Biomechanical Analysis of Subpectoral Biceps Tenodesis

Effect of Screw Malpositioning on Proximal Humeral Strength

Simon A. Euler,*† MD, Sean D. Smith,* MSc, Brady T. Williams,* BS, Grant J. Dornan,* MSc, Peter J. Millett,*‡§ MD, MSc, and Coen A. Wijdicks,* PhD
Investigation performed at the Department of BioMedical Engineering, Steadman Philippon Research Institute, Vail, Colorado, USA

Background: Humeral fracture after subpectoral tenodesis of the long head of biceps tendon (LHB) is a rare but devastating complication.

Purpose: To determine whether malpositioned (laterally eccentric) tenodesis screw placement has an influence on humerus strength reduction compared with central placement.

Study Design: Controlled laboratory study.

Methods: Two groups, each consisting of 10 matched pairs of human humeri, were used for this study. Biceps tendons were fixed subpectorally with 8-mm screws in unicortical 8-mm sockets. In the first group, the socket was placed concentrically in the bicipital groove and the tendon was fixed with an interference screw. In the second group, the socket was malpositioned 30% eccentrically to the lateral (tension) side of the humerus. Contralateral humeri remained intact as positive controls. Specimens were aligned in 40° of abduction, and a uniaxial compressive force was applied to the humeral head until failure. Strength reduction was reported as percentage reduction in ultimate failure load between paired humeri. Relative defect size was calculated as a percentage of the total humeral width at the height of the tenodesis.

Results: Laterally eccentric malpositioned biceps tenodeses significantly decreased humeral strength compared with intact (mean change, −25%; SD, 23%; $P = .017$), while concentrically placed biceps tenodeses did not (mean change, −10%; SD, 15%; $P = .059$). A linear regression between relative defect size and strength reduction in the malpositioned group showed a significant negative linear correlation (beta = −2.577; $R^2 = 0.423$; $P = .042$).

Conclusion: Humeral fracture after subpectoral tenodesis of the LHB is a complication that may be minimized with careful surgical technique. Laterally eccentric malpositioned biceps tenodesis caused significant reduction (25%) in humeral strength, which might be clinically relevant and contribute to postsurgical humeral shaft fracture. Strength reduction was also significantly correlated with relative defect size. Surgeons using this technique should ensure central and orthogonal placement of the socket, especially in smaller individuals. This study lends biomechanical evidence to support the clinical procedure of a correctly, concentrically placed tenodesis screw.

Clinical Relevance: These biomechanical results indicate that in a clinical setting, special attention should be drawn to patient selection for LHB tenodesis. This study reveals that central screw positioning is critical, particularly in high-impact and overhead athletes, as well as for patients with small humeral widths or osteoporotic bone quality. Alternative surgical options such as smaller screws or other fixation methods might be considered to diminish the postoperative risk of humeral fracture.

Keywords: shoulder; biceps tendon; humeral strength; interference screw

Open subpectoral biceps tenodesis is one of the most common shoulder procedures and is performed in response to injury of the long head of the biceps tendon (LHB) or surrounding soft tissue.[13] Excellent results and very low complication rates have been reported for biceps tenodesis with interference screws.[11,13,15,18,22] Although the hole is drilled through an open approach, overlying soft tissue often prevents direct visualization of the bicipital groove and the drill placement if the medial and lateral borders of the humeral cortices are not fully exposed. This may lead to eccentric malpositioning of the screw and potential

The American Journal of Sports Medicine, Vol. 43, No. 1
DOI: 10.1177/0363546514554563

iatrogenic breaching of the humeral cortex. Biomechanically, cortical defects caused by screws or drill holes have been shown to significantly reduce bone strength when compared with an intact control.[4,7,19,25]

