lunate fossa [18]. To investigate the articular cavity of the radius a line was drawn from the dorsal to the palmar edge of the articular surface. Then, the distance to the deepest point of the joint surface was measured perpendicular to the latter [19]. Postoperatively, an articular step-off or gap was recorded.

To evaluate posttraumatic osteoarthritis the Knirk and Jupiter [20] classification system was used. Grip strength was evaluated using the mean of three standard dynamometer measurements (Jamar, Therapeutic equipment, Irvington, NY, USA). Results are expressed as percentage of the uninjured wrist, taking the non dominant hand into consideration by subtraction of 10 % from the measured value. Pain was evaluated with the visual analogous scale and management of daily living was scored with the DASH. Data comparison for independent samples was performed by either a non-parametric Man-Whitney test or a *t* test for normally distributed data. Paired samples were evaluated with a non-parametric Wilcoxon test or a *t* test for paired samples according to the distribution pattern. Statistical significance was set at a *p* value below 0.05.

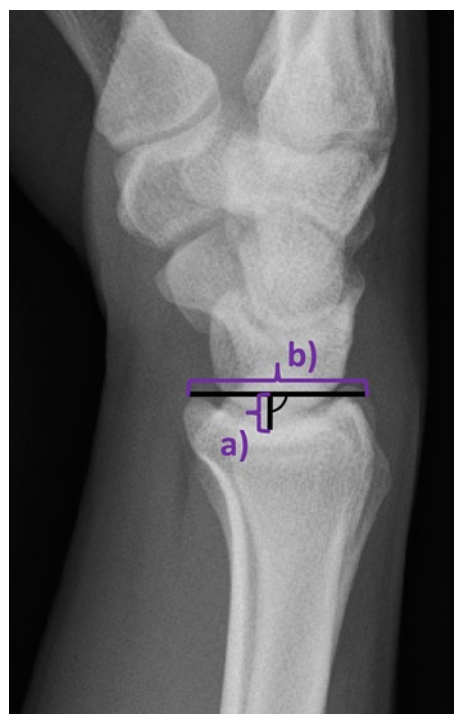


Fig. 1 Measurement of articular cavity depth (a) and the anteroposterior distance (b) on lateral X-rays

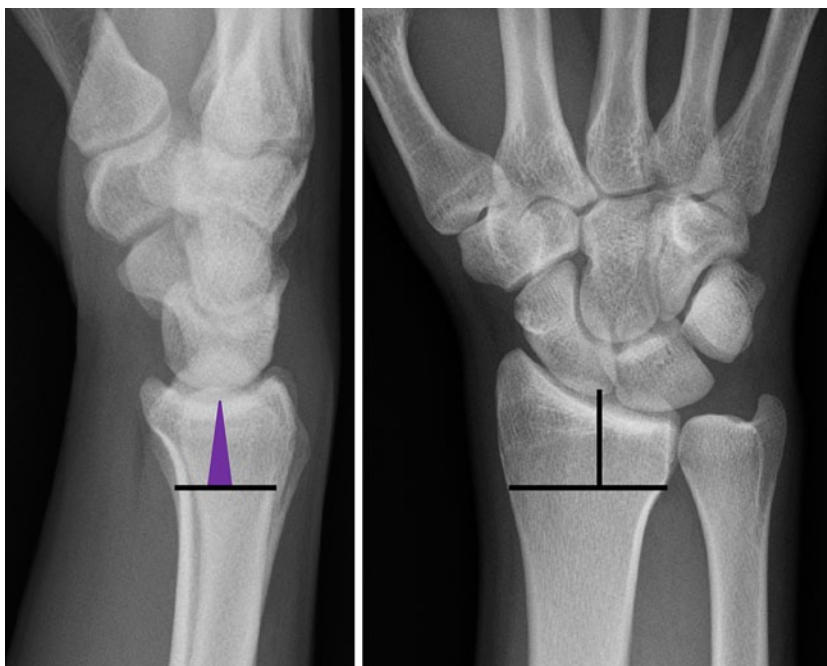
To biomechanically investigate and better interpret clinical findings, we also performed a biomechanical investigation of six fresh frozen human upper extremity specimens (Fig. 2). Therefore, an increased depth of the articular radius surface was simulated (Fig. 3). For biomechanical testing, specimens were dissected at the distal end of the humerus and cleared of all soft tissue except for the tendons of the extensor carpi radialis longus and brevis, the extensor carpi ulnaris, the flexor carpi radialis, the flexor carpi ulnaris and the abductor pollicis longus muscle. Furthermore, the interosseous membrane as well as stabilizing ligaments of the wrist and radioulnar joint and the wrist joint capsule were preserved. Testing was performed by active agonistic and antagonistic actuation of pneumatic muscles connected to the tendons of the specimens (Fig. 2). By different actuation of the agonistic and antagonistic muscles motion of the wrist joint in the sagittal plane was produced with a motion range of approximately 60° [21]. Used forces for muscle pull were derived from the literature [22, 23]. Sagittal wrist motion was recorded with an ultrasound-based motion analysis system (Zebris, Winbiomechanics, Isny, Germany). To evaluate intraarticular biomechanics, a piezo-resistive sensor (wrist 4201, Tekscan Inc., South Boston, MA, USA) was inserted in the wrist joint via a dorsal capsulotomy according to Berger et al. [24]. The specimens were tested in two different states:



