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Humeral Torque in Professional Baseball Pitchers

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Background: Spontaneous fracture of the humeral shaft in throwers is a rare but well-known phenomenon. Although it has been hypothesized that the biomechanics of the throw cause such fractures, it is not clear how or when the fractures occur in the pitching motion.

Methods: The torque acting about the long axis of the humerus was calculated in 25 professional baseball pitchers throwing in game situations.

Results: Peak humeral axial torque reached a mean value of 92 ± 16 Nm near the time of maximum shoulder external rotation at the end of the cocking phase. This torque tended to externally rotate the distal end of the humerus relative to its proximal end. The direction of the torque was consistent with the external rotation spiral fractures of the humerus noted to occur in throwers. The magnitude of the peak humeral torque averaged 48% of the theoretical torsional strength of the humerus, suggesting that repetitive stress plays a role in humeral shaft fractures.

Conclusions: Fractures are most likely to occur near the time of maximum shoulder external rotation when humeral torque peaks. Pitchers whose elbows were more extended at stride foot contact tended to have lower peak humeral torques.

Keywords: pitching mechanics; humerus; fracture; shoulder

Spontaneous fractures of the humeral shaft have been reported due to throwing objects such as grenades, handballs, softballs, baseballs, snowballs, and javelins.[5,6,20,21,26,27,29,30] Although thankfully not a common injury, these "ball-thrower's fractures"[21,30] have been reported in the medical literature for more than 200 years. The vast majority of case reports have involved recreational athletes, but a few notable exceptions have occurred in high-profile professional baseball pitchers.[2,4] Ball-thrower's fractures are generally spiral fractures of the humeral shaft, sometimes involving butterfly fragments.[5,6,20,21,26,27,29,30] The spiral shape suggests they arise from torsion of the humerus about its long axis.[27] Most authors have reported that the fractures originate near the junction of the middle and distal thirds of the humerus, although the fractures are often more proximal in adolescents than in adults.[6,20,27]

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Several different mechanisms of humeral shaft fractures while throwing have been proposed. Many of the early theories were based entirely on anecdotal evidence and have previously been discussed.[6] Chao et al[6] dismissed theories that cited antagonistic muscle action between the deltoid and brachialis muscles or between the abductors of the arm and the brachialis muscle, stating that neither of these theories satisfactorily explained fractures in the distal third of the humeral shaft. Several authors have concluded that "uncoordinated muscular violence," poor throwing mechanics, or fatigue plays a role in the genesis of such fractures, although there is little scientific evidence on which to base such claims.[5] Chao et al[6] evaluated 139 cases of humeral shaft fractures in soldiers throwing grenades, as well as some simple experimental data, and concluded that the torsional forces acting on the humerus during the throwing motion result in an unbalanced dynamic equilibrium that causes humeral shaft fracture. These authors were the first to provide some experimental data to support their conclusions.

Because humeral shaft fractures usually occur during a maximal-effort throwing motion,[27] the forces acting on the upper extremity during the throw are the likely cause. However, it is not clear how the biomechanics of the throwing motion result in fracture, nor is it clear when during the motion the fractures might occur. At least three different portions of the throwing motion have been implicated as the most likely time for fracture occurrence.[6,8,20,21,27,38] Even though several theories of fracture mechanism have been suggested, there is little biomechanical evidence to support any of the claims. It is also unclear whether fatigue is a necessary prerequisite for fracture or whether a catastrophic fracture can occur without preexisting damage.[5,29,38]

The large shoulder and elbow forces generated during the pitching motion have been well documented.[3,9-14,16,28,34,36] However, the relationship between pitching biomechanics and torsional stress acting on the humerus has not been studied. The aims of the current study were to (1) compare the torsional stresses acting on the humerus during the pitch to the torsional strength of the humerus, (2) provide a biomechanical explanation of the mechanism of humeral shaft fractures during a pitch, and (3) identify the phase or phases of the pitching motion during which fractures are most likely to occur. In doing so, we hope to clarify the mechanism of humeral shaft fracture and provide empirical evidence to support the most likely existing theories.

