Biomechanical Comparison of Dart-Throw Motions after Partial Wrist Fusions

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Abstract

Background Multiple partial wrist fusions exist for the management of arthritic disease. Limited information is available on their effect on wrist range of motion in the dart-throwing direction of wrist motion, even though it is used in most activities of daily living.

Purpose The purpose of this study was to measure the retained motion for different orientations of dart-throwing motion for seven different partial wrist fusions and proximal row carpectomy (PRC).

Methods Eight fresh frozen right cadavers were tested with the wrist intact and followed simulated fusions. Fusions were performed using an external fixation technique and included scaphocapitate, scapholunate (SL), capitolunate, radiolunate, radioscapholunate, scaphotrapeziotrapezoid, 4 corner fusion, and PRC.

Results In the intact wrist, the average arc of wrist motion with the wrist oriented at 20 degrees away from the flexion-extension axis was significantly larger than at any other orientation of motion. All partial wrist fusions and the PRC had significantly smaller average dart-throw arc of motion compared with intact at an orientation 20 and 25 degrees away from flexion-extension. The SL fusion provided a significantly larger arc of motion than most of the other fusions at most orientations.

Conclusion/Clinical Relevance This study provides a comprehensive compilation of the range of motion in a functional plane, "the dart-throw motion," for limited wrist fusions and PRC. These data provide the clinician with important information that can be used to educate patients regarding expectations after surgery.

Keywords
- carpal arthrodesis
- dart-throwing motion

Introduction

The common threads of debilitating pain and restricted functionality of the upper extremity accompany the various forms of wrist arthritis. Given the complex relationship with the articulations of eight carpal bones, the distal radius and intricate soft-tissue constraints, various wrist arthrodeses have been the major workhorse for surgical management of this pathology. The goal of partial wrist arthrodesis is to provide pain relief while preserving wrist motion, thereby restoring functionality.

One factor that may impact the selection of a specific wrist arthrodesis is the range of motion allowed after arthrodesis. Two in vitro studies quantified the loss of planar flexion-extension and planar radioulnar deviation for up to 11 simulated fusions.[1,2] Several in vivo studies have also evaluated motion in a unidirectional plane, flexion-extension, or radioulnar deviation.[3,4] Cohen et al reviewed the clinical outcomes in the literature of proximal row carpectomy (PRC) and four-corner arthrodesis procedures and found comparable results in postoperative motion. They found PRC resulted in an average flexion-extension arc that was 62% of the

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contralateral wrist, compared with 58% after 4-corner arthrodesis. DiDonna et al showed that patients maintained 62% flexion, 60% extension, 47% radial deviation, and 73% ulnar deviation after PRC compared with the contralateral side.

As shown by Palmer et al, however, most activities of daily living require a combination of wrist flexion-extension and radioulnar deviation, known as the dart-throwing motion.[5] This is an arc of motion starting in wrist extension and radial deviation moving to wrist flexion and ulnar deviation. The dart-throwing arc of motion has been found to be important in all forms of daily activity.[6,7] One complicating factor is that people have different dart-throwing motions (orientations). Vardakastani et al found, using goniometric measurements in live healthy patients, the orientation of the dart-throwing motion plane relative to the flexion–extension axis ranged from 28° to 57°.[8] Crisco et al, using cadaveric arms, found that the wrist motion was oriented obliquely to the direction of pure flexion-extension by $26.6° \pm 4.4°$.[9] The largest wrist range of motion was a mean of $111.5° \pm 10.2°$, oriented 30° from pure flexion, in the direction of ulnar flexion.

Studies of retained wrist motion after partial wrist fusion are quite limited, especially in the oblique functional plane of the dart-throwing arc. Kane et al looked at relative contributions of the radiocarpal (radioscapholunate) and midcarpal (pancarpal) joints to dart-thrower's motion and found comparable reductions with each.[10] Got et al compared 2-bone fusion (capitolunate [CL]), 3-bone fusion (lunocapitohamate) and 4-corner fusion (4CF) and found that equivalent motion, except for pure flexion and radial deviation, is possible with 2-bone, 3-bone and 4CF.[11]

The purpose of this study was to measure the retained motion for different orientations of dart-throwing motion for seven different partial wrist fusions and PRC. We hypothesized that restriction of arc of motion would be greatest for fusions crossing the radiocarpal joint, followed by inter row fusions, and least affected by intrarow fusions. We also hypothesize that scapholunate (SL) fusion would have the least effect on overall change in range of motion and orientation of motion.

