Postoperative Restoration of Upper Extremity Motion and Neuromuscular Control During the Overhand Pitch

Evaluation of Tenodesis and Repair for Superior Labral Anterior-Posterior Tears

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Background: Superior labral anterior-posterior (SLAP) tears are a common cause of shoulder pain and dysfunction in overhand throwers. Treatment outcomes remain unpredictable, with a large percentage of athletes unable to return to sport. There is considerable debate about the optimal treatment between debridement, repair, and tenodesis.

Hypothesis: Labral repair more closely restores neuromuscular control and motion during the overhand pitch than tenodesis of the long head of the biceps.

Study Design: Controlled laboratory study.

Methods: Eighteen pitchers, including 7 uninjured controls, 6 players pitching after SLAP repair, and 5 players pitching after subpectoral biceps tenodesis (BT), underwent simultaneous surface electromyographic measurement at 1500 Hz and motion analysis at 120 Hz with a 14-camera markerless motion analysis system and high-speed video (120 Hz) to confirm accurate motion tracking. Patients had undergone surgery at least 1 year previously and had returned to pitching with a painless shoulder.

Results: No significant differences were observed in the long head of the biceps muscle, short head of the biceps muscle, deltoid, infraspinatus, or latissimus activity between controls, patients after SLAP repair, and patients after BT. The variability from pitch to pitch for each study participant was similar between groups. Based on visual inspection of the activity time plots, BT appeared to more closely restore the normal pattern of muscular activation within the long head of the biceps muscle than did SLAP repair. There were no significant differences between controls and postoperative patients in the majority of pitching kinematics; however, pitchers after SLAP repair showed significantly altered patterns of thoracic rotation ($P = .034$) compared with controls and were significantly less likely to fall into previously published normal values for lead knee flexion at front foot contact ($P = .019$).

Conclusion: While both BT and SLAP repair can restore physiologic neuromuscular control, pitchers who undergo SLAP repair may exhibit altered patterns of thoracic rotation when compared with controls and pitchers who undergo BT.

Clinical Relevance: While both tenodesis and SLAP repair can restore physiologic neuromuscular control, SLAP repair may alter pitching biomechanics.

Keywords: shoulder; glenoid labral; shoulder; biceps tendon; baseball/softball; motion analysis/kinesiology; superior labral anterior-posterior (SLAP) tear; biomechanics; general

Superior labral anterior-posterior (SLAP) tears are found in 6% to 26% of shoulder arthroscopic procedures, and the rising incidence of repair has far outpaced the rising incidence of shoulder arthroscopic surgery.[36] Overhead throwing is a common causative factor associated with SLAP tears.[4] Pitching is one of the fastest human motions, with arm internal rotation velocities exceeding 7000 deg/s in professional pitchers.[19] These speeds place enormous forces and torques upon the shoulder, with forces regularly exceeding 1000 N in professional pitchers.[19] These forces and the compensatory structural, neuromuscular, and proprioceptive changes that pitchers undergo to be able to produce these forces[3,7,15] have been implicated in the pathogenesis of SLAP tears.[8]

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Although controversial, operative treatment most frequently consists of repair of the labrum and biceps anchor.[4,8,54] While excellent clinical outcomes with SLAP repair have been reported in some series,[5,17,23,32,44] others have reported disappointing results, with 40% to 60% of patients dissatisfied and experiencing persistent shoulder pain or inability to return to throwing.[4,10,54] A recent systematic review found a pooled rate or return to preinjury level of play of 64% among all athletes.[27] Results for overhead throwers are worse, with a return to preinjury level of play of 22% to 60%.[10,23,32,35] While failure can be multifactorial, labral repair may result in permanent alterations in pitching biomechanics, preventing pitchers from regaining command and velocity. Given these relatively poor results, several authors have proposed that primary biceps tenodesis (BT) may provide superior results. In a recent prospective clinical trial in older nonoverhead athletes, rates of return to preinjury level of play were 37.5% in patients in the repair group versus 100% in the BT group.[4] In the same series, 100% of those patients revised from SLAP repair to tenodesis returned to their preinjury level of play.[4] These results call into question whether SLAP repair or BT would provide superior outcomes for overhead athletes or manual laborers with SLAP tears. Given that the mean age of these patients was much higher than that of the typical throwing population and that none were pitchers, the clinical applicability of these results to the overhand-throwing athlete remains unknown.

Because the role of the long head of the biceps muscle (LHBM) and its proximal tendon in glenohumeral function remains unknown,[§] surgeons have been hesitant to perform BT on overhand throwers because of concerns that this procedure may lead to either a loss of control or velocity or a predisposition toward future injuries. Even a minor biomechanical role for the LHBM in glenohumeral function could be important in high-demand motions such as overhand throwing.

To date, no in vivo motion analysis of pitching after BT and SLAP repair compared with pitching uninjured has been performed to inform surgeons about the biomechanical consequences of the operative treatment of these injuries upon the overhand pitch. To the best of our knowledge, no in vivo motion analysis has been performed after any arthroscopic surgical intervention in the glenohumeral joint. Electromyographic (EMG) analysis in the upper extremity has traditionally involved the placement of fine-needle electrodes,[25,26,29,33,34] a process that is uncomfortable for patients and exposes them to a small risk of infection. In addition, until recently, electrodes were wired to an amplifying box worn as a backpack or vest. Cables could easily hinder free movement. Motion analysis has traditionally involved the placement of reflective markers upon the patient,[1,12,42,43,58,59] which is a cumbersome process. Variability in marker placement[28,49] may lead to analysis inaccuracies.[38,40] These obstacles have prevented EMG and motion analyses of postoperative pitching. In addition, no previous studies have compared EMG activity in the short and long heads of the biceps; all previous studies have looked at the biceps as a whole. However, as wireless surface EMG and markerless motion analyses[11,41] are being developed, these techniques allow more rapid collection of data without any patient discomfort, and thus, such analyses may potentially be clinically useful in postoperative patients.

