Relationships Among Shoulder Rotational Strength, Range of Motion, Pitching Kinetics, and Pitch Velocity in Collegiate Baseball Pitchers

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Abstract

Cross, JA, Higgins, AW, Dziuk, CC, Harris, GF, and Raasch, WG. Relationships among shoulder rotational strength, range of motion, pitching kinetics, and pitch velocity in collegiate baseball pitchers. *J Strength Cond Res* 37(1): 129–135, 2023—Throwing shoulder injuries are the most common type of injury experienced by baseball pitchers. Weakness in the shoulder musculature and insufficient throwing arm range of motion are both risk factors for developing a shoulder injury. The goal of this study was to determine correlations among shoulder rotational strength, range of motion, pitching kinetics, and pitch velocity in collegiate pitchers. Thirteen uninjured male college pitchers were evaluated. Clinical measures included shoulder internal and external rotation range of motion, peak isokinetic internal and external rotator strength, and peak isometric internal and external rotator strength. Three-dimensional biomechanics were assessed as subjects threw from an indoor pitching mound to a strike zone net at regulation distance. Pearson's correlations were used to assess the associations among the clinical measures and throwing metrics. Five significant correlations were found between peak shoulder compressive force and strength, and 4 significant correlations were found between pitching velocity and strength (p < 0.05). No significant correlations were found between range of motion and pitching kinetics or velocity. Our results suggest that as shoulder rotational strength increases, the peak shoulder compressive force and pitch velocity both increase. Knowledge of relationships between strength metrics and pitching biomechanics may allow for improved strength training routines with the goal of increasing velocity without increasing injury risk.

Introduction

Although there are approximately 25,000 collegiate baseball players each year, there is a paucity of literature regarding collegiate baseball injury epidemiology and prevention (25). In an epidemiologic study reporting on 16 years of National Collegiate Athletic Association men's baseball data, injury rates were 3 times higher in games compared with practice, with 5.78 per 1,000 athlete-exposures (10). Pitchers accounted for 15.3% of in game injuries, with upper extremity injuries the majority of reported injuries (10). Two critical points in the pitching cycle have been implicated as mechanisms of injury for the shoulder: (a) the instant of peak internal rotation (IR) torque during arm cocking and (b) the instant of peak compressive force during arm deceleration (17). Higher pitching velocity also results in higher kinetics values in the throwing arm (15,16) and has been correlated with injuries in pitchers (7,29). Injuries to the throwing shoulder are the most common type of injury experienced by pitchers and include overuse tendinitis, rotator cuff tears, glenoid labrum fraying, labral detachment, and capsular laxity problems (35). Injury prevention strategies for collegiate players are drawn from the youth and professional levels as more research is needed into specific college baseball preventive measures (25).

Shoulder joint angular velocities have been reported at over 7,000°·s⁻¹ during the acceleration phase of pitching (25). Shoulder internal rotators contract concentrically during the acceleration phase, whereas the external rotators contract eccentrically during the deceleration phase of pitching. Weakness in the shoulder musculature, specifically of the rotator cuff, has been proposed as a risk factor for developing a
shoulder injury in baseball pitchers \((6,12,14,31,35)\). The ratio of shoulder external rotation (ER) to IR is often calculated to identify rotational imbalances \((2,5,12,14,20,22,26-28,30,32)\). A functional ER/IR ratio that compares eccentric ER (ER\textsubscript{ecc}) and concentric IR (IR\textsubscript{con}) muscles has been used to assess the acceleration phase of throwing \((28,32)\). In a study analyzing college pitchers, it was found that high acceleration phase functional strength ratio (ER\textsubscript{ecc}/IR\textsubscript{con}) and decreased shoulder IR\textsubscript{con} peak torque may be linked to the development of shoulder injuries in baseball pitchers \((32)\). Currently, only 1 study links shoulder strength to pitching kinetics, finding that isometric shoulder IR strength was positively correlated with the shoulder ER moment during pitching in high school baseball pitchers \((23)\).

