대한정형외과 스포츠의학회지 제 2 권 제 1 호 2003
J. of Korean Orthop. Soc. Sports Med. 2003; 1: 62-70

청소년기 야구 투수의 상완골 회전력: 소아 야구 견 및 상완골 후염의 발달에 미치는 영향

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목적: 청소년기야구투수의견관절의운동학및동력학을통해소아야구견및상완골후염의발달에대한역학적측면을분석하고자하였다.

대상및방법: 모의 게임을통해 14명의청소년기야구투수에서관절운동학과상완골에작용하는총힘및회전력을계산하였다.

결과: 상완골에 작용하는 주된힘은평균 378±81 N의 장력으로공이손을 떠난 직후에정점을이루었다. 상완골에 작용하는 주된 회전력은 상완골의 장축에 대한 외 회전력으로 투구 동작의 약 73% 시기에 정점을 나타냈으며 정점의 평균 회전력은 35.3±6.7 Nm이었다. 이러한회전력은성인의상완골골절을발생시킬수있는회전력의약 66%이다.

결론: 상완골회전력은투구하는손의상완골후염의증가를발달시키는방향이었다. 따라서후기거상기동안의큰회전력으로 부터 발생되는 전단 응력은상대적으로약한근위 상완 성장판에 변형을초래할 수있다. 또한투구중상완골에 발생되어진 외회전력은투구동작중성장판에작용하는회전응력이소아 야구 견을일으키는 기전이될수 있다는가설을 뒷받침해준다.

색인단어: 상완골에작용하는회전력, 소아야구견, 상완골후염

INTRODUCTION

The effects of repetitive throwing on developing athletes are not well understood, in part because there is little data describing the biomechanics of youth pitchers, and in part due to the unique aspects of the developing skeleton. Joint laxity, underdeveloped musculature, and open epiphyseal plates are three unique aspects of the developing skeleton[15]. The epiphyseal plate, where growth occurs, is weaker than surrounding ligaments, so adolescents are likely to sustain epiphyseal plate injuries in instances when skeletally mature athletes would sustain tendon or ligamentous injuries.

The plasticity of the developing skeleton has been blamed for the development of little league shoulder. This injury, which was first described in 1953 and has been presented in case study form by several different authors, often presents as a pain during throwing that is localized to the proximal humerus and accompanied by radiographic evidence of widening of the proximal humeral epiphysis[3,15,24]. Little league shoulder has also been called osteochondrosis of the proximal humeral epiphysis, proximal humeral epiphyseolysis, or a rotation stress fracture of the proximal humeral epiphyseal plate, among others[3]. The exact cause of little league shoulder is unknown, but several authors have hypothesized that it is due to the significant rotational stress applied to the proximal humeral physis during the act of throwing[3,24].

While potentially resulting in overuse injuries, the plasticity of the immature skeleton also provides the capability to adapt to applied loads in a beneficial way. Skeletal adaptations to repetitive sport activities have been noted in youth and adult athletes. Throwing athletes demonstrate more retrotorsion of the humerus, or a more posteriorly directed humeral head axis relative to the elbow axis, in their dominant arms[21]. Increased retrotorsion in the dominant arm of throwers might be a beneficial

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* 본 논문의 요지는 2002년도 제 4차 아시아 견관절 학술대회 및 2002년도 대한정형외과스포츠의학회 학술대회에서발표되었음.

adaptation in pitchers, allowing increased external rotation before the constraints of the anterior capsule and ligaments are activated[21]. The increased external rotation angle extends the arm-cocking phase of the throw, providing a greater angle over which to accelerate the arm and ball.

It is not clear when during the lifespan the retrotorsion occurs in throwing athletes. However, the cartilage growth plates may provide a convenient location for such changes to occur. The possibility that increased humeral retrotorsion occurs at the epiphysis is supported by three observations. First, humeral torsion angle changes throughout the growth period, but stops once skeletal maturity is reached and the epiphyses fuse[21]. Second, the cartilage of the epiphyses is known to best resist tension and have little resistance to torsion[12]. Finally, growing articular cartilage is weaker than adult cartilage and is weakest during growth spurts such as human pubescence[2]. Therefore, if humeral retrotorsion occurs at the epiphyses, the bony changes noted in adult pitchers would have to occur prior to the age of 20 when the humeral epiphyses close[24].

