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Original Article

Ulnar impaction syndrome with different operative methods: a comparative biomechanical study

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Abstract: Objective: Ulnar impaction syndrome seriously impairs wrist and hand function. Three main treatment procedures are available; however, little systematic research on the post-operation changes in wrist biomechanics currently exists. This study aimed to determine the long-term effects of these procedures and the optimal treatment methods for ulnar impaction syndrome. Methods: Twenty-four cases of fresh upper limb specimens were randomized into four groups: (1) the control group, (2) the ulnar-shortening operation group, (3) the Sauvé-Kapandji procedure group (distal radioulnar arthrodesis and intentional distal ulnar pseudoarthrosis), and (4) the Darrach procedure group (distal ulna resection). After keeping the wrist in a neutral position, a pressure sensitive film was applied. Starting at 0 N, the load was increased gradually at a speed of 0.1 N/s until reaching 200 N and then maintained for 60 s by the CSS-44020 series biomechanical machine. Then, the pressure sensitive films from each group were measured, and the results were analyzed with SPSS software. Results: The mean pressure and force on the ulna in the groups followed a decreasing trend from the control group, Sauvé-Kapandji procedure group and ulnar-shortening operation group. The mean pressure of the scaphoid fossa and the force on distal aspect of the radius in the groups followed an increasing trend from the control group, Sauvé-Kapandji procedure group, ulnar-shortening operation group and Darrach procedure group. This study found no significant differences in the mean pressure of the scaphoid fossa and the force on distal aspect of the radius between the Sauvé-Kapandji procedure group and the ulnar-shortening operation group. The Sauvé-Kapandji procedure group showed the greatest mean pressure on lunate fossa. Conclusions: In this comprehensive analysis of wrist biomechanics, the ulnar-shortening operation was superior to the Sauvé-Kapandji procedure and Darrach procedure, which adequately maintained the anatomical relationships of the wrist.

Keywords: Biomechanics, the Darrach procedure, the Sauvé-Kapandji procedure, the ulnar-shortening operation, ulnar impaction syndrome

Introduction

Distal radioulnar joint disorders have long received attention, but insufficient research regarding this joint has resulted in a lack of reliable treatments for many of its diseases. Ulnar impaction syndrome can cause medial wrist pain related to excessive load bearing across the ulnar aspect of the wrist [1]. This disease seriously impacts the function of distal radioulnar joints and the radiocarpal joint, which can further affect hand function. Ulnar impaction syndrome is due to impaction between the carpal bones and the ulnar head. Long-term keyboard and mouse use, among many other factors, may lead to the syndrome [2]. Early pathological changes, including cartilage injury and bone marrow edema, and terminal changes, such as osteonecrosis and osteoarthritis, can lead to serious dysfunction, which affects the person's daily life and work activities. Early diagnosis and treatment can reduce the disability rate and markedly improve the quality of life for patients. Currently, there are many studies on wrist biomechanics. In 2010, several authors produced a systematic assessment of distal radioulnar joint reconstruction after distal radius fracture by the Darrach and Sauvé-Kapandji procedure [3]. Nevertheless, there remains a need for more comprehensive research on the biomechanical changes in the wrist after treatment for ulnar impaction syndrome with the Darrach procedure, Sauvé-Kapandji procedure and ulnar-shortening operations. The biome-

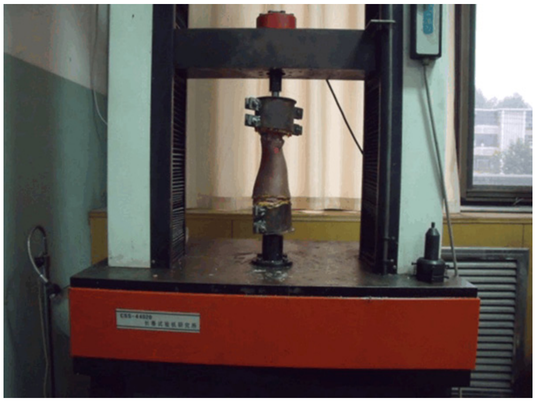

Figure 1. Specimens are mounted on the base of the experimental frame, which was kept in the neutral position.

chanical changes in the wrist under normal conditions and after these three procedures are fully analyzed in this study, which will provide important guidance to clinicians.

