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Relationship of shoulder internal and external rotation peak force and rate of force development to throwing velocity in high school and collegiate pitchers

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ABSTRACT

The purpose of this research was to characterize the difference between high school (HS) and collegiate pitcher's throwing velocity, shoulder internal (IR) and external rotator (ER) maximum strength (Fmax) and rate of force development (RFD) and explore relationships between these measures. Competitive HS and collegiate pitchers ($n = 26$) participated in a single session assessment in which shoulder rotator isometric Fmax and RFD were quantified via a portable strain gauge device and throwing velocity via radar. Paired t-tests, stepwise linear regression models and correlational analyses were used to answer the questions of interest. No significant differences ($p > 0.05$) in pitching velocity were observed between HS and collegiate pitchers, and all pitchers were pooled into one sample for subsequent analyses. For both IR and ER models, the explained variance of Fmax with throwing velocity was small ($R^2 = 0.12$–0.13). RFD and arm length did not contribute to the models. Large correlations ($r \geq 0.50$; $p < 0.001$) were observed between IR and ER for Fmax and RFD measures, as well as between Fmax and RFD for IR and ER. In terms of throwing velocity, having strong IR and ER Fmax capabilities would seem more important than the ability to express force quickly in this cohort.

1. Introduction

Throwing is an athletic skill fundamental to numerous sports. In baseball it has evolved further into a more specialized form known as pitching, where a pitcher's main objective is to minimize opponent scoring ability. To this end, increasing throwing velocity is a prized attribute in pitchers, giving less time for opposing hitters to make solid contact. Strategies to improve throwing velocity have been heavily researched and consist of non-specific (i.e., various methods of resistance training) and specific methods (i.e., throwing weighted balls) (Job et al., 2022). In tandem with training, it is important to have a better understanding of the measures associated with throwing velocity to provide guidance for these training interventions.

High-level pitching requires adequate anatomy, mobility, strength and coordination (Chu et al., 2016). Authors comparing high- and low-velocity pitchers reported the former have anatomical advantages such as height and forearm length and consistently produced more force throughout their delivery compared to low-velocity pitchers (Matsuo et al., 2001). The throwing motion is complex; forces created by the lower body and core compound throughout the throwing motion creating high forces on the shoulder joint leading to ball release (Chu et al., 2016; Fleisig et al., 1999; Lintner et al., 2008). As a result, shoulder internal rotation (IR) velocity can exceed 6,500 degrees per second across youth to professional pitchers (Fleisig et al., 1999). Following ball release, deceleration relies on adequate strength from the external rotators (ER) and posterior shoulder musculature to dissipate large forces that may exceed bodyweight (Chu et al., 2016; Fleisig et al., 1999; Jobe et al., 1984). Thus, strengthening the shoulder rotators to contribute to and withstand the demands of throwing are paramount for pitchers.

Researchers reported positive associations of throwing velocity with throwing arm isometric IR peak torque in HS ($r = 0.678$, $p = 0.004$) (Clements et al., 2001) and college pitchers ($r = 0.592$–0.613, $p < 0.05$) (Cross et al., 2023; Higgins, 2019), and isometric ER peak torque with college pitchers ($r = 0.567$–0.727, $p < 0.05$) (Cross et al., 2023; Higgins, 2019). Such information could be useful to guide training, however,

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most research has used expensive in-lab isokinetic dynamometry, limiting integration into practice. Recently developed strain gauge technology (Job et al., 2024b – Under Review; Pichardo et al., 2024) might provide utility in characterizing qualities underlying throwing velocity, which can be easily integrated into training and monitoring practices. For example, the ratio between ER and IR strength could be an interesting metric, with decreased ratios due to ER weakness having been associated with throwing arm injuries (Byram et al., 2010; Shitara et al., 2017). Moreover, other variables such as rate of force development (RFD) which are commonly assessed with isokinetic dynamometry, may provide additional insight into throwing performance. The relationship between shoulder rotator RFD and throwing velocity is currently unknown, however, more practical equipment like strain gauge technology has been used with acceptable relative consistency measuring RFD in baseball pitchers (Job et al., 2024b – Under Review). Understanding the relationships of isometric shoulder rotator strength and throwing velocity with portable, high-sampling equipment provided the primary focus of this article.

Many HS baseball players strive to continue their playing careers at the collegiate level. Practically very large differences (Cohen's d = 1.25) (Sawilowsky, 2009) in throwing velocity have been reported between levels (29.1–33.0 m/s and 34.3–36.6 m/s for HS and collegiate pitchers, respectively) (Cross et al., 2023; Fleisig et al., 2009; Fleisig et al., 1999; Scarborough et al., 2021; Stodden et al., 2005), therefore improving throwing velocity would seem critical for advancement. One explanation for the differences in velocity between the two levels could be attributed to greater muscular strength and anthropometric advantages (Fleisig et al., 1999; Matsuo et al., 2001). Very large differences (Cohen's d = 1.65–1.75) in shoulder rotator strength measured with hand-held dynamometry (HHD) have also been noted between HS and collegiate pitchers. Shoulder IR Fmax ranged from 127.2–203.6 N and ER from 120.1–138.4 N for HS pitchers (Hurd and Kaufman, 2012; Hurd et al., 2011; Shitara et al., 2017; Tyler et al., 2014). Expectedly, college and minor league pitchers (age = 21 ± 2 years) reported greater shoulder rotator Fmax production (IR = 232.5 ± 48.1 N, ER = 179.5 ± 37.3 N) (Mullaney et al., 2005). Understanding the relationship between throwing velocity and underlying physical characteristics (i.e., strength), and awareness of those relationships across pitching levels, may provide information to enhance training.

