Biomechanical Performance of Baseball Pitchers With a History of Ulnar Collateral Ligament Reconstruction

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Background: A relatively high number of active professional baseball pitchers have a history of ulnar collateral ligament reconstruction (UCLr) on their throwing elbow. Controversy exists in the literature about whether professional baseball pitchers regain optimal performance after return from UCLr. It has been suggested that pitchers may have different biomechanics after UCLr, but this has not been previously tested.

Hypothesis: It was hypothesized that, compared with a control group without a history of UCLr, professional pitchers with a history of UCLr would have (1) significantly different throwing elbow and shoulder biomechanics; (2) a shortened stride, insufficient trunk forward tilt, and excessive shoulder horizontal adduction, characteristics associated with ''holding back'' or being tentative; (3) late shoulder rotation; and (4) improper shoulder abduction and trunk lateral tilt.

Study Design: Controlled laboratory study.

Methods: A total of 80 active minor league baseball pitchers (and their 8 Major League Baseball organizations) agreed to participate in this study. Participants included 40 pitchers with a history of UCLr and a matched control group of 40 pitchers with no history of elbow or shoulder surgery. Passive ranges of motion were measured for each pitcher's elbows and shoulders, and then 23 reflective markers were attached to his body. The pitcher took as many warm-up pitches as desired and then threw 10 full-effort fastballs for data collection. Ball speed was recorded with a radar gun. The reflective markers were tracked with a 10-camera, 240-Hz automated motion analysis system. Eleven biomechanical parameters were computed for each pitch and then averaged for each participant. Demographic, range of motion, and biomechanical parameters were compared between the UCLr group and the control group by use of Student *t* tests (significance set at $P < .05$).

Results: All hypotheses were rejected, as there were no differences in pitching biomechanics between the UCLr group and the control group. There were also no differences in passive range of motion between the 2 groups.

Conclusion: Compared with a control group, active professional pitchers with a history of UCLr displayed no significant differences in shoulder and elbow passive range of motion and no significant differences in elbow and shoulder biomechanics.

Clinical Relevance: Clinical studies have previously shown that 10% to 33% of professional pitchers do not return to their preinjury level; however, the current study showed that those pitchers who successfully return to professional baseball after UCLr pitch with biomechanics similar to that of noninjured professionals.

Keywords: Tommy John surgery; elbow varus torque; kinematics; kinetics

A recent survey by Conte et al[4] revealed that 16% of active professional pitchers (major leaguers and minor leaguers) have a history of ulnar collateral ligament reconstruction (UCLr). Cain et al[3] reported that 89% of professional baseball pitchers returned to professional baseball (74% returned to their previous level). A long-term follow-up of these patients showed that the minor league pitchers averaged 4.2 years in professional baseball after the surgery.[19] The major league pitchers in the clinical series pitched in professional baseball for 7.5 years after their return, but only about half of that time was at the major league level.[19] Three studies reported return-to-play statistics after UCLr for major league pitchers[6,14,16]; the return-to-play rates in

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those studies varied from 67% to 97%. One of the studies reported improved performance statistics after surgery,[6] while the other 2 investigations found decreased performance.[14,16] Furthermore, 2 other studies have shown that professional pitchers with a history of UCLr may undergo shoulder surgery[19] or more elbow surgery (Conte et al., unpublished) later in their career.

Pitching biomechanics has been studied extensively, including descriptions of elbow stress and UCL injury mechanism. Stress on the UCL is greatest when the elbow is flexed to about 90° and the shoulder is near its maximum external rotation.[8] At this point, peak internal rotation torque is produced about the shoulder to decelerate external rotation and initiate internal rotation. Peak elbow varus torque is also produced at this point, as osseous and soft tissues must maintain elbow integrity to decelerate the cocking of the arm and initiate its forward rotation with the shoulder's internal rotation.[8] Of the approximately 90 N·m of elbow varus torque during pitching,[5,11,13,20] about 50 N·m is generated by tension of the UCL.[8] However, cadaveric research has shown that the UCL can provide only about 32 N·m of elbow varus torque.[8,12] Although both biomechanical modeling and cadaveric research have limitations and inaccuracies, these studies support the explanation that peak tension in the UCL is dangerously high when the pitcher's arm is externally rotated, and repetitive pitching can create tears in the anterior bundle of the UCL.