Fig. 2 Biomechanical test-setup with the specimen in extension. Range of motion was recorded by an ultrasound-based system (a). The intraarticular sensor was inserted dorsally into the radiocarpal joint (b)

1. Intact specimen with inserted pressure sensor.
2. Specimen with simulated malunion of the distal radius articular surface displaying a deepened articular cavity and inserted pressure sensor.

Fig. 3 To simulate an increased intraarticular cavity, saw cuts were performed as sketched in the X-ray and a polyethylene wedge was inserted between the volar and dorsal ulnar fragment



For the deepened articular cavity a 4-part fracture [18] was created by osteotomies 2 cm below the distal radial joint surface, in the interfossal ridge and by separation of the dorsal and volar ulnar fragment [25]. A triangular-shaped wedge was inserted between the two ulnar fragments and a palmar osteosynthesis plate applied for stable fixation without gap or step-off.

Range of motion (RoM), contact area and mean contact pressure of the distal radial surface and tendon forces were measured. Contact characteristics were further subdivided into separate values for the scaphoid and lunate fossa. All values were taken in maximum flexion, maximum extension, and neutral position of the wrist joint. Changes are expressed as percent of the intact specimen. For data comparison a Wilcoxon test was used. Statistical significance was set at a p value below 0.05. p values between 0.05 and 0.1 were considered as a statistical trend.

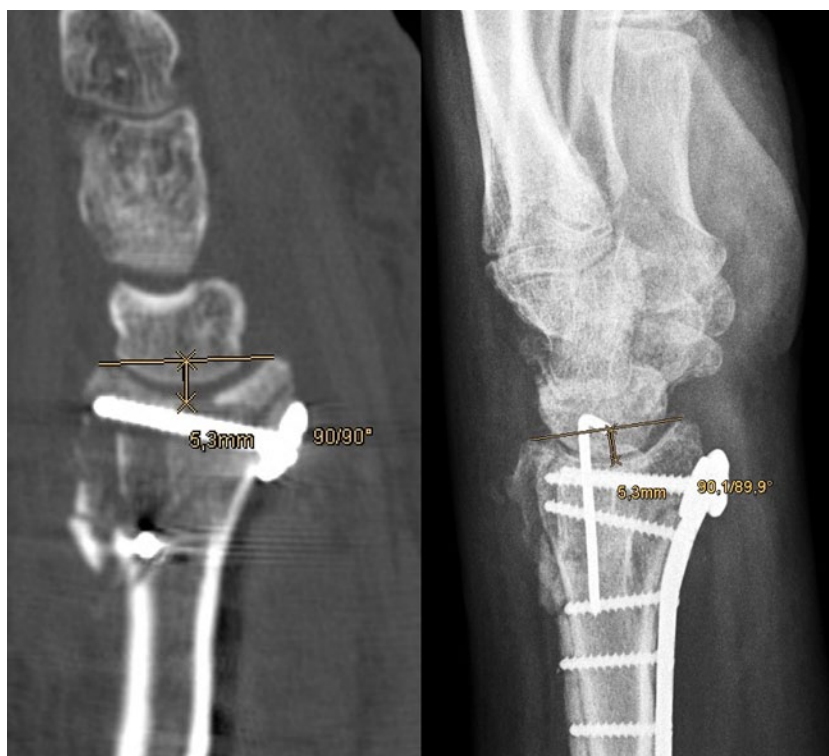
Results

Patients with intraarticular distal radius fracture

Descriptive

Radiologically measured intraarticular cavity depth was 4.6 mm postoperatively and increased to 4.8 mm (SD 1.1) at follow-up for the injured wrist (i.e., Fig. 4). On the uninjured side cavity depth was 3.6 mm (SD 0.7) leaving an average difference of 1.3 mm when compared to the fractured wrist. A remaining articular gap >2 mm was present

Fig. 4 Postoperative CT-scans and X-rays were used to measure posttraumatic cavity depth in the lateral view. Results measured from X-rays could be confirmed by measurements performed from CT-scans



in four patients with a C3 type fracture. An articular step-off >2 mm was noticed in two patients with a type C2 fractures and in five type C3 fractures. Six of those eleven patients presented with severe osteoarthritis of the radiocarpal joint.