Methods

Eight fresh frozen right cadaver wrists (average age 60 years; 1 female, 7 males; average height 177 cm; average weight 89 kg) were tested. The data from one wrist was excluded due to a contracture.

Each wrist was stabilized by inserting a pin into the humerus, stabilizing the distal radius and ulna to a support frame, and attaching an electromagnetic motion sensor to the dorsum of the third metacarpal. The elbow was positioned at 90 degrees of flexion and the forearm at neutral forearm rotation. Proximally, the radius and ulna were then pinned with two Kirschner wires to maintain neutral forearm rotation. Motion of the wrist was assumed to be equivalent to the motion of the third metacarpal, which was measured relative to an electromagnetic source (►**Fig. 1**). In the intact wrist and all simulated fusions

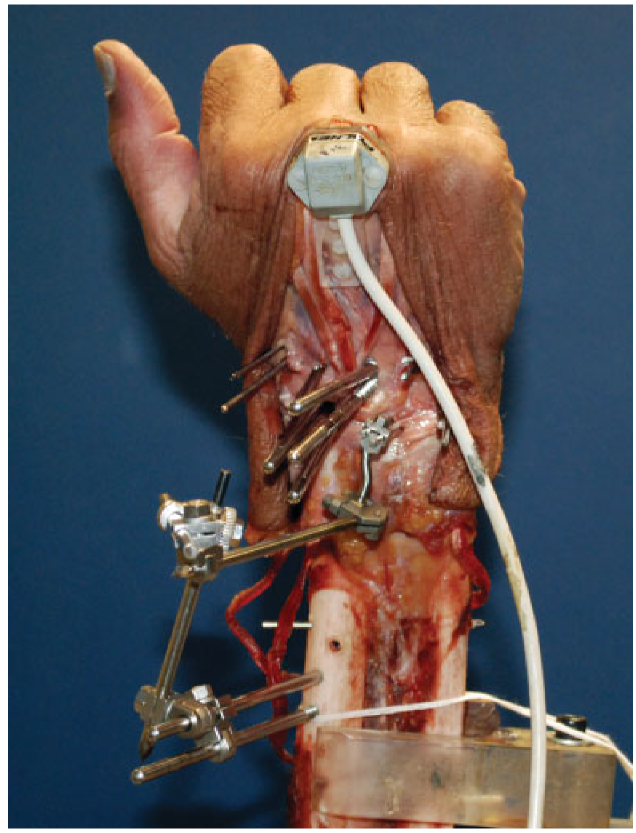

Fig. 1 Example of a radiolunate (RL) fusion using an external fixation frame. An electromagnetic motion-detecting sensor is mounted directly on the third metacarpal.

(described below), wrist flexion-extension and radioulnar deviation were acquired at a rate of 83 Hz as the wrist was moved passively through a circumduction motion for 60 seconds by two testers. The circumduction motion was a cyclic motion going from radial deviation to flexion to ulnar deviation to extension and then back to radial deviation. Each tester grasped the distal third metacarpal and applied only enough force to cause the circumduction motion without causing joint liftoff. To ensure reproducibility of each circumduction motion, each tester moved the wrist repeatedly before data was recorded. Limits of wrist motion in each direction were determined, and the wrist was palpated to detect any impingement or liftoff. Data was recorded as the tester slowly moved the wrist while feeling for any liftoff or impingement. After data collection, the motion was plotted to check for any noticeable outliers in the motion repetitions, and if found, the trial was repeated. To simplify presentation of the findings, the results for tester 1 are reported here. The results for tester 2 are reported in the **supplementary data** (available in the online version). In the case of the simulated PRC, data was collected for 60 seconds in the first two arms and for 120 seconds in the last six arms to allow more time to smoothly perform the PRC circumduction motions. A minimum of four circumduction motions were repeated during the 60 or 120 seconds.

