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Biomechanical comparison of two biplanar and one monoplanar reconstruction techniques of the acromioclavicular joint

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Abstract

Introduction The purpose of this proof-of-concept study was to investigate the biomechanical performance of two surgical techniques, namely (1) the double Tight-Rope fixation with an additional acromioclavicular FiberTape fixation (DTRC) and (2) the fixation of the clavicle to the acromion and coracoid in a bipodal manner (Bipod) using a Poly-Tape and FiberTape. Both techniques intend to address vertical and horizontal instability after acromioclavicular dislocation. They were compared with the commonly used (3) double Tight-Rope (DTR) technique, which only stabilizes the clavicle to the coracoid.
Materials and methods The acromioclavicular joint (ACJ) of 18 composite Sawbone shoulder specimens (6 per reconstruction group) were tested for posterosuperior elongation (70N cyclical load, 1500 cycles), load-to-failure and stiffness.
Results After 1500 cycles, the DTRC, Bipod and DTR group showed an elongation of 0.45 mm (SD 0.14 mm), 1.19 mm (SD 0.54 mm), and 0.46 mm (SD 0.15 mm), respectively. Although the elongation of the Bipod group was increased when compared to the other two groups (Bipod versus DTRC $p = 0.008$; Bipod versus DTR $p = 0.006$), the difference was less than 0.7 mm. The DTRC showed a higher load-to-failure of 656.1N (SD 58.1 N) compared to the Bipod [531.1 N (SD 108.2N) ($p = 0.039$)] and DTR group [522.8 N (SD 32.8 N) ($p = 0.033$)].
Conclusion The DTRC and the DTR group resulted in similar low elongation, while the elongation in the Bipod technique was slightly higher. Even though this difference of 0.7 mm shows statistical significance, it most likely has no clinical relevance. When testing in posterosuperior direction, which is the clinically relevant load vector, an additional fixation of the clavicle to the acromion did not reduce elongation in this study. It is, furthermore, questionable if the benefit of an increased load-to-failure in combination with no improvement in elongation and stiffness as seen in the DTRC group outweighs the possible risks and increased costs coming with the DTRC refixation.

Keywords Acromioclavicular joint dislocation · Arthroscopically assisted · Bipod · Double Tight-Rope · Tight-Rope · Rockwood · Cerclage

Abbreviations

ACJ	Acromioclavicular joint
AC	Acromioclavicular
AP	Anterior–posterior
CC	Coracoclavicular
DTR	Double Tight-Rope
DTRC	Double Tight-Rope fixation with an additional acromioclavicular FiberTape fixation
N	Newton
SD	Standard deviation

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Introduction

To date, over 150 different ACJ refixation techniques have been proposed, but none of these techniques have gained widespread acceptance. There are several possible reasons for this: first, some techniques such as hook plate and CC screw fixation require a second surgery, which may increase morbidity. Second, complications such as Kirschner wire migration [1], acromion osteolysis and implant-associated fractures [2], screw pull-out, and/or loss of reposition [3, 4] have been reported. Third, a remaining horizontal instability has been reported in up to 43% of the patients after isolated CC stabilization [5]. It has been shown that this horizontal instability can be substantially reduced by adding an additional AC cerclage to the CC fixation [6, 7]. This is in line with the biomechanical study, which showed that horizontal stability is mainly mediated by the AC ligaments, while vertical stability is mainly mediated by the CC ligaments [8].

Two minimally invasive arthroscopically assisted techniques were presented, which address vertical instability by fixing the clavicle to the coracoid and horizontal instability by fixing the clavicle to the acromion, namely (1) the double Tight-Rope repair in combination with an acromioclavicular cerclage (DTRC) and (2) the Bipod reconstruction including acromioclavicular repair (Bipod) [9, 10].

The purpose of this proof-of-concept laboratory study was to evaluate the elongation behavior after cyclic loading, load-to-failure and stiffness of these two minimally invasive surgical methods and compare them to the well-studied double Tight-Rope technique (DTR), in which the clavicle is only fixed to the coracoid. We hypothesized that the DTRC- and Bipod techniques would provide similar biomechanical properties with respect to elongation after cyclical loading, load-to-failure and stiffness. Our second hypothesis was that the DTRC- and the Bipod technique would improve substantially biomechanical stability compared to the DTR technique, mainly because of the additional stabilization of the clavicle to the acromion.

