A comparative biomechanical study of radial versus dorsal plating for trapeziometacarpal arthrodesis

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ABSTRACT

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Trapeziometacarpal arthrodesis is used for the treatment of advanced arthritis. Insufficient stabilization of the joint may lead to nonunion or hardware problems after arthrodesis. The purpose of this study was to compare the biomechanical properties of dorsal versus radial plate fixation of the trapeziometacarpal joint in ten pairs of fresh-frozen cadaveric hands. The biomechanical performance of each group was measured for stiffness in extension and flexion and load to failure using cantilever bending tests. The stiffness in extension was lower in the dorsally positioned group than in the radially positioned group (12.1 versus 15.2 N/mm, respectively). Load to failure was comparable between both groups (53.9 versus 50.9 N, respectively). A radially positioned locking plate for trapeziometacarpal arthrodesis may be biomechanically advantageous.

Key words : **trapeziometacarpal joint, osteoarthritis, arthrodesis, locking plate**

1. Introduction

Arthrodesis of the trapeziometacarpal joint (TMJ) is an option for the treatment of advanced osteoarthritis, preserving grip strength by maintaining length.1 The patient satisfaction rate after fusion is reported to be 60%–100%.2 Complications such as nonunion (5%–30% of cases)3,4 and hardware problems (6%–54% of cases)5 remain concerns. Recently, there have been attempts to overcome these problems by various methods, including an additional oblique interfragmentary screw,6 bone graft,7 and a V-shaped osteotomy.8 These techniques aim to create a more stable structure and increase the union rate after TMJ arthrodesis.

Various locking plates have also been described for TMJ joint arthrodesis.9 A plate placed on the tension side of the joint is generally better from a biomechanical perspective.10,11 The dorsal side of the TMJ, however, becomes the compression side when the joint extends.12,13 For this reason, we hypothesized that radial positioning of the plate would be more biomechanically advantageous than dorsal positioning of the plate in TMJ arthrodesis.

The purpose of this study was to compare the biomechanical properties of a dorsally positioned plate and a radially positioned plate in TMJ stabilization and to analyse the correlation between anatomical profiles and biomechanical properties.

2. MATERIALS AND METHODS

2.1. Specimen preparation

Twenty hands were dissected from ten fresh frozen human cadavers. The thumb metacarpal bones and trapeziums (n=20 specimens) were removed, with the joint capsules and surrounding ligament complexes preserved. There were three male and seven female specimens, with a median age of 82 years (IQR 68–85). No specimen had evidence of underlying pathology. Paired cadaveric hands were divided into two groups (n=10 per group): dorsally positioned locking plate (Group A); or radially positioned locking plate (Group B). Each group was randomly assigned a left- or right-side hand, using a paired specimen to minimize potential differences across groups. Before dissection, the pulp of the thumb was positioned against the radial aspect of the middle phalanx (of the index finger) to provide adequate opposition of the thumb's tip and the index finger. The joint was then temporarily fixed by running a 1.1mm Kirschner (K)-wire through the thumb metacarpal bone to the trapezium, to obtain the optimum position for arthrodesis. To simulate the arthrodesis, the two bones were connected with a 2.0mm 6-hole TriLock plate (Aptus Hand, Medartis, Basel, Switzerland) and the plate was bent to fit the contour of the TMJ (Figures 1 and 2). A digital

calliper was used to measure the length, maximum and minimum width of thumb metacarpal bone and the height and width of the trapezium. These measurements were used for correlation with biomechanical properties. The distance between the joint and the contact with the testing machine was measured for later determination of bending moments. After fixation, all ligaments were cut to minimize any confounding effect. The trapezium of each specimen was secured to a customized round jig 4 cm in width and 3 cm in height using unsaturated polyester resin (EC-304, Aekyung Chemical Co., Seoul, Korea). Before securing with resin, the plate, screw tip and metacarpal bone were covered with removable silicone to avoid additional support by the resin and to maintain free space between the specimen and the resin. The proximal articular surface and soft tissue of the trapezium were removed for securing the surfaces to the resin. The cadaveric specimens were kept frozen at -20℃ and thawed only twice during the experiment, for initial harvesting and fixation, and again for biomechanical testing.