Fusions were performed using an external fixation technique. Two self-drilling pins were placed percutaneously into each carpal bone and the distal radius parallel to each other.

Depending upon the bone, either 2- or 3.5-mm diameter pins were used. The two pins in each bone were then clamped together to minimize error from pin loosening and/or rotation around one fixed point. Pin placement was performed using fluoroscopy to ensure proper radiocapitolunate alignment and bicortical pin placement without mechanical block to motion in the carpal joints. The following seven different partial fusions were tested: scaphocapitate (SC), scapholunate (SL), CL, radiolunate (RL), radioscapholunate (RSL), scaphotrapeziotrapezoid (STT), 4CF, and PRC. While STT fusion was performed with the wrist in resting extension and radial deviation without a radial styloidectomy, all other partial fusions were in a neutral wrist position. 4CF was performed with a ligament-sparing dorsal approach to the wrist and excising the scaphoid before locking the external fixation device with the wrist in neutral.[12]

For each circumduction motion, the flexion-extension and radioulnar deviation motion was extracted from 5 to 55 seconds for the intact motion and all fusions, so that the analyzed data would not be affected by any artifacts as the motion was started or ended. In the case of the PRC in the last six arms, data was extracted from 5 to 115 seconds of the motion. Flexion and radial deviation were defined as positive. Three geometric properties of the circumduction motion were computed, in part, based on the work by Nagurka and Hayes (►Fig. 2) during the first complete circumduction motion of a trial.[13] The area within the circumduction motion was computed and represented a general indicator of the amount of wrist motion that was allowed. The centroid of that area, relative to neutral flexion-extension and neutral radioulnar deviation, was computed; this represents the point about which the motion is centered (positive xbar is radial deviation, positive ybar is flexion). Finally, the principal axes of the circumduction motion were computed. If one visualizes the circumduction motion as being an oval, the angle that the principal (long) axis of the oval makes relative to the flexion-extension axis was determined. A positive increasing angle corresponded to a motion that was oriented more toward positive radial deviation and less toward extension (more of a dart-throw motion).

For all circumduction motions during a trial, the range of motion that a dart throw might have until it intersected the boundary of the circumduction was determined (►Fig. 3). This range of motion was based on using the centroid of the area of motion as its origin. Thus, the amount of flexion-extension and radioulnar deviation during 13 different motions was computed as an arc of motion. These 13 motions included a pure flexion-extension motion, a pure radioulnar deviation motion, and 11 motions that were oriented at increasing degrees away from the flexion-extension axis (20, 25, 30, 35, 40, 45, 50, 55, 60, 65, and 70 degrees). At each position, for each wrist and for each fusion, the average arc as well as the maximum arc during the circumduction motion was determined.