Materials and methods

A total of 18 fourth generation Sawbones scapulae in combination with clavicles (Pacific Research Laboratories Inc., Vashon, WA, USA) were used for this study. The specimens were prepared by four authors (MOS, SJ, GF, and JS) and were randomized into three groups, namely the DTRC group ($n=6$), the Bipod reconstruction group ($n=6$), and the DTR group ($n=6$). Testing the intact AC joint was not possible due to the fact that we used Sawbone specimens.

Study group preparation

For the DTR group, the fixation technique was previously published [11, 12]. In brief, the K-wire was placed on the clavicular surface about 25 mm medial to the ACJ line for the first transclavicular–transcoracoidal bone tunnel. The bone tunnel in the coracoid was placed close to the base of the coracoid. The K-wire was subsequently overdrilled with a 4 mm drill bit. In the same manner but about 46 mm medial to the ACJ, the second bone tunnel was placed in the clavicle. The second coracoidal tunnel was drilled slightly more distally to the first tunnel. The two titanium Endobutton Tight-Rope devices containing 4 strands continuous loop of No. 5 FiberWire (Arthrex Inc., Naples, Florida, USA) were inserted via a shuttle wire into the two transclavicular–transcoracoidal bone tunnels. Before securing the Tight Ropes with six alternating half hitches on top of the clavicle, the superior cortical margin of the lateral clavicle was aligned with the superior cortical margin of the acromion (Fig. 1).

For the DTRC group, an additional 2 mm hole was drilled in horizontal manner lateral of the previously vertically placed clavicular bone tunnels. A second drill hole was placed in a 45° angle relative to the frontal plane of the body into the acromion. A FiberTape (Arthrex Inc.) was then shuttled through the two previously placed holes and the suture was knotted on top of the clavicle (Fig. 2).

In the Bipod group, a 4.5 mm drill was used to create a first tunnel 25 mm medial to the ACJ, from posterosuperior to anteroinferior, recreating the axis of the trapezoid ligament (Fig. 3). Another tunnel was placed 21 mm further medially to the first tunnel. The location of these drill holes matched the location of the CC ligaments as demonstrated by Rios et al. [13]. The FiberTape (Arthrex Inc.) in combination with a 20 × 500 mm Poly-Tape (Neoligaments, Leeds, UK) was passed through the first tunnel from superior to inferior. We used this combination, because FiberTape has shown a high initial pull-out strength and Poly-Tape has shown to allow for tissue ingrowth, which might improve long-time strength.

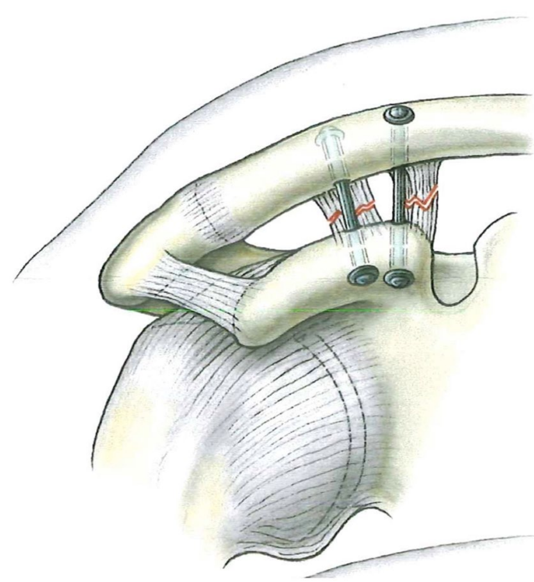

Fig. 1 Final configuration of the double Tight-Rope fixation is shown. In this reconstruction method, only the coracoclavicular ligaments are reconstructed