Because retrotorsion is a twisting of the humerus about its long axis, changes in retrotorsion angle due to the application of external forces would be due to torques acting about the long axis of the humerus. If the biomechanics of the throwing motion were to result in torsional stresses in humeral shaft, they could lead to the development of humeral retrotorsion or at least hinder the progression of humeral anteversion that occurs during normal development[6,18].

Because rotation forces acting on the humerus during the pitching motion have been implicated in the development of both little league shoulder and humeral retrotorsion, we designed the current study to quantify the torsional stresses to which the humerus is subjected during the pitching motion. The aims of the current study were to quantify the kinematics, joint kinetics, and torsional stresses acting on the humerus in youth pitchers, to provide a biomechanical explanation of the development of humeral retrotorsion, and to provide a biomechanical basis for the existing theory describing the cause of little league shoulder. Better understanding of the genesis of humeral retrotorsion and little league shoulder will help guide training and treatment regimens for youth baseball pitchers.

MATERIALS AND METHODS

Two high speed video cameras were used to videotape fourteen 13 year old youth baseball pitchers at 120 frames/s. All subjects were male right hand dominant youth baseball pitchers. The subjects pitched from an indoor pitching mound to a catcher situated at a regulation distance (14 m) from the mound. The video cameras were oriented to obtain front and dominant side views. From the videotapes, the locations of 21 body landmarks were manually digitized in each camera view from 50 ms prior to the ball leaving the glove to 500 ms after ball release[26]. The three-dimensional locations of each of the digitized landmarks were calculated using the direct linear transformation method[1]. Three-dimensional position data was filtered using a fourth order butterworth filter with a cutoff frequency of 13 Hz, as determined by residual analysis[29]. From the three-dimensional marker coordinates, the kinematics of the pitching elbow and shoulder were calculated throughout the pitching motion using a standard technique[5,8,9,25].

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[4,27], and scaled to the height

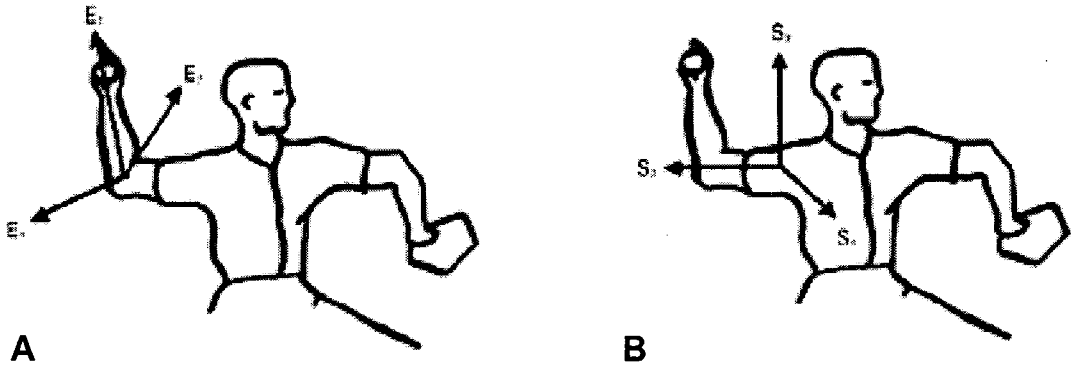

Fig. 1. Definition of the local (A) elbow and (B) shoulder coordinate systems

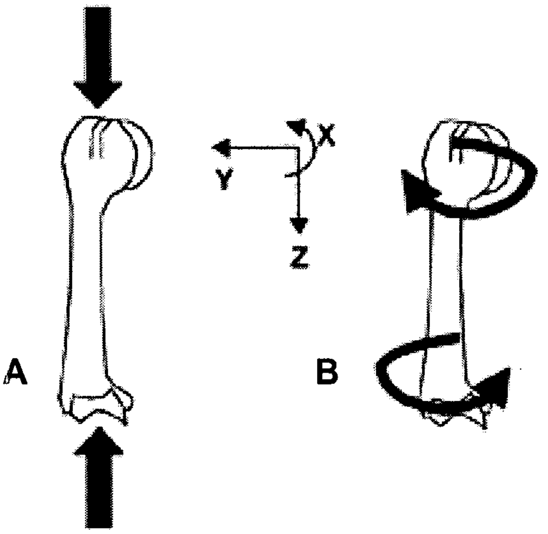

Fig. 2. Sign conventions for (A) humeral compression, (B) Fz and humeral torque. Arrows represent the positive direction. Depending on its direction, Fz represents either a state of bone tension or compression. Humeral torque represents a situation where the distal humerus is being twisted internally or externally relative to the proximal end about its long axis.