Pitching requires the glenohumeral joint to undergo a large range of motion (ROM) at a high velocity while maintaining joint stability. Baseball pitchers often develop a shift in dominant arm glenohumeral shoulder rotational ROM that increases ER ROM and decreases IR ROM compared with the nondominant arm \((3,5,13,21,38)\). In 2 different studies, Wilk et al. \((36,37)\) found that pitchers with insufficient throwing arm shoulder ER and pitchers with glenohumeral IR deficit are at a higher risk of shoulder injury and shoulder surgery. In high school pitchers, Hurd and Kaufman \((23)\) found that ER ROM was inversely related to shoulder IR torque.

Relationships among shoulder strength, ROM, throwing kinetics, and pitch velocity have not been examined in a collegiate population. Determining correlations may aid in identifying potential for performance decline and injury from throwing shoulder rotational strength and ROM. The goal of this study was to determine correlations among shoulder rotational strength, ROM, kinetics, and pitch velocity in collegiate pitchers. We hypothesized that positive correlations exist between shoulder rotational strength and pitching kinetics, whereas negative correlations exist between shoulder ROM and pitching kinetics. We also hypothesized that there are positive correlations between strength metrics and pitch velocity.

Methods

Experimental Approach to the Problem

The study has a cross-sectional design, including clinical ROM and strength testing, along with pitching motion analysis to test whether clinical measures are associated with pitching metrics. Subjects underwent 2 testing sessions: clinical measurements and 3-dimensional (3D) motion analysis. A minimum of 2 days between the tests was required to ensure maximal effort and minimize fatigue. The first session measured the clinical variables of the shoulder using a goniometer and dynamometer. In the second session, a pitching assessment was performed using a 3D motion analysis system.

Subjects

Thirteen male college pitchers (mean ± SD, age: 21 ± 2.3 years, height: 184.9 ± 7.8 cm, mass: 90.9 ± 13.5 kg, 10 right-handed, 5 Division III, 8 Division I club team) participated in the study. Pitchers with injuries in the previous 12 months or prior shoulder or elbow surgery on the throwing arm were excluded. The study was approved by the Medical College of Wisconsin institutional review board. Subjects were informed of the benefits and the risks of the study prior to signing written informed consent to participate in the study.
Procedures

Clinical Measures

Passive ROM, isokinetic and isometric shoulder strength data were obtained during the clinical measures testing session. A standardized warm-up included static and dynamic stretches. The static warm-up included the overhead triceps, arm-across deltoid, and forearm wrist flexion and extension stretches, all held for 10 seconds. The dynamic warm-up included jumping jacks, arm circles forward and backward, and band exercises of 10 repetitions each including flies, reverse flies, and IR and ER rotation at zero- and ninety-degree shoulder abduction. The jumping jacks were performed first to elevate the heart rate, followed by the static stretches, and concluding with the dynamic stretches. Passive shoulder external and IR ROM was measured with the subject laying supine with the upper arm at 90° shoulder abduction, in the scapular plane, and 90° elbow flexion. The scapular stabilization method was used because it is the most clinically relevant glenohumeral ROM measurement techniques (37). The same investigators in the same roles tested ROM for all subjects. A long-armed clinical goniometer (Jamar, 7540 EZ read, 20 cm) with a bubble level secured to the reference arm was used to facilitate proper alignment. Testing consisted of moving the subject's arm through a full arc of motion until an end point was reached. The beginning of scapular tilt was used to determine the end range or motion. Two measurements were performed for each motion measured, with the average used for analysis. Repeatability of goniometric measures was excellent, with intraclass correlation coefficient (ICC) values ranging from 0.979 to 0.981.

Shoulder strength testing was performed using a Biodex 3 dynamometer (Biodex Corp., Shirley, NY). The Biodex was calibrated according to user manual instructions before each subject was tested. The subject was seated with their arm positioned to mimic the throwing motion: 90° shoulder abduction, 90° elbow flexion, and 30° horizontal shoulder abduction to place the arm in the scapular plane. The position was used based on specificity of muscular function and arm position with respect to the throwing motion (14,26,30). The order of testing was (a) isokinetic ER, (b) isokinetic IR, and (c) isometric testing in both directions. The subject was given a thirty-second rest period between tests in the same rotation direction and a 2-minute break between different test sets. After a brief explanation of the testing procedures, all tests were performed with the nondominant arm first to familiarize the subject with the protocol before switching to the dominant arm.

