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Conformational Changes in the Carpus During Finger Traps Distraction

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Abstract

Introduction—Wrist distraction is a common treatment maneuver used clinically for the reduction of distal radial fractures and mid-carpal dislocations. Wrist distraction is also required during wrist arthroscopy to access the radiocarpal joint and has been used as a test for scapholunate ligament injury. However, the effect of a distraction load on the normal wrist has not been well studied. The purpose of this study was to measure the 3-D conformational changes of the carpal bones in the normal wrist as a result of a static distractive load.

Methods—The dominant wrists of 14 healthy volunteers were scanned using computed tomography at rest and during application of 98N of distraction. Load was applied using finger traps and volunteers were encouraged to relax their forearm muscles and to allow distraction of the wrist. The motions of the bones in the wrist were tracked between the unloaded and loaded trial using markerless bone registration. The average displacement vector of each bone was calculated relative to the radius as well as the interbone distances for 20 bone-bone interactions. Joint separation was estimated at the radiocarpal, midcarpal and carpal-metacarpal joints in the direction of loading using the radius, lunate, capitate and 3rd metacarpal.

Results—With loading, the distance between the radius and 3rd metacarpal increased an average of 3.3 ± 3.1 mm in the direction of loading. This separation was primarily located in the axial direction at the radiocarpal (1.0 ± 1.0 mm) and midcarpal (2.0 ± 1.7 mm) joints. There were minimal changes in the transverse direction within the distal row, although the proximal row narrowed by 0.98 ± 0.7 mm. Distraction between the radius and scaphoid (2.5 ± 2.2 mm) was 2.4 times greater than between the radius and lunate (1.0 ± 1.0 mm).

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Conclusions—Carpal distraction has a significant effect on the conformation of the carpus, especially at the radiocarpal and midcarpal joints. In the normal wrist, external traction causes twice as much distraction at the lunocapitate joint than at the radiolunate joint.

Keywords

Carpal; Kinematics; Distraction; Scaphoid; Lunate

Introduction

Wrist distraction is a common treatment maneuver with a variety of clinical uses. External traction on the wrist has been shown to assist in the reduction of intra-articular distal radius fractures, where the tension across the fracture by the soft tissues is used to help align the fracture fragments (i.e. ligamentotaxis) ¹. Wrist distraction is required during wrist arthroscopy to access the radiocarpal, midcarpal and radioulnar joints ^{2,3} and it has been used as a test for scapholunate ligament injury ^{4,5}.

Much of what is currently known about the biomechanics of wrist distraction has been obtained from cadaver testing. Simple axial distraction studies have reported a large variability in the load-deformation behavior of individual wrists ⁶, and a subsequent investigation of 3-D carpal kinematics during wrist distraction has demonstrated that distraction alters carpal bone motion, specifically that it reduces radiocarpal motion during extension and increases radiocarpal motion during flexion ⁷.

Accurate data on distraction-induced changes in the carpus has applications for both clinicians and basic scientists. A handful of studies have suggested that carpal distraction is associated with negative clinical outcomes ^{8,9}. While some authors have the opinion that distraction can cause neural damage ^{10,11}, at this point causation has not been definitively established. An understanding of the conformational changes in the carpus during distraction *in vivo* will be useful for the establishment of safe limits for distractive maneuvers used to diagnose wrist ligament injury. From a basic science perspective, data on bone motions during distraction provide crucial input values for computer models designed to estimate the mechanical properties of the carpal ligaments.

Accordingly, the purpose of this study was to quantify the three dimensional changes in separation and rotation of the bones in the normal carpus induced by static distractive loading. In addition, given that carpal bone size ¹² and ligamentous laxity vary with gender ¹³⁻¹⁵, we investigated whether there were any gender-related differences in bone-to-bone separation with distraction.

Methods

Volunteer Recruitment and CT Scanning

After obtaining IRB approval, 14 healthy right-hand dominant volunteers (7 male and 7 female; average age 24.9 years, range 21-30) were recruited into the study. Exclusion criteria included a history of significant wrist injury, wrist surgery, or any systemic or metabolic disease that could alter the soft tissue structures in the wrist.