Methods

Specimens and preparations

After the specimens were completely thawed, they were amputated at the metacarpophalangeal joints and proximal to Lister's tubercle (20 cm away). A radialis incision was made in the wrist, and then the joint capsule was opened between the extensor pollicis longus and extensor pollicis brevis tendons. Similarly, an ulnar transverse incision was made in the distal ulnar styloid process, and the joint capsule was opened between the flexor carpi ulnaris and extensor carpi ulnaris tendons. Pressure sensitive films were cut according to the shape of the carpal articular surface of the radius and ulna and then sealed with polyethylene in case of fluid impregnation of the tissue.

Operation methods

Ulnar-shortening operation: An ulnar incision in the wrist and removal of the extensor carpi ulnaris tendon and flexor carpi ulnaris tendon, respectively, exposed the ulnar diaphysis. The ulnar diaphysis was amputated transversely, and the amputated bone was removed. Finally, an anatomical plate was applied for internal fixation.

The Sauvé-Kapandji procedure: This operative technique was performed using an ulnar approach. A segment of ulna (usually 1.5 cm) was resected at the site approximately 3 cm proximal to the ulnar styloid process. The articular surface of the distal radioulnar joint should be resected to ensure that two good cancellous surfaces are exposed. The caput ulnae was kept close to the incisura ulnaris and then fixed to the distal radius with two Kirschner wires. The central cancellous bone of the excised segment should be added to the gap in the pseudarthrosis. The space left by the resection should be filled with the pronator quadratus and then sutured to the peritendineum of extensor carpi ulnaris.

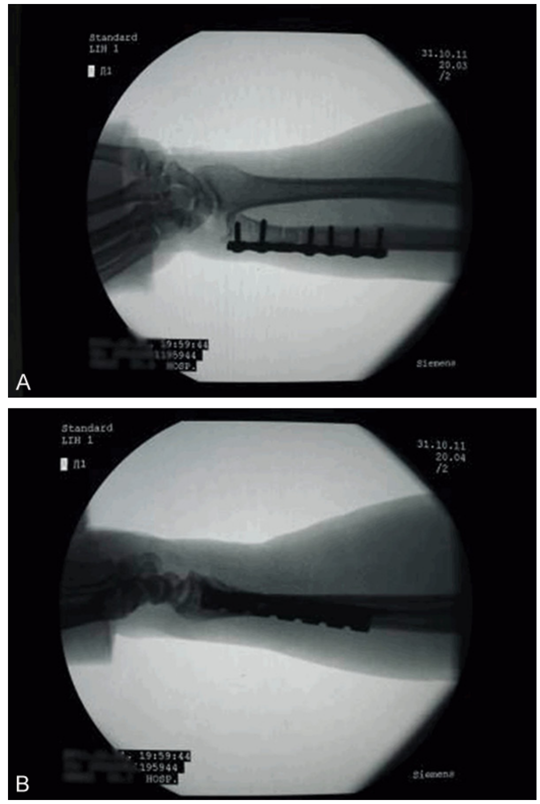

Figure 2. A. Posteroanterior radiograph after the ulnar-shortening operation. B. Lateral radiograph after the ulnar-shortening operation.

The Darrach procedure: An ulnar longitudinal incision was made over the distal ulna, and the head and distal end of the ulna were adequately exposed. Then, the caput ulnae with or without the TFCC were excised at the site just 3-9 cm proximal to the ulnar styloid process.

Mechanical testing

After the specimens were embedded in the custom mold by denture acrylic mounting onto the base of the experimental frame (**Figure 1**),