MATERIALS AND METHODS

Two high-speed video cameras were used to videotape 25 professional pitchers at 120 frame/s while competing in preseason games. The data were collected during the 1998 Major League Baseball Cactus League Season in Arizona. The video cameras were placed behind home plate and behind either first or third base to film each pitcher from front and dominant side views. The locations of 21 body landmarks were manually digitized in each camera view from 50 milliseconds prior to the ball leaving the glove to 500 milliseconds after the ball was released.[37] The three-dimensional locations of each of the digitized landmarks were calculated using the direct linear transformation method.[1] Three-dimensional position data were filtered using a fourth-order Butterworth filter with a cutoff frequency of 13 Hz, as determined by residual analysis.[40] From the three-dimensional marker coordinates, the kinematics of the pitching elbow and shoulder were calculated throughout the pitching motion using a standard technique.[9,11,13,36] Definitions of the elbow and shoulder angles used in this study are shown in Figure 1.

Joint kinetics at the shoulder and elbow were computed using an inverse dynamics approach. The arm and ball were modeled as a series of four rigid links. The arm links were connected by ball-and-socket joints. Body segment mass and inertia parameters were taken from the literature[7,39] and scaled to the height and mass of the subject using the technique described by Hinrichs.[22] Joint resultant forces and torques were calculated for each joint in the inertial reference frame. Local segment-based reference frames were established at the shoulder and elbow joints based on digitized skeletal landmarks. The joint resultant forces and torques were projected onto each of these reference frames to provide anatomical relevance. Internal forces and torques acting along or about anterior-posterior, medial-lateral, and distal-proximal axes (Figure 2) at the shoulder and elbow were computed using a standard technique.[9,11]

To evaluate the likelihood of fracture and the relationship between throwing biomechanics and fracture risk, the humeral axial torque was calculated during the inverse dynamics procedure. Torque on the humerus varies slightly from its distal end (torque at the elbow) to its proximal end (torque at the shoulder). However, when expressed in the same humeral coordinate system, the difference between the torques at the shoulder and elbow is negligible due to the low mass and rotational inertia of the upper arm about its long axis. Therefore, humeral axial torque is essentially the internal rotation torque at the shoulder, which tends to twist the humerus about its shaft. By definition, when humeral torque is positive, the distal end of the humerus is being rotated externally relative to the proximal end (Figure 3). We hypothesized that the humeral axial torque, which will be referred to hereafter as "humeral torque," is related to incidence of humeral shaft fracture since it results in torsional stress in the shaft of the long bone.

Kinetic data were normalized in time to facilitate comparisons among players and so that mean values could be calculated. The pitching motion was considered to start 50 milliseconds before the ball first left the pitcher's glove (Figure 4). The normalization procedure forced stride foot contact (SFC) to occur 40% through the pitch cycle, maximum shoulder external rotation (MER) to occur at 80% of the pitch cycle, ball release (REL) to occur at 90% of the pitch cycle, and the pitching motion to end at the instant of maximum internal rotation (MIR) of the shoulder (100%). These times represent approximate mean normalized values from a sample group of subjects. The cocking phase occurs between SFC and MER, whereas the acceleration phase spans from MER to REL. The pitching motion was considered to end at MIR. Time normalization was chosen to eliminate slight differences in timing between pitchers while allowing analysis of kinematic and kinetic data occurring before SFC and after REL.

Data from the fastest pitch thrown for a strike by each of the 25 professional pitchers were analyzed. Only fastballs were studied. This group of pitchers was selected from a larger group of 40 pitchers due to their similar pitched ball speeds. Limiting the range of pitched ball speeds limits the effect of ball velocity on joint kinetics, and since maximal stress values were of interest, only the fastest pitch was analyzed. Mean values (±1 SD) of shoulder and elbow kinematic data and humeral torque were computed from the time-normalized data and compared with humeral strength data from in vitro studies in the literature as well as from theoretical calculation of humerus strength.

