

## The Effect of Pitching Biomechanics on the Upper Extremity in Youth and Adolescent Baseball Pitchers

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### Abstract

**Background** Increased pitch counts have been linked to increased complaints of shoulder and elbow pain in youth baseball pitchers. Improper pitching mechanics have not been shown to adversely affect the upper extremity in youth pitchers.

**Hypothesis** The correct performance of 5 biomechanical pitching parameters correlates with lower humeral internal rotation torque and elbow valgus load, as well as higher pitching efficiency, in youth and adolescent pitchers.

**Study Design** Descriptive laboratory study.

**Methods** In sum, 169 baseball pitchers (aged 9–18) were analyzed using a quantitative motion analysis system and a high-speed video while throwing fastballs. The correct performance of 5 common pitching parameters was compared with each pitcher's age, humeral internal rotation torque, elbow valgus load, and calculated pitching efficiency.

**Results** Motion analysis correlated with video analysis for all 5 parameters ( $P < .05$ ). Youth pitchers (aged 9–13) performing 3 or more parameters correctly showed lower humeral internal rotation torque, lower elbow valgus load, and higher pitching efficiency ( $P < .05$ ).

**Conclusions** Youth pitchers with better pitching mechanics generate lower humeral internal rotation torque, lower elbow valgus load, and more efficiency than do those with improper mechanics. Proper pitching mechanics may help prevent shoulder and elbow injuries in youth pitchers.

**Clinical Relevance** The parameters described in this study may be used to improve the pitching mechanics of youth pitchers and possibly reduce shoulder and elbow pain in youth baseball pitchers.

### Keywords:

baseball youth baseball biomechanics pitching

Shoulder and elbow pain in youth baseball pitchers is a well-recognized phenomenon.<sup>1,14,22,24,28,37</sup> Numerous authors have attempted to define the risk factors for shoulder and elbow injury in youth baseball pitchers.<sup>21,24,25,34</sup> An increased number of pitches thrown and the use of breaking pitches have both been implicated in youth baseball injuries.<sup>7,24,25</sup> Improper pitching mechanics has been suggested as a possible risk factor for injury, but this has not been shown in previous biomechanical or clinical studies.<sup>11,24,32</sup>

Pitching mechanics are generally taught to youth pitchers as based on the accepted teaching of pitching coaches<sup>19,31</sup> or through comparative video or motion analysis, using elite-level pitchers as models.<sup>6,16</sup> With few exceptions,<sup>11,24,32,33</sup> most previous biomechanical studies on pitching have reported on adult elite-level pitchers.<sup>5,10,29,33,39,40</sup> The knowledge gained from these studies, although providing important information about pitching biomechanics, is difficult to apply toward improving the mechanics of the youth pitcher. Because of the popularity of youth baseball and the potential for injury, there is a need for pitching instruction that combines the scientific validity of the motion analysis laboratory and the ease of use of an on-field video camera. The purpose of this study was to define the relationship between common biomechanical errors in youth pitchers and joint stress in the upper extremity using motion and video analysis. Understanding this relationship may provide applicable instructional information for the youth pitcher in improving safety and performance.

### MATERIALS AND METHODS

In sum, 169 pitchers from local youth baseball leagues and high school baseball teams volunteered to participate in the study. Inclusion criteria consisted of uninjured youth baseball pitchers between the ages of 9 and 18 (all participants denied any history of upper extremity injuries in the pitching arm). Two age ranges (9–13 and 14–18) were created to allow for comparison between the younger and physiologically immature youth pitchers and the older, more developed adolescent pitchers. The study protocol was approved by the institutional review board of the Centinela-Freeman Medical Center. Informed consent was obtained from all participants and their guardians.