Computed tomography (CT) images were generated of each subject's dominant wrist with a GE Lightspeed 16 CT scanner (GE Healthcare, Waukesha, WI). Scanning was performed with the wrist positioned in the center of the gantry, using a 14 cm scan field of view and tube settings of 80kVp and 80mA. This yielded images with an in-plane resolution of 0.3mm × 0.3mm. The slice interval was 0.6mm.

Subjects were positioned prone on the scanning table, with their dominant arms extended above their heads along the center of the CT table, and their hands oriented in a pronated neutral position (palm flat on the CT table). Scans were performed in both the loaded and unloaded state. An additional reference scan was performed with the wrist in neutral to yield images for the segmentation and registration algorithms. For scans in the unloaded state, the wrist was first briefly loaded and then unloaded. The scans were then performed immediately after the weight was removed. This sequence minimized wrist motion between the unloaded and loaded states. For scans in the loaded state, nylon finger traps and a dead weight were used to apply and distribute 98N (10 kg) equally across all five digits. The dead weight was attached to the finger traps with a short cord, routed over a pulley at the end of the scanning table. During scanning, the subjects were instructed to relax their forearm muscles and allow the load to distract their wrist. The 98N load was comfortably tolerated by the study subjects, and is consistent with loads used in previous studies¹⁶⁻¹⁹.

Carpal Tracking

Changes in bone location and posture were determined to within 0.5 mm and 1 degree using established markerless registration methodologies²⁰. In brief, the radius, ulna, carpals, and metacarpals for each volunteer were manually segmented from the reference neutral scan, yielding 3-D surface models (Mimics 9.11, Materialise, Leuven, Belgium). Bone centroids and inertial axes were calculated from the 3-D surface models of each fully-imaged bone (assuming uniform density)^{21,22}. “Alternate centroids” were created for the partially imaged bones. For the radius and ulna, the alternate centroids were defined by the origins of their respective coordinate systems (described below) and for the metacarpal bones alternate centroids were defined by points manually selected at the approximate center of the metacarpal heads.

To create a common reference frame for between-subject analysis, a radius-based coordinate system (RCS) was defined for each subject using readily identifiable anatomic landmarks²¹. The x-axis was defined by the long axis of the radius (positive proximal), the y-axis was oriented in the radial direction (defined by a vector orthogonal to the x-axis and passing through the radial styloid), and the z-axis was oriented palmarly, orthogonal to both the x- and y-axes (calculated as the cross-product of the x- and y-axes). The origin of the coordinate system was located at the point on the radiocarpal surface of the radius model intersected by the x-axis, typically at the ulnar edge of the radioscapoid fossa. An analogous coordinate system was defined for the ulna, however, for this coordinate system the y-axis was oriented towards the ulnar styloid instead of the radial styloid.

The location of each bone in the unloaded and loaded positions was calculated using custom C++ software (GNU gcc, Free Software Foundation, Boston, Massachusetts). Loading-induced changes in location and posture were calculated using custom Matlab code (The MathWorks, Natick, Massachusetts) after the radii were registered to the radii in the neutral reference scan to eliminate the influence of slight shifts in forearm position between scans. Overall wrist position was defined by the orientation of the long axis of the third metacarpal with respect to the radius-based coordinate system, and forearm pronation/supination was calculated as the rotation of the radius about the ulna. Individual bone rotations were described using helical axis of motion variables. Rotations were analyzed in terms of their unsigned magnitudes, as well their rotations in flexion/extension, radial/ulnar deviation and pronation/supination.

Centroid Displacement—Centroid displacement was computed as the vector connecting the location of a given bone's centroid in the unloaded position to the location in the loaded position, relative to the mathematically fixed radius. The magnitude of the vector defined the distance the centroid displaced. The direction of the displacement vector was described in terms

of its components along the y (flexion/extension) and z-axes (radial/ulnar deviation) of the radial coordinate system.

Centroid Spacing—Centroid spacing was defined as the scalar distance between the centroids of two bones, and was computed for 20 separate bone-to-bone combinations (Table 1). Distraction-induced changes in centroid spacing were calculated as the differences in the distance between the bone centroids in the loaded and the unloaded states, with positive values indicating separation of the selected pair and negative values indicating closing. In addition to the 20 adjacent bone-bone distances, the width of the proximal row (the distance between the scaphoid and triquetrum centroids), and the width of the distal row (the distance between the trapezium and hamate centroids) were also computed.