The specific aims of this study were to evaluate and compare the activity of the short head of the biceps muscle (SHBM) and LHBM in the overhead pitching motion in uninjured collegiate pitchers, pitchers after type II SLAP repair, and pitchers after BT; to correlate this activity with the throwing phase using high-speed motion analysis; and to evaluate and compare upper extremity kinematics and timing during the overhand pitching motion in the 3 groups studied. We hypothesized that (1) the EMG activity in pitchers after SLAP repair would more closely resemble that of uninjured pitchers compared with pitchers after BT, given the "anatomic" nature of the repair, and that (2) the operative treatment of SLAP tears with repair or tenodesis would result in the restoration of physiologic pitching timing and motion in those patients able to return to play.

MATERIALS AND METHODS

This study was approved by our institutional review board (protocol #11090808). All participants signed informed consent forms. A local collegiate team contributed their pitchers as the controls, all of whom were currently pitching

[§]References 4, 30, 47, 48, 50, 53, 55, 61, 62.

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without pain and had no history of any injuries to the shoulder. Postoperative patients were recruited from the operative logs of the 3 senior authors (A.A.R., B.J.C., B.F.). All patients in the tenodesis group underwent mini-open subpectoral BT with tendon fixation with the Bio-Tenodesis Screw system (Arthrex Inc). All patients in the SLAP repair group underwent arthroscopic repair of the superior labrum and biceps anchor. A mixture of knotless and knotted repairs and simple and mattress suture configurations were used, depending on the tear pattern and the preference of the surgeon. The anchor position also varied, depending on the tear pattern. In all cases, at least 2 anchors were used. All patients had pitched before their injury and had returned to full painless baseball play postoperatively, and all patients had undergone surgery at least 1 year previously. No participants were aware of the hypothesis of the study. In all cases, the dominant extremity was tested, and in postoperative pitchers, the postoperative arm was tested. All testing was performed in our human motion analysis laboratory. No pre hoc power analysis was performed, as no data existed comparing either the upper extremity kinematics or the biceps EMG activity in controls versus postoperative pitchers for this experimental model; thus, as many players as possible were recruited. Eighteen pitchers, including 7 uninjured controls, 6 players pitching after SLAP repair, and 5 players pitching after BT, were recruited.

Data Collection

The following subjective information was collected from all participants at the time of testing: age, number of years pitching, highest level of play, number of years pitched at the highest level of play, number of games pitched per season, in-season hours spent per week pitching, off-season hours spent per week pitching, injury history, nonoperative treatment history, operative treatment history, Kerlan-Jobe Orthopaedic Clinic (KJOC) shoulder and elbow score, American Shoulder and Elbow Surgeons (ASES) score, Disabilities of the Arm, Shoulder and Hand (DASH) score, DASH-Sport score, University of California, Los Angeles (UCLA) score, Constant score, visual analog scale (VAS) for pain, and Short Form–12 (SF-12) quality of life subscale. The following objective information was collected from all participants: height; weight; upper arm length; lower arm length; upper arm circumference at the axilla, midpoint, and epicondyles; lower arm circumference at the radial head, midpoint, and styloids; and shoulder range of motion in both arms including forward flexion, internal rotation at 90° of abduction, external rotation at 90° of abduction, external rotation in adduction, and abduction.

Surface EMG data of the muscle activity from each patient were collected using a TeleMyo transmitter and receiver (model 2400T/2400R, Noraxon Inc). Before electrode application, the skin was cleaned using antimicrobial wipes. Self-adhesive dual Ag/AgCl electrodes (Noraxon Inc) were placed on the palpable muscle bellies of the LHBM, SHBM, middle head of the deltoid, and infraspinatus in parallel to the muscle fibers at the midpoint of the muscle, with the muscle held in midflexion to optimize the signal (Figure 1). For the LHBM and SHBM electrodes, if the bulk of the biceps muscle was split into thirds, the LHBM electrodes lay at the junction of the lateral and middle thirds, and the SHBM electrodes lay at the junction of the middle and medial thirds, with a minimum of 3 cm between the electrodes of the short and long heads mediolaterally to avoid cross-talk as previously described.[6,16,53] Infraspinatus surface electrodes were applied obliquely (ie, at 60°) with respect to the floor, inferior to the trapezius and inferior to the scapular spine. Mediolaterally, if the distance between the medial scapular border and the posterior glenohumeral joint line was divided into thirds, the infraspinatus electrodes were applied at the junction of the middle and medial thirds. The electrodes were applied over the palpable muscle bulk with the arm in adduction and resisted external rotation. The EMG signals were preamplified (500×) near the electrodes, band-pass filtered between 10 and 500 Hz, and sampled at a rate of 1500 Hz.[51]

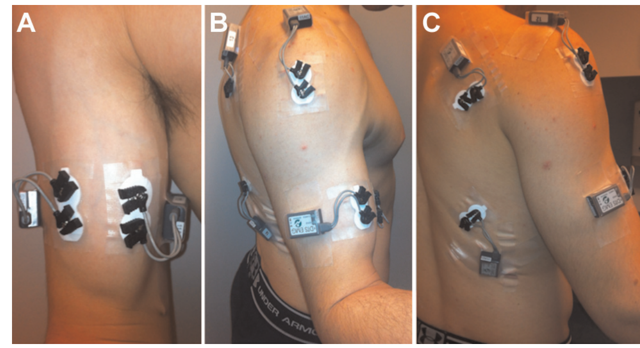

Figure 1. Electrode placement. (A) Anterior view demonstrating electrode placement on the long and short heads of the biceps. (B) Lateral view demonstrating electrode location on the middle head of the deltoid. (C) Posterior view demonstrating electrode placement on the infraspinatus and latissimus dorsi.