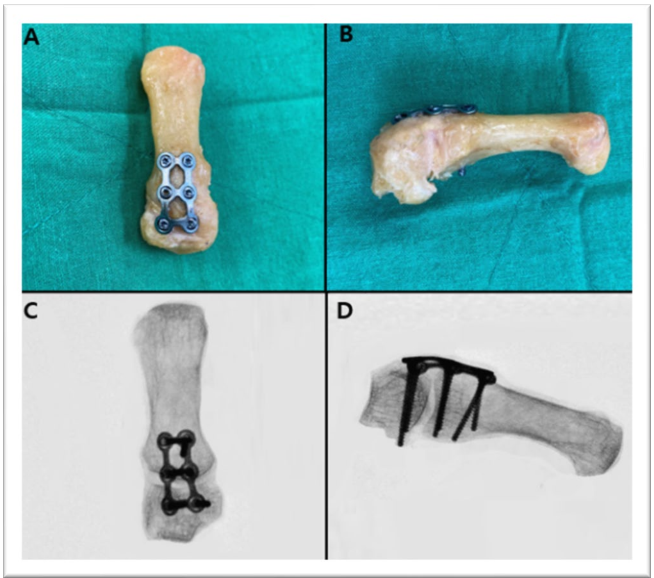

Figure 1. Dorsally fixed group. Specimen preparation after dorsal plating (a, b) and radiographic scanning (c, d).

Figure 2. Radially fixed group. Specimen preparation after radial plating (a, b) and radiographic scanning (c, d).

2.2. Biomechanical testing

The biomechanical performance of each group was measured primarily for stiffness in extension using cantilever bending tests. Stiffness in flexion and load to failure were also measured as secondary outcomes. The mechanical loading tests were carried out by an electrohydraulic materials test system (model 3366; Instron Co. Ltd, Norwood, MA, USA) and axial loads were measured and controlled using a calibrated load cell (Instron Co. Ltd). All specimens were separated from a customized jig and fixed on a testing machine frame with eight clamping screws (Figure 3). The long axis of the metacarpal bone was positioned at 45° to the vertical loading axis. The cantilever bending test set-up and the 45° angle system were used to simulate the compressive and shear forces applied to the TMJ during a pinch grip activity.14,15 The custom fixture was adjusted left and right as required to align the head of the metacarpal bone with the centre of the load cell.

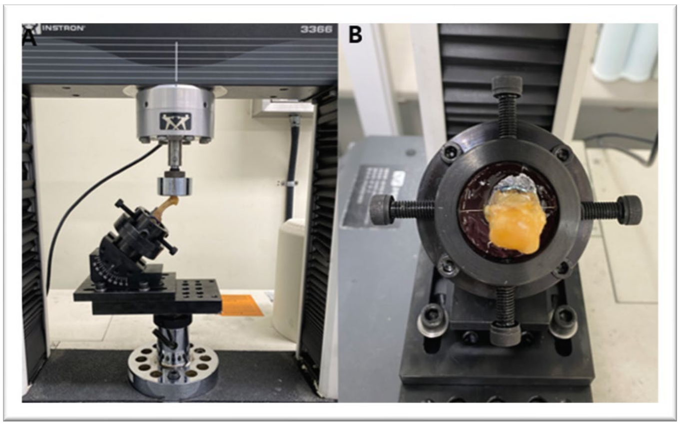

Figure 3. Cantilever bending test setup. (a) Long axis of the metacarpal bone set at 45° to the vertical loading axis and (b) Rounded specimens were clamped by screws.

2.3. Data analysis and statistical tests

We used mean and standard deviation to report normally distributed continuous data, with median and interquartile range (IQR) used to report non-normal data. Anatomical measurements are presented as means and 95% confidence intervals. The load– displacement curve was assessed for stiffness, single load to failure and bending moment. Stiffness was determined using the slope from the linear region of the load–displacement curve, resulting from the fifth successive stiffness test. Single load to failure was determined at the point of failure, defined as a sudden change in the load–displacement curve due to loss of fixation. The required sample size was calculated from a pilot study that used the first three paired specimens to determine the mean value of stiffness in extension. The mean and standard deviation for each group in the pilot study was 12.4N/mm (SD 1.5) for Group A (dorsally positioned locking plate) and 15.9N/mm (SD 2.6) for Group B (radially positioned locking plate). Based on these data, six specimens were required to provide 80% power at an a level of 0.05 and eight specimens to provide 95% power. In this pilot study conducted in the same setting, we confirmed that 20N of force did not cause plastic deformation and stiffness, therefore, was measured in increasing loads up to 20 N.