Despite associations of improper pitching biomechanics with pitching velocity, elbow load, and shoulder load,[13] there are no published data regarding whether pitchers with a history of UCLr use different biomechanics than pitchers without such an injury history. The purpose of this study was therefore to compare the biomechanics of professional pitchers with a history of UCLr to that of a control group of professional pitchers with no history of surgery to their throwing elbow or shoulder. Four specific hypotheses were tested. The first hypothesis was that throwing elbow and shoulder biomechanics would be different between the UCLr group and control group. The second was that the UCLr group would display a shortened stride, insufficient trunk forward tilt, and excessive shoulder horizontal adduction, characteristics associated with "holding back" or being tentative. Third, shoulder external rotation at the instant of front foot contact was compared, testing the theory that pitchers with UCL injuries are late in cocking their arm. The final hypothesis was that the UCLr group would have different arm and trunk angles in the frontal plane than the control group, as improper shoulder abduction and trunk lateral tilt have been previously linked with increased elbow varus torque.[17]

MATERIALS AND METHODS

This study was approved by the Baptist Healthcare System Institutional Review Board. Eight Major League Baseball (MLB) organizations agreed to participate in the study during 2014 spring training, providing subjects and space for data collection. As compensation for their participation, each organization received a free biomechanical evaluation from the investigators for each pitcher tested. These MLB organizations searched their medical records to identify any of their active minor league pitchers who had undergone UCLr during the past 48 months. The upper limit for time since UCLr was set at 4 years (48 months) to limit the effect of factors such as aging, minor injuries, diminished velocity, and changes in pitching approach that accumulate over time. Four years is also the estimated career length in MLB after returning from UCLr.[6,19] No minimum time since UCLr was set for inclusion; instead, the criterion was that a participant had to be an active pitcher in spring training competing for a roster position. Athletes who were still in the rehabilitation process after UCLr were not active pitchers in spring training and were thus excluded from the study. For each pitcher included in the UCLr group, the organization selected a matched control pitcher at the same league level (A, AA, AAA) who had no history of elbow or shoulder surgery in his throwing arm and who had been completely healthy for 12 months before his evaluation.

TABLE 1
Demographic Comparison Between the UCLr and Control Groups[a]

	UCLr Group (n = 39)	Control Group (n = 38)	*P*
Age, y	23.4 ± 1.9	21.4 ± 2.0	<.01[b]
Height, m	1.88 ± 0.06	1.91 ± 0.05	.08
Weight, kg	95.1 ± 10.3	96.3 ± 11.4	.64
Ball velocity, m/s	37.9 ± 1.7	38.3 ± 1.4	.28

[a]Data are expressed as mean ± SD. UCLr, ulnar collateral ligament reconstruction.
[b]Significant difference between groups ($P < .05$).

Test dates were then agreed upon with each organization, and the investigators used a 10-camera automated Raptor motion capture system (Motion Analysis Corp). The system was brought to the organization's spring training facility on the designated dates and set up around a practice pitching mound outdoors or in a tented facility.

Review of the medical history revealed that 3 of the subjects tested had a history of arm surgery unrelated to UCL. Data for these 3 subjects were removed from the study, leaving data for 77 pitchers (39 in the UCLr group and 38 in the control group) for analysis. There were no significant differences in height, weight, or ball velocity during testing between the UCLr group and the control group, but the UCLr group was significantly (2 years) older (Table 1). All 39 pitchers in the UCLr group had a history of one UCL reconstruction, while none had a history of UCL revision surgery. The length of time from the most recent UCL surgery to biomechanical testing averaged 30.5 months (range, 10.8-46.6 months).

Before testing, each participant completed informed consent, pitching history, and medical history forms. Passive range of motion was then measured for both arms by certified athletic trainers or physical therapists who were employed by the team or part of the research team. Elbow extension,

Figure 1. Motion capture of a fastball pitch.

shoulder external rotation in the supine position with 90° of shoulder abduction, and shoulder internal rotation in the supine position with 90° of shoulder abduction were measured with a bubble goniometer as previously described.[22,23] During measurement of internal and external rotation, the scapula was only stabilized by body weight from the supine position, the humeral head was not stabilized, and the arm was rotated until tissue resistance occurred.

The athlete then changed into the testing clothing consisting of body-fit shorts, baseball socks, spikes, and baseball cap. Twenty-three reflective markers (10-mm diameter) were attached to the participant. These included markers attached bilaterally to the distal end of the third metatarsal, lateral malleolus, lateral femoral epicondyle, greater trochanter, lateral superior tip of the acromion, lateral humeral epicondyle, and ulnar styloid. Additional markers were placed on the medial humeral epicondyle, mid-forearm, radial styloid, and dorsal surface of the hand on the throwing extremity. Four markers were attached to a baseball cap on the front, back, top, and right sides of the head. The athlete warmed up by throwing with a teammate on the open field followed by warm-up pitches on the mound. Once the pitcher indicated he was ready, motion data were captured at 240 Hz for 10 fastballs pitched from the pitching mound to a catcher behind home plate located 18.4 m from the mound, as in a game environment. The reflective markers were tracked by the motion capture system while ball speed was measured with a calibrated radar gun (Figure 1).