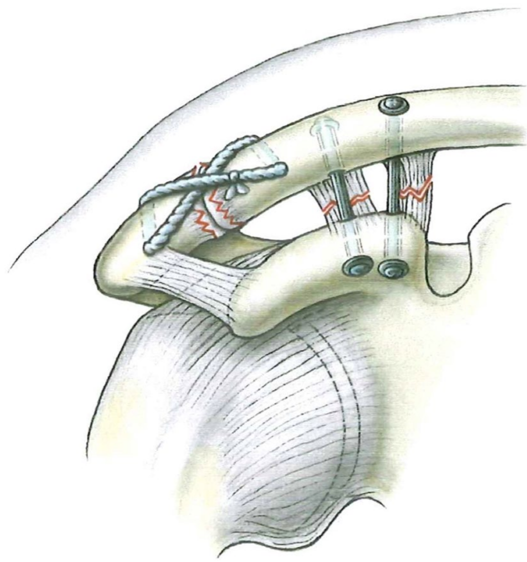

Fig. 2 Final configuration of the coracoclavicular double Tight-Rope fixation with acromioclavicular FiberTape cerclage is shown

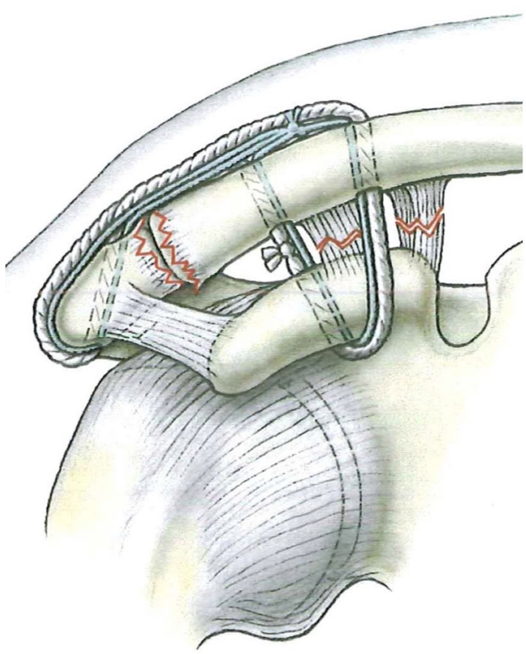

Fig. 3 Final configuration of the Bipod acromioclavicular repair is shown. The Poly-Tape and FiberTape are passed vertically and horizontally in different paths to prevent subcutaneous prominence of the Poly-Tape suture knot

The tapes then were shuttled under the coracoid and passed through the second clavicular tunnel from inferior to superior. The FiberTape was tied on top of the clavicle and was left uncut to form the second loop. Then, a 4.5 mm tunnel was placed in the acromion approximately 10 mm lateral to the ACJ in the middle of the anteroposterior diameter of the acromion, through which the remaining medial end of the FiberTape and the free medial remnant of the Poly-Tape were shuttled from the top through the acromion tunnel. This second limb prevents horizontal displacement of the clavicle at the ACJ, and further reinforces the vertical reduction.

Biomechanical testing

A servo-hydraulic material testing machine (Zwick/Roell, Zwick GmbH & Co., Ulm, Germany), equipped with a 1 kN tension–compression load cell, was used to perform the biomechanical testing. The load axis was chosen in the direction of the natural resulting force vector going from anteroinferior to posterosuperior. We chose this direction, because it more closely reflects the direction of dislocation in a clinical setting postoperatively, where the clavicle not only dislocates in superior but also in posterior direction relative to the scapula.

Custom-built clamps were used to fix the scapula to the base of the material testing machine (Fig. 4). The clavicle was rigidly fixed to the sensor of the material testing machine using custom-built clamps. The force-control mode was used to determine the ACJ motion. All the tests were performed at room temperature (18°–23°). The scapula was positioned according to Ludewig et al. [14] with an internal rotation of 33°, an upward rotation of 2° and a posterior tipping of 8°. The lateral clavicle was positioned with respect to the acromion, so that the superior cortical margin of the lateral clavicle was aligned with the superior cortical margin of the acromion. The clavicle was positioned in 28° retraction with respect to the transverse plain of the thorax [14].