The biomechanical properties of the two groups (radially or dorsally positioned plate) were compared using a paired t-test. A stepwise linear multiple regression analysis was done after

the univariate analyses to identify independent variables that were predictive of biomechanical properties. All continuous variables were tested for normality using the Kolmogorov–Smirnov test. Statistical significance was set at p<0.05.

3. RESULTS

Biomechanical properties are described in Table 1. Cantilever bending testing revealed that stiffness in extension (which simulates grasping) was significantly lower in the dorsally positioned locking plate group when compared with the radially positioned locking plate group. Conversely, stiffness in flexion (which simulated pinching) was significantly lower in the radially positioned locking plate group. There was no significant difference between stiffness in flexion and extension in the radially positioned locking plate group (p=0.064). Load to failure showed no significant difference between groups. In most cases, the cadaveric bone failed before the fixation constructs, except for one specimen in Group B. No constructs failed at the bone–resin interface.

Table 1. Results of the stiffness and load to failure tests.

Outcome measures (SD)	Group A (*n*=10)	Group B (*n*=10)	*p*-value
Stiffness in extension, N/mm	12.1 (1.9)	15.2 (4.1)	**0.029**
Stiffness in flexion, N/mm	18.7 (5.3)	14.8 (2.9)	**0.034**
Single load to failure, N	53.9 (4.9)	50.9 (14.4)	0.516
Bending moment, Nm	2.3 (0.2)	2.2 (0.6)	0.464

Significant values shown in bold font.

The anatomical characteristics of the metacarpal bone and trapezium are shown in Table 2. There was no significant correlation between the anatomical features and biomechanical properties except for the length of thumb metacarpal with stiffness in flexion. A stepwise multiple regression analysis demonstrated that a longer thumb metacarpal length (p=0.020) was associated with stiffness in flexion (adjusted r2=0.227; regression coefficient=2.069).

Table 2. Anatomical characteristics associated with biomechanical properties.

Variables (95% CI)	All (*n*=20)	Stiffness in extension	Stiffness in flexion	Load to failure
Length of thumb metacarpal, mm	42.7 (42.1 to 43.2)	0.967	**0.020**	0.734
Maximum width of metacarpal, mm	16.4 (15.8 to 17.0)	0.059	0.224	0.405
Minimum width of metacarpal, mm	11.4 (11.1 to 11.7)	0.151	0.769	0.941
Width of trapezium, mm	21.1 (20.5 to 21.7)	0.394	0.124	0.779
Height of trapezium, mm	14.4 (13.8 to 15.0)	0.198	0.327	0.807

Significant values shown in bold font.

4. DISCUSSION

This study has shown that specimens with radially positioned plates showed superior stiffness in extension and comparable load to failure, when compared with specimens with dorsally positioned plates. The stiffness in flexion was inferior in the radially positioned plate group. The length of the thumb metacarpal was the only anatomical measurement associated with biomechanical properties (stiffness in flexion).

There are few biomechanical studies on fixation strength in TMJ arthrodesis. Stokel et al.16 compared the biomechanical properties of four different types of fixations using K-wires. They used five specimens per group and reported superior biomechanical properties for the tension band technique in torsion and the cerclage technique in flexion–extension. TMJ arthrodesis is now usually done using plates or headless compression screws (HCSs) rather than K-wires because of a lower incidence of revision surgery.17 Sehjal et al.13 carried out a biomechanical analysis of five TMJ fixation models, including K-wires, crossed HCSs, compression plating and locked compression plating in porcine forefoot specimens. Crossed HCS showed the greatest overall stability in abduction–adduction and flexion– extension).