Joint Distraction—Joint distraction was defined as the change in the axial (x-axis) component of the centroid spacing (in the direction of loading) and was computed at the radiolunate, radioscapoid, lunocapitate, and third carpometacarpal joints. Overall wrist distraction was computed as the change in distance between the centroids of the radius and third metacarpal.

Statistics

Paired Student's t-tests were used to determine if distraction altered overall wrist position (i.e. flexion/extension or radial/ulnar deviation of the third metacarpal with respect to the radius) or forearm pronosupination.

Joint separation at the radiolunate, radioscapoid, lunocapitate, and third carpometacarpal joints was evaluated using three-factor mixed linear model, with one between-subjects factor (gender) and two within-subject factors (joint and loading). The mixed linear modeling was performed using SAS *proc mixed* (SAS, Cary, NC), with an unstructured variance-covariance error construct for the interaction of bone $\times$ loading within a given subject.

Results

In the unloaded state, the average wrist position was $2 \pm 8^\circ$ of flexion, $8 \pm 6^\circ$ of ulnar deviation and $37 \pm 31^\circ$ of forearm pronation. Distractive loading induced small rotations in the overall position of the wrist and forearm. Loading significantly reduced ulnar deviation by $3 \pm 3^\circ$ to $5 \pm 4^\circ$ ($p < 0.01$). The increase in wrist extension ($3 \pm 5^\circ$ to $1 \pm 4^\circ$ of extension) and the increase forearm supination ($3 \pm 7^\circ$ to $34 \pm 33^\circ$ of pronation) were not statistically significant ($p = 0.09$).

Overall, rotation of all the carpal bones caused by distractive loading was $1.4 \pm 5.8^\circ$ in extension, $0.1 \pm 3.3^\circ$ in radial deviation, and $1.8 \pm 3.3^\circ$ in supination ($n = 112$: 14 volunteers $\times$ 8 carpal bones/volunteer). Of all the carpal bones, the scaphoid rotated the most, primarily in extension ($4.1 \pm 5.1^\circ$) and radial deviation ($3.3 \pm 3.6^\circ$).

Centroid Displacement

With the exception of the lunate and triquetrum, the centroids of all the carpal and metacarpal bones displaced distally with respect to the radius and slightly dorsally (in the direction of distractive loading) with load application. The lunate and triquetrum centroids translated distally and dorsally, but they also had a large component of radial translation compared to the other bones (Figures 1 and 2, and Table 2). The average centroid displacement for a given bone ranged from a low of 2.2 ± 1.7 mm for the lunate, to more than 6.1 ± 3.4 mm for the first metacarpal.

Centroid Spacing

As expected, centroid spacing generally increased throughout the wrist with distraction. The only substantial decrease in centroid spacing occurred between the lunate and radius (-1.0 ± 1.0 mm), due to the relatively large radial component of the lunate's motion that closed the gap between its centroid and the alternate centroid on the radiocarpal surface of the radius. Otherwise the changes in centroid distances within the proximal row were all less than 0.1mm and the changes in centroid distances within the distal row were all less than 0.25mm (Figure 3 and Table 1). Overall, the width of the proximal row (the distance between the scaphoid and triquetrum centroids) decreased 0.98 ± 0.7 mm with loading and the width of the distal row (the distance between the trapezium and hamate centroids) increased 0.17 ± 0.3 mm.

Joint Distraction

With loading, the carpus lengthened by an average of 3.3 ± 3.1 mm (x-axis dimension between the radius and third metacarpal centroids). Separation was clearly visible at the radiocarpal joint and between the carpal rows (Figure 3). On average, the wrists of the female subjects distracted nearly twice (187%) as much as wrists of the male volunteers (4.3 ± 3.7 mm vs. 2.3 ± 2.3 mm), though there was no statistically significant relationship between gender and distraction ($p=0.26$).