To gain understanding into the effects of pitching biomechanics on humeral torque, a stepwise multiple linear regression analysis was used to assess the effects of 66 kinematic variables on the magnitude of peak humeral torque generated during the pitching motion. First, Pearson correlation coefficients were computed for the relationship of each kinematic variable with humeral torque (normalized to percentage body weight times height). The variables that were significantly correlated ($P < .05$) with humeral torque were entered into the mul-

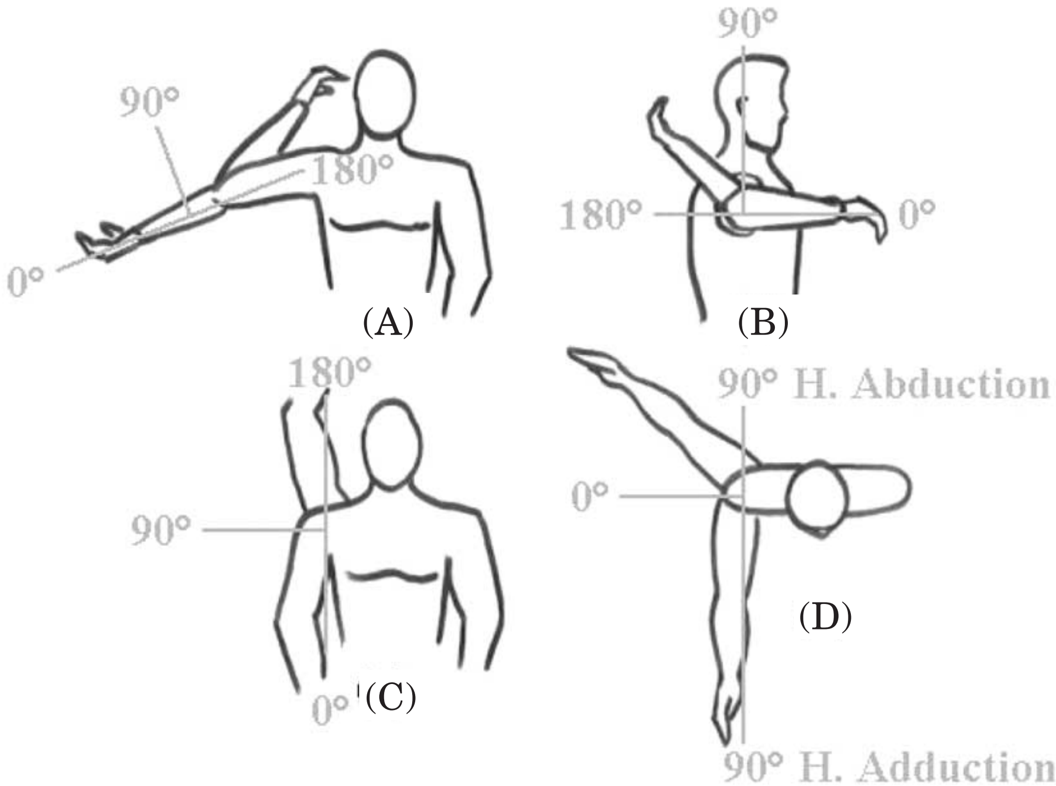

Figure 1. Definition of elbow and shoulder angles used in this study: A, elbow flexion; B, shoulder external rotation; C, shoulder abduction; and D, shoulder horizontal abduction and adduction.