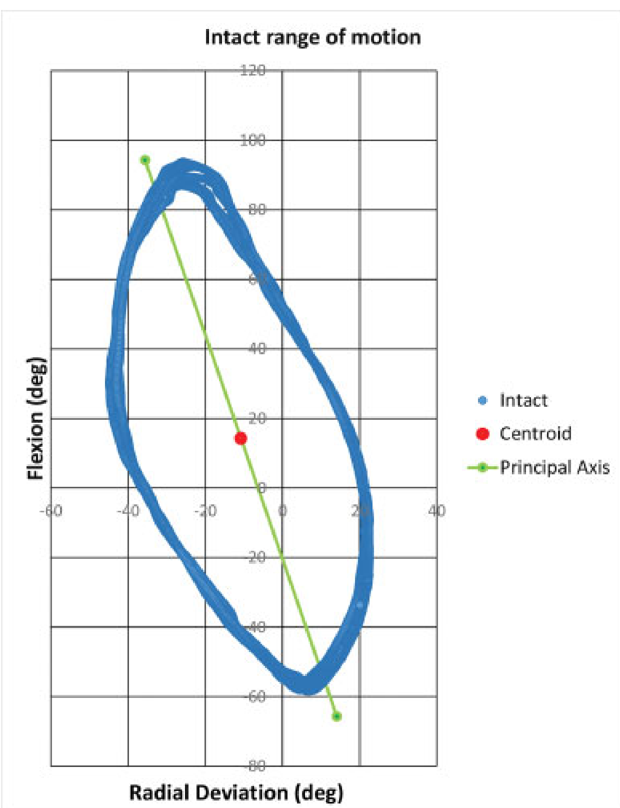

Fig. 2 Example of data collected: circumduction area of motion is the area within the oval, centroid of motion is the centroid of that area, and the principal axis of the circumduction motion is measured relative to the flexion-extension axis.

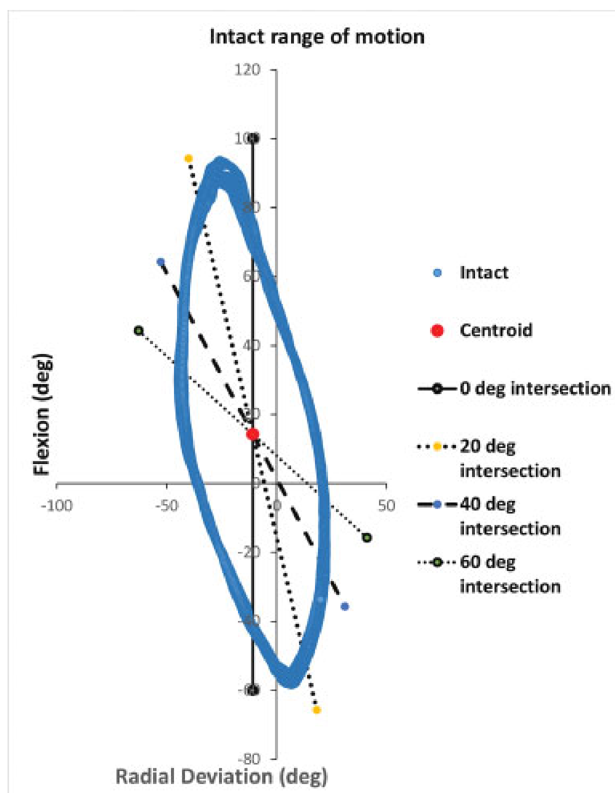

Fig. 3 Dart-throwing arc for four different orientations (0, 20, 40 and 60 degrees) going through the centroid. Length of line contacting borders of oval represents the range of motion for that dart-throw orientation.

A one-way repeated measures analysis of variance with a Bonferroni correction for multiple comparisons was used to compare the amount of area and the orientation of the principal axis among the various fusions, intact wrist, and PRC. This same method was used to compare the arc of motion allowed for the various fusions at each of the dart-throw orientations.

Results

Arc of Motion in Different Directions in the Intact Wrist

The arc of wrist motion with the wrist oriented at 20 degrees away from the flexion-extension axis (slightly oriented toward the radioulnar deviation axis) was significantly larger than any of the other arcs, with one exception (►**Table 1**). Specifically, the 20-degree orientation average arc was significantly larger than any of the others ($p < 0.034$) and the maximum arc was larger than any of the others ($p < 0.02$), except for the 25-degree orientation ($p = 0.067$).

Effect of Different Fusions or PRC on Arc of Motion

To simplify the presentation of the results, only the average arc of motion of the first tester is presented here (►**Table 2**). All the results are included in the **supplementary data** (available in the online version) for the rest of the tester 1 and tester 2 data.

All partial wrist fusions and PRC had significantly smaller average dart-throw arcs of motion compared with intact at an orientation 20 and 25 degrees away from flexion-extension ($p < 0.02$ and $p < 0.024$, respectively). At all orientations, the SC and CL had a significantly smaller average dart-throw arc of motion compared with the intact ($p < 0.021$ and $p < 0.018$, respectively). Additionally, at orientations of 20, 25, 30, 35, 40, 45, 50 and 55, the RL, RSL, STT and 4CF had significantly smaller average dart-throw arcs of motion compared with the intact ($p < 0.036$, $p < 0.001$, $p < 0.02$, and $p < 0.034$, respectively).