Overall, no arthritis was noticed in two patients, 45 patients presented with stage 1 OA and 34 patients with stage 2 OA according to the Knirk and Jupiter classification system.

Average range of motion in the sagittal plane was 114.1° [SD 18.4; flexion 61.7° (SD 9.1), extension 52.4° (SD 12)]. In the frontal plane there was a mean RoM 55.6° [SD 11.0, ulnar deviation 34.1° (SD 6.7), radial deviation 21.5° (SD 7.0)].

Grip strength of the injured wrist was 85 % of the uninjured side (38.7 kg, SD 12.2 vs 45.6 kg, SD 11.8). Pain on the visual analogous scale was 1.5 (SD 2.2) at follow-up. DASH values were 7.5 points (SD 12) on average.

Comparative

There was a statistically significant difference in articular cavity depth between patients with stage 1 arthritis (mean depth 4.1 mm) and patients with stage 2 arthritis (mean depth 5.8 mm, $p < 0.05$). Furthermore, we found a statistically significant correlation between an increased ap distance and arthritis grading (20.3 mm for stage 1; 21.7 mm for stage 2, $p < 0.05$). Concerning RoM, patients with stage 2 arthritis had a decreased sagittal range of motion

of 108.4° (SD 22.0) compared to those with stage 1 arthritis (118.2°, SD 14.3; $p = 0.03$). Statistical comparison for patients without OA and presence of arthritis were not calculated as there were only two patients without OA. However, there was no difference when comparing different stages of arthritis in DASH ($p = 0.73$), pain ($p = 0.89$), grip strength ($p = 0.33$) or RoM in the frontal plane ($p = 0.52$).

Biomechanical simulation of an increased articular cavity

In the investigated cadaveric specimens there was an increase in articular cavity depth of 0.9 mm on average (3.7 mm, SD 0.3 for the intact specimen; 4.6 mm, SD 0.2 for the specimens with simulated malunion). The difference was statistically significant ($p < 0.05$).

During active motion of the wrist in the sagittal plane we found a significantly decreased range of motion for those specimens with an increased articular cavity depth to 69 % RoM of the intact specimen ($p < 0.05$).

For the specimens with an increased intraarticular cavity in neutral wrist position contact area decreased by 51, 40, and 47 % (scaphoid and lunate fossa and total radius surface, respectively) when compared to the intact state. In maximum extension, there was also a decrease in contact area (of 54, 42, and 50 % for the scaphoid and lunate fossa and the total radius surface, respectively). In maximum flexion, contact area decreased by 54, 34, and 42 % for the mentioned locations, respectively.

Intraarticular measurements generally showed a decreased contact area in specimens with an increased articular cavity depth. The difference was statistically significant for all locations in neutral wrist position, as well as in maximum extension when compared to the intact state ($p < 0.05$). In maximum flexion the decrease in contact area was statistically significant for the scaphoid fossa and the total radius surface ($p < 0.05$).

In neutral position, contact pressure in specimens with an increased articular cavity increased by 129 and 113 % for the scaphoid and lunate fossa as well as for the total radius surface (by 129 %) when compared to the intact state. In maximum extension there was an increase by 118, 221, and 122 % for the mentioned locations. In maximum flexion contact pressure in specimens with an increased cavity depth was increased by 1.6 in the scaphoid fossa, was fourfold in the lunate fossa and doubled for the total radius surface.

Contact pressure increased on all locations when the specimens with increased articular cavity depth were compared to the intact state. The differences were statistically significant for the scaphoid and total radius surface in neutral position ($p < 0.05$). In maximum extension the difference was significant for the scaphoid fossa ($p < 0.05$). In maximum flexion it was statistically significant for the total radius surface ($p < 0.05$). For the lunate fossa there was a statistical trend towards an increased pressure in the extremes of motion (p 0.05–0.1).