The TMJ permits multiplanar motions including adduction–flexion during lateral pinch, abduction–flexion during palmar pinch and abduction–extension during grasp.12 In our study,

the radially positioned plate showed comparable stiffness in flexion and extension, but the dorsally positioned plate showed lower stiffness in extension. When the locking plate is on the dorsal aspect of the TMJ, bending forces during flexion would put the plate on the tension side, but it would be on the compression side during TMJ extension. The relationship between locking plate position and bending force direction has been reported for the tarsometatarsal joint. Witkowski et al.11 compared the stability of dorsally and medially positioned plates in first tarsometatarsal joint arthrodesis. Both groups underwent mechanical testing simulating ground reaction force on the hallux. A medially positioned locking plate showed better stability and smaller displacement than the dorsally positioned group (compression side) owing to their greater vertical bending stiffness. Similarly, Drummond et al.10 compared dorsal, plantar and medial plate positions in first tarsometatarsal joint arthrodesis. The biomechanical performance of each construct was tested by cantilever bending. Notably, the dorsal plate position (compression side) was not superior to either plantar or medial plate positioning in any measured outcome.

This study has several limitations. First, the mean age of the cadavers that the specimens were harvested from was older than those who are generally candidates for TMJ arthrodesis surgery. To reduce variation and potential risks to bone condition, we used matched pairs of specimens and minimized freeze–thaw cycles. Second, when clinically performing arthrodesis with a locking plate, bone surfaces are prepared and a bone graft may be used. We focused solely on the biomechanical comparison of different locking plate positions, without preparation of the joint surfaces. Third, in this study, bone failure preceded plate failure, a scenario that is not commonly seen clinically. Biomechanical testing cannot robustly reproduce the complexity of in vivo conditions, and these results cannot be interpreted as directly related to nonunion rates in clinical practice. Future biomechanical studies should focus on construct failure during repetitive loading.

5. CONCLUSION

In conclusion, a radially positioned locking plate of the TMJ showed superior stiffness in extension and comparable load to failure versus a conventional, dorsally positioned plate for arthrodesis of the joint. These results provide information for healthcare providers considering arthrodesis of the TMJ. However, further studies are still needed to determine the clinical effectiveness of these findings.

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Abstract in Korean

무지의 대능형중수간 관절 유합술시 잠김 금속판의 위치에 따른 생체역학적 비교 연구

연구 배경 및 목적: 관절 유합술은 진행된 무지의 대능형중수간 관절염의 치료법 중 하나로, 불충분한 고정은 고정 실패나 불유합의 원인이 될 수 있다. 잠김 금속판을 통한 무지의 대능형중수간 관절 유합술시 고식적으로 금속판은 관절의 배측에 위치하게 된다. 일반적으로 금속판은 관절의 인장측에 위치하는 것이 생체역학적으로 유리한데, 무지 대능형중수간 관절의 배측은 굴곡시에는 인장측이 되지만, 신전시에는 압박측이 된다. 이 연구의 목적은 무지의 대능형중수간 관절에서 잠김 금속판이 배측과 요측에 위치하는 것에 따른 생체역학적 안정성을 비교하는 것이다.

연구 재료 및 방법: 10 구의 카데바 수부 좌, 우 대응표본을 대상으로 하였으며 무지의 중수골과 대능형골을 2.0mm 잠김금속판을 이용하여 배측과 요측에서 고정하였다. 굴곡/신전 강성을 측정한 후 단회 항복 강도를 측정하였다.

연구 결과: 신전 강성은 요측 잠김 금속판군 (15.2 ± 4.1 N/mm) 과 배측 잠김 금속판군 (12.1 ± 1.9 N/mm) 간에 통계적으로 유의미한 차이를 보였다 ($p=0.029$). 단회 항복 강도(N)는 두 군간 유의미한 차이를 보이지 않았다 ($p=0.516$).

결론: 무지의 대능형중수간 관절 유합술시 잠김 금속판을 요측에 위치시킨 군은 고식적으로 배측에 위치시킨 군에 비해 우월한 신전 강성과 비교할만한 단회 항복 강도를 보였다. 하지만 이러한 결과가 임상적으로 효용이 있을지는 추가 연구가 필요하겠다.

핵심되는 말 : 대능형중수간 관절, 골관절염, 관절 유합술, 잠김 금속판