Recently, Rios et al[18] and Dein et al[3] reported cases of proximal humeral fractures at the site of the tenodesis, presumably due to weakening of the cortex (Figure 1). Although only described in case reports so far, instances of proximal humeral fracture after biceps tenodesis or other procedures, which create significant holes, keyholes, or troughs in the humeral shaft, have been reported.[3,5,6,17,18,23] Most of the fractures were associated with a malpositioned screw or drill hole.[3,6,18] The most frequent mechanism of injury for proximal humeral fractures is direct compression load in abduction, typically described as a fall onto the outstretched hand.[9] However, strength reduction of the humeral diaphysis after biceps tenodesis has never been quantified. Furthermore, the biomechanical consequences of concentric and malpositioned (eccentric) biceps tenodesis in response to compressive forces with the arm abducted, similar to a fall on the outstretched hand,[10] have yet to be investigated.

The purpose of this study was to determine whether malpositioned (laterally eccentric) tenodesis screw placement affects humerus strength compared with central placement. We hypothesized that (1) laterally eccentric tenodesis screw placement would cause significant strength reduction compared with intact humeri and (2) concentric placement would not cause significant reduction in the strength of the humerus compared with the intact controls.

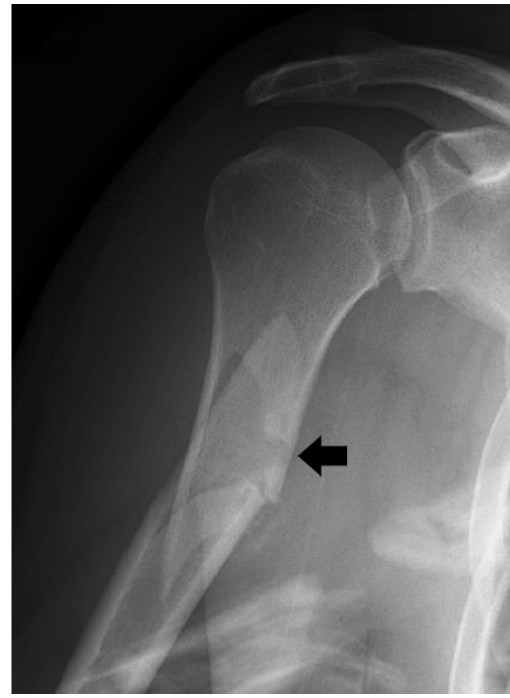

Figure 1. Anteroposterior (AP) radiograph of a right shoulder in a 43-year-old male patient. The patient suffered a low-velocity simple slip and fall on his outstretched arm 4 months after long head of the biceps tenodesis (8-mm interference screw). The humeral fracture line clearly includes the tenodesis drill hole. Black arrow: drill hole.

MATERIALS AND METHODS

Specimen Preparation

Twenty matched pairs (n = 40) of fresh-frozen human cadaveric shoulders (11 male, 9 female; mean age, 53.2 years; range, 44-63 years) were used for this study. Paired specimens were randomly distributed between 2 homogeneous groups (concentric group: concentrically placed tenodesis screw [A], intact [B]; malpositioned laterally eccentric group: laterally eccentric placed tenodesis screw [A], intact [B]). Dual-energy x-ray absorptiometry (DEXA) bone mineral density (BMD) measurements were performed (mean BMD, 0.489 g/cm^2; range, 0.345-0.608 g/cm^2) to prevent BMD biases between groups. According to the World Health Organization, all specimens with a T-score less than 2.5, as measured at the forearm (one-third radius), were considered to be osteoporotic and were excluded from this study. Before preparation, specimens were thawed at room temperature for 24 hours. The humeri were isolated and dissected free of all soft tissue. All LHBs were preserved. Specimens were visually inspected, and no preexisting injuries or prior surgeries were identified. The distal humeri were potted to a depth 14 cm distal to the superior region of the head in polymethylmethacrylate (PMMA; Fricke Dental International Inc) in a custom cylindrical mold, with the long axis of the humerus in line with the cylindrical axis of the mold. Before potting, screws were inserted circumferentially into the distal end of the humeri to ensure rigid fixation in the PMMA.