Both isokinetic external and IR tests alternated between concentric and eccentric contractions, with 5 repetitions performed in each direction. The isokinetic testing strength was measured at 3 speeds: 90, 180, and 270°·s\(^{-1}\), similar to previous methods (2,20,26,27,30,32,34). All 3 velocities were tested for ER, followed by IR. Full ER and IR were allowed during testing. For isokinetic testing, concentric ER (ER\(_{\text{con}}\)), ER\(_{\text{ecc}}\), IR\(_{\text{con}}\), and eccentric IR (IR\(_{\text{ecc}}\)) peak torque normalized to body mass (Nm·kg\(^{-1}\)) were recorded at all 3 velocities. The peak torque was the highest muscular force output at any moment during the repetition. Concentric ER/IR (ER\(_{\text{con}}\)/IR\(_{\text{con}}\)), ER\(_{\text{ecc}}\)/IR\(_{\text{ecc}}\), and ER\(_{\text{ecc}}\)/IR\(_{\text{con}}\) ratios using the normalized peak torque were calculated.

Isometric testing was performed with the subject's arm positioned in 90° shoulder abduction, 90° elbow flexion, 30° horizontal shoulder abduction, and 90° ER, similar to previous methods (21). The arm is in this position during the pitching cycle just before and after ball release as the arm begins to decelerate (11). The isometric test alternated between ER and IR. Three repetitions of 5 seconds were performed in
each direction. For isometric testing, isometric ER (ERi) and IR (IRi) (Nm·kg⁻¹) were recorded, and ERi/IRi ratios using the normalized peak torque were calculated.

Motion Analysis Testing
Eight Raptor-E cameras (Motion Analysis Corporation, Santa Rosa, CA) were positioned around an artificial mound to capture the motion of pitchers at 300 frames per second. Forty-seven reflective markers (12.5 mm diameter) were attached to the subjects bilaterally on the acromion process, midpoint of the lateral humerus, medial and lateral epicondyle, midpoint of the ulna, radial styloid, ulnar styloid, midpoint of the third metacarpal, anterior and posterior superior iliac spine, greater trochanter, midpoint of the lateral femur, medial and lateral femoral condyle, midpoint of the lateral tibia, medial and lateral malleolus, calcaneus, head of the third metatarsal, as well as on C7 and T10 vertebrae, sternoclavicular notch, xiphoid process, and on the baseball hat on the front, back, sides, and top. The same standardized warm-up used for clinical testing was performed in addition to their normal throwing progression before pitching. Once the subjects were instrumented and warmed up, a static trial was recorded with the subject standing on the mound facing home plate, arms at 90° shoulder abduction, 90° elbow flexion, and 90° IR (palms parallel to the ground). Ten fastballs were recorded with pitches thrown into a strike zone net, which was used to record the location of each pitch. Velocity was recorded using a Stalker Sport 2 radar gun (Stalker Sports Radar, Richardson, TX) set up directly behind home plate and the netting. Home plate was positioned at a regulation distance of 18.4 m from the pitching rubber. The 3 fastest strikes were analyzed. Marker data were identified in Cortex (Motion Analysis Corporation) and processing with Visual 3D (C-Motion, Germantown, MD) using a biomechanical pitching model (1). Shoulder compressive force and shoulder IR torque were calculated from the motion analysis data using inverse dynamics. Torque was normalized to body mass (in kilograms) and height (in meters), and force was normalized to body mass (in kilograms) to allow for subject-to-subject and population comparisons and to investigate correlations with arm strength and ROM.