and mass of the subject using the technique described by Hinrichs[14]. 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 (A-P), medial-lateral (M-L), and distal-proximal (D-P) axes (Fig. 1) at the shoulder and elbow were computed using a standard technique[5,8].

To evaluate the likelihood that pitching biomechanics is related to development of humeral retrotorsion, the net humeral forces and torques were calculated. These values were calculated as the difference between force and torque values at the proximal and distal ends of the bone, when the resultant at each end of the bone was expressed in the same local humeral coordinate system. These net humeral forces and torques were assumed to indicate the overall state of stress applied to the humerus at any given time. The net humeral axial torque about the D-P axis of the humerus tends to twist the humerus about its shaft. When this value is positive, the proximal end of the humerus is being rotated externally relative to the distal end (Fig. 2). A net positive humeral axial force causes compression along the long axis of the humerus. We hypothesized that the net humeral axial torque, which will be referred to hereafter as humeral torque, is related to the development of humeral retrotorsion and little league shoulder since it results in torsional stress about the shaft of the humerus during the pitching motion.

Kinetic data was normalized in time to facilitate comparisons among players and so mean values could be calculated. 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. These times represent approximate mean normalized values from a sample group of subjects. The cocking phase occurs between SFC and MER, while the acceleration phase spans from MER to REL. 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 pitchers were analyzed. Only fastballs were studied. Mean values (±1 SD) of shoulder and elbow kinematic data and net humeral force and torque components were computed from the time-normalized data and compared with data in the literature. Mean values provided are the mean of peak values from each individual subject, and therefore may be larger than the peaks demonstrated on the graphs which are the mean for all subjects at each percent of the pitching motion.

RESULTS

The mean age, height, and mass of the subjects is provided in Table 1. The mean pitch speed was 21.6±1.8 m/s (range 17.8 to 23.7 m/s). The shoulder was abducted from 84° to 94° throughout most of the pitching motion and approximately 94° at release (Fig. 3A). Horizontal abduction changed from 18° to 4° during the cocking phase and reached approximately 0° at release (Fig. 3B). The maximum external rotation angle of the shoulder averaged. 166±9°, and at release the shoulder was externally rotated 143±22° (Fig. 4A). The peak internal rotation angular velocity of the shoulder averaged 12,459±5884°/s, occurring just after to ball release in 12 of the 14 subjects (Fig. 4B). The elbow was flexed between 54° and 88° throughout the cocking phase, and then rapidly extended to 25±14° at

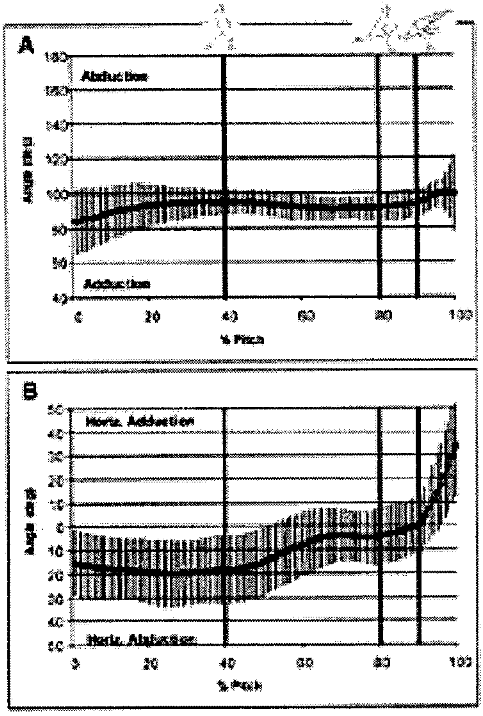

Fig. 3. Mean (± SD) shoulder kinematics: (A) abduction and adduction, and (B) horizontal abduction and horizontal adduction. Vertical lines represent SFC, MER and REL.