Kinematic and kinetic parameters were calculated during each pitch trial as previously described.[10,24] Elbow flexion and 3 components of shoulder motion (external-internal rotation, abduction, and horizontal adduction-abduction) were computed. Stride length was measured as the distance from the pitching rubber to the front ankle at the instant of front foot strike, expressed as a percentage of the pitcher's height. Trunk forward tilt was the angle between the superior axis of the trunk and the global x-direction in the global x-z plane, where x was the direction from the pitching rubber to home plate and z was vertically upward. Trunk lateral tilt was the angle between the superior axis of the trunk and the global y-direction in the global y-z plane. Elbow extension velocity was the time derivative of elbow flexion, multiplied by -1. Shoulder internal rotation velocity was the time derivative of shoulder external rotation, multiplied by -1. Elbow varus torque, shoulder internal rotation torque, shoulder horizontal adduction torque, and shoulder proximal force were computed by use of the motion data; estimated mass properties of the ball, hand, upper arm, and forearm; and the principles of inverse dynamics. Each joint torque and force was reported as the load applied by the proximal segment onto the distal segment. The mean value was computed for each parameter for each participant over 10 trials. Although pitchers were instructed to throw all fastballs down the middle of the strike zone at full effort, all 10 trials were recorded and analyzed regardless of accuracy or velocity to reduce the number of pitches thrown in the testing condition.

An a priori power analysis was performed before participant recruitment began. Two primary outcome measures—maximum elbow flexion and maximum shoulder external rotation—were analyzed to determine the minimum sample size required for detecting significant, clinically relevant differences between the UCLr group and control group. Based on data previously collected,[5,9,11,15] it was determined that to detect significant differences in these measurements of 10° or greater at an α level of .05 with 80% power, a minimum of 21 subjects would be needed in both the control and UCLr groups. All statistical tests were performed with JMP 10 (SAS Institute). Two-tailed Student t tests were used to test for significant differences ($P < .05$) between the UCLr and the control groups.

RESULTS

There were no significant differences in shoulder and elbow passive range of motion between the 2 groups (Table

TABLE 2
Passive Range of Motion in Degrees Compared Between the UCLr and Control Groups[a]

	UCLr Group (n = 39)	Control Group (n = 38)	*P*
External rotation			
Dominant shoulder	121 ± 12	119 ± 10	.41
Nondominant shoulder	114 ± 13	111 ± 15	.38
Internal rotation			
Dominant shoulder	56 ± 13	53 ± 14	.37
Nondominant shoulder	58 ± 12	58 ± 12	.76
Elbow extension			
Dominant elbow	177 ± 8	177 ± 7	.98
Nondominant elbow	178 ± 6	177 ± 5	.46

[a]Data are expressed as mean ± SD. UCLr, ulnar collateral ligament reconstruction.

2), and no differences were found in elbow and shoulder biomechanics (Table 3). The UCLr group showed no signs of a "holding back" mechanism, as there were no differences in stride length, horizontal adduction, and forward trunk tilt in comparison to the control group. The UCLr group also exhibited no signs of late shoulder rotation or modified trunk and arm position in the frontal plane.

DISCUSSION

The hypothesis that elbow or shoulder biomechanics would be different between the UCLr group and control group was rejected. There were no significant differences in elbow or shoulder angle, velocity, torque, or force between the UCLr group and the control group, suggesting that successful UCL reconstruction and rehabilitation do not result in deficits in elbow function. This is more encouraging than results of a recent study of pitchers with a history of shoulder superior labrum anterior-posterior (SLAP) repair.[15] Compared with a matched control group, pitchers with a history of SLAP repair had insufficient horizontal abduction at front foot strike and insufficient maximum external rotation. The investigators attributed those biomechanical deficiencies to anatomic changes in the structure of the shoulder due to the surgical repair. The current study also found no significant differences in passive range of motion between the UCLr group and the control group.

The second hypothesis investigated whether the UCLr group was tentative or cautious when they returned to pitching. Since the biomechanical characteristics of these pitchers were not measured before their elbow injuries, it was not possible to unequivocally quantify whether any of them are now consciously or subconsciously holding back. Clinical experience in our biomechanics laboratory indicates that pitchers who have difficulties after injury often display a "holding back" mechanism. Compensation in pitching biomechanics to alleviate the stress on the elbow may lead to decreased performance (ball velocity, pitch accuracy and movement, pitching statistics, pitching quantity) and may increase the stress on the shoulder, although there is no direct evidence that this does occur. This second hypothesis was also rejected, as the UCLr group did not display "holding back" biomechanics. Again, these results contrast with those of Laughlin et al[15] in their examination of pitching mechanics after SLAP repair. Those pitchers were found to pitch with a significantly more upright trunk at the moment of ball release.