Table 1. Experimental results for the distal aspect of the ulna and radius

Specimen	Mean Pressure Ulna	Contact Area Ulna	Force Ulna	Contact Area Radius	Force Radius
1	0.34	233.55	80.15	111.17	102.87
2	0.33	224.93	74.99	112.24	98.48
3	0.31	235.18	73.66	117.73	105.42
4	0.30	229.88	69.93	120.14	97.87
5	0.31	224.58	70.25	117.44	103.32
6	0.28	219.88	61.17	113.65	102.81
7	0.25	193.96	47.64	143.39	121.66
8	0.25	199.84	48.96	153.50	131.81
9	0.30	209.96	62.95	149.64	124.20
10	0.25	224.09	55.31	148.95	126.16
11	0.24	210.42	51.17	153.98	118.58
12	0.24	190.24	45.81	155.01	131.39
13	0.29	218.08	63.68	135.48	121.17
14	0.26	226.87	59.08	124.88	115.99
15	0.27	249.60	67.99	116.61	117.14
16	0.25	208.70	51.80	130.17	114.06
17	0.26	208.57	55.23	148.65	121.17
18	0.26	207.41	53.70	133.90	119.38
19				151.21	168.77
20				166.7	170.01
21				157.34	172.01
22				171.31	167.72
23				164.25	167.04
24				173.53	174.82

The results in rows 1-6 are from the control group, rows 7-12 are from the ulnar-shortening operation group, rows 13-18 are from the Sauvé-Kapandji procedure group, and rows 19-24 are from the Darrach procedure group.

suitable pressure sensitive films were inserted into the wrist joint through the radialis and ulnar incisions, respectively. Care was taken to avoid stressing the pressure sensitive film in this process. After keeping the wrist in a neutral position, the pressure on the wrist was increased from 0 N to 200 N at a speed of 5 N/s and then maintained for 60 s at 200 N using the CSS-44020 series biomechanical machine. When the biomechanical test was finished, posteroanterior and lateral X-rays of the wrist were taken to verify that the ulna was not displaced (**Figure 2**). All specimens were tested with the same method, and the mean was obtained after testing each specimen three times.

Data acquisition and analysis

The stressed areas of the distal radioulnar joint, reflected on the pressure sensitive films, were determined by the colored area on each pressure sensitive film. Concentric circles with different radii were drawn on the pressure sensitive film, simply using the centers of the colored areas as the circles' centers. Then, the circles were divided at 60-degree intervals. The FDP 301 pressure densitometer measured the pressure, and the FDP 303 recording instrument documented the data. The images recorded on the pressure sensitive film were then uploaded to a computer. Finally, AutoCAD 2007 was used to analyze the colored area, and the mean was obtained by testing each colored area three times. Because this study was a small sample volume test with irregular variance, the rank transformation nonparametric test was applied. The Kruskal-Wallis test was used for comparative study between the four groups. The differences between any two groups were analyzed with the Mann-Whitney rank sum test with Bonferroni correction.

Table 2. Experimental results for the scaphoid fossa and lunate fossa

Specimen	Mean Pressure Scaphoid Fossa	Contact Area Scaphoid Fossa	Force Scaphoid Fossa	Mean Pressure Lunate Fossa	Contact Area Lunate Fossa	Force Lunate Fossa
1	0.43	52.49	22.57	0.38	58.68	22.30
2	0.45	53.67	24.15	0.33	58.57	19.33
3	0.42	51.32	21.55	0.51	66.41	33.87
4	0.44	57.50	25.30	0.52	62.64	32.57
5	0.47	54.94	25.82	0.44	62.5	27.50
6	0.42	52.13	21.89	0.34	61.52	20.92
7	0.69	64.23	46.25	0.70	79.16	55.41
8	0.60	67.77	40.66	0.48	85.73	41.15
9	0.55	62.85	30.8	0.50	86.79	43.40
10	0.52	70.35	36.58	0.44	78.6	34.58
11	0.49	66.96	28.12	0.35	87.02	30.46
12	0.66	61.52	43.06	0.41	93.49	38.33
13	0.44	57.66	25.37	0.46	77.82	35.80
14	0.49	56.29	27.58	0.56	68.59	38.41
15	0.49	52.36	25.66	0.49	64.25	31.48
16	0.52	57.52	29.91	0.47	72.65	34.15
17	0.50	69.74	34.87	0.46	78.91	36.30
18	0.52	58.86	30.61	0.53	75.04	39.77
19	0.69	62.26	42.96	0.56	88.95	49.81
20	0.73	78.71	57.46	0.62	87.99	54.55
21	0.75	77.34	58.01	0.60	80.00	48.00
22	0.72	82.62	59.49	0.51	88.69	45.23
23	0.74	78.89	58.38	0.57	85.36	48.66
24	0.83	82.09	68.13	0.62	91.44	56.69

The results in rows 1-6 were from the control group, rows 7-12 were from the ulnar-shortening operation group, rows 13-18 were from the Sauvé-Kapandji procedure group, and rows 19-24 were from the Darrach procedure group.