Before measuring muscle activity during pitching, the maximal amount of muscle activity in each participant's individual muscles was determined to serve as an internal control. Three consecutive trials of 3- to 5-second manual muscle testing (MMT) were performed. For both the long and short heads of the biceps brachii, MMT involved maximal isometric elbow flexion force with the forearm in supination against a fixed flat surface and the elbow flexed at 90°. For the deltoid, MMT involved maximal shoulder abduction force with the humerus at 90° of abduction and neutral rotation. For the infraspinatus, MMT involved maximal external rotation force with the arm in adduction and neutral rotation. For the latissimus, MMT involved adduction force with the arm held in 90° of abduction and external rotation, accomplished by having the patient perform a pull-up. Each patient showed activity in the biceps with resisted flexion. Maximal activity (100% MMT) was defined as the 1-second interval with the highest EMG activity and was used to normalize all EMG signals. Raw EMG signals were rectified and smoothed

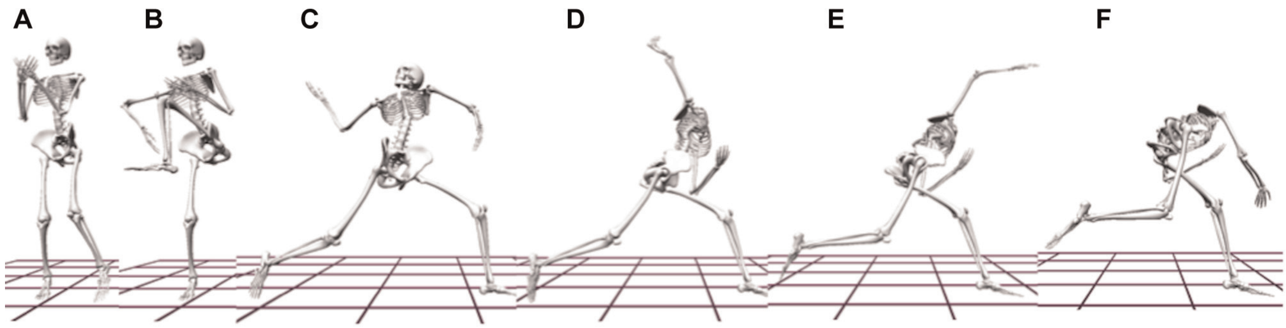

Figure 2. The position of the player at the beginning of each phase of the pitch: (A) initiation of movement begins wind-up, (B) separation of the hands and maximal knee flexion begin stride, (C) front foot contact begins cocking, (D) maximal shoulder external rotation begins acceleration, (E) ball release begins deceleration, and (F) maximal shoulder internal rotation begins follow-through.

using a root mean square algorithm with a window of 50 milliseconds before MMT normalization.[51]

Motion data were collected at 120 Hz with a 14-camera 3-dimensional markerless motion capture system (Biostage, Organic Motion). This system contains walls and a floor constructed of reflective material. The system synthesizes the shadow of the patient within the system from 14 different angles to reconstruct the 3-dimensional hull of the patient. The system was first extensively optimized for the overhand pitching motion. A regulation-size pitching mound was constructed and coated in a reflective coating so as to be invisible to the system. In all cases, patients wore tight-fitting, black long-sleeve shirts and pants to improve patient tracking.

Testing Protocol

After electrode application, patients were provided with as much time as necessary to perform their routine warm-up. Once patients felt ready to pitch at 100% velocity, they then performed 5 pitches while EMG and motion data were collected simultaneously. Data were retained from multiple pitches for each patient as they have been shown to have significant variation from pitch to pitch.[18] High-speed (120 Hz) video was also collected to determine the moment of ball release and to allow verification of motion analysis data. All pitches were fastballs pitched from the wind-up position. Ball velocity was collected with a radar gun (Speedster III, Bushnell). In addition, patients were asked to subjectively "rate" each pitch on a 1-to-5 scale, with 5 being the best pitch with regard to speed, control, and likelihood to have produced a strike. Only those pitches with a score of $\geq$3 of 5 were recorded. Because of size limitations within our laboratory, pitchers threw over a distance of 5 m.

Data Analysis

All analyses were performed in Excel X (Microsoft Corp) and SPSS v 18 (IBM Inc). Each data point both within the EMG and motion data was assigned to a pitching phase[33] as follows: the wind-up phase extended from the first movement to the highest point to which the lead leg was raised, the stride phase extended until front foot contact, the cocking phase extended until maximal shoulder external rotation, the acceleration phase extended until ball release, the deceleration phase extended until maximal internal rotation, and the end of the pitch was defined as lagging foot strike (Figure 2).[19] Front foot contact was used as the defining event to coordinate video and motion analysis data.

The EMG signals were converted to microvolts, and baseline activity (as defined by the mean activity during the 1.5 seconds before pitch initiation) was subtracted. The EMG signals were rectified, smoothed using a root mean square algorithm with a window of 50 milliseconds, and normalized to the MMT values. Data from muscles in which EMG activity during the pitch was near zero or greater than 250% of MMT were excluded. Excluded pitches (n = 20 from a total of 89) did not significantly differ in ball velocity from nonexcluded pitches. The mean EMG activity for each patient, each muscle, and each pitch phase for each pitch was calculated and compared between groups. Each EMG data point between front foot contact (0% of the pitch) and ball release (100% of the pitch) was assigned a percentage within the pitch[15] and plotted to allow a more granular comparison of EMG activity between patients. The peak EMG activity for each patient and each muscle for each pitch as well as the timing of the peak relative to the percentage of the pitch was calculated and compared between groups. Coefficients of variation of the peak amplitude and timing were calculated both within each pitcher and between pitchers for each variable. The overall mean between-pitcher coefficients of variation were compared with the mean within-pitcher coefficients of variation using a Z test. Within-pitcher coefficients of variation were compared between groups to determine whether BT or SLAP repair alters neuromuscular variability between pitches. In addition, EMG measurements within control pitchers were compared within muscles and within phases with existing norms for collegiate players.[13,25,26,33] Data were tested for normality using the Kolmogorov-Smirnov test and analysis of variance (ANOVA), or Kruskal-Wallis tests with post hoc Tukey or Mann-Whitney U tests were used as appropriate based upon data normality.