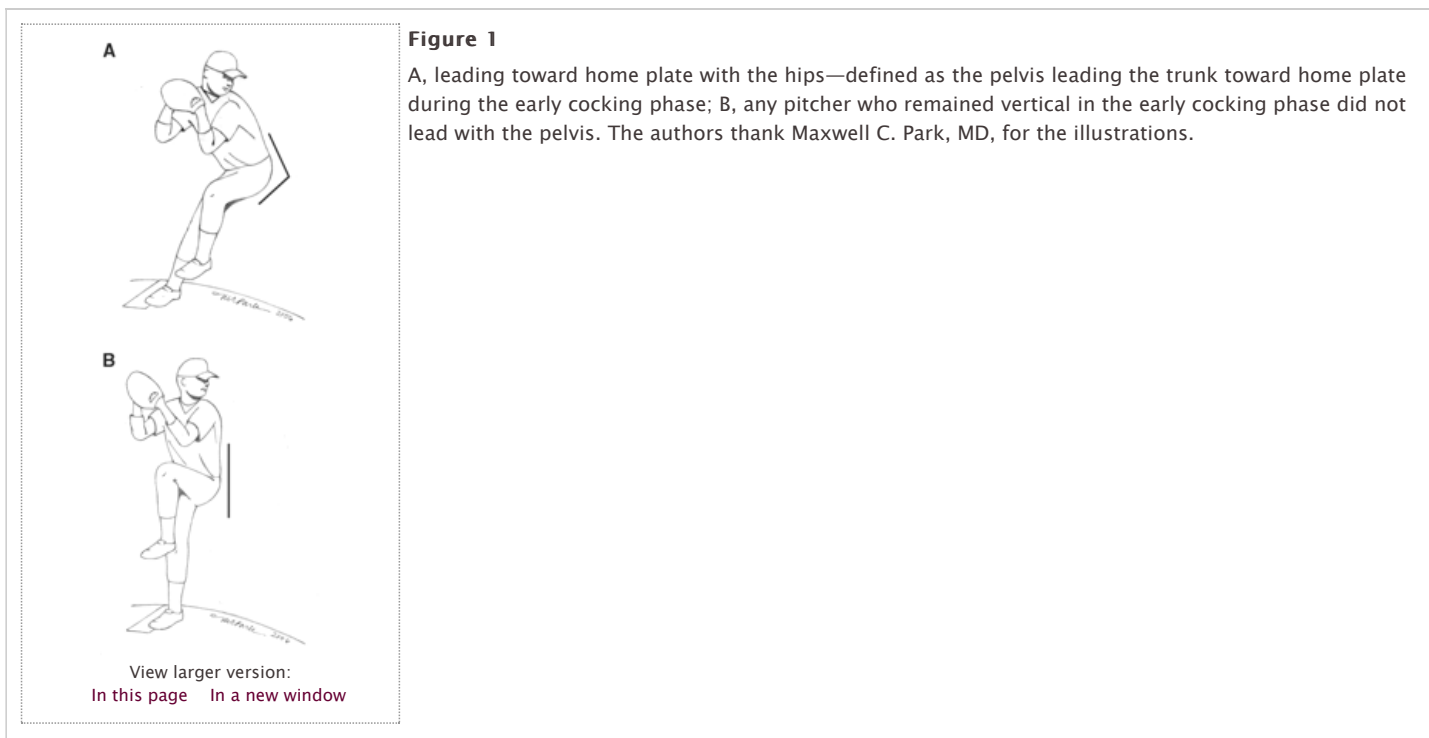
All participants performed 5 fastball pitches under continuous motion analysis and high-speed video analysis. Pitching analysis was preceded by warm-up pitches and stretching. Pitches were thrown from an indoor pitching mound (ProMounds, Inc, Winthrop, Massachusetts) into a net 25 feet away with a targeted strike zone 33 inches above ground level. A speed gun (JUGS Sports, Tualatin, Oregon) was positioned 5 feet behind the net, in line with the targeted strike zone, to measure ball velocity.

Continuous motion analysis was performed using eight 240-Hz cameras positioned around the pitcher. Each participant had a set of 2.5-cm spherical reflective markers placed on the skin, overlying 34 anatomical landmarks and secured with adhesive tape. An upper-body marker set, combined with the Helen Hayes lower-body marker set,<sup>20</sup> created a full-body configuration that was used to bilaterally define the hip, knee, ankle, shoulder, elbow, and