Results

Biomechanical testing of the ulna

Results from the FDP 303 recording instrument revealed that the mean pressure for the distal aspect of the ulna was 0.31 N/mm^2 (SD 0.023 N/mm^2) in the control group; 0.27 N/mm^2 (SD 0.15 N/mm^2) in the Sauvé-Kapandji procedure group; and 0.25 N/mm^2 (SD 0.023 N/mm^2) in the ulnar-shortening operation group (**Table 1**). The force was 71.69 N (SD 6.36 N) in the control group; 58.58 N (SD 6.25 N) in the Sauvé-Kapandji procedure group; and 51.97 N (SD 6.29 N) in the ulnar-shortening operation group. There was a statistically significant difference in the mean pressure, contact area and force on the ulna between the three groups (P=0.05). We also found no statistically significant difference (P=0.0167) in the mean pressure and force between the ulnar-shortening operation group and the Sauvé-Kapandji procedure group. The results showed that the mean pressure and force on the ulna in the groups followed a decreasing trend from the control group, Sauvé-Kapandji procedure group and ulnar-shortening operation group.

Biomechanical testing of the scaphoid fossa, lunate fossa and distal aspect of the radius

The mean pressure for the scaphoid fossa was 0.438 N/mm^2 (SD 0.019 N/mm^2) in the control group; 0.493 N/mm^2 (SD 0.029 N/mm^2) in the Sauvé-Kapandji procedure group; 0.575 N/mm^2 (SD 0.120 N/mm^2) in the ulnar-shortening operation group; and 0.743 N/mm^2 (SD 0.047 N/mm^2) in the Darrach procedure group (**Table 2**). The force for the distal aspect of the radius was 101.80 N (SD 2.97 N) in control group; 107.90N (SD 10.45 N) in the Sauvé-Kapandji procedure group; 125.63 N (SD 14.31 N) in the