Statistical Analyses
Descriptive statistics including mean and standard deviation were calculated for all variables. Shapiro-Wilk tests and histograms were used to test the normality of the metrics. Scatterplots were examined for linearity to determine appropriate correlation test. Associations examined were linear; thus, 2-tailed Pearson’s correlation coefficients were used to determine correlations between clinical measures and biomechanical metrics. Clinical measures included ROM (ER, IR, and total), isokinetic measures (ERcon, ERecc, IRcon, IRecc, ERcon/IRcon, ERecc/IRecc, and ERecc/IRcon), and isometric measures (ERi, IRi, and ER/IRi). Biomechanical metrics included normalized peak shoulder IR torque (nSIRT), normalized peak shoulder compressive force (nSCF), and pitch velocity. The strength of a correlation was assessed as weak (0.1 < |r| < 0.3), moderate (0.3 < |r| < 0.5), or strong (|r| > 0.5) (2). A significance level of p < 0.05 was chosen. Statistical testing was performed with SPSS statistical software (version 26; IBM Corporation, Armonk, NY).

Results
The 13 healthy male college pitchers who participated in this study had an average pitching velocity of 34.5 ± 1.8 m·s⁻¹. Group means and standard deviations of the clinical and biomechanical measures were calculated (Table 1). Correlations were investigated to identify relationships among clinical measures of arm strength and ROM and biomechanics of the pitching motion (Table 2). No significant correlations
were found between nSIRT and clinical measures. Five significantly strong correlations were found between nSCF and strength, including ER<sub>i</sub>, ER<sub>i</sub>/IR<sub>i</sub>, and ER<sub>con</sub> at 90°·s<sup>−1</sup>, ER<sub>con</sub> at 180°·s<sup>−1</sup>, and IR<sub>con</sub> at 180°·s<sup>−1</sup> (Table 2 and Figure 1). Four significantly strong correlations were found between pitching velocity and strength, including ER<sub>i</sub>, IR<sub>i</sub>, and ER<sub>con</sub> at 90°·s<sup>−1</sup> and ER<sub>con</sub> at 180°·s<sup>−1</sup> (Table 2 and Figure 2).

Table 1 - Group results for clinical and biomechanical variables of interest.*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Clinical measures</strong></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td></td>
</tr>
<tr>
<td>ER ROM (°)</td>
<td>110.2 ± 8.8</td>
</tr>
<tr>
<td>IR ROM (°)</td>
<td>71.7 ± 12.5</td>
</tr>
<tr>
<td>Total ROM (°)</td>
<td>181.9 ± 17.9</td>
</tr>
<tr>
<td><strong>Isometric strength</strong></td>
<td></td>
</tr>
<tr>
<td>ER&lt;sub&gt;i&lt;/sub&gt; strength (Nm·kg&lt;sup&gt;−1&lt;/sup&gt;)</td>
<td>31.9 ± 8.3</td>
</tr>
<tr>
<td>IR&lt;sub&gt;i&lt;/sub&gt; strength (Nm·kg&lt;sup&gt;−1&lt;/sup&gt;)</td>
<td>45.7 ± 13.3</td>
</tr>
<tr>
<td>ER&lt;sub&gt;i&lt;/sub&gt;/IR&lt;sub&gt;i&lt;/sub&gt; strength ratio</td>
<td>0.71 ± 0.12</td>
</tr>
<tr>
<td><strong>Isokinetic strength</strong></td>
<td></td>
</tr>
<tr>
<td>90°·s&lt;sup&gt;−1&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>ER&lt;sub&gt;con&lt;/sub&gt; strength (Nm·kg&lt;sup&gt;−1&lt;/sup&gt;)</td>
<td>38.9 ± 9.1</td>
</tr>
<tr>
<td>ER&lt;sub&gt;ecc&lt;/sub&gt; strength (Nm·kg&lt;sup&gt;−1&lt;/sup&gt;)</td>
<td>42.2 ± 11.2</td>
</tr>
<tr>
<td>IR&lt;sub&gt;con&lt;/sub&gt; strength (Nm·kg&lt;sup&gt;−1&lt;/sup&gt;)</td>
<td>58.4 ± 15.9</td>
</tr>
<tr>
<td>IR&lt;sub&gt;ecc&lt;/sub&gt; strength (Nm·kg&lt;sup&gt;−1&lt;/sup&gt;)</td>
<td>85.4 ± 16.9</td>
</tr>
<tr>
<td>ER&lt;sub&gt;con&lt;/sub&gt;/IR&lt;sub&gt;con&lt;/sub&gt; strength ratio</td>
<td>0.69 ± 0.15</td>
</tr>
<tr>
<td>ER&lt;sub&gt;ecc&lt;/sub&gt;/IR&lt;sub&gt;con&lt;/sub&gt; strength ratio</td>
<td>0.50 ± 0.12</td>
</tr>
<tr>
<td>ER&lt;sub&gt;ecc&lt;/sub&gt;/IR&lt;sub&gt;ecc&lt;/sub&gt; strength ratio</td>
<td>0.76 ± 0.24</td>
</tr>
<tr>
<td><strong>Biomechanical measures</strong></td>
<td></td>
</tr>
<tr>
<td>Peak nSIRT (Nm·m&lt;sup&gt;−1&lt;/sup&gt;·kg&lt;sup&gt;−1&lt;/sup&gt;)</td>
<td>0.42 ± 0.08</td>
</tr>
<tr>
<td>Peak nSCF (N·kg&lt;sup&gt;−1&lt;/sup&gt;)</td>
<td>8.92 ± 0.84</td>
</tr>
<tr>
<td>Pitch velocity (m·s&lt;sup&gt;−1&lt;/sup&gt;)</td>
<td>34.5 ± 1.8</td>
</tr>
</tbody>
</table>