wrist joints, as well as the upper- and lower-limb segments. The marker-based optical system was housed in a 130-m<sup>2</sup> laboratory with cameras positioned to allow for a 5.0 × 2.0 × 0.3 m (L × W × H) indoor mound. The data from the 8 cameras interfaced with the Real-Time Motion Capture System (Motion Analysis Corporation, Santa Rosa, California). Strobe control was set at 200 Hz, whereas camera rate was fixed at 120 Hz for full pixel resolution. Because most throwers deliver a pitch with consistent mechanics,<sup>11,29</sup> a single pitch with complete data acquisition was routinely chosen for motion analysis.<sup>9,38</sup> This pitch (the closest to a strike) was agreed upon by 3 independent observers (2 orthopaedic surgeons and 1 physical therapist). The humeral internal rotation torques (HIRTs) and elbow valgus loads (EVLs) were calculated using the inverse dynamics technique previously described.<sup>8,9</sup> The HIRTs and EVLs were expressed in absolute units (N · m) and in terms normalized by body weight and height.

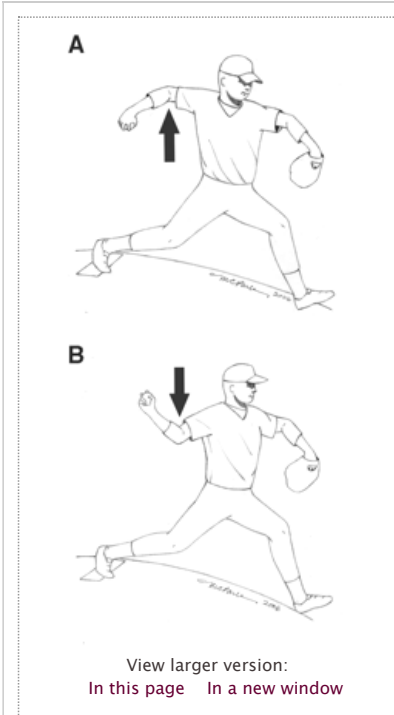
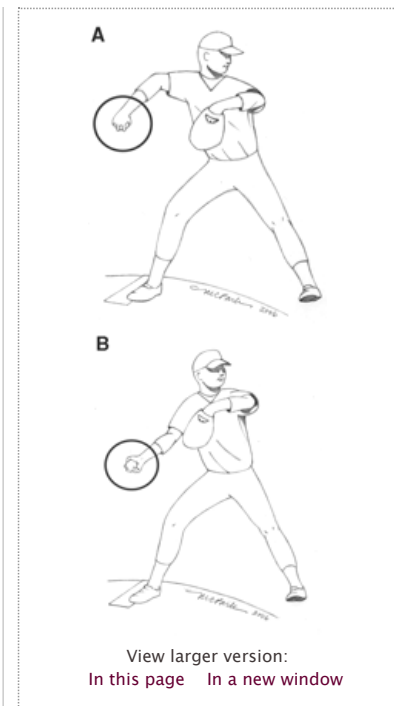
Video analysis was also performed using 2 high-speed digital video cameras at a rate of 250 frames per second. One camera was placed in front of the pitcher (home plate), and the other was placed lateral to the pitcher (first base for left-handed pitchers and third base for right-handed pitchers). The same best pitch (closest to a strike) used for motion analysis was chosen by the 3 independent observers and analyzed with respect to 5 biomechanical parameters of pitching considered to be common errors in youth pitching (as described in relation to the phases of pitching previously defined).<sup>5,12,29,38</sup> The ability of the pitcher to properly perform each parameter was graded as a *yes* or *no* by each observer after reviewing the selected pitch from both camera angles. The observers chose *yes* or *no* subjectively as they would for an on-field analysis. For example, if the hand was on the side of the ball, the observers would subjectively rate it *on top of ball* or *not on top of ball*. The 3 ratings provided by the observers were averaged to provide 1 value for each participant (if 2 were *yes* and 1 was *no*, the rating would be a *yes*). For the motion analysis data, the parameter was rated *correct* or *incorrect* on the basis of an accepted range agreed on by the observers. The accepted range was based on a collective review of the plotted motion analysis data from the various phases of the pitching cycle. The 5 biomechanical parameters were as follows:

- **Parameter 1—Leading with the hips:** Correct performance was defined as the pelvis leading the trunk toward home plate during the early cocking phase (Figure 1A). Any pitcher who remained vertical in the early cocking phase did not lead with the hips (*incorrect*, Figure 1B).
- **Parameter 2—Hand-on-top position:** Performance was defined in terms of whether the throwing hand was on top of the ball (forearm in pronation; *correct*, Figure 2A) as it comes out of the glove during early cocking or under the ball (forearm in supination; *incorrect*, Figure 2B).
- **Parameter 3—Arm in throwing position:** Correct performance was defined as the elbow reaching its maximum height (glenohumeral abduction) by stride foot contact (Figure 3A). Any pitcher whose elbow was not at its highest point by stride foot contact did not have the arm in throwing position (*incorrect*, Figure 3B).
- **Parameter 4—Closed-shoulder position:** Correct performance was defined as the lead shoulder being in a closed position, pointing toward home plate at stride foot contact (Figure 4A), rather than in an open position (*incorrect*, Figure 4B).
- **Parameter 5—Stride foot toward home plate:** Correct performance was defined in terms of whether the stride foot was pointed toward home plate at stride foot contact (Figure 4A) or not (*incorrect*, Figure 4B).



**Figure 2**

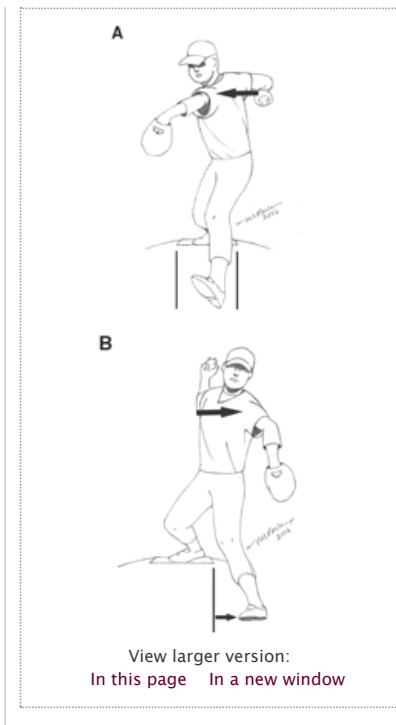
A, hand-on-top position—defined as the throwing hand being on top of the ball (forearm in pronation) as it comes out of the glove during early cocking; B, hand under the ball (forearm in supination). The authors thank Maxwell C. Park, MD, for the illustrations.



**Figure 3**

A, arm in throwing position—defined as the elbow reaching its maximum height (glenohumeral abduction) by stride foot contact; B, any pitcher whose elbow was not at its highest point by stride foot contact did not have the arm in throwing position. The authors thank Maxwell C. Park, MD, for the illustrations.

**Figure 4**  
*Parameter 4:* A, closed-shoulder position—defined as the lead shoulder being in a closed position and pointing toward home plate at stride foot contact; B, open position. *Parameter 5:* A, stride foot toward home plate—defined as the stride foot being pointed toward home plate at stride foot contact; B, foot not pointed toward home plate. The authors thank Maxwell C. Park, MD, for the illustrations.



The calculations for HIRT and EVL were based on the motion analysis data, using inverse dynamics technique previously described.<sup>8,9</sup> The selected values for HIRT and EVL were based on the maximum values on the plotted data from the continuous motion analysis. These values were expressed in absolute units and normalized by body weight and height—that is, normalized HIRT (nHIRT) and normalized EVL (nEVL). The values were normalized as follows:  $HIRT / BW (kg) \times H (cm)$  and  $EVL / BW (kg) \times H (cm)$ . Both HIRT and EVL have been described as measures of the forces exerted on the shoulder and elbow joint during pitching.<sup>33,34</sup> Finally, nHIRT and nEVL were divided by ball velocity to measure pitching efficiency. These ratios indicate the amount of stress that the shoulder and elbow experience for a given pitch velocity generated (the higher the value, the lower the efficiency).

Two sets of data were analyzed for the 5 pitching parameters—a quantitative data set from the motion analysis and a dichotomous data set from the high-speed video analysis. The results of the data sets were compared to each other, to evaluate the accuracy of high-speed video analysis versus continuous motion analysis. The results of the pitching analysis were also compared to HIRT, nHIRT, EVL, nEVL, nHIRT/velocity, and nEVL/velocity to evaluate the effect of the pitching parameters on upper extremity joint stress.