Surgical Technique

Specimens were alternately distributed between the concentric group (mean age, 53.8 years [range, 44-63 years]; mean BMD, 0.490 g/cm^2 [range, 0.345-0.605 g/cm^2]; 5 male, 5 female) and the malpositioned group with laterally eccentric placement (mean age, 52.5 years [range, 44-58

[§]Address correspondence to Peter J. Millett, MD, MSc, The Steadman Clinic, 181 W Meadow Drive, Suite 400, Vail, CO 81657, USA (e-mail: drmillett@thesteadmanclinic.com).
*Steadman Philippon Research Institute, Vail, Colorado, USA.
[†]Department of Trauma Surgery and Sports Traumatology, Medical University Innsbruck, Innsbruck, Austria.
[‡]The Steadman Clinic, Vail, Colorado, USA.

One or more of the authors has declared the following potential conflict of interest or source of funding: P.J.M. receives royalties and is a consultant for Arthrex, and has stock/stock options in VuMedi and Game Ready. S.A.E. is an international research fellow sponsored by Arthrex. Arthrex provided direct financial support and donation of surgical equipment.

years]; mean BMD, 0.488 g/cm^2 [range, 0.388-0.608 g/cm^2]; 6 male, 4 female) from highest to lowest BMD, resulting in 10 matched pairs per group. The first pair was randomly assigned by flipping a coin. There were no significant differences between the groups regarding BMD, age, width, and sex. One humerus from each pair was prepared according to 1 of the 2 tenodesis techniques, and the contralateral humerus was left intact. All tenodesis holes were drilled 7.4 cm distal to the superior tip of the humeral head, as described by Werner et al. ("Biceps Tenodesis: How Low Do You Go? A Comparison of Arthroscopic Suprapectoral and Open Subpectoral Techniques." Presented at American Academy of Orthopaedic Surgeons, 2014). Standardized 8-mm holes were drilled in all specimens, creating unicortical 8-mm sockets. The medial-lateral width was recorded at this location. For the concentric group, a guide wire was inserted bicortically in the center of the humeral shaft from anterior to posterior following the extension of the bicipital groove.

For the laterally eccentric group, a guide wire was also inserted bicortically, placed in a position laterally eccentric to the center of the humerus by a distance equal to 30% of the medial-lateral width. In all but 1 specimen, which had a very small diameter of 18.2 mm, the lateral cortex stayed intact. Orthogonal placement in relation to the exact lateral level of the humeral shaft was obtained in all specimens. One centimeter of the biceps tendon was then whip-stitched by use of a suture (FiberLoop; Arthrex). One of the suture limbs was passed through the tenodesis driver, and an 8 × 12–mm polyetheretherketone (PEEK) tenodesis screw (Tenodesis Screw, PEEK vented, 8 × 12 mm; Arthrex) was inserted, fixing the corresponding biceps tendon. Residual free ends of the suture were tied over the screw. To ensure consistency and reproducibility and allow for sufficiently powered comparisons between groups, 8-mm tenodesis screws were used for all specimens. Furthermore, 8 mm–diameter screws are the most commonly used for this application in the literature.[13,15] Relative defect size was determined as the quotient of drill hole diameter and the humeral width at the height of the tenodesis, reported as a percentage. For both concentric and laterally eccentric groups, a hole diameter of 8 mm was taken as a basis for the calculation of the relative defect sizes.

Biomechanical Testing

The humeri were biomechanically tested by use of a dynamic tensile testing machine (ElectroPuls E10000; Instron Systems). The accuracy and repeatability of this system have been verified to be equal to or better than 0.24% of the indicated force. The humeri were oriented in 40° of abduction by use of a custom steel fixture and were rigidly fixed to the base of the test frame. A uniaxial compressive force was applied to the humeral head with a flat plate, which was rigidly fixed to the actuator of the test frame, to simulate contact with the shoulder roof (Figure 2). This generated loading conditions similar to a 2-point bending test. Specimens were compressed until failure at a displacement controlled rate of 10 cm/min.[28] Ultimate failure load was recorded for each specimen, and