*ROM = range of motion; ER = external rotation; IR = internal rotation; i = isometric; con = concentric; ecc = eccentric; nSIRT = normalized shoulder internal rotation torque; nSCF = normalized shoulder compression force.

Table 2 - Pearson's correlation results.*

<table>
<thead>
<tr>
<th></th>
<th>nSIRT</th>
<th></th>
<th></th>
<th>Pitch velocity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>p</td>
<td>r</td>
<td>p</td>
<td>r</td>
</tr>
<tr>
<td><strong>ROM</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ER ROM</td>
<td>−0.163</td>
<td>0.594</td>
<td>0.310</td>
<td>0.303</td>
<td>0.384</td>
</tr>
<tr>
<td>IR ROM</td>
<td>0.065</td>
<td>0.832</td>
<td>−0.030</td>
<td>0.922</td>
<td>−0.056</td>
</tr>
<tr>
<td>Total ROM</td>
<td>−0.035</td>
<td>0.911</td>
<td>0.131</td>
<td>0.670</td>
<td>0.149</td>
</tr>
<tr>
<td><strong>Isometric strength</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ER&lt;sub&gt;i&lt;/sub&gt; strength</td>
<td>−0.125</td>
<td>0.685</td>
<td>0.230</td>
<td>0.450</td>
<td>0.567</td>
</tr>
<tr>
<td>IR&lt;sub&gt;i&lt;/sub&gt; strength</td>
<td>0.098</td>
<td>0.749</td>
<td>0.561</td>
<td>0.046†</td>
<td>0.613</td>
</tr>
<tr>
<td>ER&lt;sub&gt;i&lt;/sub&gt;/IR&lt;sub&gt;i&lt;/sub&gt; strength ratio</td>
<td>−0.502</td>
<td>0.081</td>
<td>−0.675</td>
<td>0.011†</td>
<td>−0.312</td>
</tr>
<tr>
<td><strong>Isokinetic strength</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90°·s&lt;sup&gt;−1&lt;/sup&gt;</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>180°·s⁻¹</td>
<td></td>
<td></td>
<td>270°·s⁻¹</td>
<td></td>
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</tr>
<tr>
<td><strong>ER_con strength</strong></td>
<td>0.072</td>
<td>0.135</td>
<td>0.049</td>
<td>0.124</td>
<td>-0.141</td>
</tr>
<tr>
<td><strong>ER_ecc strength</strong></td>
<td>0.014</td>
<td>0.007</td>
<td>-0.141</td>
<td>0.124</td>
<td>0.063</td>
</tr>
<tr>
<td><strong>IR_con strength</strong></td>
<td>-0.127</td>
<td>0.040</td>
<td>-0.124</td>
<td>-0.066</td>
<td>-0.024</td>
</tr>
<tr>
<td><strong>IR_ecc strength</strong></td>
<td>-0.178</td>
<td>-0.106</td>
<td>-0.063</td>
<td>-0.066</td>
<td>-0.018</td>
</tr>
<tr>
<td><strong>ER_con/IR_con strength ratio</strong></td>
<td>0.299</td>
<td>0.183</td>
<td>-0.066</td>
<td>0.052</td>
<td>-0.180</td>
</tr>
<tr>
<td><strong>ER_ecc/IR_con strength ratio</strong></td>
<td>0.029†</td>
<td>0.326</td>
<td>-0.180</td>
<td>0.555</td>
<td>-0.366</td>
</tr>
<tr>
<td><strong>ER_ecc/IR_ecc strength ratio</strong></td>
<td>0.657</td>
<td>0.560</td>
<td>0.566</td>
<td>0.561</td>
<td>0.561</td>
</tr>
<tr>
<td><strong>ER_ecc/IR_con strength ratio</strong></td>
<td>0.015†</td>
<td>0.560</td>
<td>0.566</td>
<td>0.361</td>
<td>0.361</td>
</tr>
</tbody>
</table>