**STATISTICAL METHODS**

The nonparametric Wilcoxon rank sum test was used to compute *P* values for comparing the means and medians of variables between the video and motion analysis groups. The Wilcoxon test was also used for comparing continuous variables between the 2 age groups and for comparing the number of pitching parameters performed correctly (1, 2, 3, or 4) between the 2 age groups. Correlations between the 5 pitching variables and HIRT, nHIRT, EVL, nEVL, nHIRT/velocity, and nEVL/velocity were assessed using the nonparametric Spearman correlation coefficient. Nonparametric methods were used because the continuous data were not normally distributed. The *P* values for comparing dichotomous variables by age group were computed using Fisher exact test.

**RESULTS**

The study included the 169 pitchers (27 left-handed and 142 right-handed) who completed motion and video analyses. All participants were male, with a mean age of 13.4 years (range, 9–18). There were 86 pitchers in the youth pitcher group and 83 pitchers in the adolescent pitcher group (Table 1). The results for the video analysis of the 5 pitching parameters agreed with those of the motion analysis (Table 2). This correlation was accomplished by comparing the *yes* or *no* answer from the video analysis with a single data point for each pitching parameter on the continuous motion data. The continuous data point was selected by the 3 observers for each of the 5 pitching parameters; the values represent body angles and percentages in the pitching cycle for the parameter being analyzed.

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**TABLE 1**  
 Age, Height, and Weight of the 2 Age Groups

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**TABLE 2**  
 Correlation Between Video and Motion Analysis for Correct Versus Incorrect Performance of the 5 Pitching Parameters

Video analysis also revealed that the adolescent pitchers performed better with regard to the number of pitching parameters performed correctly compared with the youth pitchers (Table 3). The adolescent group performed an average of 2.96 of the 5 parameters correctly, compared with 2.78 in the youth pitcher group ( $P = .042$ ). Furthermore, 80.7% of the adolescent pitchers performed 3 or more parameters correctly, compared with only 64.0% in the younger age group ( $P = .017$ ). A perhaps unexpected finding showed that youth pitchers correctly performed *stride foot toward home plate* at 86%, compared with 66% for the adolescent group ( $P = .004$ ).

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**TABLE 3**

Youth Group Versus Adolescent Group on Video Analysis: Parameters Performed Correctly

Video analysis in the adolescent group showed that *leading with the hips* was associated with higher nHIRT and nEVL, as well as lower pitching efficiency (nHIRT or nEVL / velocity) (Table 4). Video analysis in the youth pitcher group showed that participants who correctly performed *hand-on-top position* generated lower nHIRT ( $P = .015$ ) and nEVL ( $P = .011$ ) and had higher pitching efficiency (Table 5).

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**TABLE 4**Adolescent Group and *Leads With Pelvis* Parameter: Video Analysis

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**TABLE 5**Youth Group and *Hand on Top* Parameter: Video Analysis

Youth pitchers were found to have lower nHIRT and nEVL and higher pitching efficiency (nHIRT/velocity) when performing more of the parameters correctly on video analysis (Table 6). Participants who performed 1 or 2 parameters correctly had higher nHIRT and nEVL and lower nHIRT/velocity when compared with those who performed 3 parameters correctly. This relationship was also found between those who performed 3 parameters correctly versus those who performed 4 parameters correctly ( $P < .05$ ). No statistically significant correlation was found between the number of parameters performed correctly and lower torque or EVL in the adolescent pitchers.

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**TABLE 6**

Youth Group and Number of Correctly Performed Parameters: Video Analysis

*Hand-on-top position* and *closed-shoulder position* are 2 of the more easily observed and commonly discussed parameters among pitching coaches. Analysis of these 2 parameters together revealed that pitchers of all ages (youth and adolescent) who performed these parameters correctly were more efficient (lower nHIRT/velocity and nEVL/ velocity) than those who performed both parameters incorrectly ( $P = .035$  and  $.042$ , respectively), irrespective of total number of parameters performed correctly (Table 7).