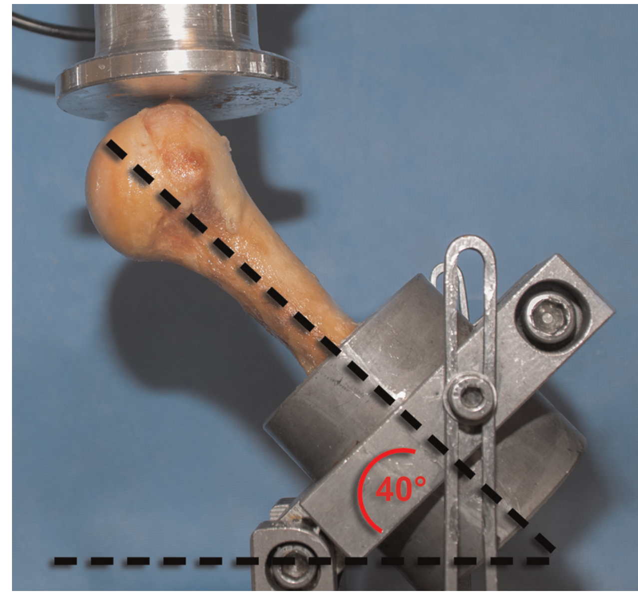

Figure 2. Test setup: Anterior view of an intact right humerus positioned in the testing jig, oriented in 40° of abduction. A compressive 2-point bending force was applied to simulate contact with the shoulder roof.

strength reduction was determined as the percentage reduction in ultimate failure load between paired intact and surgically prepared humeri. Ultimate failure load was defined as the maximum force before catastrophic failure.

Statistical Analysis

An a priori sample size calculation indicated that 10 specimens per group would be sufficient to detect an effect size of 1 for matched-pairs testing with 80% power. Wilcoxon signed-rank tests were used to compare the paired intact and surgically prepared specimens, while Mann-Whitney *U* tests were used to compare percentage reduction in ultimate failure strength between technique groups. Linear regression analysis was performed to model humeral strength reduction and relative defect size. Statistical significance was declared for $P < .05$. All statistical analyses were performed by a biostatistician using IBM SPSS Statistics, version 20.

RESULTS

Strength Reduction

Among the intact humeri, the average ultimate failure load was 2351 ± 851 N (range, 1426-3734 N) in the laterally eccentric group and 2490 ± 933 N (range, 1346-4339 N) in the concentric group. Laterally eccentric placed biceps tenodesis significantly decreased humeral strength compared with intact (mean change, −507 ± 503 N [range, +240 to −1364 N]; $P = .017$). Additionally, concentric

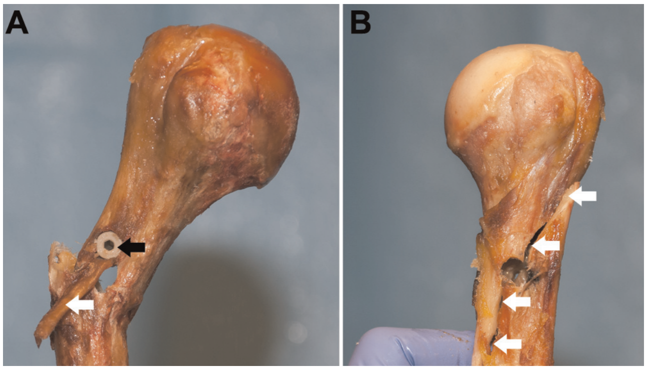

Figure 3. Representative fracture pattern of tenodesed humeri. (A) Anterior view on a right humerus, prepared with a laterally eccentric tenodesis screw (black arrow, polyetheretherketone tenodesis screw; white arrow, long head of the biceps tendon). (B) Anterior view on a left humerus, prepared with a centered tenodesis drill hole (white arrows: fracture line, including the centered drill hole; screw and long head of the biceps tendon fell off during failure in this specimen).

placed biceps tenodesis did not significantly reduce humeral strength compared with intact (mean change, −289 ± 353 N [range, +82 to −885 N]; P = .059). Mean percentage strength reduction compared with intact was −25% ± 23% in the laterally eccentric group (range, +6% to −56%) and −10% ± 15% in the concentric group (range, +28% to −25%).