nSIRT = normalized shoulder internal rotation torque; nSCF = normalized shoulder compression force; ROM = range of motion; ER = external rotation; IR = internal rotation; i = isometric; con = concentric; ecc = eccentric.

†Correlation significant ($p < 0.05$).

**Figure 1.**: Scatter plots of nSCF and (A) isometric IR; (B) isometric ER/IR ratio; (C) concentric ER at 90°·s⁻¹; (D) concentric ER at 180°·s⁻¹; and (E) concentric IR at 180°·s⁻¹. ER = external rotation; IR = internal rotation; nSIRT = normalized shoulder internal rotation torque; nSCF = normalized shoulder compressive force.
Discussion

Our results provide insight into relationships between shoulder rotational strength and pitching kinetics and performance in collegiate pitchers, with several significant correlations identified between strength and peak shoulder compressive force and between strength and pitching velocity. Our hypothesis that correlations exist between clinical measures and pitching kinetics was found to be partially true, as we found significant correlations between shoulder rotational strength and peak shoulder compressive force. Our hypothesis that positive correlations exist between strength metrics and pitch velocity was found to be true. These findings identify relationships that may enhance pitching performance.

Strong positive correlations were found between shoulder IRi strength ($r = 0.561$), IRcon strength ($180^\circ\cdot s^{-1}$, $r = 0.615$), and ERcon strength ($90^\circ\cdot s^{-1}$, $r = 0.560$ and $180^\circ\cdot s^{-1}$, $r = 0.622$) with peak shoulder compressive force. Strong positive correlations were also found between ERi strength ($r = 0.567$), IRi strength ($r = 0.613$), ERcon strength ($90^\circ\cdot s^{-1}$, $r = 0.657$ and $180^\circ\cdot s^{-1}$, $r = 0.603$), and pitch velocity. Indicating that as shoulder rotational strength increased, the shoulder compressive force increased, along with an increase in pitching velocity. Three of the 4 correlations with ball velocity involved the external rotators, suggesting that external rotator strength may be a key metric to pitch velocity. A strength training program focusing on increasing external rotator strength is needed to determine whether training-specific strength metrics increase velocity.