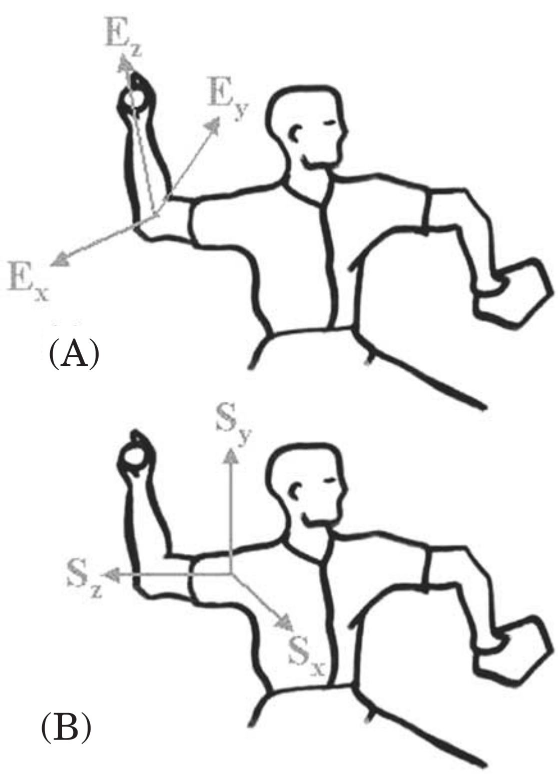

Figure 2. Definitions of the local (A) elbow and (B) shoulder coordinate systems.

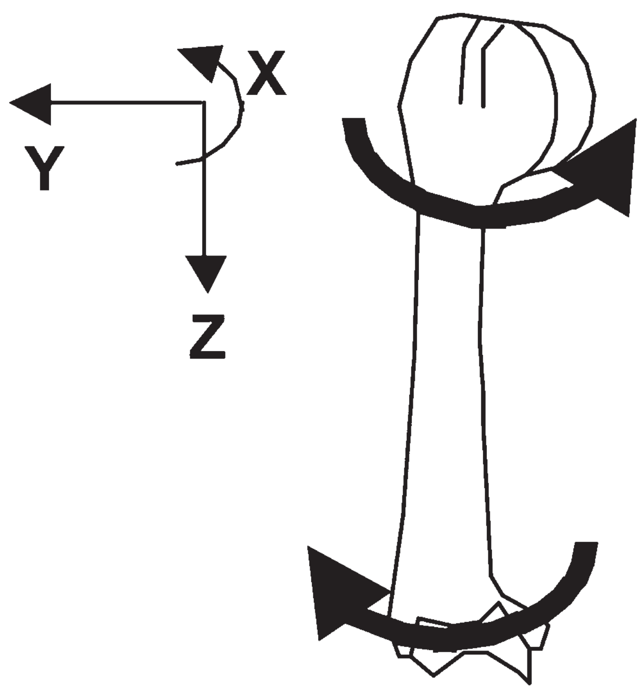

Figure 3. Sign convention for humeral torque. A positive value for humeral torque represents a situation where the distal humerus is being externally rotated about its long axis relative to the proximal end.

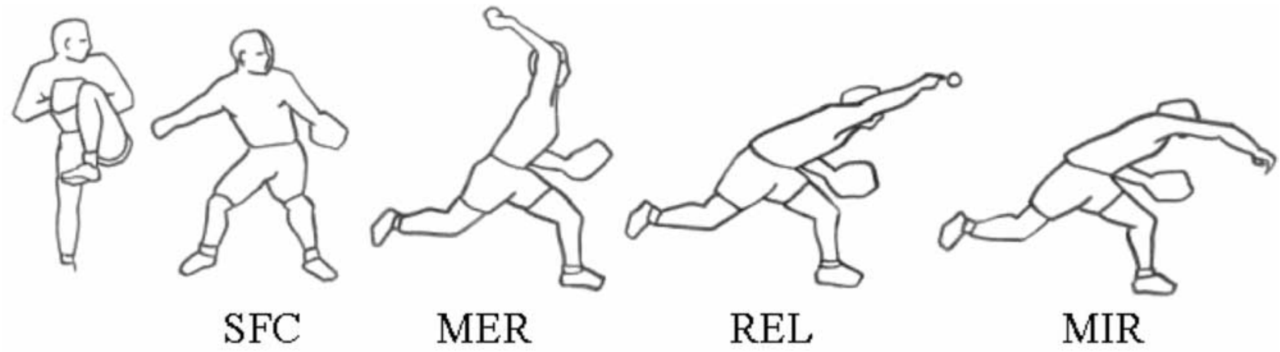

Figure 4. Important events during the throwing motion used to define the phases of the pitch. SFC, stride foot contact; MER maximum shoulder external rotation; REL, ball release; MIR, maximal shoulder internal rotation.

tiple regression analysis to determine the optimal combination of variables for predicting peak humeral torque.