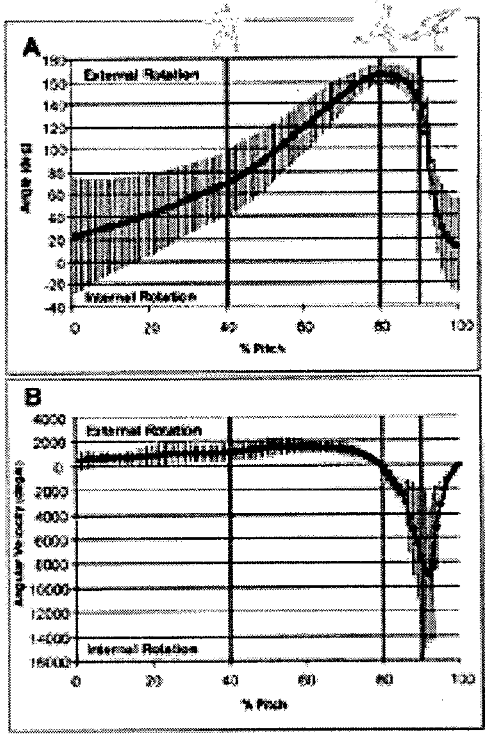

Fig. 4. Mean (± SD) shoulder kinematics: (A) external and internal rotation angle, and (B) external and internal rotation angular velocity.

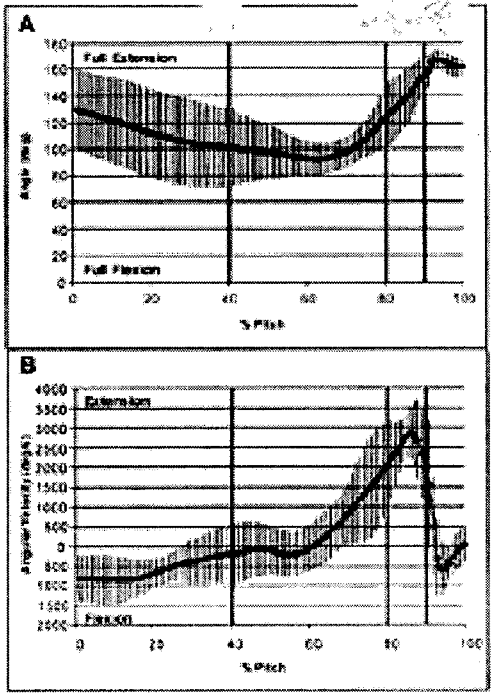

Fig. 5. Mean (± SD) elbow kinematics: (A) flexion angle, and (B) flexion and extension angular velocity. Vertical lines represent SFC, MER and REL.

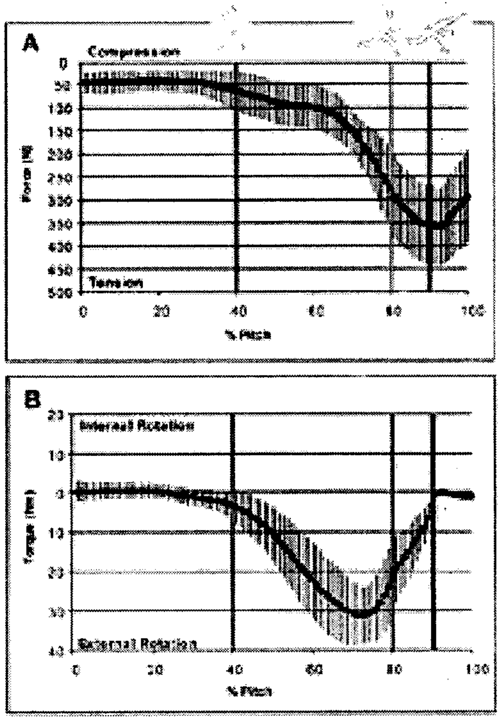

Fig. 6. Mean (± SD) humeral kinetics: (A) tension and compression, (B) humeral internal or external rotation torque. Vertical lines represent SFC, MER and REL.

Table 1. Mean, standard deviation (S.D.), and range of values describing the subject population.

