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Biomechanical analysis of conventional anchor revision after all-suture anchor pullout: a human cadaveric shoulder model

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Hypothesis and background: The possibility of implanting a conventional anchor at the pullout site following all-suture anchor failure was evaluated in a biomechanical cadaveric model. The hypothesis of the study was that anchor revision would yield equal biomechanical properties.
Methods: Ten human humeri were obtained, and bone density was determined via computed tomography. After all-suture anchor (n = 5) and conventional 4.5-mm anchor (n = 5) insertion, biomechanical testing was conducted. Following all-suture anchor pullout, a conventional 5.5-mm anchor was inserted at the exact site of pullout (n = 5) and biomechanical testing was reinitiated. Testing was conducted using an initial preload of 20 N, followed by an unlimited cyclic protocol, with a stepwise increasing force of 0.05 N for each cycle at a rate of 1 Hz until system failure. The number of cycles, maximum load to failure, stiffness, displacement, and failure mode, as well as macroscopic observation at the failure site including diameter, shape, and cortical destruction, were registered.
Results: The defect following all-suture pullout showed a mean diameter of 4 mm, and conventional revision was possible in each sample. There was no significant difference between the initial all-suture anchor implantation and the conventional anchor implantation or the conventional revision following all-suture failure regarding mean pullout strength, stiffness, displacement, or total number of cycles until failure.
Conclusion: Conventional anchor revision at the exact same site where all-suture anchor pullout occurred is possible and exhibits similar biomechanical properties.
Level of evidence: Basic Science Study; Biomechanics

Keywords: Shoulder surgery; arthroscopy; rotator cuff; suture anchor; all suture; pullout

Approval of the institutional review board was obtained from the Ethical Review Committee (Hamburg, Germany; study no. WF-27/17).

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All-suture anchors (ASAs) are increasingly used in arthroscopic rotator cuff repair.[2,3,13] In contrast to conventional anchor systems, ASAs are entirely composed of suture material. Their anchorage principle is based on an expansion of the suture material within the cancellous bone. The dilated anchor is then pulled until it is directly underneath the cortex, where it will stay permanently. Preservation of native bone material through the use of smaller pilot holes is claimed to be a main advantage of ASAs compared with conventional anchor systems.[6] After dilatation of the anchor hole, its diameter increases and is comparable to that of conventional anchors but with a smaller pilot hole within the cortical shell.[1] Biomechanical evaluation of ASAs in comparison to conventional anchors remains controversial, yielding either similar or slightly inferior results regarding maximum pullout strength, displacement, and stiffness.[9,12,13] Although the most common failure site of rotator cuff repairs is the suture-tendon interface, anchor pullout can occur in conventional anchors as well as ASAs. Owing to the different anchorage principle of ASAs, diverging pullout mechanisms may take place.[1,2] The difference in diameter of the pilot hole and the dilated ASA underneath the cortex may result in greater damage to the cortex.[1] Anchor revision after ASA pullout may therefore be a critical point that has not been investigated so far.

Therefore, the aim of this study was to evaluate whether it is possible to reimplant a conventional anchor at the site of pullout following ASA failure, as well as to compare the biomechanical properties between the initial operative fixation and the revision. The hypothesis was that anchor revision would yield equal biomechanical properties.

Methods

A biomechanical investigation was performed, and a total of 10 human humeral bones (5 matched pairs) were collected from donors aged between 50 and 73 years. Each specimen was scanned using a 16-row computed tomography scanner (Brilliance 16 CT; Philips Healthcare, Hamburg, Germany) with a solid calibration phantom (Bone Density Calibration Phantom; QRM, Möhrendorf, Germany) to determine the volumetric bone mineral density in terms of calcium hydroxyapatite (in milligrams per cubic centimeter) (Avizo 5.1; VSG, Burlington, MA, USA).[16,23] On the day of testing, each thawed humerus was perpendicularly transected at the mid-diaphyseal level and all overlying soft tissue was dissected to expose the bone surface of the greater tuberosity, as well as the junction of the greater tuberosity and the humeral head articular surface. The specimen was potted upright in a steel tube, and the distal end was fixed using a methylmethacrylate solution (Technovit 4004; Hereaus Kulzer, Hanau, Germany). Fixation was performed up to 2 cm proximal to the lower humeral bone–cartilage junction. Throughout preparation and testing, the specimens were wrapped in moist tissue to preserve the constitution of the tissue. The experiments were performed at room temperature in a normal room environment.