RESULTS

The mean age, height, and mass of the subjects are provided in Table 1. The mean pitch speed was 38.8 ± 2.0 m/s (range, 36.2-44.3 m/s). The kinematic data are very similar to data presented previously for professional baseball pitchers.[9,11,28] The shoulder was abducted from 90° to 110° throughout most of the pitching motion (Figure 5A), and horizontal abduction increased from 30° of horizontal abduction during the cocking phase to approximately 10° of horizontal adduction at release (Figure 5B). Maximum external rotation angle of the shoulder averaged 182 ± 13° (Figure 5C). This represents a combination of glenohumeral and scapulothoracic motions, as well as trunk hyperextension.[14] The elbow was flexed between 100° and 80° throughout the cocking phase and then rapidly extended to 20 ± 7° at release. Minimum elbow flexion reached 16 ± 7° immediately after the ball was released (Figure 6).

The torque about the shaft of the humerus reached a value of 92 ± 16 Nm about 80% through the pitching motion (Figure 7). The direction of this torque tended to rotate the distal end of the humerus externally relative to the proximal end (external rotation torque). The humeral torque curve peaked immediately prior to MER, at the end of the cocking phase and beginning of the acceleration phase. After REL, the humeral axial torque was approximately zero throughout the rest of the pitching motion.

The correlation analysis identified six kinematic variables that were significantly linearly related to peak humeral torque: (1) elbow extension angular velocity at shoulder maximal internal rotation, (2) duration of the cocking phase (SFC to MER), (3) stride length, (4) shoulder abduction angle at SFC, (5) shoulder external rotation angle at SFC, and (6) elbow angle at SFC. After entering each of these variables into the multiple regression analysis, an equation explaining 40% of the variability in humeral torque was generated using a single variable:

TABLE 1
Mean, Standard Deviation (SD), and Range of Values Describing the Subject Population

	Age	Height (m)	Mass (kg)	Ball V (m/s)
Mean	26.8	1.88	88.7	38.8
SD	2.9	0.05	9.2	2.0
Range	19-30	1.78-2.01	70.3-107.0	36.2-44.3

$$\text{Humeral Torque } (\%\text{BW} \times \text{Ht}) = 8.1 - .033 \times \nu,$$

where ν is the elbow flexion angle at SFC (deg). The r value for this equation was 0.64.

DISCUSSION

The forces and torques acting on the humerus during the pitching motion are consistent with the spiral fracture pattern commonly seen in pitchers.[27] An internal rotation torque is created at the shoulder prior to MER while the humerus and forearm are still externally rotating.[13] The internal rotators, especially subscapularis, pectoralis major, and latissimus dorsi, are applying this internal rotation torque at the proximal end of the humerus.[18,19] At the distal end of the humerus, the forearm and hand are creating an external rotation torque on the humerus, evidenced by the large varus torque required at the elbow at the same instant.[36] The result is a torque acting about the long axis of the humerus. This torque is for all practical purposes the same as the shoulder internal rotation torques presented by other authors.[11,13,15] The peak value of 92 ± 16 Nm reported in the current study agrees well with the 90 ± 20 Nm found by Feltner and Dapena[11] for eight collegiate pitchers and is slightly larger than the values reported by Fleisig et al: 68 ± 15 Nm for 60 professional pitchers[15] and 67 ± 11 Nm for a group of 26 elite adult pitchers.[13]