Fracture Pattern

All intact specimens either failed at the humerus-potting junction or failed due to spiral fracture originating at the subcapital region of the humeral head. Eight of the specimens prepared with laterally eccentric screw placement failed at the drill hole (80%) (Figure 3A). One of the remaining specimens failed at the potting, and 1 specimen failed due to spiral fracture originating at the subcapital region of the humeral head. Seven of the humeri prepared with concentric screw placement failed at the potting (70%). Two of the remaining specimens failed at the drill hole, and 1 specimen failed due to spiral fracture originating at the subcapital region of the humeral head (Figure 3B).

Humeral Width and Relative Defect Size

Medial-lateral humeral width at the proximal-distal height of the tenodesis drill hole varied highly across all specimens (mean ± SD, 23.9 ± 3.8 mm; range, 17.2-35.3 mm). Variability between paired specimens was not negligible (mean absolute value of difference, 0.58 ± 0.45 mm [range, 0.03-2.02 mm]; mean absolute percentage difference 2.59% ± 2.4% [range, 0.1%-11.1%]). For the laterally eccentric group, there was a significant and approximately linear correlation between relative defect size and strength reduction (beta = −2.577; R^2 = 0.423; P = .042) (Figure 4). Notably, the 5 smallest laterally drilled humeri (<22 mm humeral width) exhibited the 5 largest strength reductions, each of 20% or more.

DISCUSSION

The present study found a significant reduction in humeral strength caused by malpositioned (laterally eccentric) biceps tenodesis screw placement. Concentrically placed tenodesis screws did not significantly weaken humeral strength. Furthermore, the linear correlation between strength reduction and relative defect size demonstrated the increased risk for significant strength reduction in smaller humeri. These results indicate that laterally eccentric placement of biceps tenodeses may place the patient at a higher risk of fracture at time zero. Increased emphasis should be made on surgical technique ensuring concentric placement of the biceps tenodesis, especially in at-risk populations such as contact and collision athletes, overhead athletes, patients with small humeri, and patients with low BMD.[1,3,21]

Low complication rates have been reported for open subpectoral tenodesis of the LHB.[15,18] Rios et al[18] showed a complication rate of 3%, and Nho et al[15] reported 6%. However, humeral fracture with the fracture line passing through the tenodesis hole has been described as a rare but devastating complication.[3,18,23] Animal studies have shown that a 20% bicortical defect of the long bone diameter, created by screws or drill holes, significantly reduces bony strength by 23% to 38%.[4,7,12] In the present study, the 5 smallest specimens in the laterally eccentric group (width, <22 mm; relative defect size, >36%) all experienced strength reductions in excess of 20%. The smallest specimen (width, 18.2 mm), in which the lateral cortex was partially reamed, experienced strength reduction of 50%. Resistance to torsion and bending is known to be directly proportional to the diameter of the long bone and may therefore reduce the fracture risk.[20,27] As the humeral diameter increases proximally, the relative defect size decreases accordingly. Theoretically, in an arthroscopic suprapectoral tenodesis procedure, the screw is placed more proximally and would therefore reduce the relative defect size. However, the most common reason to perform a subpectoral tenodesis instead of a more proximal tenodesis is the concern for potential persistent pain from tendinopathy if the tendon is retained more proximally in the bicipital groove.[22]