	Age	Height (m)	Mass (kg)	Ball V (m/s)
Mean	13	1.54	43.8	21.6
S.D.	-	0.08	8.6	1.8
Range	-	1.42-1.69	33.7-66.4	17.9-23.7

release. Minimum elbow flexion reached 8 ± 4° shortly after the ball was released (Fig. 5A). The peak elbow extension angular velocity was 3,346 ± 643°/s with the range of 1,992 to 4,322°/s. The peak occurred between MER and REL, and the mean extension velocity at ball release was 1958 ± 1360°/s (Fig. 5B).

The largest net force acting on the humerus was an axial force causing tension (Fig. 6A). This force was largest in magnitude, 378 ± 81 N, just after to ball release when the shoulder internal rotation velocity was near its maximum (Fig. 4B). Additional force components also tended to push the humerus in the anterior and lateral directions. These components peaked at 148 ± 26 N and 137 ± 29 N approximately 63% and 72% through the pitching motion, respectively.

Moderate net bending torques were also produced about the A-P and M-L axes of the humerus. These torques tended to cause tension in the lateral and anterior portions of the humeral shaft, and peaked at approximately 21 ± 5.9 Nm and 29 ± 6.8 Nm about 61% and 76% through the pitching motion, respectively. The largest net torque about the humerus was humeral torque about the long axis of the humerus which reached a maximum of 35.3 ± 6.6 Nm about 72% through the pitching motion (Fig. 6B). This torque was directed such that it tended to rotate the distal end of the humerus externally relative to the proximal end. Humeral torque peaked prior to MER, during the late cocking phase. After ball release, the humeral torque value was approximately zero throughout the rest of deceleration and follow-through portions of the pitching motion.

DISCUSSION

Youth baseball pitchers frequently suffer from overuse injuries, most likely due to either poor throwing technique or to the inherent susceptibility of the developing skeleton. However, biomechanical studies of youth pitchers are rare[10)], so there is little data from which to draw conclusions regarding injury mechanisms in youth pitchers. This study was designed to present some additional shoulder kinematic and kinetic data for youth baseball pitchers. More importantly, we will relate that data to the mechanisms of development of little league shoulder and humeral retrotorsion in light of some of the unique aspects of the developing skeleton.

Our data related to kinematic data in the literature

Most of the biomechanical data that has been collected has focused on the throwing motions of adult pitchers[8-11,25)]. The one major exception is the article by Fleisig et al.[10)] that compared the biomechanics of youth, high school, college, and professional baseball pitchers. Surprisingly, none of the temporal variables were significantly different between the groups, and very few of the kinematic variables were significantly different. Ball speed was the only kinematic variable that was significantly different between all four groups. However, the eight joint forces and torques studied were all significantly different among groups[10)].

There are two important findings from our kinematic data. First, the peak shoulder internal rotation angular velocity is larger than that described for adult baseball pitchers[5,10,20)]. The peak angular velocity of shoulder internal rotation averaged 12,458°/s in this group of subjects, with the peak angular velocity occurring just after ball release (Fig. 4B). Pappas et al.[20)] reported the peak internal rotation velocity in adult baseball pitchers was 7,450°/s with the peak angular velocity occurring 5ms before ball release. Since there was a rapid angular excursion from 122° to 48° of shoulder rotation prior to ball release, a large peak acceleration was found[20)]. Other authors have reported similar findings[5,10,11,22)].

The second kinematic finding was that the large angular velocities in the youth pitchers are coupled with smaller angular excursions of both the shoulder and elbow joints compared with professional pitchers. Fleisig et al.[9)] reported that at the end of cocking phase the arm was externally rotated 165°, abducted 94° and horizontal adducted 11°, and the elbow was flexed 95° in adult professional pitchers. At the deceleration phase, the arm was externally rotated 64°, abducted 93° and horizontal adducted 6°, while the elbow was flexed 25°. Our previous studies in adult professional baseball pitchers agree with the data above[22]. In contrast, the youth pitchers in the current study had their arms externally rotated 154°, abducted 85° and horizontal adducted 4°, while the elbow was flexed 66° at the end of cocking phase. At the deceleration phase, the arm was externally rotated 129°, abducted 88° and horizontal adducted 0°, while the elbow was flexed 33° (Fig. 3-5). Therefore, the ranges of motion of the shoulder and elbow joints in our subjects during pitching are less than those of the adult professional pitchers reported elsewhere[10,20,22].