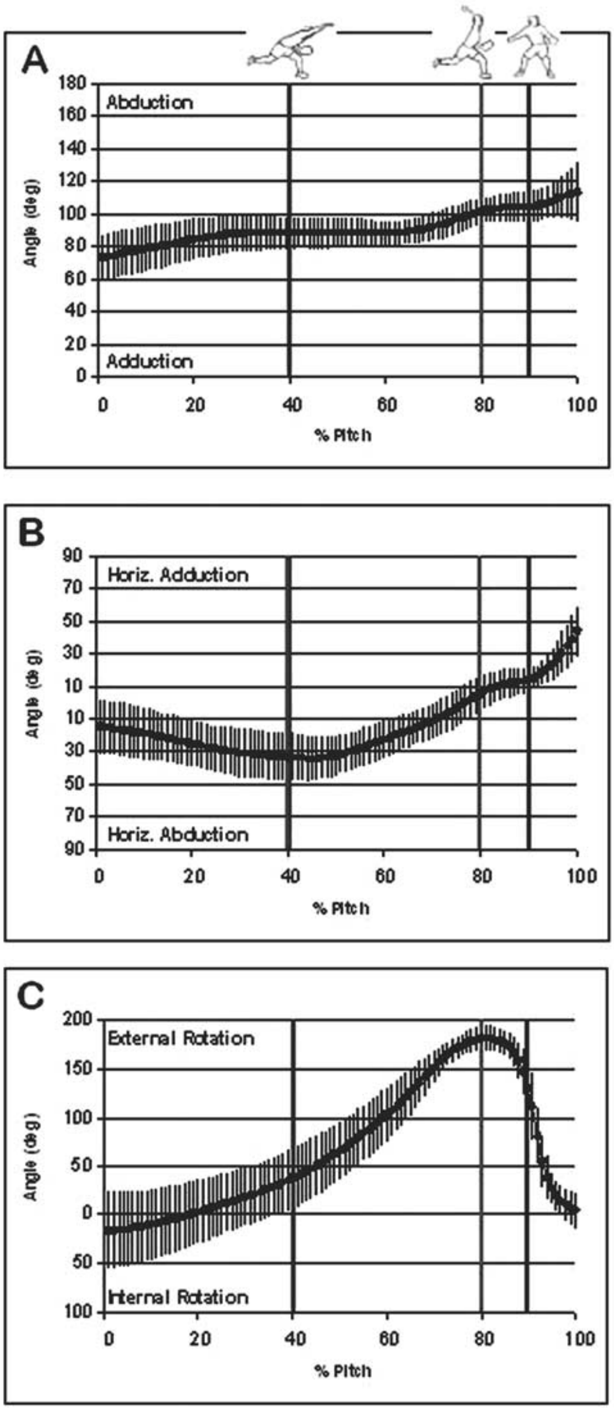

Figure 5. Mean (±SD) shoulder kinematics. A, abduction and adduction; B, horizontal abduction and adduction; and C, external and internal rotation. Vertical lines represent stride foot contact, maximum shoulder external rotation, and ball release.

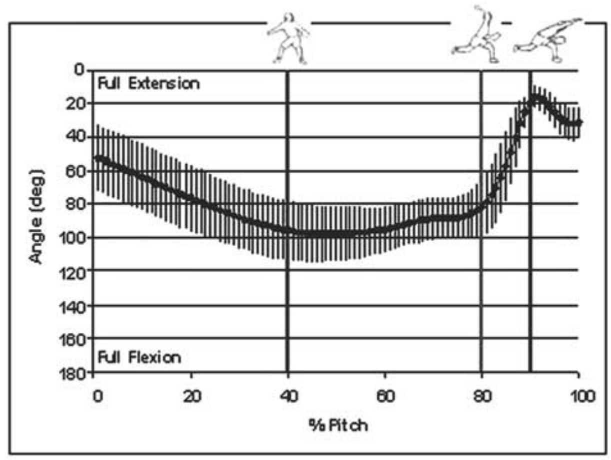

Figure 6. Mean (±SD) elbow kinematics. Vertical lines represent stride foot contact, maximum shoulder external rotation, and ball release.