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**TABLE 7**Mean Values for Both Groups on Outcome Measures: *Hand on Top* and *Closed Shoulder* Parameters

## DISCUSSION

The popularity of organized youth baseball makes our understanding of injuries in this population paramount from a public health standpoint.<sup>1,14,22,23,37</sup> Little Leaguer's shoulder, Little Leaguer's elbow, and other physal injuries constitute the most common injury pattern in the skeletally immature thrower; these physal injuries are thought to be caused by the repetitive microtrauma of throwing and, particularly, pitching.<sup>3,4,13,17</sup> The primary contributor to injuries is thought to be overuse, which affects young pitchers and catchers<sup>1,15,24-26,28</sup> more commonly than it does other position players. This overuse occurs throughout the course of a single game, season, or year in the developing baseball player, with all aspects of overuse contributing to increased risk.<sup>24,30</sup> Pitch type (breaking ball versus fastball) and velocity (high) have been implicated as risk factors in young pitchers.<sup>24,30</sup> Although improving pitching mechanics has been advocated as a means of improving the performance and, possibly, the safety of the developing pitcher,<sup>6,16,19,31</sup> previous studies have yet to show that poor pitching mechanics increases risk of injury to young pitchers.<sup>24</sup>

Previous studies of pitching mechanics in youth and adult throwers have shown that certain mechanics of the pitching motion have a quantifiable effect on joint stress.<sup>2,33,40</sup> Sabick et al<sup>34</sup> reported on elbow valgus torque in 14 youth pitchers throwing fastballs. They found that maximum external rotation, maximum abduction-adduction, maximum horizontal flexion-extension torque, and maximum internal-external rotation torque correlated with higher elbow valgus torque, after controlling for body height and weight. The authors also reported on the HIRT and shoulder distraction force in 14 elite youth baseball pitchers. Their data suggested that these parameters contribute to the development of proximal humeral epiphysiolysis as well as humeral retroversion. Although these studies provide insight into how the kinematic and kinetic parameters of pitching affect joint stress and possibly contribute to adaptive changes, the information provided is difficult to apply when trying to teach a young thrower to pitch in a manner that decreases the stresses experienced at the shoulder and elbow joint. The goal of our study was to examine the effect of common biomechanical errors on the upper extremity of youth pitchers. The biomechanical parameters chosen for testing were based on two criteria. First, they are simple errors that are generally considered

poor mechanics common to youth pitchers. Second, they are errors that we believe parents and coaches in the field could detect—that is, requiring little expertise and minimal equipment cost. Identifying mechanical flaws that are detectable through only motion analysis in a laboratory setting is of little benefit to the average youth pitcher. It is impractical and financially difficult for most youth pitchers to undergo such an analysis.

The 5 biomechanical parameters studied were evaluated with respect to HIRT and EVL to determine their likely contribution to shoulder and elbow pain in youth pitchers. Although increased kinetics (high HIRT and EVL) cannot be proven to increase the risk of injury,<sup>11</sup> knowledge of functional anatomy and mechanics allows the clinician to draw informed conclusions with regard to cause of injury.<sup>27,33,34</sup> In addition, we evaluated our 5 parameters with respect to pitching efficiency, which we defined as the ratio of nHIRT and nEVL to ball velocity (with higher values representing lower efficiency). These efficiency parameters normalize high- and low-velocity throwers by examining the HIRT and EVL in relation to ball velocity (ie, how much stress the joints are experiencing per mile per hour, as generated in ball velocity), thus giving us a better idea of the isolated effect of the pitcher's mechanics rather than the measurement of the strength, size, and effort of a particular pitcher. Efficiency measurements may also allow us to better understand the effect of pitching mechanics on the longevity of a pitcher's career. Although it is not advisable to increase pitch counts or pitch velocity in the young thrower,<sup>24,30</sup> pitchers will increase the volume and velocity of their pitches as they proceed to higher levels of play; therefore, decreasing the HIRT and/or EVL for a given pitch velocity may decrease the cumulative microtrauma experienced in the pitcher's shoulder and elbow over years of pitching.

The dichotomous video analysis in our study correctly described the performance of each pitching parameter as measured on continuous motion analysis. Video analysis found statistically significant differences between those who correctly and incorrectly performed each parameter as measured on motion analysis, thereby suggesting that video analysis may be a reasonable surrogate for continuous motion analysis as performed in the laboratory.