Our data related to little league shoulder

The rotational stress acting on the proximal humerus during the pitching motion has been blamed for the development of little league shoulder in youth or adolescent baseball players[3]. However, this mechanism has never been definitively proven. The injury is thought to be the result of repeated trauma to the growth plate, possibly resulting in a fatigue fracture of the proximal humeral physis or in a local inflammatory reaction to repeated growth plate trauma[24].

The suggestion that repetitive rotational stresses are likely the cause of little league shoulder is supported by the structural and material properties of epiphyseal cartilage. Epiphyseal growth cartilage is more susceptible to injury due to repetitive microtrauma than is adult cartilage[2]. The epiphyseal plate is composed of four cell layers. The zone of hypertrophy is the area where cartilage cells are aligned in vertical columns with little structural matrix[3,12]. Fractures are most common in this area because it is the weakest portion of the epiphyseal plate[12]. The growth plate is structurally most resistant to tension and least resistant to torsion. It is especially weak during periods of rapid long bone growth, such as puberty[2]. This fact is supported by the observation that acute proximal humerus fractures are more likely to involve the epiphyseal plate in 13 to 16 year olds than in younger athletes[3].

The mean peak humeral torque for this group of subjects was 35.3±6.7 Nm. The amount of torque necessary to cause a fatigue fracture of the humeral epiphyses in skeletally immature throwers is unclear. However, torsional tests on human cadaver humeri suggest that the strength of the humerus is between 45 and 53 Nm[19,23]. Therefore the torque being generated during the pitching motion is more than half that required to break the elderly adult femur. Since cartilage is known to be weaker than bone, and fatigue fractures are caused by repetitive loading below the fracture threshold of a material, the torsional stresses acting on the humerus during the pitching motion are likely large enough to cause the type of damage to the epiphyseal cartilage seen in little league shoulder.

Our data related to development of humeral retrotorsion

Increased retrotorsion of the humeral head in the throwing arm of adult throwers has been reported by multiple authors[16,21]. However, it is not really known how this increase in humeral retrotorsion develops. We will provide a biomechanical argument to explain the mechanism of this bony change in throwing shoulders, using our data and consideration of the existing literature[22,26].

The forces and torques acting on the humerus during the pitching motion are consistent with the development of humeral retrotorsion. Near the end of the cocking phase, just prior to MER, an internal rotation torque is created at the shoulder while the humerus and forearm are still externally rotating[9]. The internal rotators, especially subscapularis, pectoralis major, and latissimus dorsi, are applying this internal rotation torque at the proximal end of the humerus[13]. At the distal end of the humerus, the forearm and hand are creating an external rotation torque on the humerus, evidenced by the large valgus torque generated at the elbow at the same instant[25]. The result of the opposing torques at the two ends of the humerus (internal rotation at the proximal humerus and external rotation at the distal end) near the end of the cocking phase is a large net torque acting about the long axis of the humerus. The direction of this net humeral torque is such that the distal end of humerus is externally rotated relative to the proximal end. The direction of the torque acting on the humerus is consistent with the direction of increased humeral retrotorsion noted in the dominant arms of throwers compared to their nondominant arms[21].

The opposing torques at two ends of the humerus generates a shear stress in the humeral shaft. The fact that the cartilage of the epiphyseal plate is weak in resistance torsional stresses suggests that the epiphyseal plate is the weakest portion of the humerus and a location where deformation may occur. We propose that repeated external rotation torques applied to the humerus during the late cocking phase of the pitching motion lead to the increase in humeral retrotorsion of the throwing arm over time. The torsional stress required to deform the cartilage of the humeral epiphyses in skeletally immature throwers is unclear. Therefore, we cannot prove that the humeral torque generated during the throw is sufficient to cause the development of humeral retrotorsion. However, our data clearly show that a torque is generated about the long axis of the humerus during the throwing motion and that torque acts in the direction that would cause increasing retrotorsion of the humerus. Additional research is necessary to investigate the relationship between humeral torque and the development of humeral retrotorsion.