Clinically, refractures of long bones after implant removal are well described, especially when the hole is drilled eccentrically and malplaced, potentially comprising the cortex.[8,16] Furthermore, at the height of the terminating bicipital groove, an eccentrically placed screw hole most likely includes the groove's flanking dense bone and may weaken the bone even more.[23] Bony stability has been shown to significantly diminish after implant removal,[24] and some authors have even suggested avoiding any athletic activity for up to 4 months after implant removal from long bones.[14] The present study demonstrated significant time-zero strength reduction following laterally eccentric biceps tenodesis. In this situation, the reamed hole is filled by the interference screw, which

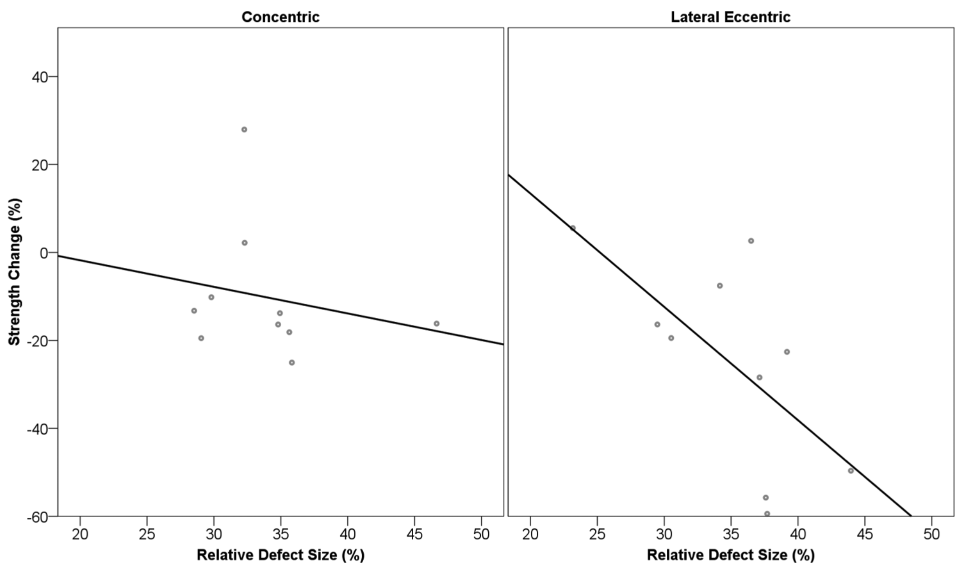

Figure 4. Plot of strength reduction versus relative defect size for each group with linear regression lines. In the laterally eccentric group (right plot), there was a significant correlation between relative defect size and strength reduction.

may help reduce the effects of the cortical defect, especially in compression.[9] A worst-case scenario may be a malpositioned tenodesis hole where the interference screw has been displaced from the drill hole, creating an "empty hole" situation.[26]

Humeral fracture during high-impact overhead sport activities has been reported in the literature.[1,3] Branch et al[1] published a case series of 12 baseball pitchers who suffered a spontaneous fracture of the humerus during the throwing motion without any former injury or surgery to the humerus. Recently, Dein et al[3] reported a humeral fracture after LHB tenodesis in a baseball pitcher. Forces during a throwing motion can be extraordinarily high, and torques have been reported as high as 92 N·m in professional baseball pitchers.[21] These reports indicate that fracture risk may be especially high in throwing athletes, who generate extremely high forces and torques on the humerus. However, based on the average failure load observed in the present study for the laterally eccentric group (1843 N), even a simple fall on the humerus could create forces high enough to cause fracture.[2]

Surgically, subpectoral tenodesis of the LHB can be a technically demanding procedure because the surgeon has to work in close proximity to the neurovascular structures, and the overlying musculature can limit visualization. While the reported incidences of fracture after biceps tenodesis are low, based on the data from the present study, malpositioning of the screw with eccentric screw placement could be a contributing and preventable risk factor. Typically, radiographs are not obtained after this type of procedure, so the true incidence of malpositioning is largely unknown. The results of the present study certainly highlight the importance of proper surgical technique to ensure concentric screw placement. Stress concentration at the drill hole was reduced in the case of concentric screw placement relative to laterally malposition screws, as the majority of specimens in the concentric group (70%) did not fracture at the level of the drill hole, and the stress concentration created by concentric screw placement did not influence strength and failure mechanism in most specimens. However, failure at the screw hole in most laterally eccentric screw placement specimens highlights the effect of creating a stress riser near the cortex border. Therefore, in some instances, additional surgical exposure may be needed to ensure proper socket placement.