Motion data were analyzed similarly. Previously described kinematic factors were measured and compared (Table 1).[1,14,15,19,45] Each motion data point between

TABLE 1
Kinematic Variables for Controls, Pitchers After BT, and Pitchers After SLAP Repair[a]

Kinematic Variable	Controls	Pitchers After BT	Pitchers After SLAP Repair
Ball velocity, m/s	30 ± 2	27 ± 2	27 ± 2
Stride length at foot strike, % of height	73 ± 4	66 ± 6	69 ± 6
Lead knee flexion at foot strike, deg	30 ± 10	21 ± 9	18 ± 18
Trunk rotational orientation at foot strike, deg	25 ± 28	35 ± 27	15 ± 15
Trunk flexion at foot strike, deg	13 ± 7	5 ± 8	4 ± 8
Shoulder ER at foot strike, deg	38 ± 26	53 ± 39	51 ± 34
Shoulder abduction at foot strike, deg	89 ± 22	90 ± 24	103 ± 9
Elbow flexion at foot strike, deg	88 ± 19	71 ± 32	70 ± 40
% of pitch at onset of trunk rotation	30 ± 16	12 ± 10	9 ± 11
% with trunk rotation onset before front foot contact	14 ± 24	43 ± 39	59 ± 34
Maximal shoulder ER, deg	147 ± 12	134 ± 14	127 ± 20
% of pitch at maximal shoulder ER	71 ± 9	64 ± 19	69 ± 14
Maximal shoulder abduction during cocking, deg	111 ± 19	117 ± 24	108 ± 10
Elbow flexion at maximal shoulder ER, deg	72 ± 10	77 ± 14	81 ± 20
Lead knee flexion at ball release, deg	37 ± 16	50 ± 15	43 ± 15
Forward trunk tilt at ball release, deg	5 ± 4	1 ± 1	2 ± 2
Lateral trunk tilt at ball release, deg	14 ± 8	12 ± 13	7 ± 9
Shoulder abduction at ball release, deg	96 ± 15	97 ± 8	98 ± 12
Shoulder rotation at ball release, deg	86 ± 26	70 ± 24	86 ± 18
Elbow flexion at ball release, deg	70 ± 17	68 ± 12	63 ± 22
Duration of cocking phase, ms	151 ± 43	158 ± 72	148 ± 11
Duration of acceleration phase, ms	57 ± 17	71 ± 27	47 ± 20
Duration of foot strike to ball release phase, ms	208 ± 33	229 ± 46	195 ± 19

[a]Values are reported as mean ± SD. All differences were nonsignificant except that the study pitchers were significantly more likely to exhibit altered patterns of trunk rotation compared with controls (P = .028). BT, biceps tenodesis; ER, external rotation; SLAP, superior labral anterior-posterior.

TABLE 2
Kinematic Variables With Previously Published Normal Values for Collegiate Pitchers and Percentage of Controls Within Normative Values[a]

Kinematic Variable	Previously Published Normal Range[b]	% of Controls Within Normal Range, mean ± SD
Stride length at foot strike, % of height	66-74[21]	69 ± 38
Shoulder ER at foot strike, deg	5-71[21,59]	88 ± 21
Elbow flexion at foot strike, deg	70-102[21]	27 ± 28
Maximal shoulder ER, deg	171-185[21]	0 ± 0
Elbow flexion at maximal shoulder ER, deg	85-103[59]	7 ± 19
Forward trunk tilt at ball release, deg	26-40[21]	0 ± 0
Lateral trunk tilt at ball release, deg	14-32[21]	57 ± 45
Shoulder abduction at ball release, deg	87-105[21]	57 ± 45
Shoulder rotation at ball release, deg	23-70[21,59]	58 ± 35
Duration of cocking phase, ms	100-160[59]	52 ± 41

[a]ER, external rotation.
[b]When 2 previous studies both published normal values, a wider range incorporating both previous ranges was adopted.

initiation of the pitching motion (0% of the pitch) and maximal shoulder internal rotation (100% of the pitch) was assigned a percentage within the pitch.[15] In addition, where possible, kinematic factors were compared with existing norms for collegiate players (Table 2).[21,59]

RESULTS

For the demographic data, the mean age at the time of testing was significantly higher for the SLAP repair group (28.0 ± 4.2 years) compared with the BT group (22.4 ± 2.1 years; P = .015) and control group (21.4 ± 1.7 years; P = .003). The mean time of follow-up was significantly longer for patients after SLAP repair (5.9 ± 2.5 years) than after BT (2.0 ± 1.7 years; P = .033). For all study participants, the highest level of play was collegiate or higher; 1 control participant played semiprofessionally. Otherwise, there were no significant differences between groups in height, weight, pitching experience, age at the time of surgery, upper extremity dimension, or shoulder range of motion (P > .07 in all cases). All postoperative pitchers

TABLE 3
Outcome Scores for Controls, Pitchers After BT, and Pitchers After SLAP Repair[a]

Outcome Measure	Controls	Pitchers After BT	Pitchers After SLAP Repair
American Shoulder and Elbow Surgeons	98 ± 1	95 ± 4	88 ± 7
DASH	1 ± 1	3 ± 3	3 ± 4
DASH-Sport	0 ± 0	19 ± 27	35 ± 15
Visual analog scale for pain	0.3 ± 0.3	0.8 ± 0.8	1.7 ± 1.2
Kerlan-Jobe Orthopaedic Clinic	89 ± 8	66 ± 21	50 ± 14
Constant	98 ± 3	94 ± 4	95 ± 4
University of California, Los Angeles	33 ± 2	33 ± 2	31 ± 3
SF-12 physical component	56 ± 3	54 ± 4	54 ± 4
SF-12 mental component	55 ± 6	57 ± 4	57 ± 4

[a]Values are reported as mean ± SD. All differences were nonsignificant except that the study pitchers were significantly more likely to exhibit altered patterns of trunk rotation compared with controls (P = .028). BT, biceps tenodesis; DASH, Disabilities of the Arm, Shoulder and Hand; SF-12, Short Form–12 quality of life; SLAP, superior labral anterior-posterior.

had arthroscopically confirmed type II SLAP tears. In all cases, this was the first operative intervention. Two patients within the BT group underwent concomitant, extensive labral and intra-articular debridement, and 2 patients within the SLAP repair group also underwent concomitant subacromial decompression and repair of partial-thickness rotator cuff tears.