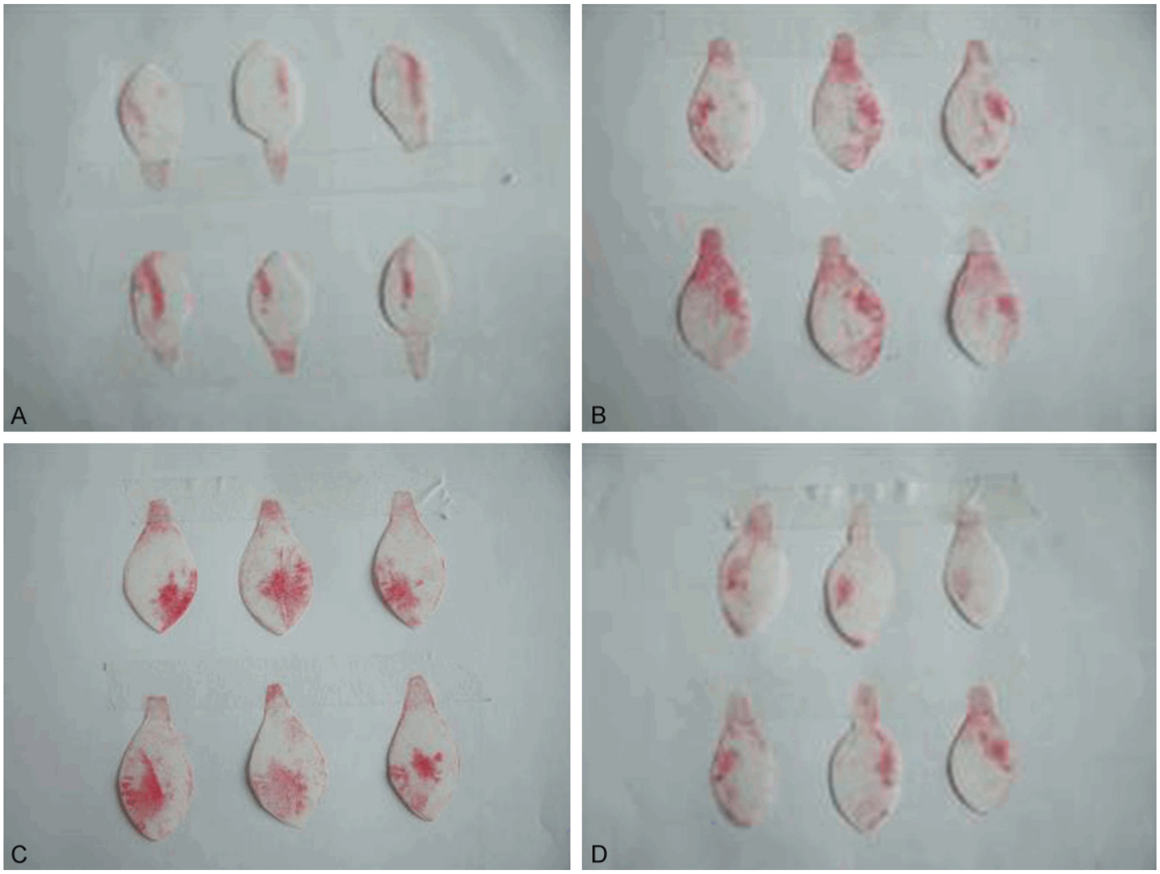

Figure 3. A. Pressure sensitive film of the distal aspect of the radius in the control group. B. In the Sauvé-Kapandji procedure group. C. In the ulnar-shortening operation group. D. In the Darrach procedure group.

ulnar-shortening operation group; and 164.99 N (SD 5.39 N) in the Darrach procedure group. The differences (*P*=0.05) in the mean pressure of the scaphoid fossa and the force on the distal aspect of the radius between each group were distinct, except the difference (*P*=0.0083) between the Sauvé-Kapandji procedure group and the ulnar-shortening operation group. We also found that the mean pressure of the scaphoid fossa and the force on distal aspect of the radius in the groups followed an increasing trend from the control group, Sauvé-Kapandji procedure group, ulnar-shortening operation group and Darrach procedure group.

No significant difference in the mean pressure of the lunate fossa was found between each group, except that the difference between the control group and the Sauvé-Kapandji procedure group was statistically significant. In addition, the minimum mean pressure was found in the control group, and the maximum mean pressure was found in the Sauvé-Kapandji procedure group.

Discussion

The two sheet-type of pressure sensitive film consists of an A film and a C film, with the coated surfaces in contact. The film gains coloration with increasing pressure. (**Figure 3**) Different pressures lead to different amounts of micro-encapsulate bursting, which affects the extent of color development. Not only can pressure sensitive film measure the contact area and pressure, but it can also test the pressure distribution accurately and precisely enough to meet the requirements of this experiment. The range of coloration is variable because the pressure sensitive film develops color by chemical reaction under different temperatures and humidities in the present study, the specimens were thawed one day in advance to attain the required temperature and humidity. Due to the range limits of the pressure sensitive film, very high or low pressures lead to information loss and therefore cannot be measured. As previously reported, 7.85% of the information is lost using pressure sensitive film for measurement [4]. To yield credible measurement results, super-low pressure sensitive film was used, and the control group was established.

As illustrated by the X-ray films, the length of the ulna in the control group, ulnar-shortening operation group, and the Sauvé-Kapandji procedure group decreased, which in turn led to decreasing pressure, stress area and force on the ulna in these three groups. There was a positive correlation between the ulnar length and the pressure, stress area and force on the ulna. However, when the variance increased from neutral to 2.5 cm positive, ulnocarpal load increased by approximately 20%. Decreasing the variance by 2.5 cm lowers the transmission force from 20% in the neutral variant to 5% [5]. A positive correlation between the ulnar variance and radioulnar distance has been reported [6]. Additionally, other researchers have reported that a wrist with a larger ulnar variance has a higher likelihood of subluxation of the distal radioulnar joint [7]. The Sauvé-Kapandji procedure group and the ulnar-shortening operation group showed a shortening of ulnar length, which changed the force on the ulna and improved the etiology of ulnar impaction syndrome. Such results are the biomechanical foundation of symptom improvement in the clinic.