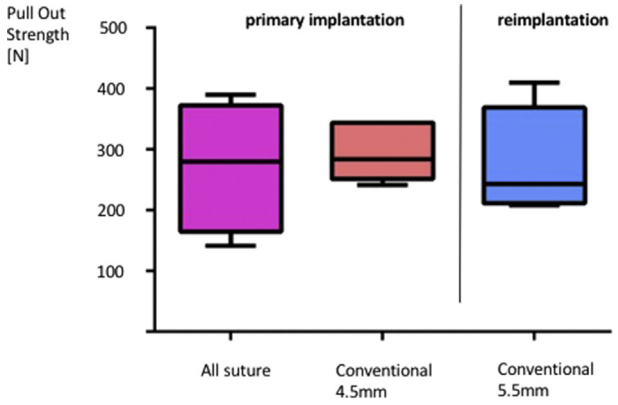

Figure 1 Box plot comparing maximum pullout strength for primary implantation of all-suture and conventional 4.5-mm anchors, as well as revision with a conventional 5.5-mm anchor.

Three different anchor types were tested: a commercially available ASA with a drill size of 2.8 mm and a diameter greater than 5 mm after dilatation (Y-Knot RC; ConMed, New York, NY, USA), a conventional 4.5-mm suture anchor (CrossFT; ConMed), and a conventional 5.5-mm suture anchor (CrossFT). First, the ASA and the conventional 4.5-mm suture anchor were individually tested in 5 humeri each. Following anchor pullout of the ASA, anchor implantation using the conventional 5.5-mm suture anchor was performed at the exact site where pullout had occurred ($n = 5$). Anchor implantation was performed according to the manufacturer's instructions with an implantation angle of 90° to the cortical bone. Anchor placement for each anchor type was performed medially, adjacent to the articular margin and within the proximal anterior part of the greater tuberosity 1 cm posterior to the bicipital groove, as previously described.[10,13,21] For the ASA, the second of the different circumferential laser marks on the inserter was chosen, ensuring a similar anchor depth in each sample.

After anchor insertion, the emerging suture threads were wrapped around a pulley and secured with clamps. The clamp-to-anchor distance was chosen to be 10 cm as previously published.[13] Because the load was applied via the threads and not the cuff muscle, the humeral head was protected with a plastic cover. This avoided the previously reported unphysiological suture failure by cutting through the bone.[18] Biomechanical testing was performed using a servo-hydraulic testing machine (MTS 858.2; MTS Systems, Eden Prairie, MN, USA; Fig. 1). The loading protocol was designed to simulate the rehabilitation phase after rotator cuff repair as follows: Starting with a preload of 20 N, a cyclic testing protocol at a rate of 1 Hz with a stepwise increase to the maximum pullout force was performed at a 90° angle regarding the anchor and bone surface. The respective upper peak load started at 50 N and increased by 0.05 N during each cycle (Fig. 2).[8,17,19] Cyclic extension was continued until system failure. Recorded data for each pullout test included the number of completed cycles, maximum pullout force, and construct's apparent stiffness. Furthermore, failure mode and anchor displacement were registered. Displacement was defined as the difference between the initial construct length after preload and the subsequent clamp-to-anchor distance. Video analysis was performed throughout the experiments to ensure accurate follow-

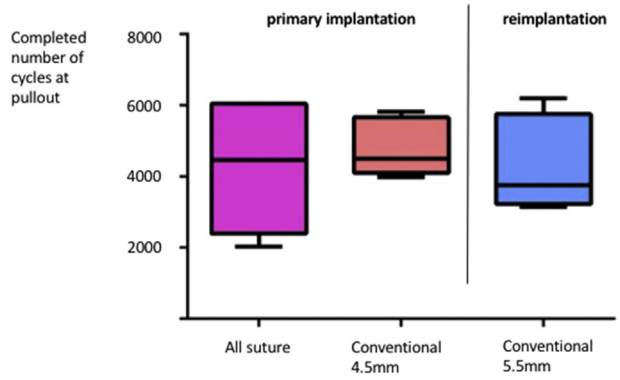

Figure 2 Box plot comparing the number of completed cycles until pullout for primary implantation of all-suture and conventional 4.5-mm anchors, as well as revision with a conventional 5.5-mm anchor. Slight differences in the linear relation between the number of completed cycles and the recorded maximum pullout strength are due to the individually adjusted control unit of the testing machine.