Most outcome scores were significantly worse for patients after SLAP repair than for controls (ASES: P = .004; DASH: P = .006; DASH-Sport: P = .003; and VAS: P = .021) (Table 3) or patients after BT. Patients after SLAP repair had significantly worse KJOC scores than did controls, as did patients after BT (P = .041 for BT; P < .001 for SLAP repair; P = .161 when the operative groups were compared). Constant, UCLA, SF-12 physical component, and SF-12 mental component scores were not significantly different between groups (P > .057). Ball velocity was lower for patients after SLAP repair (P = .032) and after BT (P = .015) compared with controls (P = .010), but the difference between the 2 postoperative groups was not significant (P = .89).

Mean within-pitcher coefficients of variation were significantly lower than mean between-pitcher coefficients of variation, suggesting that pitchers are electromyographically consistent from pitch to pitch (Z = –4.015, P < .00001). For the biceps, there were no significant differences between mean values for control pitchers and previously published values (P > .53 for all phases). For the deltoid, the controls had significantly lower activity during stride and deceleration and significantly higher activity during cocking than previously published values (P = .0017, .003, and .0229, respectively; otherwise, P > .06) but no differences in activity during wind-up, acceleration, or follow-through. For the infraspinatus, the control pitchers had significantly lower activity during the cocking phase than previously published values but no differences in activity during any other phase (P = .0191; otherwise, P > .05). For the latissimus, the control pitchers had significantly lower activity than previously published during the acceleration phase but no differences in activity during any other phase (P = .0003; otherwise, P > .15). Overall, for 79% of comparisons between muscles and phases, there were no significant differences between our controls and previously published norms, confirming our testing methodology to be externally valid.[13,25,26,33]

No statistically significant differences could be determined when the EMG activity for each muscle was compared with respect to activity during each pitching phase, peak activity, peak timing, and coefficients of variation (P > .10 in all cases) (Table 4 and Figure 3).

Postoperative pitchers were significantly more likely to demonstrate altered trunk rotation patterns (P = .028) (Table 1). Tukey post hoc analyses demonstrated these differences to be isolated to patients after SLAP repair, with P = .034 versus P = .092 for patients after BT. While both controls and pitchers after BT demonstrate a peak in thoracic rotation in late cocking/early acceleration at 80% of the pitch as the potential energy is transmitted from the lower extremity through the thorax and then into the humerus, thoracic rotation in pitchers after SLAP repair did not occur until late acceleration near 100% of the pitch (Figure 4B). There were no significant differences in any of the other 21 measured kinematic variables (P > .06 in all cases) (Table 1 and Figure 4).

When kinematic data were compared with previously published norms, significantly more pitches thrown by controls (69% ± 38%) and patients after BT (24% ± 25%) were within previously published norms of 29° to 47° for lead knee flexion at foot strike[21] than those thrown by patients after SLAP repair (16% ± 26%) (P = .019). For the duration of the cocking phase, significantly more pitches thrown by patients after SLAP repair (82% ± 26%) and controls (52% ± 41%) were within previously published norms of 100 to 160 milliseconds than those patients after BT (23% ± 34%) (P = .033). Otherwise, there were no significant differences in the proportion of kinematic factors that fell within previously published norms (Table 2).[21,59] The majority of pitches thrown by controls for the majority of measured kinematic factors fell within previously published normal values (Table 2).[21,59]

TABLE 4
Surface EMG Peak Values and Coefficients of Variation[a]

Variable	Surface EMG Peak Value, mean ± SD			Coefficient of Variation[b]	
	Controls	Pitchers After BT	Pitchers After SLAP Repair	Within-Pitcher Variability	Between-Pitcher Variability
Maximal muscular contraction,[c] % MMT					
LHBM	97 ± 48	88 ± 49	103 ± 72	0.18	0.57
SHBM	120 ± 85	98 ± 89	125 ± 90	0.18	0.25
Deltoid	98 ± 88	64 ± 19	46 ± 18	0.22	0.71
Infraspinatus	70 ± 56	87 ± 49	30 ± 12	0.21	0.29
Latissimus dorsi	48 ± 59	17 ± 17	40 ± 35	0.18	0.82
Peak muscular contraction timing within a pitch,[d] %					
LHBM	72 ± 7	64 ± 14	68 ± 25	0.41	0.45
SHBM	61 ± 15	72 ± 12	66 ± 26	0.24	0.76
Deltoid	54 ± 23	47 ± 19	43 ± 23	0.11	0.11
Infraspinatus	83 ± 14	93 ± 4	92 ± 5	0.24	1.16
Latissimus dorsi	79 ± 17	94 ± 4	69 ± 26	0.21	0.25

[a]BT, biceps tenodesis; EMG, electromyographic; LHBM, long head of the biceps muscle; MMT, manual muscle testing; SHBM, short head of the biceps muscle; SLAP, superior labral anterior-posterior.
[b]In all cases, within-pitcher variability was lower than between-pitcher variability.
[c]100% MMT was defined as the 1-second interval with the highest EMG activity.
[d]0% = stride foot contact; 100% = ball release.