As is the case with any cadaveric biomechanical investigation, this study has inherent limitations. First, this is a time-zero, in vitro biomechanical model and does not account for the biologic aspects and effects of healing that occur in vivo. Therefore, the results of this study cannot be extrapolated to time points beyond the time-zero repair. Additionally, this model used simplified loading conditions to simulate a fall with the arm abducted and did not account for the complex loading conditions and constraints generated in vivo by the various muscle and soft tissue attachments or a model in which torque is applied, as may be more relevant in throwing sports. The proximal-distal height of the tenodesis socket was standardized for all specimens, regardless of humerus length. Although this neglected interspecimen anatomic variability, it allowed for a more consistent and reproducible comparison between groups. A group with 7 mm–diameter sockets, which are also commonly used clinically, was not tested in the present study. Future studies should investigate the influence of tenodesis socket diameter on humeral strength.

CONCLUSION

Humeral fracture after subpectoral tenodesis of the LHB is a complication that may be minimized with careful surgical technique. Laterally eccentric malpositioned biceps tenodesis caused significant reduction in humeral strength of 25%, which might be clinically relevant and contribute to postsurgical humeral shaft fracture. Strength reduction was also significantly correlated with relative defect size. Surgeons using this technique should ensure central and orthogonal placement of the socket, especially in smaller individuals. This study lends biomechanical evidence to support the clinical procedure of a correctly concentric placed tenodesis screw.

ACKNOWLEDGMENT

The authors acknowledge Barry Eckhaus and Angelica Wedell for their assistance with the photos presented in the manuscript, and Kelly Adair for acquiring surgical supplies.