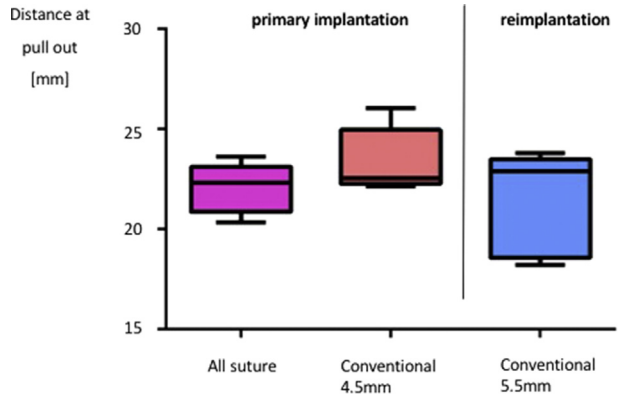

Figure 3 Box plot comparing the clamp-to-anchor distance at pullout for primary implantation of all-suture and conventional 4.5-mm anchors, as well as revision with a conventional 5.5-mm anchor.

through at every point in time. After ASA pullout, the occurring cortical pullout hole was examined and its widest diameter was measured using a standardized millimeter scale. The shape and possible cortical fragmentation were registered as well. Statistical analysis was performed with analysis of variance using SPSS software (version 21; IBM, Armonk, NY, USA) with a significance level of $\alpha = .05$.

Results

Determination of volumetric bone mineral density revealed similar values in both groups (126 ± 25 mg/cm^3 in ASA/revision group [n = 5] and 127 ± 30 mg/cm^3 [n = 5] in 4.5-mm conventional anchor group; $P = .81$). Revision with the 5.5-mm conventional anchor system at the previous drilling site worked without fail; thus, biomechanical testing was

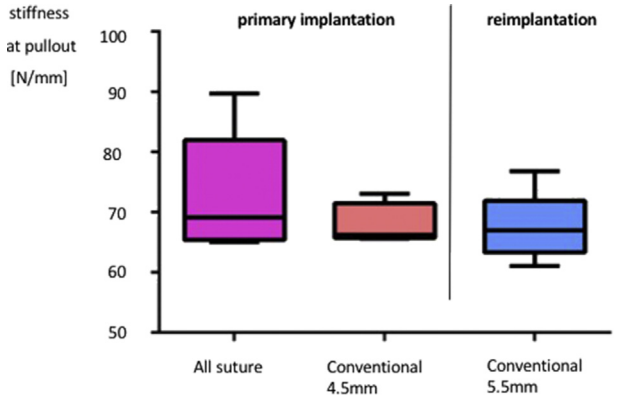

Figure 4 Box plot comparing stiffness at pullout for primary implantation of all-suture and conventional 4.5-mm anchors, as well as revision with a conventional 5.5-mm anchor.

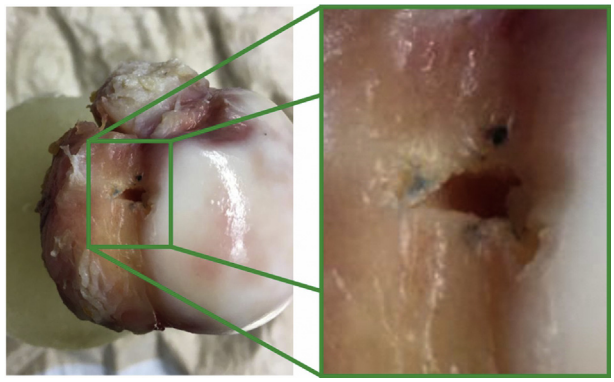

Figure 5 Example of oval, multifragmentary cortical bone defect as a result of all-suture anchor pullout.

possible in all specimens. All tested anchors failed via anchor pullout during biomechanical testing.

Biomechanical comparison of all 3 tested anchor types revealed that the 4.5-mm conventional anchor system resisted a pullout strength of 295 N, followed by the 5.5-mm system (281 N) and the ASA (271 N). Statistical analysis showed no significant difference between the different anchor types ($P = .9$, Fig. 3) and, consequently, due to the linear relation, also showed no significant difference regarding the absolute number of recorded cycles until system failure ($P = .81$, Fig. 4).

Throughout the experiments, the clamp-to-anchor distance was recorded to determine whether any differences in displacement between the 3 different anchor systems would occur. No significant changes could be detected on comparison of the 4.5-mm anchor, 5.5-mm anchor, and ASA systems ($P = .28$, Fig. 5). All 3 systems showed similar stiffness without any significant difference ($P = .45$, Fig. 6).

Examination of the ASA pullout hole revealed a mean diameter of 4 mm (range, 3-5 mm) and either a round or oval hole. Of 5 samples, 3 showed multifragmentary cortical destruction whereas 2 showed a clear edge (Table I, Fig. 5).

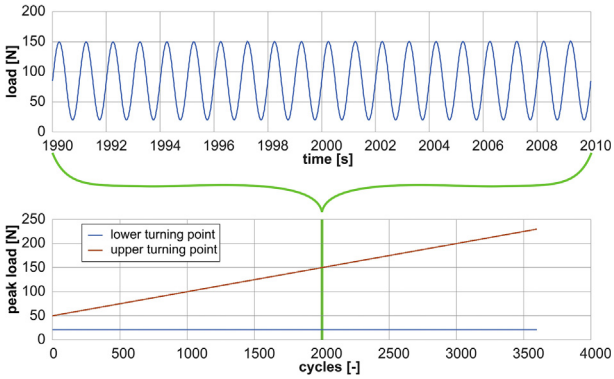

Figure 6 Cyclic loading protocol.