The shoulder compressive force peaked just after ball release, during arm deceleration. An increase in peak shoulder compressive force after ball release may result in rotator cuff muscle tensile failure and may tear the anterosuperior glenoid labrum (17). A strong negative correlation was also found between ER/IR strength and peak shoulder compressive force ($r = -0.675$), indicating that as the ER/IR strength ratio decreases, the shoulder compressive force increases. This negative ER/IR correlation aligns with the positive IR correlation, in that as the internal rotators increase in strength without strengthening the external rotators, the ER/IR ratio decreases. Having adequate shoulder strength is needed to resist distraction at the shoulder during arm deceleration (17). To investigate further, a strength training program focusing on increasing internal rotator concentric and external rotator eccentric strength is needed to determine whether training-specific strength metrics have an effect on shoulder kinetics.
Only 1 previous study has investigated correlations between shoulder rotational strength and ROM and pitching kinetics (23). Hurd and Kaufman (23) reported a significant negative correlation between ER ROM and shoulder IR torque. Although the total ROM was comparable between studies (current: 182 ± 18° vs. Hurd: 185 ± 14°), Hurd and Kaufman (23) reported an increased ER ROM (+17°) and decreased IR ROM (−19°) compared with the current study. These differences may be why the current study did not find similar significant correlations between ROM and kinetics. Hurd et al. (22) also reported lower ER strength (−15 Nm·kg−1), lower IR strength (−21 Nm·kg−1), and increased peak nSIRT (+0.2 Nm·m−1·kg−1) compared with the current study. The lack of relationship between shoulder IR torque and strength measures or ROM in the current study suggests these variables not statistically related for the population studied, possibly due to the differences mentioned above. Although pitcher height was similar (current: 185 ± 8 cm vs. Hurd et al. 183 ± 7 cm), body mass of the college pitchers in the current study (91 ± 14 kg) was higher than the high school pitchers (83 ± 12 kg) examined in the Hurd study (23). Biomechanical differences such as stride length, knee flexion, shoulder ER, trunk tilt, and joint velocities have been found among various levels of competition (18,19).

In comparing our strength ratios with another study involving college pitchers, our concentric ratios (ERcon/IRcon: 0.69–0.73) were similar to what Mikesky et al. (26) found (ERcon/IRcon: 0.69–0.72), whereas our eccentric ratios (ERecc/IRecc: 0.50–0.46) were lower pitchers (ERecc/IRecc: 0.80–0.62). This highlights the need to normalize the strength and biomechanical measures to body mass. Direct comparison of our results to previous literature was also limited due to differences in subject skill level, strength testing position, and testing speed. Several investigators have studied shoulder rotational strength in pitchers at multiple levels of competition (2,5,6,8,12,14,20,22,23,26,27,30–32,34). Although in general, shoulder IR strength is greater than ER strength in pitchers' dominate arms, subject arm positioning and testing speed both influence the strength tests performed. Many studies testing isokinetic strength in pitchers use a seated or standing position, with the shoulder abducted 90° and the elbow flexed 90° because it mimics the throwing motion (2,14,26,28,30,34). Others use a modified neutral position with the pitcher seated, shoulder in the scapular plane, and elbow bent to 90° to minimize shoulder impingement during testing (2,27,32). In comparing studies that examined the college pitcher's isokinetic strength at 300°·s−1, Mikesky et al. (26) reported the highest values of concentric and IRecc strength (ERcon: 53.3 ± 2.8 Nm, ERecc: 63.0 ± 3.1 Nm, IRcon: 84.0 ± 7.7, IRecc: 108.7 ± 6.8 Nm) in a seated position with the shoulder abducted 90° and the elbow flexed 90° compared with Noffal (28) with a similar arm position but with the subject supine instead of seated (ERcon: 30.8 ± 4.8 Nm, ERecc: 55.0 ± 6.6 Nm, IRcon: 48.4 ± 9.6 Nm, IRecc: 71.8 ± 9.4 Nm). Vogelpohl and Kollock (32) tested subjects seated with their arm in a modified neutral position and had the lowest reported ER strength values, with IR strength values falling between values reported by Mikesky and Noffal (ERcon: 18.5 ± 3.4 Nm, ERecc: 45.3 ± 10.9 Nm, IRcon: 55.8 ± 8.1 Nm, IRecc: 81.4 ± 8.4 Nm). Varying isokinetic test velocities also yield different results. As the speed of the movement increases, concentric peak torque decreases and eccentric peak torque increases or remains the same (2,14,20,26,30,34). Although higher testing speeds may be more relevant to baseball considering the rotational velocity of the shoulder during pitching (up to 7,000°·s−1) (11), higher testing speeds show less accuracy due to the subjects slowing down at the end range in fear of injury (4,8,32).