Preconditioning of constructs was performed for 15 cycles using 10N of load. The force measurement was first set to 0N for recalibration and after that specimens were cycled 1500 times at a constant velocity rate of 3 mm/sec with 70N of load in posterosuperior and with 15N of load in anteroinferior direction. A force of 70N has been used, because this represents the force applied to the shoulder during postoperative physical therapy [15]. Displacement of the lateral clavicle with respect to the scapula and force was recorded over the 1500 cycles. We chose 1500 cycles, because elongation did only occur up 1500 cycles. Load-to-failure testing in posterosuperior direction with velocity of 1 mm/sec was performed after these 1500 cycles in all the specimens. Failure was defined as the first significant decrease in load seen on the load–displacement graph. Linear stiffness was calculated by measuring the slope from the linear portion of the curve.

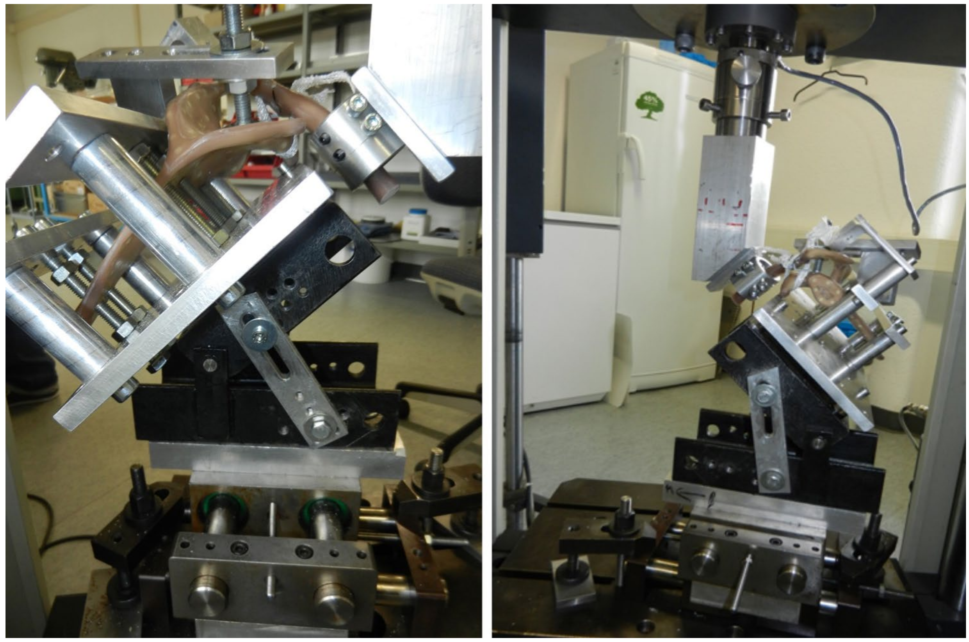

Fig. 4 Biomechanical testing setup

Data analysis

Statistical analysis was performed using repeated measures one-way analysis of variance (ANOVA) with Tukey post hoc test to assess the load-to-failure and linear stiffness. A repeated measures two-way ANOVA with Tukey post hoc test was used to compare the displacement over the 1500 cycles of stretching. Data are presented as mean and standard deviation (SD). The statistical significance was set at $p < 0.05$. Using a priori power analysis, a sample size of 6 specimens per group was determined to detect a clinical relevant difference of 2 mm [16] in displacement after cyclic loading between constructs with an alpha value of 0.05 and a power of 0.8. Data capture and analysis was performed by two investigators (M.S., S.J.) using prism graph pad version 6.

Results

There was no visible evidence of FiberTape or Poly-Tape failure or suture breakage in any specimen. In all the specimens, the load-to-failure of the implants exceeded the load-to-failure of the Sawbone specimens. Qualitative analysis of the failure modes showed a fracture of the coracoid in all the specimens followed by a fracture of the acromion in the DTRC and the Bipod group. There was no suture fretting.

First, we investigated the elongation after 1500 cycles of loading in posterosuperior direction of all the three reconstruction methods.

Overall, the timepoints from 0 to 1500 cycles, the DTRC- and DTR group both showed significant smaller elongation in posterosuperior direction when compared to the Bipod group (DTRC versus Bipod: $p = 0.008$, 95% CI: − 0.99 to − 0.13; DTR versus Bipod: $p = 0.008$, 95% CI: − 0.94 to − 0.13), respectively (Fig. 5).