REFERENCES

1. Branch T, Partin C, Chamberland P, Emeterio E, Sabetelle M. Spontaneous fractures of the humerus during pitching: a series of 12 cases. *Am J Sports Med*. 1992;20(4):468-470.
2. Chapman MW, Madison M, Martin RB. Fracture healing and closed treatment of fractures and dislocations. In: Chapman MW, Szabo RM, Marder RA, et al, eds. *Chapman's Orthopaedic Surgery*. 3rd ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2001:220-305.
3. Dein EJ, Huri G, Gordon JC, McFarland EG. A humerus fracture in a baseball pitcher after biceps tenodesis. *Am J Sports Med*. 2014;42(4):877-879.
4. Edgerton BC, An KN, Morrey BF. Torsional strength reduction due to cortical defects in bone. *J Orthop Res*. 1990;8(6):851-855.
5. Friedel R, Markgraf E, Schmidt I, Donicke T. [Proximal humerus shaft fracture as a complication after keyhole-plasty. A case report]. *Unfallchirurgie*. 1995;21(4):198-201.
6. Gyulai M. [Humeral fracture after keyhole tenodesis]. *Magy Traumatol Orthop Helyreallito Seb*. 1990;33(3):234-236.
7. Ho KW, Gilbody J, Jameson T, Miles AW. The effect of 4 mm bicortical drill hole defect on bone strength in a pig femur model. *Arch Orthop Trauma Surg*. 2010;130(6):797-802.
8. Kirchhoff C, Braunstein V, Kirchhoff S, et al. Outcome analysis following removal of locking plate fixation of the proximal humerus. *BMC Musculoskelet Disord*. 2008;9:138.
9. Kress TA, Snider JN, Porta DJ, Fuller PM, Wasserman JF, Tucker GV. Human femur response to impact loading. In Cesari D, Charpenne A, eds. *Proceedings of the 1993 International IRCOBI Conference on the Biomechanics of Impact*. Bron, France: IRCOBI Secretariat; 1993:93-104.
10. Lill H, Josten C. [Proximal and distal humerus fractures in advanced age]. *Orthopade*. 2000;29(4):327-341.
11. Mazzocca AD, Cote MP, Arciero CL, Romeo AA, Arciero RA. Clinical outcomes after subpectoral biceps tenodesis with an interference screw. *Am J Sports Med*. 2008;36(10):1922-1929.
12. McBroom RJ, Cheal EJ, Hayes WC. Strength reductions from metastatic cortical defects in long bones. *J Orthop Res*. 1988;6(3):369-378.
13. Millett PJ, Sanders B, Gobezie R, Braun S, Warner JJ. Interference screw vs. suture anchor fixation for open subpectoral biceps tenodesis: does it matter? *BMC Musculoskelet Disord*. 2008;9:121.
14. Mueller ME. *Manual of Internal Fixation*. 2nd ed. New York, NY: Springer; 1979.
15. Nho SJ, Frank RM, Reiff SN, Verma NN, Romeo AA. Arthroscopic repair of anterosuperior rotator cuff tears combined with open biceps tenodesis. *Arthroscopy*. 2010;26(12):1667-1674.
16. Ochs BG, Gonser CE, Baron HC, Stockle U, Badke A, Stuby FM. [Refracture of long bones after implant removal: an avoidable complication?]. *Unfallchirurg*. 2012;115(4):323-329.
17. Reiff SN, Nho SJ, Romeo AA. Proximal humerus fracture after keyhole biceps tenodesis. *Am J Orthop*. 2010;39(7):E61-E63.
18. Rios D, Martetschläger F, Horan MP, Millett PJ. Complications following subpectoral biceps tenodesis with interference screw fixation. *J Shoulder Elbow Surg*. 2013;22(10):e26.
19. Rosson J, Egan J, Shearer J, Monro P. Bone weakness after the removal of plates and screws: cortical atrophy or screw holes? *J Bone Joint Surg Br*. 1991;73(2):283-286.
20. Rüedi TP, Buckley RE, Moran CG, eds. *AO Principles of Fracture Management*. 2nd ed. Davos, Switzerland: AO Publishing; 2007.
21. Sakai K, Kiriyama Y, Kimura H, et al. Computer simulation of humeral shaft fracture in throwing. *J Shoulder Elbow Surg*. 2010;19(1):86-90.
22. Sanders B, Lavery KP, Pennington S, Warner JJ. Clinical success of biceps tenodesis with and without release of the transverse humeral ligament. *J Shoulder Elbow Surg*. 2012;21(1):66-71.
23. Sears BW, Spencer EE, Getz CL. Humeral fracture following subpectoral biceps tenodesis in 2 active, healthy patients. *J Shoulder Elbow Surg*. 2011;20(6):e7-e11.
24. Smith SD, Wijdicks CA, Jansson KS, et al. Stability of mid-shaft clavicle fractures after plate fixation versus intramedullary repair and after hardware removal. *Knee Surg Sports Traumatol Arthrosc*. 2014;22(2):448-455.
25. Spiegl UJ, Smith SD, Euler SA, Dornan GJ, Millett PJ, Wijdicks CA. Biomechanical consequences of coracoclavicular reconstruction techniques on clavicle strength. *Am J Sports Med*. 2014;42(7):1724-1730.
26. Suchenski M, McCarthy MB, Chowaniec D, et al. Material properties and composition of soft-tissue fixation. *Arthroscopy*. 2010;26(6):821-831.
27. Tencer AF. Biomechanics of fractures and fixation. In: Bucholz RW, Heckman JD, Court-Brown C, eds. *Rockwood and Green's Fractures in Adults*. 6th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2005:3-36.
28. Yoon RS, Dziadosz D, Porter DA, Frank MA, Smith WR, Liporace FA. A comprehensive update on current fixation options for two-part proximal humerus fractures: a biomechanical investigation. *Injury*. 2014;45(3):510-514.