DISCUSSION

While the role of the LHBM in glenohumeral function has been previously debated,[4,30,39,50,53,55,61,62] the disappointing results of SLAP repair with respect to return to play are well accepted.[10,23,27,32,35] Clinically, there has been some support for BT as the primary management of type II SLAP lesions.[4] However, given the unknown role of the long head of the biceps in the throwing motion,[4,30,39,50,53,55,61,62] the implications of BT on return to throwing have been unclear. Several differences were noted between pitchers after SLAP repair and uninjured controls, specifically, altered patterns of trunk rotation, a higher likelihood of lead knee flexion outside of previously published norms, a higher likelihood of a cocking phase duration outside of previously published norms, and a visual trend, not statistically supported, toward superior restoration of physiologic LHBM activity in patients after BT as compared with those after SLAP repair. However, the vast majority of comparisons demonstrated no significant differences between controls, pitchers after BT, and pitchers after SLAP repair both within neuromuscular activation patterns and variability and motion analysis data, demonstrating that both SLAP repair and BT are capable of restoring neuromuscular control and pitching kinematics in select patients.

Within this same issue of the *American Journal of Sports Medicine*, Laughlin et al[37] have published a markered motion analysis comparing pitchers' status after SLAP repair and normal controls. They identified differences in maximal external rotation, horizontal shoulder abduction, and forward trunk tilt at ball release. While our study did not find significant differences in these variables, we found a trend toward decreased maximal external rotation in pitchers after SLAP repair as compared with normal controls. Differences in specific findings between our study and Laughlin et al's study may be due to changes in operative technique given that their data was collected over a 14 year period, differences in sample size, differences in markered vs markerless motion analysis, differences in the level of play between cohorts, differences in the rehabilitation status of the tested players, and heterogeneity in the operative techniques and surgeons included. However, despite these differences, their study independently arrived at the same conclusion as our study: SLAP repair alters pitching biomechanics.

Several previous studies have been conducted to determine the EMG function of the long head of the biceps. A previous EMG analysis comparing pitchers with anterior instability to those without demonstrated an increase in bicipital activity, theorized to be either compensatory for the increased laxity or indicative of underlying neuromuscular imbalance.[25] The same study group has demonstrated no difference in bicipital EMG activity between control pitchers and those with ulnar collateral ligament insufficiency[26] and relatively more bicipital EMG activity in youth than in professional pitchers.[29] Moreover, BT does not affect glenohumeral translation during range of motion in vivo when evaluated with biplanar fluoroscopy.[24] However, to the best of our knowledge, there are no previous examinations of postoperative pitchers or of LHBM as compared with SHBM activity that can be used for comparison with our data. When our controls were compared with previously published norms,[13,25,26,33] for 79% of comparisons between muscles and phases, there were no significant differences. There were no differences for any phase for the biceps. Small differences between our patients and those in previous studies within the deltoid,

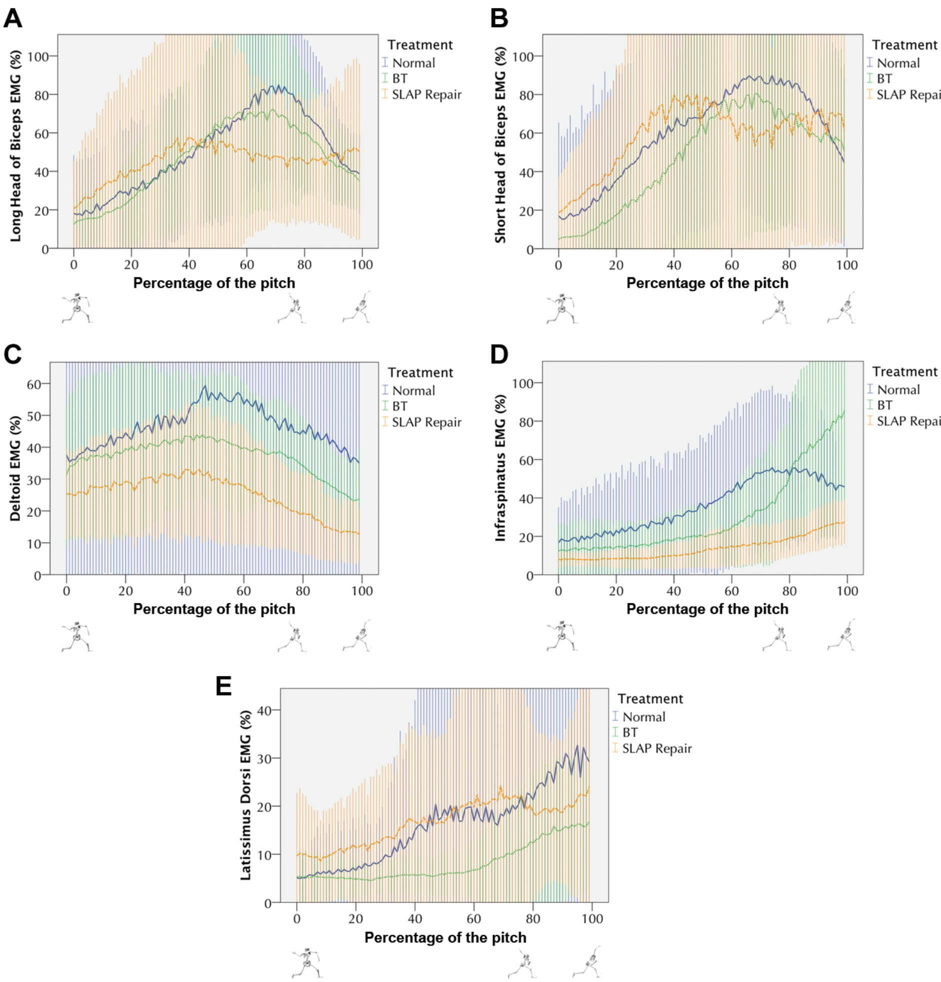

Figure 3. Mean surface electromyographic activity in the (A) long head of the biceps muscle, (B) short head of the biceps muscle, (C) deltoid muscle, (D) infraspinatus muscle, and (E) latissimus dorsi muscle as a percentage of manual muscle testing as compared with the percentage of the pitch, with 0% being front foot contact and 100% being ball release. BT, pitchers after biceps tenodesis (dotted line); SLAP, pitchers after superior labral anterior-posterior repair (dashed line). Images below each graph demonstrate the position of the pitcher at each point during the pitch. Bars represent SDs.

infraspinatus, and latissimus may be because of differences in measurement between fine-wire and surface EMG. In particular, for a broad deep muscle covered with more subcutaneous adipose tissue, such as the deltoid, surface EMG may not provide as accurate a measurement as fine-wire EMG.