Elongation in the DTRC group after 1500 cycles was 0.45 mm (SD 0.14 mm) compared to 1.19 mm (SD 0.54 mm) in the Bipod group ($p = 0.008$, 95% CI: 0.19 to 1.29), and 0.46 mm (SD 0.15 mm) in the DTR group (DTRC versus DTR $p = 0.999$, 95% CI: − 0.58 to 0.59; Bipod versus DTR $p = 0.006$, 95% CI: 0.22 to 1.26) (Fig. 6a).

Second, we evaluated the load-to-failure after 1500 cycles. The DTRC group showed a significant higher load-to-failure [656.1 N (SD 58.1 N)] compared to the Bipod

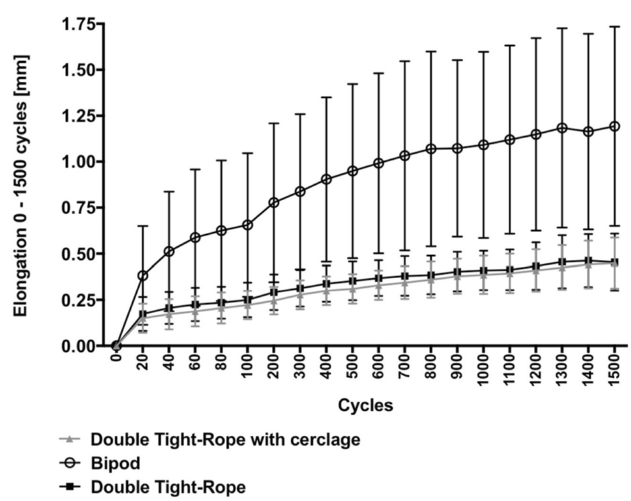

Fig. 5 Results from elongation during cyclic loading

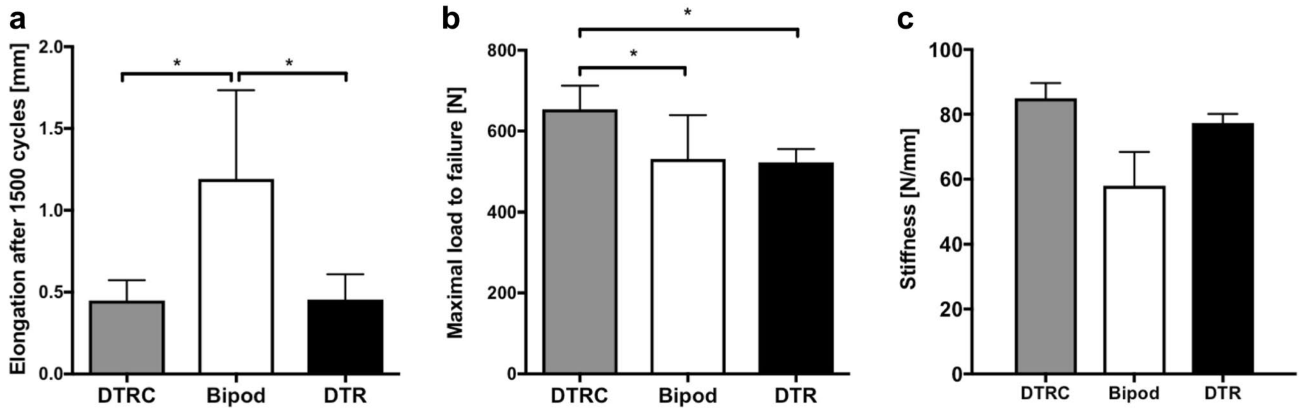

Fig. 6 **a**–**c** Results from **a** elongation after cyclic loading, **b** load-to-failure and **c** stiffness

group [531.1N (SD 108.2N)] and the DTR group [522.8N (SD 32.8N)] (DTRC versus Bipod $p=0.039$, 95% CI = − 240.2 to − 5.6; DTRC versus DTR $p=0.033$, 95% CI = − 252.5 to − 10.1). With the numbers available, no difference was found between the Bipod and the DTR group ($p=0.979$, 95% CI: − 103 to 119.8) (Fig. 6b).