The average pitching velocity for collegiate pitchers in our study (34.5 ± 1.8 m·s−1) fell between previously reported velocities for high school (33.1 ± 1.2 m·s−1) and college (36.6 ± 1.2 m·s−1) (18). Another study of professional and collegiate pitchers reported a high ball velocity group of 38.4 ± 0.6 m·s−1 and a low ball velocity group of 33.2 ± 0.9 m·s−1 (26). The lower pitch velocity in the current study is
likely reflective of the Division III and Division I club level pitchers used. Pitch velocity is a key factor in delivering an effective pitch. Results have varied regarding the relationship between shoulder rotational strength and pitch velocity \(^{(4,8,26)}\). In agreement with the current study, Clements et al. \(^{(8)}\) found a positive correlation in adolescent players between IRi strength and velocity. Although Mikesky at al. \(^{(26)}\) found no correlations between peak concentric or IRecc and ERecc torques with pitching velocity in collegiate pitchers, they found a positive correlation between the shoulder ERcon/ERecc ratio at 3.7 rad·s\(^{-1}\) \((\sim 212°·s^{-1})\) and pitching velocity. Bartlett et al. \(^{(4)}\) found no correlations in professional pitchers between velocity and IRcon or ERcon strength at 90°·s\(^{-1}\). Differences in strength testing methodology, level of competition, and pitch velocity testing explain why some results conflict with the current study. To assess pitching velocity, Bartlett and Clements did not have the players throw off a pitching mound, and Mikesky et al. used in-game velocity to determine average fastball speed \(^{(4,8,26)}\).

Although there were several significant correlations found, there were some limitations in the study. One limitation was the small sample size, with 10 of the 13 pitchers being right handed. Warner et al. \(^{(13)}\) found significant differences between 5 kinematic variables during the pitching cycle between right- and left-handed pitchers. With data from only 13 pitchers to perform statistical analysis, smaller differences may go undetected and increased the possibility of type II error, along with not enough subjects to determine whether handedness influenced the associations found. With the lower level of collegiate pitchers used in the study, different correlations may be found in higher level collegiate players and should be explored more. The effort and apprehension level of the subjects may have decreased the accuracy of the strength measures. Subjects were instructed to give maximum effort, but effort level cannot be fully controlled. Although the nondominant arm was tested first for shoulder strength to familiarize the subject with the protocol, the study did not allow for submaximal contractions before testing. This may have allowed for increased comfort with the strength testing. The order of strength testing was also not randomized. Although the 2 test sessions were separated by a minimum of 2 days, subjects were not prohibited from exercising or throwing between the test sessions. Finally, although the correlations in our study were significant, they were determined at a single time point. To assess the outcome of clinical measures on pitching performance and injury, a study with preseason and postseason measurements, along with injury tracking, is needed.

**Practical Applications**

The results of this study show the relationships that exist between shoulder rotational strength and pitching kinetics and performance in collegiate pitchers. Three strength metrics (IR, ERcon at 90°·s\(^{-1}\), and ERcon at 180°·s\(^{-1}\)) were positively correlated with both peak shoulder compressive force and pitch velocity. These findings suggest that strength and conditioning specialists may be able to improve pitchers’ performance, through increased ball velocity, by increasing these areas of shoulder strength. To increase pitching velocity without increasing risk of injury, pitchers must properly coordinate muscle activity \(^{(8)}\). Although upper limb muscle strength is important, pitching velocity cannot be entirely dependent on those muscles alone. Proper coordination among the upper extremity muscles and with the trunk and lower extremities is essential in throwing properly and efficiently \(^{(8)}\). Future research should incorporate trunk and lower extremity strength to determine full body contributions to pitch velocity. Knowledge of relationships between strength metrics and pitching biomechanics may allow for improved strength training routines with the goal of increasing velocity without increasing injury risk.
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