Overall (data from both genders combined), loading resulted in 1.0 ± 1.0 mm of distraction at the radiolunate joint ($p<0.01$), 2.5 ± 2.2 mm of distraction at the radioscapoid joint ($p<0.01$), and 2.0 ± 1.7 mm of distraction at the lunocapitate joint ($p<0.01$). Distraction at the lunocapitate joint was significantly greater than that at the radiolunate joint ($p<0.01$), but not the radioscapoid joint ($p=0.07$). Distraction at the third carpometacarpal joint was an order of magnitude less than that at the radiocarpal and midcarpal joints (0.2 ± 0.5 mm), and not quite statistically significant ($p=0.07$). It was, however, significantly less than distraction at the radiolunate ($p<0.01$) and lunocapitate ($p<0.01$) joints (Figure 4).

Discussion

This study was designed to determine how static distraction affects the three dimensional conformation of the carpus in live subjects. We found that the overall length of the carpus (radius to third metacarpal) increased by 3.3 ± 3.1 mm with a load of 98 N, primarily due to separation of the radiocarpal and midcarpal joints. Distraction at the third carpometacarpal joint was small (0.2 ± 0.5 mm) and not statistically significant. Almost all of the bones in the carpus also shifted dorsally with distraction, with the distal row moving more than the proximal row. In the proximal row, the scaphoid moved distally and extended slightly, as its long axis became more aligned with the long axis of the radius. Radial translation of the lunate and triquetrum towards the laterally fixed scaphoid effectively narrowed the proximal row.

In contrast to our findings regarding translation, the average rotation of the individual bones in the carpus was relatively small (less than 2° in any given direction: extension, radial deviation or pronosupination). This was more due to the lack of consistent pattern in rotation than universally low magnitude of rotation, as the total rotation for selected bones after loading was almost 10° .

We did not expect to see much if any dorsovolar or lateral compaction of the wrist during distraction, as the bones are quite congruent and tightly packed. We did, however, measure a substantial and significant decrease in centroid spacing between the radius and lunate bones. This occurred in spite of the fact that the surface of the lunate actually separated from the surface of the radius during distraction. The decrease in centroid spacing was due to radial translation of the lunate as it moved distally during distraction. This closed the gap between

its centroid and the (alternate) centroid on the radius, which was located on the radiocarpal surface of the radius.

The relative distraction of the different carpal bones is consistent with ligament anatomy. In particular, the scaphocapitate and the scaphotrapezial ligament complexes are substantial structures that tightly bind the scaphoid to the capitate and trapezium^{23,24}. These structures and the similarly robust carpometacarpal ligaments with their primarily axial orientation explain the limited distraction at the STT and carpometacarpal joints²⁵. In contrast, the radiocarpal ligaments (volar radioscaphocapitate, radiolunate, ulnocarpal and dorsal radiotriquetral) are orientated oblique to the longitudinal axis of the wrist. This orientation accommodates significant mobility of the scaphoid, lunate and capitate during normal wrist motion^{26,27} but makes them less effective at resisting axial traction. Similarly, the four primary volar ligaments (radiolunate, ulnolunate, radioscaphoid and arcuate) are arranged to form two inverted “V”s that reduce the resistance to axial separation. The smaller “V” is formed by the radiolunate and ulnolunate ligaments, which originate on the radius and TFCC and insert on the lunate. The ligaments of the larger “V”, the radioscaphocapitate and arcuate ligaments, follow similar paths, but originate further laterally on the radius and ulna and insert onto the capitate²⁸⁻³¹. The longer, more peripheral and distal “V” ligaments elongate more than the shorter and more central “V” ligaments, resulting in greater distraction at the midcarpal and radioscaphoid articulations than the radiolunate joint. Similar arguments can be made for the intrinsic ligaments. Distraction between the centroids of the lunate and triquetrum and the lunate and scaphoid were very small (on the order of 0.1mm), which makes sense given the taut connections and short lengths of the interosseous ligaments³²⁻³⁶.