Third, stiffness of the reconstructs was assessed and compared between the three groups. With the numbers available, in the DTRC group, stiffness [84.9 N/mm (SD 10.4 N/mm)] was not different from either the Bipod group (58.0 N/mm, SD 25.4 N/mm) or the DTR group (77.4 N/mm, SD 6.2 N/mm) (DTRC versus Bipod $p=0.054$, 95% CI: − 54.4 to 0.45; DTRC versus DTR $p=0.767$, 95% CI: − 36.2 to 21.0; Bipod versus DTR $p=0.188$, 95% CI: − 46.8 to 8.1) (Fig. 6c).

Discussion

The purpose of this study was to evaluate the elongation behavior, strength, and stiffness of the DTRC and Bipod techniques. By comparing these techniques to the well-established DTR technique, we wanted to investigate if an additional AC cerclage improves biomechanical properties. We chose to test the dislocation of the clavicle in postero-superior direction in relation with the scapula, because it reflects the direction of the postoperative force vector.

There is evidence that the amount of translation of the lateral clavicle in anteroposterior direction positively correlates with pain [17]. It is, therefore, desirable to keep elongation as small as possible after refixation of the lateral clavicle. In our study, all three techniques showed only a low elongation value. The DTRC and the DTR group showed a similar elongation of less than 0.5 mm after 1500 cycles. In comparison, the Bipod technique resulted in a significantly higher elongation of 1.19 mm. Even though this difference of 0.7 mm shows statistical significance, it most likely has no clinical relevance [16]. Mazzocca et al. [18] performed an anatomical CC reconstruction using Fiber wire and interference screws and reported a cyclic translation of 1.4 mm (SD 0.69 mm) tested in superior direction with 70N. Even though the testing direction is slightly different, our results are comparable to these numbers. Beitzel et al. [19] performed a CC ligament reconstruction using a semitendinosus tendon in combination with different CC-reconstruction methods using either ACJ semitendinosus tendon- or FiberTape reconstruction. When applying 70N, they found a posterior translation of up to 12.8 mm and a superior translation of up to 9.8 mm in the different groups. This almost 10 times higher translation compared to our results may be explained by the different reconstruction methods and testing setup. While Beitzel et al. used a semitendinosus graft in fresh-frozen cadavers, we used a synthetic ligament with a potentially higher stiffness and synthetic bones instead of fresh-frozen cadavers. In these cadavers, the remaining soft tissue around the bones may be another reason that they had much higher translation values.

In the DTRC group, we found the reported load-to-failure strength to be significantly higher than in the Bipod- and the DTR-reconstruction group. Since even the weaker Bipod and DTR constructs exceeded the previously reported load-to-failure strengths of the native CC-ACJ complex of 462.8N (SD 43.4N) [20] (Fig. 7), it is, therefore, questionable if this higher load-to-failure strength in the DTRC construct provides any additional advantage. The significant improvement of the load-to-failure from the DTR group to the DTRC group is similar to the results reported by Shin et al. [21]. They found a significant improvement in load-to-failure from 295N (SD 9.5N) in the CC cerclage group to 443N (SD 51.2N) in the group, where an ACJ loop was added to the existing CC cerclage. In contrast to our results, Abrams et al. [22] found load-to-failure values tested in superior direction of 515.9N (SD 89.0N) in the native intact

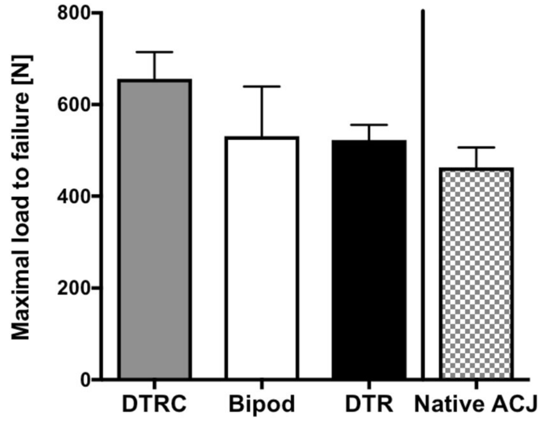

Fig. 7 Results from load-to-failure of the DTRC, Bipod and DTR group compared with the load-to-failure of the native ACJ reported by Freedman et al. [20]