Kinematic variables have been previously demonstrated as important predictors for kinetic factors. For instance, peak elbow valgus loads have been prospectively shown to be correlated with future elbow injuries and radiographic ulnar collateral ligament abnormalities,[2,31] and several of the kinematic factors identified in this study have been correlated with increased peak elbow valgus loads, such as decreased maximal shoulder external rotation,[1] decreased elbow flexion,[1,60] timing of trunk rotation relative to front foot contact,[1,22,45] and shoulder abduction.[22,60] Similar analyses have demonstrated that peak shoulder proximal forces, which may lead to rotator cuff tears and labral tears, correlate with maximal shoulder external rotation,[57] elbow flexion at ball release,[57,59] and elbow flexion at foot strike.[57] Within our dataset, several kinematic differences were found between uninjured controls, pitchers after SLAP repair, and pitchers after BT. Pitchers after SLAP repair exhibited altered patterns of trunk rotation when compared with patients after BT and controls. Multiple studies have associated this kinematic factor with higher elbow valgus loads,[1,22,45] which have been prospectively associated with an increased risk for ulnar collateral ligament injuries.[2,31] Similarly, the duration of the cocking phase was significantly longer for pitchers after tenodesis. This variable has been associated with humeral torque in professional pitchers, a factor that may be important in the development of proximal humeral epiphysiolysis or "Little Leaguer's shoulder."[52] While the biomechanical explanations for why these surgical techniques may connect with these particular kinematic alterations

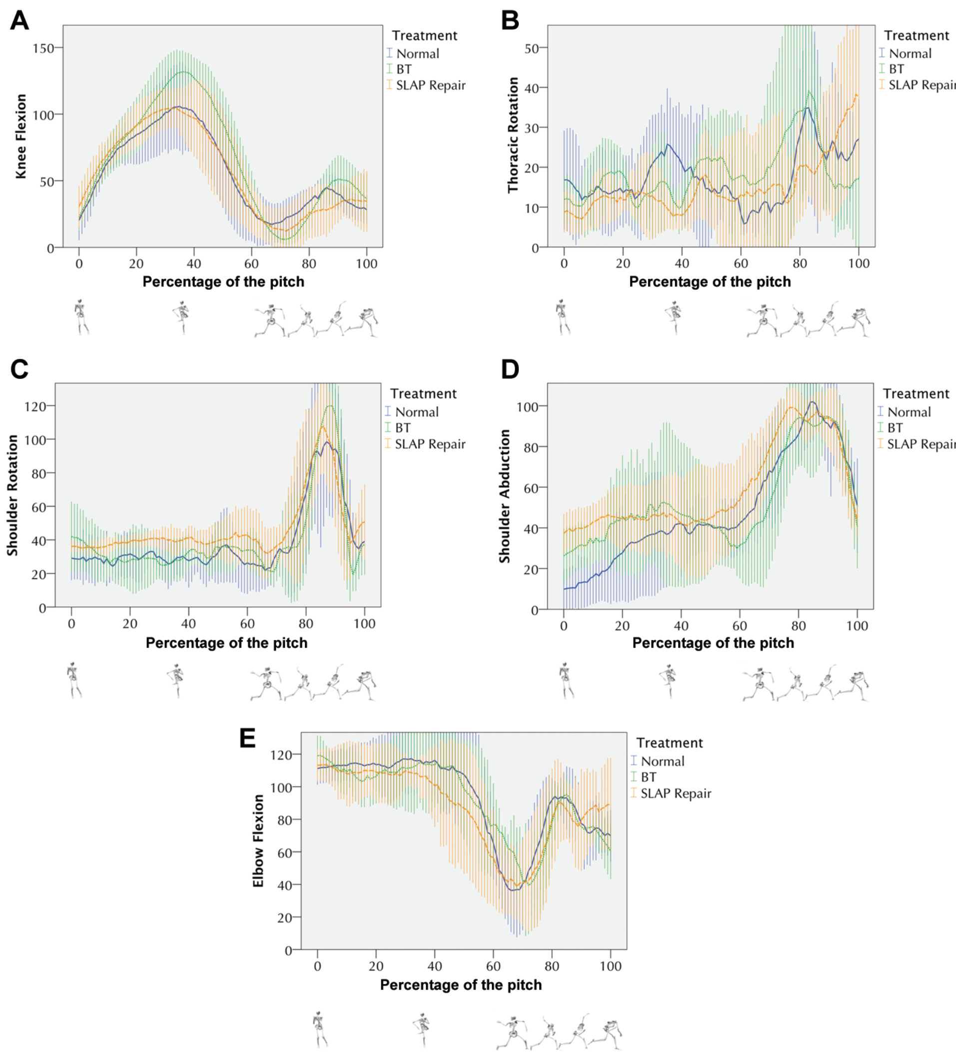

Figure 4. Mean (A) lead knee flexion, (B) thoracic rotation, (C) shoulder rotation, (D) shoulder abduction, and (E) elbow flexion as compared with the percentage of the pitch, with 0% being initiation of the pitching movement and 100% being maximal internal rotation. BT, pitchers after biceps tenodesis (dotted line); SLAP, pitchers after superior labral anterior-posterior repair (dashed line). Images below each graph demonstrate the position of the pitcher at each point during the pitch. Bars represent SDs.

remain speculative at this point, future study is warranted as these subtle kinematic variations could correlate with a risk for future injuries. Larger studies will be necessary to confirm this association because of the small sample size in this study.