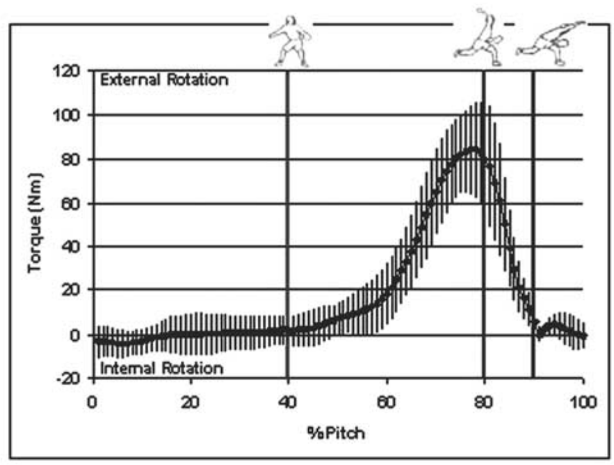

Figure 7. Mean (±SD) humeral internal and external rotation torque. Vertical lines represent stride foot contact, maximum shoulder external rotation, and ball release.

The direction of the humeral torque is such that the distal end of humerus is externally rotated relative to the proximal end. This direction is consistent with the appearance of exclusively external rotation spiral fractures noted by Ogawa and Yoshida[27] in their series of 90 patients and agrees with the fracture mechanism proposed by some authors.[6,27]

Several authors have suggested which instants during the pitch that humeral shaft fractures may be likely to occur: at the end of the cocking phase when external rotation is quickly reversed and a large internal rotation acceleration occurs,[6,8,20] during the acceleration phase just prior to release,[38] or after release when the rapid internal rotation of the humerus is decelerated.[21] Our data support the likelihood of fracture at the end of the cocking phase, near the time of MER, when the external rotation of the humerus is being decelerated. There are no corresponding peaks in humeral torque just before or just after release, suggesting that fractures are not likely at these instants. The lack of deceleration torque after release is due to the position of the arm at this point in the pitching motion.

During the deceleration phase, the elbow is nearly fully extended and the arm is horizontally adducted, leaving the arm oriented relatively anteriorly and extended. In this position, deceleration of the upper arm motion is not accomplished by an external rotation torque about the upper arm but by a compression force at the shoulder to counteract the large distraction forces caused as the trunk pulls the arm posteriorly.[37] Furthermore, the rotational moment of inertia of the arm is lowest when the elbow is extended, requiring less shoulder torque to cause a deceleration of internal rotation motion in this position. Therefore, our data do not support the theory of Hennigan et al[21] that humeral shaft fracture is likely during the deceleration phase of the pitch.

The humeral torque generated near the time of MER in the pitching motion is likely related to the pitcher's risk of suffering a humeral shaft fracture. Torsional loads result in high shear forces being generated in a plane 45° from the axis about which the torque is produced. When the shear stress exceeds the shear strength of bone, the result is a spiral fracture. Humeral shaft fractures are generally spiral in nature and are therefore consistent with shear failure of the bone due to the application of a large torsional stress. Given these facts and the humeral torque data presented, humeral shaft fractures are most likely to occur just prior to MER, when the humeral torque peaks.

Torsional strength of the humerus has been studied by several authors.[25,32,33] Schopfer et al[32] tested cadaver humeri in vitro and found a mean peak torque to failure of 53 ± 17 Nm, approximately one-half the torque applied to the humerus during a pitch. Their data agree reasonably well with that of Lin et al[25], who found torque at failure to average 45.6 ± 15.1 Nm in their cadaver specimens that ranged in age from 46 to 98 years. However, the cadaver humeri tested in most in vitro studies likely underestimate the strength of a professional pitcher's humerus. Bone is known to remodel in response to the stresses applied during sporting events,[23,24] so the humeri of professional baseball pitchers are likely larger in diameter and contain thicker and denser cortical bone than the bones tested in cadaver studies.