The third hypothesis was based upon a popular theory among coaches, the media, and online experts that the root of many UCL injuries may be repetitive pitching with late arm cocking.[1,2,7,13,18,21] The colloquial expression for late arm cocking, where the elbows are raised higher than the hands and the shoulders, is "pitching with an inverted *W*."[2,18,21] Biomechanical research has shown that late arm cocking—indicated by low external rotation at the instant of front foot contact—is associated with increased elbow varus torque.[7,13] This is because the late shoulder external rotation reduces the amount of time the shoulder has to externally rotate, achieve maximum shoulder external rotation, and then initiate shoulder internal rotation. The reduced time to decelerate back and accelerate forward requires greater shoulder internal rotation torque and greater elbow varus torque. In the current study, the UCLr group did not have a later arm cocking (ie, less external rotation at foot contact) than the control group. However, because the pitchers in the UCLr group were not tested before their injuries, it is unknown whether they had late arm cocking that contributed to their UCL injuries. A prospective study is needed to determine whether late arm cocking leads to UCL injury.

The final hypothesis was whether shoulder abduction and lateral trunk tilt were different between the UCLr group and control group. The combination of shoulder abduction and lateral trunk tilt determines the angle of the throwing extremity in the frontal plane, commonly referred to in baseball as "arm slot." Matsuo et al[17] previously simulated variations in pitching mechanics and showed that for most values of trunk lateral tilt at ball release, elbow varus torque increased when shoulder abduction was significantly greater or less than approximately 90°. This hypothesis was not supported by the current study, as shoulder abduction was maintained near 90° for the UCLr group (and the control group) from foot contact to ball release. Once again, it is unknown whether the UCLr group had the proposed pathomechanics that may have contributed to their injury, but they did not display this risk factor in their current, after-recovery mechanics.

It is important to note that the study had limitations. First, only pitchers who successfully returned to professional baseball were included. Clinical studies have shown that 10% to 33% of professional pitchers do not return to their preinjury level; biomechanical analysis of these clinical failures might show deficiencies in their pitching biomechanics after their surgery and rehabilitation. Pitchers who had UCLr and did not return to professional baseball may not have the same pitching biomechanics as those pitchers who underwent UCLr and did return to professional baseball. Therefore, our findings may not provide

TABLE 3
Biomechanical Comparison Between the UCLr and Control Groups[a]

	UCLr Group (n = 39)	Control Group (n = 38)	*P*
Arm biomechanics			
Maximum elbow flexion, deg	102 ± 15	99 ± 11	.36
Maximum shoulder external rotation, deg	176 ± 9	174 ± 9	.53
Maximum elbow varus torque, N·m	99 ± 17	99 ± 16	.86
Maximum shoulder internal rotation torque, N·m	101 ± 18	102 ± 17	.82
Maximum shoulder horizontal adduction torque, N·m	103 ± 22	106 ± 20	.58
Maximum elbow extension velocity, deg/s	2270 ± 270	2300 ± 230	.68
Maximum shoulder internal rotation velocity, deg/s	6600 ± 790	6730 ± 900	.50
Maximum shoulder proximal force, N	1250 ± 140	1280 ± 170	.39
Parameters associated with "holding back"			
Stride length, % height	83 ± 5	83 ± 5	.71
Maximum shoulder horizontal adduction, deg	14 ± 6	16 ± 7	.16
Trunk forward tilt at ball release, deg	35 ± 7	33 ± 8	.20
Arm timing			
Shoulder external rotation at foot contact, deg	45 ± 33	48 ± 29	.70
Frontal plane adjustments			
Abduction at foot contact, deg	92 ± 11	91 ± 9	.87
Abduction at ball release, deg	94 ± 7	92 ± 8	.35
Trunk lateral tilt at ball release, deg	22 ± 9	21 ± 8	.72

[a]Data are expressed as mean ± SD. UCLr, ulnar collateral ligament reconstruction.

a true reflection of throwing biomechanics exhibited by those who have undergone UCLr. Second, pitching biomechanics were not collected for the UCLr group before their initial injury; thus, comparing biomechanics before injury and after treatment within each pitcher was beyond the scope of this study. Ideally, future research should capture pitching biomechanics and other potential injury risk factors (such as previous injuries, amount of pitching, passive range of motion, and magnetic resonance and stress ultrasound imaging) at the beginning of professional careers and then prospectively link these factors with subsequent injuries. A final limitation was that the data were captured during practice pitching in spring training. There may be differences in pitching biomechanics between in-season games and spring training. This limitation existed in all previously published pitching studies, where data were captured during practice pitching outdoors or in a laboratory. The present study minimized the effect of this limitation by testing the UCLr group and matched control group together in the same environment. It is hoped that in the near future, technology will advance to allow for accurate, automated motion capture in baseball games.

In conclusion, active professional pitchers with a history of UCLr displayed no significant differences in shoulder and elbow passive range of motion and no significant differences in pitching biomechanics compared with noninjured pitchers with no history of UCLr.

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