While EMG and motion analyses are both potentially useful clinical tools to evaluate patient status after arthroscopic shoulder surgery, past usage has been prevented by the need for cumbersome and uncomfortable needle electrodes[25,26,29,33,34] and surface markers,[1,12,42,43,58,59] which are time consuming and complex to place and which may introduce variability in placement[28,49] that could contribute to analysis inaccuracies.[38,40] The development of surface EMG[9,56] and markerless motion analysis[11,41] allows for a more rapid collection of data without any patient discomfort. To the best of our knowledge, this study is the first to describe the use of these methodologies in the evaluation of postoperative pitchers. An earlier study found good agreement in kinematic measures between a marker-based system and the markerless system, reporting correlation factors from 0.89 to 1.0 for sagittal plane motion of the ankle, knee, and hip joint.[46] However, the accuracy of upper extremity measurements is unknown. Preliminary comparison between our controls and previously published normal ranges demonstrates that while most pitchers fell into normal ranges for most measured variables, there are discrepancies for elbow flexion at foot strike, maximal shoulder external rotation, elbow flexion at maximal shoulder external rotation, and forward trunk tilt at ball release. These discrepancies could be caused by differences in measurement between markered, video, and markerless systems. In particular, the markerless system may be less accurate for distal limb segments as they are smaller and thus cast a smaller shadow, which may explain poor recordings of elbow flexion. The system is also less accurate for rotational movements, which may explain poor recordings of shoulder external rotation and forward trunk tilt. However, kinematic variables evaluated by multiple markered studies in uninjured collegiate athletes often demonstrate widely varying values; for instance, while Fleisig and colleagues[21] described 23° to 35° as normal for elbow flexion at ball release, Werner and colleagues[59] described 44° to 70° as normal. Thus, differences between previously published normal values and those of our own control cohort may not be because of inaccuracies within the markerless system but instead caused by underlying variation between populations of pitchers. Moreover, in this study, we were less concerned about absolute values and more in the differences between treatment groups as all patients were evaluated with the same methodology.

This study has several limitations. Surface EMG has its shortcomings, especially for muscles in close anatomic proximity, such as the SHBM and LHBM. However, multiple previous studies have described the use of surface EMG for the LHBM and SHBM,[6,16,53] and efforts were taken to ensure adequate electrode spacing. In addition, within-pitcher coefficients of variation were less than 0.22 for all muscle peak amplitudes, and the mean between-pitcher coefficient of variation was significantly less than the mean within-pitcher coefficient of variation. Low variability was also seen for motion results, suggesting our system to be internally consistent, if untested from an external validity perspective. A second limitation is that a mixture of player levels and concomitant procedures may contribute to differences between groups.[18-20] Baseline differences between our groups with respect to age at the time of testing, time of follow-up, level of play, pitch velocity, surgical indications, and outcome scores may obscure differences between EMG data between groups and limit our ability to draw conclusions. Additionally, controls pitched significantly faster compared with patients in the operative groups. This report represents a pilot study and not a consecutive series. One specific selection bias is the inclusion of 2 patients within the SLAP repair group who had undergone repair of partial-thickness rotator cuff tears. A post hoc analysis was conducted with these patients excluded that redemonstrated the lack of a significant difference between groups in EMG findings ($P > .09$ in all cases). However, in this subgroup analysis, there were more significant kinematic differences between pitchers after SLAP repair and control pitchers, with differences in trunk flexion at foot strike ($P = .033$), trunk rotation ($P = .024$), and maximal shoulder external rotation ($P = .038$).

We observed higher mean EMG activity of the controls throughout the pitching phases, although such differences did not prove statistically significant. Also, EMG signals are known to be variable, and more patients are necessary to generate more definite results. We also did not collect preoperative motion or EMG data, and thus, it remains unknown whether our groups had comparable preoperative pitching kinematics and EMG activation. Given that preoperatively many patients were unable to pitch because of shoulder pain, which can alter kinematics and cause neuromuscular inhibition, it remains unclear if preoperative data would reflect baseline preinjury kinematic and EMG differences between patients. A larger sample size, including a larger group of controls, may be necessary to overcome this issue in future studies. In addition, while range of motion data were collected and did not differ between groups, the authors did not perform a standardized measurement of glenohumeral internal rotation deficit (GIRD) accounting for glenoid version and scapulothoracic rotation, and thus, we are not able to determine whether GIRD may have influenced our kinematic results. In addition, because EMG relies upon full restoration of physiologic neuromuscular control, patients must behave as though they are not being observed; in our own dataset, it was often noted that the data collected during the first pitch thrown after the warm-up period often showed hyperactivation or hypoactivation patterns. A markerless motion analysis system was used. The system proved reliable, as verified with high-speed video and between-pitch comparisons, showing low coefficients of variation. Future studies have to determine the system's validity in collecting kinematic and kinetic data during sport activity. Certainly, compared with traditional motion analysis systems, the athlete enjoys a new freedom of movement.

In addition, the lack of a significant difference in several of our comparisons may be because of a lack of sufficient power. A post hoc power analysis performed using mean elbow flexion at ball release, a variable chosen because it has been associated with both elbow valgus torque[1,60] and shoulder proximal force,[57,59] determined that 100 controls and 100 patients after SLAP repair would be necessary to achieve a power of 80%, although this difference is likely sufficiently small to be clinically insignificant. Given the mean EMG activity within the LHBM during the cocking phase, 500 uninjured pitchers and 500 pitchers after BT would be necessary to find a significant difference, and again, this difference is likely sufficiently small to be clinically insignificant. Given the relative infrequency of the operative treatment of these injuries with subsequent return to full painless pitching, studies of such sizes will likely be difficult for a single center and may require a multicenter effort.

CONCLUSION

While both BT and SLAP repair can restore physiologic neuromuscular control, pitchers who undergo SLAP repair may exhibit altered patterns of thoracic rotation when compared with controls and pitchers who undergo BT.

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