At all dart-throw orientations, except at the 20- and 25-degree orientations when the arc was significantly smaller than intact ($p = 0.006$ and $p = 0.024$ respectively), the SL arthrodesis did not have a significantly smaller average art of motion than the intact ($p > 0.071$). The SL had a significantly larger arc of motion than the SC, CL, RL, RSL, and 4CF at orientations of 20, 25, 30, and 35 degrees ($p < 0.036$, $p < 0.002$, $p < 0.037$, $p < 0.004$ and $p < 0.005$). The SL also had a significantly larger arc of motion than the SC, CL, RSL, STT, and 4CF at orientations of 40 and 45 degrees ($p < 0.002$, $p < 0.004$, $p < 0.003$, $p < 0.003$, and $p < 0.039$). The SL continued to have a significantly larger arc of motion than the SC, CL, RSL, and STT at orientations of 50, 55, 60, 65, 70 degrees and radioulnar deviation ($p < 0.006$, $p < 0.045$, $p < 0.013$, and $p < 0.02$). The RL arthrodesis had a larger arc of motion than the RSL at all orientations ($p < 0.049$), except at 45 degrees ($p = 0.07$) and 50 degrees ($p = 0.068$).

Table 1 Arc of motion that is possible in different directions in the intact wrist (degrees, [SD])

Orientation	Average arc	Maximum arc
Flexion-extension axis (0 degrees)	93.5 (11.8)	97.4 (12.7)
20 degrees	116.2 (14.5)	118.9 (15.3)
25 degrees	108 (12.2)	110.7 (12.6)
30 degrees	99.4 (10.6)	102 (10.8)
35 degrees	90.8 (9.4)	93.3 (9.4)
40 degrees	82.9 (8.4)	85.1 (8.5)
45 degrees	76.2 (7.7)	78 (7.8)
50 degrees	70.2 (7.2)	71.9 (7.3)
55 degrees	65.2 (7.0)	67 (7.4)
60 degrees	60.8 (6.9)	62.6 (7.2)
65 degrees	57.2 (6.9)	58.9 (7.0)
70 degrees	54.2 (6.7)	62.6 (7.2)
Radioulnar deviation axis (90 degrees)	46.6 (6.1)	47.6 (6.4)

Abbreviation: SD, standard deviation.
Note: Average arc of motion is the average of the average arcs during a circumduction motion. Maximum arc of motion is the average of the maximum arc of motion measured during a circumduction motion. See Supplementary Table S1 (available in the online version) for Tester 2 results.

Area of Circumduction Motion

All fusions, except the SL fusion, caused a significant reduction in the area ($p < 0.01$) compared with the intact (►**Fig. 4**). The SL fusion had a nonsignificant ($p = 0.057$) trend to be less than intact.

The area of circumduction motion for the SC fusion was significantly larger than the CL fusion ($p = 0.038$). The SL fusion area was significantly larger than the CL fusion ($p = 0.026$) and the RSL fusion ($p = 0.01$). The RL fusion was significantly larger than the RSL fusion ($p < 0.001$).

Orientation of Circumduction Motion Relative to the Flexion-extension Axis

Both the SC ($p = 0.031$) and STT fusions ($p = 0.015$) had a smaller angle of orientation than intact (►**Fig. 5**). The SC had a smaller angle than the SL ($p = 0.001$), the RL ($p = 0.008$), or the RSL ($p = 0.002$). The SL had a larger angle than the STT ($p = 0.001$) and the PRC ($p = 0.042$). Both the RL and RSL fusions had a larger angle than the STT ($p = 0.002$) and the PRC ($p < 0.013$). An increase in this orientation angle indicates that the motion was oriented more toward the radial deviation axis and less toward the extension axis.