It remains unclear why most of the carpal bones translated dorsally and radially with distraction. The “V” shaped volar ligaments are reported to be stronger than the dorsal ligaments²⁹, and cadaver studies have suggested that distraction is arrested by the volar ligaments before the dorsal ligaments reach their maximum length^{7,37}. Assuming that the volar ligaments do restrain distraction, the bones would be expected to translate volarly, towards their attachments. Therefore the mechanism by which the carpal bones translated dorsally and radially remains to be identified, but likely includes a complex interaction between ligament morphology, ligament stiffness and the geometry of the articulations.

Our measured distractions are similar to those previously reported. Bartosh and Saldana³⁷ found an average of 3mm of overall wrist distraction in 19 cadaver wrists, regardless of the amount of load used. Loebig et al.⁶ performed distractions on twelve cadaveric wrists using a standard servohydraulic mechanical testing device. They measured almost 2.5 times as much distraction at 80N of load than we did at 98 N (almost 8 mm vs. 3.3 ± 3.1 mm). However, it is difficult to make direct comparisons between the two data sets because their testing was done *in vitro* and their specimens were stripped of all skin and soft tissue, with the exception of the wrist capsule and ligaments. That said, it is possible to compare *relative* bone motions to a maximum of 3.3mm of distraction, which was the average for our subjects. At 3.3mm of distraction, Loebig et al.⁶ found that lunocapitate distraction was 2.4 times as much as radiolunate distraction, which is consistent with our findings. Similarly, they measured 2.2 times more distraction at the radioscaphoid joint than the radiolunate joint, which is consistent with our findings⁶.

In light of the large distractions reported in the study by Loebig et al.⁶, we must acknowledge the possibility that our data under-represents carpal bone motion during wrist distraction. Although we asked our volunteers to relax during loading, and we made an effort to confirm relaxation via palpation of the forearm muscles, it is possible that some may have resisted the loading via active forearm muscle contraction. We did have subjects whose wrists distracted only nominally, and others whose joints distracted substantially more, as evidenced by our

large sample variances. At this point it is impossible to determine whether the differences were volitional or simply a reflection of normal variability in joint laxity, as generalized joint laxity was not quantified during the screening examination prior to enrollment.

Our analysis of the influence of gender on wrist compliance revealed no statistically significant difference in overall wrist distraction between our male and female volunteers, despite nearly a twofold difference in the axial component of the radius-to-third metacarpal centroid spacing ($2.3 \pm 2.3\text{mm}$ vs. $4.3 \pm 3.7\text{mm}$, respectively). The lack of significance persisted even after we normalized our data by wrist size (i.e. third metacarpal length), which is known to differ with gender¹². There are two interpretations for our finding: Either there is no gender-related difference in wrist compliance, or there is a difference and our study was not sufficiently powered to detect it. Of the two, we feel the later is more likely, given the large difference in the means and large sample variances.

Clinically, carpal distraction is used to help align the fragments in comminuted distal radial fractures¹. Previous studies have suggested that distraction of the wrist is a potential source of complications and adverse outcomes^{8,9,38}. To be maximally effective for fracture reduction, the effect of distraction should be localized to the radiocarpal joint³⁹. However, we found greater separation at the midcarpal joint than at the radiocarpal joint (e.g. twofold more separation at the lunocapitate joint than at the radiolunate joint). Accordingly, it must be recognized that distractive changes at the midcarpal joint are significantly greater than at the radiocarpal joint and there is a risk of damaging soft tissues, if too much force is applied³⁷.

Wrist distraction is also used clinically as an aid in the diagnosis of scapholunate ligament injury. For the “carpal stress tests” the examiner places a 5kg (49N) distractive load across the wrist and evaluates the step-off between the scaphoid and lunate⁴ or scapholunate diastasis⁵ on posteroanterior radiographs or fluoroscopy. Our findings suggest caution when interpreting the results of the step-off technique. We found the scaphoid displaces an average of 2.4 times further than the lunate in healthy subjects, a result that might be interpreted as pathological. Admittedly, our loading protocol differed from that used clinically (i.e. we used 10kg applied to all five digits with the arm horizontal, as opposed to 5kg (plus the weight of the arm) applied to the thumb and/or thumb and first finger with the forearm arm vertical, and we measured centroid displacements as opposed to “edge” step-off or scapholunate diastasis). However, our results suggest that the uninjured scapholunate joint might be more compliant than previously appreciated. The scapholunate diastasis test⁵ may be more conservative, as we found only a nominal ($<0.1\text{mm}$) change in scapholunate centroid spacing with loading.