When appropriate dimensions for the humerus of an athletic male[23] are used to calculate shear stress in the shaft of the humerus with an applied torque of 92 Nm (the peak torque in our data), a maximum shear stress of 32.8 MPa results. Strength of cortical bone in shear is approximately 68 Mpa,[31] resulting in a safety factor for pitching of 2.07. Looked at the other way, if all the humeral torque is transmitted to the humeral shaft, a professional baseball pitcher uses approximately 48% of his bone's shear strength capacity during each pitch. These data suggest that the humerus is not normally at risk for fracture when a pitcher throws a fastball and hints that repetitive stress plays a role in the genesis of these fractures. Stresses much lower than failure stress can lead to bone fracture in a fatigue-loading situation. Our data do not rule out the possibility raised by Branch et al[5] that fracture of the humerus during a pitch could be caused by a single pitch, however, since the pitchers in this study had peak humeral torques as high as 128 Nm, or 40% above the group mean. This torque value, coupled with only a 10% decrease in the diameter of the humeral shaft (about a 2.5-mm difference), results in a shear stress that exceeds the cortical bone shear strength.

Simply comparing dynamic pitching biomechanics data to bone strength data from in vitro studies is actually oversimplifying the problem. Bone strength is sensitive to loading rate. Differences between loading rates in the laboratory and those occurring during pitching suggest that the data are not directly comparable. In addition, simple torsion is generally simulated in laboratory tests, but the situation is much more complicated in vivo. There are additional components of force and torque acting on the humerus at the same time the humeral torque peaks. All of the force and moment components contribute to the state of stress in the bone, which changes as a function of time.

The complex loads applied to the humerus during the pitching motion may ameliorate or exacerbate the shear stress caused by axial torque. Gainor et al[17] suggested that large compressive axial loads are generated on the humerus by the elbow flexors and extensors during the pitch, thereby protecting the humerus from shear stress induced by torque. In contrast to Gainor's assertion, we calculated a net distraction force at the shoulder and elbow of approximately 1000 N. Distraction decreases ultimate strength when combined with a torsional stress.[35] However, the average distraction in this study increases the shear stress on the humerus by less than 3%, so distraction and compression are not dominant factors in determining bony failure.

In reality, the state of tension or compression of the humeral shaft likely varies along its length depending on where muscle insertions are located and depending on muscle activation levels that change dynamically throughout the pitch. In addition, the existence of microfractures or other discontinuities in the bone leads to stress concentrations that locally increase the stress dramatically. These complexities can be addressed only by sophisticated computer modeling of the upper extremity.

The multiple regression analysis was performed to identify pertinent kinematic parameters related to increased humeral torque that can be evaluated by pitching coaches. Surprisingly, a single factor emerged as the best predictor of peak humeral torque. Pitchers whose elbows were more extended at SFC tended to have lower peak humeral torque values. This could be related to the rotational inertia of the forearm and hand, which decreases as the arm extends past 90°. Further analysis will be needed to determine if elbow flexion angle at SFC is causally related to humeral torque. However, it appears that keeping the elbow extended at SFC is related to decreased values of humeral torque.

In summary, our findings show that during the late cocking phase of the pitching motion, there is a large external rotation torque acting about the shaft of the humerus. This torque is consistent with the mechanism of humeral shaft fracture during a pitch proposed by Ogawa and Yoshida.[27] The humeral external rotation torque is larger than the published torsional strength of the humerus based on cadaver studies and approximately 48% of the torsional strength of an athlete's humerus. The data suggest that fractures occur at or near the time of MER when humeral torque peaks since humeral torque is a dominant factor causing stress in the humeral shaft. Further research is needed before we fully understand the relationship between humeral torque and the likelihood of humeral shaft fracture because the skeletal geometry and complex loading patterns acting on the arms of professional baseball pitchers are not well represented by in vitro cadaveric studies.

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