Discussion

The purpose of this study was to measure the retained motion for different orientations of dart-throwing motion for seven different partial wrist fusions and PRC. Previous studies have demonstrated that the mechanical axis of the intact human wrist is oriented obliquely to the anatomic axes.[5,9] Brigstocke et al tested seven different activities of

Table 2 Average arc of motion for different fusions at different orientations of a dart-thrower's motion from flexion/extension axis (degrees)—Tester 1

Orientation	Fusion								
	Intact	SC	SL	CL	RL	RSL	STT	4CF	PRC
Flexion-extension axis (0 degrees)	93.5	76.4	80.8	55.0	58.8	41.2	75.5	59.8	72.8
20 degrees	116.2	72.5	102.4	59.0	82.5	54.1	67.1	64.8	70.3
25 degrees	108.0	67.6	98.1	59.1	80.0	56.7	60.7	65.2	68.0
30 degrees	99.4	62.3	91.9	58.4	74.5	57.1	55.3	65.0	63.1
35 degrees	90.8	57.2	85.0	57.0	68.9	55.4	50.1	64.3	58.1
40 degrees	82.9	52.9	78.0	55.0	63.5	52.7	45.6	62.8	54.5
45 degrees	76.2	49.3	71.7	52.3	58.6	49.8	42.1	60.0	50.8
50 degrees	70.2	46.2	66.3	49.7	54.5	46.5	39.4	57.2	48.2
55 degrees	65.2	43.7	61.6	47.4	50.9	43.2	37.0	54.7	45.4
60 degrees	60.8	41.3	57.6	45.1	47.8	40.1	35.1	52.2	43.0
65 degrees	57.2	39.5	54.1	43.1	45.0	37.1	33.4	50.2	41.2
70 degrees	54.2	38.0	51.2	41.6	42.6	34.4	32.3	48.2	40.3
Radioulnar deviation axis (90 degrees)	46.6	34.9	44.0	37.2	36.3	27.8	29.7	42.4	37.2

Abbreviations: 4CF, 4-corner fusion; CL, capitolunate; PRC, proximal row carpectomy; RL, radiolunate; RSL, radioscapholunate; SC, scaphocapitate; SL, scapholunate; STT, scaphotrapeziotrapezoid.

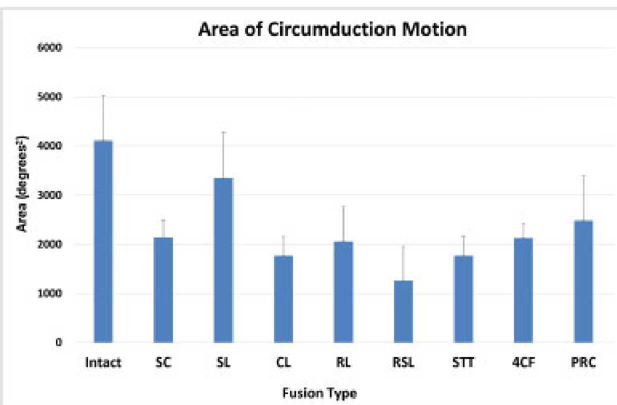

Fig. 4 Average area of circumduction motion. All partial fusions except scapholunate (SL) caused significant decrease in area compared with intact.

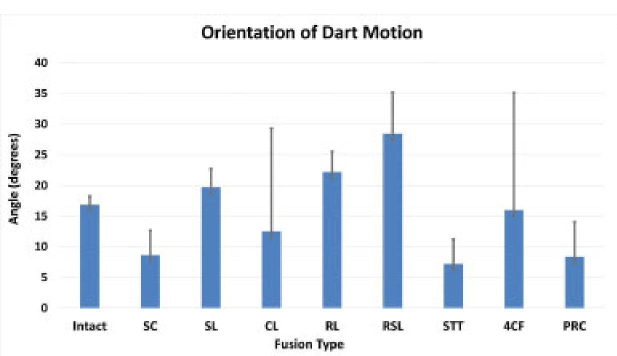

Fig. 5 Orientation of circumduction motion relative to the flexion-extension axis for the seven partial fusions performed and proximal row carpectomy (PRC).