Discussion

This study demonstrates that implantation of a 5.5-mm conventional anchor at the exact site where ASA pullout occurred is possible and provides similar biomechanical properties. Anchor pullout, while not being the most common failure mechanism following rotator cuff repair, is a critical problem in suture anchors, which can lead to rotator cuff instability.[20-22] Whereas conventional anchors are concentrically shaped and their corresponding cortical implantation hole matches the largest diameter, ASAs have a smaller entering hole in the cortex to provide secure subcortical fixation of the anchors. Therefore, less native bone material is affected, leaving a smaller footprint within the greater tuberosity. Furthermore, ASAs are less expensive and are thought to have better visibility on magnetic resonance imaging.[1,6,15] Especially regarding ASAs, pullout and its treatment options have hardly been investigated so far. On the basis of the findings of this study, the initial insertion of an ASA provides a salvage option in case of pullout using a standard-sized conventional anchor. Regarding conventional anchors, the pullout mechanism is compared to a windshield wiper–type motion especially when placed at an acute angle.[4,21] Owing to the morphologic difference of ASAs, this mode of failure may not be probable using all-suture systems. ASA pullout bears the risk of uncontrolled cortical destruction. This assumption could not be confirmed in this study, which revealed a mean cortical pullout diameter of 4 mm. All-suture pullout failure might, therefore, be due to not only cortical destruction but also possibly migration through the pilot hole.

The maximum pullout strength between the ASA before and the conventional anchor after revision did not show any significant difference, with a mean maximum strength of 281 ± 86.6 N and 271 ± 106 N, respectively. This finding exhibited no differences in biomechanical properties and indicates that a secure bone-anchor interface can be reestablished. The absolute strength needed for pullout in both anchor types still appears to be lower compared with

Table I Macroscopic characteristics of cortical defect due to all-suture anchor pullout

Sample	Diameter, mm	Shape	Cortical characteristics
1	3	Oval	Multifragmentary
2	4	Round	Smooth
3	4	Oval	Multifragmentary
4	4	Oval	Multifragmentary
5	5	Round	Smooth

recent biomechanical studies of Barber and Herbert[1,2] and Barber et al[3] reporting a maximum pullout strength of 547 ± 160 N for the same 5.5-mm conventional anchor and 603 ± 156 N for the same 2.8-mm ASA. However, they used cortical porcine bone instead of human humeral bone, which was used in our study. The differences in specimens and, moreover, the younger age of animal bones most likely explain the difference—especially given that studies with human samples showed lower values as well.[9,10,13]

Kramer et al[11] demonstrated the necessity of at least a 2-mm distance between 2 ASAs in a glenoid model to preserve biomechanical characteristics, and in several biomechanical studies, anchor displacement of 5 mm has often been used as a cutoff for system failure.[1,2,7,14] In our study, no significant difference regarding anchor displacement could be detected, even though the exact site with prior ASA pullout and associated bone damage was used. Concerning intraoperative anchor revision, increasing displacement may not be a problem based on these biomechanical results. However, the interpretation of absolute numbers must be carefully performed because the distances measured in this study represent displacement of the whole system—including suture stiffness—and not just isolated anchor failure. The hypothesis that anchor revision following pullout may be a feasible solution is furthermore underlined by the fact that the overall stiffness of the conventional revision surgical procedure is similar to the prior ASA implantation and that, in contrast to other studies, a more realistic unlimited cyclic fatigue loading model is used. Poor bone quality and cystic alterations at the suture anchor position are complicating factors during anchor implantation. A few salvage options have previously been described such as the buddy anchor technique, rescue anchor technique, or compaction bone grafting to fill a cyst.[5] Even though comparable biomechanical properties were shown in our study following anchor revision, further investigation is needed to determine whether this is a salvage option in osteoporotic bone as well.

The findings of this study are limited owing to the biomechanical nature of the study. Furthermore, because different ASAs vary substantially in their morphologic shape and size, different destruction mechanisms within the cortical and spongious bone may occur and could lead to different results when products from other manufacturers are used. Additional limitations include the

missing suture-tendon interface, which was not investigated in this study.

Conclusion

This study demonstrates that there is no difference in load to failure between ASAs and conventional anchors. Furthermore, if pullout of an ASA occurs, adequate fixation can be achieved with a 5.5-mm anchor placed at the exact location of pullout without compromising ultimate fixation.

Disclaimer

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