Youth pitchers (aged 9–13) and adolescent pitchers (aged 14–18) were separately analyzed to distinguish 2 populations. The youth pitchers represent skeletally and physiologically immature pitchers who are at a generally developmental stage in baseball<sup>17,32</sup>; many play multiple positions and have had varied coaching experience as pitchers. The adolescent pitchers represent more physiologically developed athletes who are approaching or have already reached skeletal maturity; they have generally progressed further in their pitching skill and play, primarily as pitchers on their club or high school team. There was a significant difference in the number of pitching parameters performed correctly between the 2 groups, with the adolescent pitchers more likely to perform more parameters correctly. The implication of this finding is that the 5 parameters studied may be developmental milestones for the youth pitchers as they improve their mechanics over years of learning to pitch. It is not clear whether these parameters develop as a function of coaching and instruction or whether athletes more easily perform them as neuromuscular function improves with age. Most of the pitching parameters analyzed in our study require proper timing and the coordination of upper extremity, trunk, and lower extremity movements.<sup>35,36</sup> Future researchers may want to evaluate the effect of improving core strength and pelvic stabilization on these pitching parameters in developing throwers.

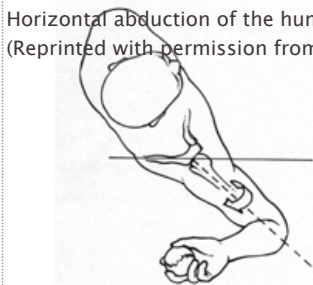
Video analysis of the adolescent throwers found that correctly performing the parameter *leading with the hips* was associated with higher HIRT, higher EVL, and lower pitching efficiency. This perhaps unexpected result can be explained by the fact that this parameter was correctly performed by almost all participants (160 of 169 pitchers). As such, leading with the hips (ie, initiating weight transfer early in the pitching motion while delaying pelvic rotation) may be a necessary way to generate ball velocity at the cost of increasing HIRT and EVL. This may not hold true in the higher-level thrower. Aguiñaldo et al<sup>2</sup> looked at the timing of pelvic rotation and showed that delayed pelvic rotation is more common in elite-level pitchers than in youth and high school pitchers; in addition, it resulted in a more efficient transfer of energy during the pitching motion. Of note, the values for HIRT and EVL in those adolescent pitchers who correctly performed this parameter are similar to those seen in other youth pitcher biomechanical studies.<sup>32,34</sup> Those few adolescent pitchers (9 of 169) who performed this parameter incorrectly had low HIRT and EVL values.

Another unexpected finding in the video analysis showed that youth pitchers correctly performed *stride foot toward home plate* at 86%, compared with 66% for the adolescent group ( $P = .004$ ). This can perhaps be explained by the difference in size between the youth and adolescent pitchers; the smaller legs of the youth pitchers had less of an opportunity to step out of our accepted range for correct performance. Note that correct or incorrect performance of this parameter was not a predictor for any age group with respect to higher or lower HIRT, EVL, or pitching efficiency.

Video analysis of the youth pitchers revealed that correctly performing *hand-on-top position* was associated with lower HIRT, lower EVL, and higher pitching efficiency. We believe that the hand-on-top position initiates early shoulder abduction while delaying humeral external rotation because when the forearm is pronated, the humerus remains internally rotated. This causes the shoulder to abduct while delaying humeral external rotation (Figure 2A). Delayed glenohumeral abduction and early external rotation (hand-under-ball position; Figure 2B) may lead to the arm's being "late" in the pitching motion; excessive horizontal abduction can result as the torso unwinds and the arm is not properly positioned. This extreme horizontal abduction has been called *hyperangulation*, and it has been implicated as a contributor to injury in the throwing shoulder (Figure 5).<sup>18</sup>

**Figure 5**

Horizontal abduction of the humerus beyond the plane of the scapula, or hyperangulation, which can lead to injury in the throwing shoulder. (Reprinted with permission from Jobe FW. Anterior shoulder instability, impingement, and rotator cuff tear. In: Jobe FW, ed. *Operative Techniques in Upper Extremity Sports Injuries*. St. Louis, MO: Mosby; 1996)