daily living (ADLs) and concluded that the dart-thrower's arc of motion is important in completing ADLs.[14] We found in the intact wrist, the average arc of wrist motion with the wrist oriented at 20 degrees away from the flexion-extension axis was significantly larger than any other orientation. This is generally consistent with prior studies. Crisco et al, in a cadaver study, found that the wrist motion was oriented obliquely to the direction of pure flexion-extension by $26.6° \pm 4.4°$.[9]

All partial wrist fusions and PRC had significantly less dart-throw arc of motion compared with intact at an orientation 20 and 25 degrees away from flexion-extension. At all other orientations, SL fusion was the most accommodating, without a significant difference compared with intact wrist. Also, the average area of circumduction for the SL fusion was not significantly different from intact. This is consistent with the limited data on retained motion after SL fusion by Han et al.[15] They found minimal changes in motion after simulated SL fusion (6 degrees in dart-throwers' flexion and 5 degrees in dart-throwers' extension fluoroscopically). Our most notable findings were that the SL has a significantly larger arc of motion than other fusions in most orientations, and that the RL has a significantly larger arc of motion in most orientations and area of circumduction than RSL. Our findings are difficult to compare with existing data due to limited research on individual partial wrist fusion in this functional plane. However, Got et al found essentially equivalent motion is possible with 2-bone, 3-bone and 4CF fusions, with the exceptions of pure flexion and radial deviation.[11] Gaston et al[16] reported that their 2-bone fusions compared with their 4CF had only decreased motion in the flexion-extension plane. Our data does not conclusively support our first hypothesis that the restriction of arc of motion would be greatest for fusions crossing the radiocarpal joint, followed by interrow fusions, and least affected by intrarow fusions. It does fully support the second hypothesis that SL fusion would have the least effect on overall change in range of motion and orientation of motion.

The lack of research available on functional wrist motion after various partial wrist fusions could be due to their limited use in surgical practice. Early reports on nonunion with complications for multiple partial wrist fusions greatly reduced their use. Given the minimal surface area contact between the various carpal bones, surgical practice has heavily favored 4CF and PRC. PRC is not dependent on fusion, and the 4CF involving the hamate, triquetrum, capitate and lunate has more bone fusion mass to improve fusion rates. Wyrick et al reported on the motion retained following PRC and 4CF.[17] They found that with a PRC, the total arc of motion was 64% and the 4CF was 47% of the contralateral wrist. Cohen et al found PRC resulted in an average flexion-extension arc that was 62% of the contralateral wrist, compared with 58% after 4-corner arthrodesis.[3] Although our data did not find a significant difference between PRC and 4CF in arc of motion in different orientations or in area of circumduction, we did find similar percentages of retained motion. Area of circumduction of PRC and 4CF compared with intact was 60% and 52%, respectively, in our dataset.

We found only a few differences between various partial fusions and intact in the orientation of circumduction motion relative to the flexion-extension axis. Both the SC and STT fusions had a significantly smaller angle of orientation than intact, suggesting that the principal axis of wrist circumduction was more aligned with the flexion-extension axis and less toward an oblique axis.

The study was limited by the use of cadavers, which eliminates consideration of soft-tissue healing, capsular scarring, pain and grip strength. All of these factors are relevant in the clinical setting and can greatly alter clinical results. The circumduction motion was passively performed by hand, which might alter the extremes of motion. The same testers, however, performed all motions in all wrists. There were at least four circumduction rotations per arthrodesis with relatively small standard deviations. A strength of the study is that all partial fusions and PRC were performed on the same wrists, thus limiting confounding factors.

In conclusion, our data are consistent in showing functional wrist motion is in the oblique plane and not in pure anatomical positions. It also demonstrates that the SL fusion would have the least effect on overall change in range of motion and orientation of motion. This result is intuitive, as the scapholunate interosseous ligament links the motion of the scaphoid and lunate in the native wrist. Decisions as to which partial fusion is performed depend on multiple factors, including involved arthritic bony articulations, fusion rates, pain control, and retained motion. This study does not define which fusion should be performed, but rather provides a database on effects of motion after various partial fusions in a multidimensional functional plane. This information can aid in the surgical discussion between patient and physician regarding management of various pathologic arthritic states of the wrist.