Discussion

Unaffected wrist motion and prevention of preterm osteoarthritis after distal radius fractures are dependent on anatomic restoration of the distal radius [26, 27]. Previous studies have shown that a residual articular step-off as well as dorsal tilt exceeding 10° alter contact area and pressure distribution which may cause the onset of OA [6, 7, 9]. Also our investigations suggest that an increased depth of the articular cavity leads to an altered pressure distribution across the distal radius. This could be one reason for the higher incidence of posttraumatic OA when a deeper central impaction is present. Furthermore, motion in the sagittal plane was decreased in the investigated patients as well as during biomechanical testing of cadaver specimens. Our clinical and experimental results revealed limited active range of motion, which on the other hand suggests that the same force is required for less RoM. Limited contact area means, that more force is applied per square-millimeter of cartilage which could cause cartilage deterioration. Therefore, an increased cavity of the distal radius should be avoided to preserve the normal sliding mechanism of the proximal carpal row and to prevent posttraumatic OA in the

radiocarpal joint as well as impairment due to limited wrist motion.

The investigated patients had very low pain level although considerable wrist OA was present. Furthermore, there was no correlation between the stage of arthritis and the DASH level. Correlations for patients without OA could not be calculated due to the small amount of patients. One reason for the discrepancy between OA-levels and clinical symptoms might be a certain form of joint denervation after the bilateral approach in the investigated patients. In addition to that, the wrist consists of two rows and restricted RoM of the radiocarpal level might explain the low pain levels. Furthermore, osteoarthritis is a slowly progressing process at the upper limb which was proven by other studies [12, 26, 28].

The presence of soft tissue lesions is described to be rather the rule than the exception. Geissler et al. found soft tissue injuries in 68 % of the patients and Hanker et al. described scapholunate ligament tears in 43 % of investigated patients. Further frequently injured structures are the dorsal capsule as well as the radioscapulunate ligament [13, 29, 30]. These lesions could have an effect on wrist motion and partly be responsible for early OA as well as diminished clinical outcome or the contrary in other patients. To properly assess concomitant soft tissue lesions, intraoperative arthroscopy should be the tool of choice, as it furthermore facilitates congruent reduction of an intraarticular fracture. However, long-term results of concomitant injuries are scarce in the literature.

Our data suggests that an increased articular cavity could be the reason for radiocarpal OA. The depth of the cavity itself seems to correlate with the severity of radiocarpal joint deterioration, with more than 2 mm depth compared to the uninjured side lead to severe OA. Also an increased ap distance of more than 2 mm compared to the unaffected wrist is a positive predictor for posttraumatic OA. As described in the literature, malunion in terms of a lunate die-punch fragment, intraarticular depression or an increased dorsal tilt lead to changes in pressure distribution and force transmission [6–8]. In our biomechanical investigations an increased articular cavity depth showed the same trend as other biomechanical studies investigating wrist joint incongruity. Due to the altered shape of the distal radius in the sagittal plane, we found a significantly decreased contact area and a considerable influence on contact pressure. We believe that these changes are partly the reason for premature OA as seen in our clinical results.

Biomechanically, there was a significant decrease in range of motion after an increased articular cavity depth was simulated. Also evaluated patients experienced a decreased range of motion. We hypothesize that this decrease might not only be due to the presence of arthritis but could also be a sequel of the altered joint surface shape

itself. Wedging of the proximal row in the deepened cavity might be a reason for the biomechanically seen RoM decrease.

Our investigations merged results from clinical and biomechanical investigations. Furthermore, the biomechanical results confirmed the hypothesis that an increased depth of the distal radius surface leads to alterations in contact biomechanics which are thus thought to be one cause for early posttraumatic OA. In our opinion, the described form of distal radius malunion is one source for long-term joint degeneration and should be avoided. During surgery, an increased ap distance should be considered as an indirect measure of an inadequately restored articular surface and should thus be corrected.

These clinical and experimental results have important impact on our treatment strategy in daily practice; an increased cavity depth after a dorsally dislocated fracture is more likely to occur when a palmar tilt of 10° is preserved. Therefore, we aim for a neutral position of the articular surface in these severe crush injuries but want to restore the shape of the articular surface.

However, long-term clinical studies are mandatory to prove this strategy and in addition to that soft tissue lesions have to be taken into account.

Conclusion

Merging clinical and experimental data, this paper gives a possible explanation for the association of an altered shape of the articular surface and the development of OA.

However, in contrast to the lower limb, OA it is known to be slowly progressive in the upper limb and radiographic findings are not always associated with pain and score levels.

Nevertheless, limited active range of motion in the sagittal plane, which is a consequence of arthritis level, impairs wrist function in young and active patients. Thus, further clinical long-term studies are mandatory to observe the potential progression of the amount of OA in this group of patients with its clinical impact.

As long as we do not know the long term effects, exact reduction of the articular surface should be our gold standard to prevent degenerative OA.

Conflict of interest The authors report no conflict of interest regarding the content of this manuscript.

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