In summary, this study provides further insight into the mechanical behavior of the ligamentous carpus under distraction loads. These data may be useful clinically when considering the conformational changes that occur during wrist arthroscopy, the effect of traction on the reduction of distal radius fractures, and the diagnosis of scapholunate ligament tears. It also provides in vivo data for the development and validation of computer models of the normal wrist^{40,41}.

Acknowledgments

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Figure 1.

The vectors (light red) representing the centroid (red sphere) displacement for all subjects with distraction loading. The vectors representing the average displacement with loading are shown in green and are also visualized separately in Figure 2. The radius, ulna, scaphoid, lunate and capitate are those of a single subject's wrist in a volar (left) and radial (right) view.

Figure 2.

The average displacement vectors (green) of the centroids (red sphere) after loading. The displacement vectors and centroids are visualized with the bones of a single subject in volar (left) and radial (right).

Figure 3.

Volar view of a single wrist in the unloaded (left) and loaded (right) state in which separation at the radiocarpal and midcarpal joints is visible. The centroid of each bone is shown (red sphere). The centroid distances that were analyzed are represented as lines connecting the two respective centroids.

Figure 4.

Distractive loading caused a significant (*) increase in the centroid distances at the radioscaphoid, radiolunate and lunocapitate joints. There was a non-significant increase in the interbone distance at the 3rd carpal-metacarpal joint.

Table 1

Bone-bone interactions were measured as the change in distance between centroid spacing after loading. Each bone pair was reported in ascending order of change in centroid distance. The largest changes in centroid distance took place at the radiocarpal and midcarpal joints.

Bone -Bone		Change in Centroid Spacing (mm)
Radius	Lunate	-1.0 ± 1.0
Lunate	Triquetrum	-0.1 ± 0.1
Trapezium	Trapezoid	-0.1 ± 0.1
Trapezoid	2nd Metacarpal	0.1 ± 0.2
Lunate	Scaphoid	0.1 ± 0.5
Capitate	Hamate	0.1 ± 0.1
Trapezium	1st Metacarpal	0.1 ± 0.4
Capitate	Trapezoid	0.2 ± 0.2
Hamate	4th Metacarpal	0.2 ± 0.3
Scaphoid	Trapezium	0.3 ± 0.5
Capitate	3rd Metacarpal	0.3 ± 0.2
Scaphoid	Trapezoid	0.4 ± 1.0
Hamate	5th Metacarpal	0.6 ± 0.4
Scaphoid	Capitate	0.6 ± 0.8
Ulna	Lunate	1.1 ± 1.3
Ulna	Triquetrum	1.2 ± 1.5
Lunate	Capitate	1.6 ± 1.4
Radius	Scaphoid	1.80 ± 2.0
Hamate	Triquetrum	2.1 ± 1.4
Lunate	Hamate	3.0 ± 1.9

Table 2

Bone centroids displaced distally with components of dorsal and radial directions that differ with the bone. The lunate and triquetrum both had additional components of radial motion (See also Figures 1 and 2.).

Bone	Centroid Displacement (mm)	Displacement Vector Direction	
		Dorsal (°)	Radial (°)
Scaphoid	3.1 ± 2.5	30.5	8.7
Lunate	2.2 ± 1.7	48.8	36.1
Triquetrum	2.9 ± 1.9	44.9	33.6
Trapezoid	4.2 ± 2.9	37.9	6.1
Trapezium	4.7 ± 3.0	40.5	10.6
Capitate	3.8 ± 2.6	26.7	1.8
Hamate	4.7 ± 2.7	13.7	5.9
1st Metacarpal	6.1 ± 3.4	31.0	-3.1
2nd Metacarpal	4.5 ± 3.0	38.7	6.3
3rd Metacarpal	4.5 ± 2.8	29.8	5.1
4th Metacarpal	5.4 ± 3.0	13.9	5.3
5th Metacarpal	5.9 ± 3.0	6.3	7.0