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Video analysis of the youth pitchers revealed that performing more pitching parameters correctly was associated with lower HIRT and EVL and higher

pitching efficiency. This finding supports the use of the pitching parameters tested in teaching developing throwers how to throw more efficiently and safely. This finding was not significant in the adolescent throwers, and it may result from the number of adolescent throwers who already performed these parameters correctly; 81% of adolescent throwers performed 3 or more parameters correctly. It can also be explained by an inadequate number of participants in the adolescent subset. The pitching motion is a complex one that requires the coordination of multiple motion segments. Perhaps these commonly taught pitching parameters are basic checkpoints that can help developing youth pitchers throw more efficiently because they have yet to achieve the proper general sequence of motions. Adolescent throwers, however, already perform many of these parameters correctly and may require more refined parameters to benefit from improved biomechanics. A possible clinical implication of this finding in adolescent throwers is that overuse, rather than poor mechanics, may be the primary cause of upper extremity injuries.

*Hand-on-top position* and *closed-shoulder position* are 2 of the more commonly taught pitching parameters among pitching coaches. We analyzed these parameters together to see if performing both correctly might confer a biomechanical benefit beyond that of performing any 2 parameters correctly. For all the pitchers who correctly performed both of these parameters, compared with those performing both parameters incorrectly, a biomechanical benefit was conferred with regard to pitching efficiency (all pitchers) and to lower HIRT and EVL (youth pitchers). This was true regardless of correct performance of the other 3 parameters. This finding suggests that pitchers who can master these 2 parameters alone can improve their pitching mechanics and potentially decrease HIRT and EVL.

The questions answered in this study create even more questions about the pathomechanics of the pitching motion. How do these biomechanical parameters adversely affect the torque and load in the upper extremity and decrease pitching efficiency? We currently believe that the safest and most efficient transfer of energy from the lower extremity, through the trunk, and into the upper extremity depends on the correct timing and sequence of movements (glenohumeral abduction, scapular positioning, humeral external rotation, and trunk rotation) as much as the actual quality of the motions themselves (degree of pelvic rotation or humeral external rotation). For example, *arm in throwing position* addresses the importance of achieving humeral elevation (shoulder abduction) before significant trunk rotation occurs; that is, it can minimize hyperangulation of the shoulder. Early elevation of the throwing arm also allows the scapula to achieve a stable position before the trunk rotates and transfers energy to the upper extremity. *Closed-shoulder position* describes a common error that many coaches refer to as “opening up too soon” (Figure 4B). This early opening, or rotation of the torso in relation to stride foot contact, can increase hyperangulation of the shoulder (Figure 5). *Stride foot toward home plate*, often called “under/over rotation” by pitching coaches, may signify inefficient transfer of energy, as well as improper timing of trunk rotation. Researchers will need to perform further quantitative analysis of these pitching parameters to better define the relationship among these commonly taught parameters, joint pathomechanics, and pitching efficiency.

We acknowledge that this study has several limitations. First, the distance used from the pitching mound to the net could have altered the throwing mechanics of the pitchers. The standard 25-foot distance used in this study was thought to eliminate a variable for the pitchers (ie, different distances for different age groups). Setting up each pitcher at an age-appropriate distance is an option for future studies. Second, using only 1 pitch for the motion and video analysis does not allow for assessing trends in the pitcher’s throwing mechanics. Evaluating multiple pitches from each of the numerous participants was not reasonable within the confines of this study. Analysis of multiple pitches from all angles around the pitcher is one of the goals of this study using on-field analysis. Also, the use of pitching efficiency as an outcome measure is a novel concept not previously reported in the literature. We believe that dividing the HIRT and EVL by the pitcher’s mass was the best way to equalize the results, given the wide variation in size between the age groups. Finally, the video analysis used in the study was with cameras equipped with a rate of 240 frames per second; standard camcorders often have a slower rate. If the information in this study is to be applied to an on-the-field setting, care should be taken to ensure proper video equipment. Future studies should consider addressing the accuracy of video analysis with varying frame rates.

To our knowledge, this is the first study to quantify the effect of common pitching errors on joint stress and pitching efficiency. We hope the findings of this research can provide young pitchers, coaches, and parents with simple and scientifically based pitching instruction that can decrease pitching injuries in the upper extremity.

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## Footnotes

One or more authors has declared a potential conflict of interest: Pfizer and Major League Baseball funded this project.

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