Humeral torsion is actually a result of two separate factors: an evolutionary or primary torsion and an ontogenetic or secondary torsion caused by muscular forces acting on the humerus[7]. Krahl[18] suggests that the torsion angle increases approximately 10° during childhood and adolescence, finally stabilizing at approximately age 20. He felt that contraction of the internal and external rotators of the humerus caused a turning of the humeral shaft with respect to the proximal humeral epiphysis, directing the growth of the bone in a spiral fashion[18]. Edelson[6] measured humeral retroversion from 90 skeletons aged 4 months to 19 years at the time of death. He found that in utero and at birth the humeral head is in a markedly retroverted position. Humeral retroversion averaged approximately 65° in children from four months to four years of age and gradually decreased to average adult values of 27 to 33°. Most of the derotation to adult values occurred by the age of 8 years, with slow changes occurring from age eight until the final adult values were reached.

Although the data presented by both Krahl[18] and Edelson[6] appears contradictory since one describes and increase in humeral angle during skeletal development and the other describes a decrease, the discrepancy can be explained by the angle measurements each used to quantify humeral retroversion. Krahl et al.[17] actually measured the complement of the angle measured by Edelson[6]. Therefore, the increase in humeral angle prior to skeletal maturity noted by krahl et al.[17] actually corresponds to the decrease in humeral retroversion described by Edelson[6]. The conclusion that can be drawn from these papers is that the humerus normally goes through a gradual derotation process during the skeletal growth period. Therefore, any forces applied to the skeleton to result in an increase in humeral retrotorsion in adulthood need only delay the progression of the natural derotation. Unfortunately, the magnitude of the force needed to delay this derotation is unknown.

The epiphyseal plate is a cartilaginous disk through which skeletal growth occurs[12]. Of the four layers of cells within the epiphysis, the zone of hypertrophy is the weakest structurally and is the location of many epiphyseal injuries[12,18,28]. For this reason, the progression of humeral torsion has been localized to the proximal epiphyseal cartilage of the humerus. The close agreement between the age at which the proximal humeral epiphysis closes, at about 20 years, and the cessation of increase in the humeral torsion angle, also at about 20 years, is likely not a coincidence[18].

SUMMARY

Our findings show that during the late cocking phase of the pitching motion there is a considerable net external rotation torque acting about the shaft of the humerus. This torque may be responsible for the development of little league shoulder since it is relatively large compared the torsional strength of the humerus and it occurs chronically, every time a pitch is thrown. This torque causes rotational stresses in the proximal humerus late in the cocking phase of the throw. The humeral torque generated during the pitch is also consistent with the direction of increased retrotorsion of the humerus. Since the humerus normally derotates during growth, the torques generated during the throwing motion need only delay the derotation process to result in increased retrotorsion after skeletal maturity. Our data suggest that pitching mechanics in youth pitchers are related to overuse injury mechanisms as a result of repeated and prolonged throwing and also provide a plausible biomechanical mechanism of increased retrotorsion of the humeral head in throwing arm of the adult throwers.

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= ABSTRACT =

Humeral Torque in Youth Baseball Pitchers: Implications for the Development of Little League Shoulder and Humeral Retroversion

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Purpose: We examined the kinematics and kinetics of the shoulder in youth baseball pitchers in light of the mechanisms of development of little league shoulder and humeral retrotorsion.

Materials and Methods: The joint kinematics and the net force and torque acting on the humerus were calculated in fourteen youth pitchers throwing in a simulated game.

Results: The major force component acting on the humerus was a tensile force of 378±81 N that peaked just after ball release. The predominant torque on the humerus was an external rotation torque about the long axis of the humerus. This torque reached a peak value of 35.3±6.7 Nm about 73% through the pitching motion. This torque is approximately 66% of the torque required to fracture of the adult humerus.

Conclusions: The direction of the humeral torque was consistent with the development of increased humeral retrotorsion in the throwing arm. Shear stress arising from the high torque during the late cocking phase likely leads to deformation the relatively weak proximal humeral epiphysis. The external rotation torque applied to the humerus during the pitch also agrees with the proposed mechanism for development little league shoulder, which has been hypothesized to be due to rotational stresses acting on the epiphysis during the throwing motion.

Key Words: Torque acting on the humerus, Little league shoulder, Humeral retrotorsion

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