fresh-frozen cadaver specimen, 416.3N (SD 63.6N) in the CC-reconstruction group and 293.8N (SD 35.3N) in the group, where the CC as well as the ACJ was reconstructed using a semitendinosus graft. They concluded that the decreased load-to-failure in the CC-ACJ reconstruction group may be due to the extensive drilling holes in the lateral clavicle that were necessary to secure the CC- as well as the ACJ ligament in the clavicle. We did not see an increase in clavicle fractures due to drilling holes in the clavicle in our cohort even in the DTRC group, where three holes are drilled in the clavicle to shuttle the two Tight-Ropes and one CC cerclage.

However, all our Sawbone specimens showed a fracture of the coracoid after ultimate load-to-failure testing. Even though these fractures are rare in a clinical setting, they represent a serious complication. This and other complications such as a loss of reduction in up to 33% of the DTR cases [4, 23] have led some surgeons to abandon techniques that require the placement of holes in the coracoid, such as the DTR and DTRC. The slightly higher load-to-failure strength in the DTRC group found in our study must, therefore, be weight against these complications.

We did not find significant differences between the three groups with regard to linear stiffness. Linear stiffness of intact CC-ACJ constructs of fresh-frozen specimens is reported to be between 32.3N/mm [20] and 140N/mm [24]. Authors investigating the linear stiffness of CC-ACJ augmentations using free tendon grafts reported stiffness' of as low as 15.5N/mm [20] and as high as approximately 75N/mm [25]. Our results are comparable to these results found in the literature. Until now, it is unclear what impact stiffness has on clinical outcome after CC and ACJ reconstruction.

Limitations

This proof-of-concept study was designed to investigate the biomechanical properties of a biplanar fixation in comparison with the monoplanar fixation technique. Using Sawbone specimens offers a couple of advantages such as more reliability and less variability than cadaveric specimens. This allows for a direct comparison between different techniques even with a small sample size. Even though Sawbone specimens have shown to have biomechanical properties similar to the real bone and are, therefore, commonly used for biomechanical testing, they cannot be directly compared with an in-vivo or fresh-frozen specimen with soft-tissue attachments and the variability in bone quality seen in patients.

Another limitation is that cyclic displacement as well as load-to-failure were only tested in posterosuperior direction. Testing the specimens in posterior direction and separately in superior direction would have provided more detailed information on horizontal as well as vertical stability of the reconstructs. In this proof-of-concept study, we chose a combined posterosuperior testing direction, since this reflects physiologic postoperative direction of dislocation of the lateral clavicle in relation with the scapula.

Conclusion

We found slightly higher elongation in the Bipod group and a higher load-to-failure in the DTRC group when compared to the other tested groups. However, the difference in elongation is most likely not clinically relevant. No significant differences were found regarding stiffness. Thus, our hypothesis that an additional fixation of the clavicle to the acromion would reduce elongation and increase stiffness when testing in the direction of the postoperative loading vector in these two surgical techniques could not be confirmed. It is furthermore, questionable if the benefit of an increased load-to-failure in combination with no improvement in elongation and stiffness outweighs the possible additional risks coming along with an additional acromioclavicular cerclage. Further studies that investigate vertical and horizontal stability separately are necessary to assess the potential benefit of these additional AC cerclages.

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Authors' contributions MOS carried out the study design, participated in data acquisition, performed the statistical analysis, and drafted the manuscript. SJ conceived the testing setup, participated in data acquisition, and performed the statistical analysis. GF conceived the testing setup and participated in data acquisition. JGS carried out the study design, conceived the testing setup and revised the manuscript critically. MS conceived and carried out the study design, was involved in clinical interpretation of the data, and revised the manuscript critically. MAS conceived and carried out the study design, gave substantial contribution in interpretation of data, and drafted the manuscript. All authors read and approved the final manuscript.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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