The Sauvé-Kapandji procedure achieved distal radioulnar pseudarthrosis and thus relieved the force on the ulnar articular surface, which improved functional forearm rotation. This experiment also confirmed that the Sauvé-Kapandji procedure alleviates the force and reduces the stress area on the ulna. This procedure distributes the axial pressure created by the ulna to the radius, which increases the pressure on the radial shaft. This increase may have negatively affected the radiohumeral joint [8]. In fact, feelings of instability of the ulnar shaft proximal to the resection level and impingement of the ulnar shaft against the radius have been reported [9, 10].

The ulnar-shortening operation shortened the ulnar length, and the force created by the distal ulna was not distributed to the radius. The influence of different amounts of load on the wrist has been studied. The results showed that load on the ulnar wrist is significantly reduced when negative ulnar variance occurs but is significantly increased with positive ulnar variance [11]. With surgery, positive variance is converted to neutral or negative and, consequently, the overload between the ulnar head and carpus is decompressed [12-14]. This experiment proved that the ulnar-shortening operation relieves the force and reduces the stress area on the ulna. It has been reported that the ulnar-shortening operation is the most effective treatment method for radial shortening malformation [11]. Accordingly, considering the axial force to the radius and normal anatomy of the wrist together, the ulnar-shortening operation is the best treatment method for ulnar impingement syndrome.

The most significant indices in this experiment were the total force on the distal aspect of the radius and the pressure of the scaphoid fossa and lunate fossa. Because the total force on the distal aspect of the radius will influence the axial force on the radius, the articular surface of the scaphoid fossa and lunate fossa will be damaged when they bear too much pressure, which manifests as late complications.

The mean pressure on the lunate fossa had no statistical difference between the Sauvé-Kapandji procedure group and control group. This finding demonstrates that this procedure is not damaging to the distal aspect of the radius. Consequently, the radial articular surface does not collapse, which proves that the anatomic relationships of the wrist are well maintained by this procedure.

Amputating a segment of ulna increased the pressure on the radius in the ulnar-shortening operation group, which increased the burden on the radius. The greater the amount of ulnar shortening, the higher the peak pressure at the DRUJ [15]. Furthermore, this procedure added a great amount of pressure on the scaphoid fossa, which resulted in higher pressures than in the control group.

The biomechanics of the scaphoid fossa and lunate fossa and normal wrist anatomy were changed to a great extent in the Darrach procedure group, which is the mechanistic basis of wrist degeneration after the operation. Nevertheless, this procedure and its various modifications have been shown to compromise the ability to lift and bear loads [16]. Only considering the pressure on the scaphoid, the ulnar pseudarthrosis operation group improved more than the ulnar-shortening operation group and caput ulnae osteotomy group. However, the length of ulnar shortening in the ulnar pseudarthrosis operation group is shorter than that in the ulnar-shortening operation group in this experiment, as illustrated by the X-rays. Therefore, if it properly shortens the ulna, then the ulnar-shortening operation is superior to the ulnar pseudarthrosis operation overall.

The ulna reportedly exerts 17% of the axial pressure [17], but in this experiment the ulna received approximately 39.3% of the axial pressure. Because this experiment employed extracorporeal specimens, which decreased the muscular traction, the neutral position was not well maintained. Moreover, all three procedures were performed on normal specimens, which may have led to a deviation in the experimental results.

Retaining or reconstructing the structures that support load transmission on the wrist is important for achieving normal function [18]. Based on this biomechanical study, we believe that the ulnar-shortening operation adequately maintains the anatomical relationships of the wrist and relieves the force on the ulnar wrist. The Darrach procedure seriously damages the wrist's anatomical position and heavily adds to the force on the distal aspect of the radius, which leads to degeneration of the distal aspect of the radius post-operation. Similarly, in the Sauvé-Kapandji procedure, the radius bears almost all of the axial force after the operation. In sum, the ulnar-shortening operation is superior to the Darrach procedure and Sauvé-Kapandji procedure in the treatment of ulnar impaction syndrome.

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Disclosure of conflict of interest

None.

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