Ethical Approval

This article is a basic science study that used cadaver specimens. the authors have acquired Biosafety Committee approval for the use of cadaver material. This study did not involve any human participants and therefore should not require any Institutional Review Board (IRB) review.

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Conflict of Interest

None declared.

References

1 Gellman H, Kauffman D, Lenihan M, Botte MJ, Sarmiento A. An in vitro analysis of wrist motion: the effect of limited intercarpal arthrodesis and the contributions of the radiocarpal and midcarpal joints. J Hand Surg Am 1988;13(03):378–383

2 Meyerdierks EM, Mosher JF, Werner FW. Limited wrist arthrodesis: a laboratory study. J Hand Surg Am 1987;12(04):526–529

3 Cohen MS, Kozin SH. Degenerative arthritis of the wrist: proximal row carpectomy versus scaphoid excision and four-corner arthrodesis. J Hand Surg Am 2001;26(01):94–104

4 DiDonna ML, Kiefhaber TR, Stern PJ. Proximal row carpectomy: study with a minimum of ten years of follow-up. J Bone Joint Surg Am 2004;86(11):2359–2365

5 Palmer AK, Werner FW, Murphy D, Glisson R. Functional wrist motion: a biomechanical study. J Hand Surg Am 1985;10(01): 39–46

6 Garg R, Kraszewski AP, Stoecklein HH, et al. Wrist kinematic coupling and performance during functional tasks: effects of constrained motion. J Hand Surg Am 2014;39(04):634–642.e1

7 Moritomo H, Apergis EP, Herzberg G, Werner FW, Wolfe SW, Garcia-Elias M. 2007 IFSSH committee report of wrist biomechanics committee: biomechanics of the so-called dart-throwing motion of the wrist. J Hand Surg Am 2007;32(09):1447–1453

8 Vardakastani V, Bell H, Mee S, Brigstocke G, Kedgley AE. Clinical measurement of the dart throwing motion of the wrist: variability, accuracy and correction. J Hand Surg Eur Vol 2018;43(07): 723–731

9 Crisco JJ, Heard WMR, Rich RR, Paller DJ, Wolfe SW. The mechanical axes of the wrist are oriented obliquely to the anatomical axes. J Bone Joint Surg Am 2011;93(02):169–177

10 Kane PM, Vopat BG, Mansuripur PK, et al. Relative contributions of the midcarpal and radiocarpal joints to dart-thrower's motion at the wrist. J Hand Surg Am 2018;43(03):234–240

11 Got C, Vopat BG, Mansuripur PK, Kane PM, Weiss AP, Crisco JJ. The effects of partial carpal fusions on wrist range of motion. J Hand Surg Eur Vol 2016;41(05):479–483

12 Berger RA. A method of defining palpable landmarks for the ligament-splitting dorsal wrist capsulotomy. J Hand Surg Am 2007;32(08):1291–1295

13 Nagurka ML, Hayes WC. An interactive graphics package for calculating cross-sectional properties of complex shapes. J Biomech 1980;13(01):59–64

14 Brigstocke GHO, Hearnden A, Holt C, Whatling G. In-vivo confirmation of the use of the dart thrower's motion during activities of daily living. J Hand Surg Eur Vol 2014;39(04):373–378
15 Han KD, Kim JM, DeFazio MV, et al. Changes in wrist motion after simulated scapholunate arthrodesis: a cadaver study. J Hand Surg Am 2016;41(09):e285–e293
16 Gaston RG, Greenberg JA, Baltera RM, Mih A, Hastings H. Clinical outcomes of scaphoid and triquetral excision with capitolunate arthrodesis versus scaphoid excision and four-corner arthrodesis. J Hand Surg Am 2009;34(08):1407–1412
17 Wyrick JD, Stern PJ, Kiefhaber TR. Motion-preserving procedures in the treatment of scapholunate advanced collapse wrist: proximal row carpectomy versus four-corner arthrodesis. J Hand Surg Am 1995;20(06):965–970