This study's purpose was to determine if shoulder rotator strength (i.e., IR and ER Fmax and RFD) is an important predictor of throwing velocity, and if HS and collegiate pitchers differed in throwing velocity and shoulder rotator strength. Also, of interest was the relationship between strength measures, and whether those with high IR Fmax and RFD had similarly high ER Fmax and RFD. Given the surrounding literature it was hypothesized that: 1) HS and collegiate pitchers would differ in the variables of interest; 2) rotator strength would have a small to moderate relationship to throwing velocity; 3) those with strong IRs would have strong ERs (i.e. high correlation); and 4) the strength of association between Fmax and RFD would be relatively small. Understanding differences between HS and collegiate pitchers, the relationship of shoulder rotator strength with throwing velocity, and how strength measures are related should enable athletes and coaches to progress and individualize training programs to optimize performance and maintain arm health.

2. Materials and methods

2.1. Design

A cross-sectional design was implemented, where participants from two different playing levels completed IR and ER strength testing in a supine position and throwing velocity testing from a standing position (i.e., "the stretch"). Outcome variables (Fmax, RFD and peak throwing velocity) from these analyses were used to characterize the difference between the levels, and the relationships between strength qualities and throwing velocity for IR and ER separately.

2.2. Participants

Competitive HS and college male pitchers (see Table 1) volunteered to participate in this research during the off-season and with at least two days rest from high-intent throwing. All participants were injury free and written consent was provided by each participant and their respective parent or guardian before participation. Ethics was approved from the institutional ethics committee (AUTEC 19/445).

2.3. Procedures

Shoulder rotation strength and throwing velocity were assessed in a single session. Participants were familiarized with the assessment protocols one week prior to data collection. During the familiarization session, height, weight, and forearm length were recorded. Forearm length was measured as the distance between the olecranon process and ulnar styloid process, and was in the analysis given it's reported influence on throwing velocity (Matsuo et al., 2001).

For strength measures, continuous force–time data was collected at 1,200 Hz with a custom, wireless strain gauge comprised of an S-beam load-cell (Hawkin TruStrength, Portland, Maine). Throwing velocity was measured by a radar gun at 47 Hz (Stalker ATS II Version 5.0.2.1, Applied Concepts Inc., Richardson, TX, USA).

Two warm-ups were performed to prepare the participants for maximal isometric shoulder rotator strength testing and maximal effort throwing, respectively. The shoulder rotator strength assessment, and preceding warm-up, were always performed before the throwing velocity assessment. First, participants tested shoulder rotator strength which was preceded by a shoulder rotator focused warm-up. The warm-up for shoulder strength testing included shoulder IR and ER exercises performed regularly in training with submaximal, rubber-based resistance. Participants were positioned supine with the shoulder abducted to 90 degrees, the elbow flexed at 90 degrees and kept their non-testing arm relaxed with their hand placed on their stomach (see Fig. 1). The knees were bent with the feet flat on the floor and the elbow remained in contact with a rolled towel and the top of the strain gauge was aligned with the subject's ulnar styloid process. The device was set to measure compressive forces and was placed against a wall. An isometric test was chosen due to the simple and repeatable nature of the protocol, which resulted in acceptable typical error and relative consistency for Fmax and acceptable relative consistency for RFD (Job et al., 2024a). Additionally, testing in this position allowed for great ER outputs compared to the shoulder being abducted to 0 degrees which is likely due to greater posterior shoulder muscle recruitment (Escamilla et al., 2009)

Table 1
Pitcher characteristics.

	High school (mean ± SD)	College (mean ± SD)	Combined (mean ± SD)
n	13	13	26
Age (years)**	17.5 ± 0.9	21.3 ± 1.3	19.4 ± 2.2
Height (cm)	184.3 ± 6.6	181.8 ± 7.3	183.0 ± 7.0
Weight (kg)	80.6 ± 9.9	83.3 ± 9.5	81.9 ± 9.6
Forearm length (cm)*	29.6 ± 1.4	28.2 ± 1.9	28.9 ± 1.8
IR Fmax (N)	214.5 ± 38.1	218.4 ± 39.0	216.4 ± 37.9
IR RFD (N/s)	808.8 ± 346.3	749.2 ± 314.3	779.0 ± 325.5
ER Fmax (N)	192.8 ± 21.5	200.6 ± 33.2	196.7 ± 27.7
ER RFD (N/s)	594.5 ± 300.0	636.0 ± 323.7	615.3 ± 306.5
Throwing velocity (m/s)	36.3 ± 1.9	36.4 ± 1.3	36.4 ± 1.6

SD, standard deviation; cm, centimeters; kg, kilograms; N, Newtons; N/s, Newtons per second; m/s, meters per second.
*Significant difference between high school and collegiate pitchers $p < 0.05$.
**Significant difference between high school and collegiate pitchers < 0.001.

Fig. 1. Shoulder internal (1A) and external (1B) rotation strength testing set up.

which is advantageous for pitchers due to the throwing deceleration phase.

The researcher ensured proper set up and gave a three second countdown followed by "GO" and "RELAX" verbal cues to start and end the trial after a 3-second contraction. The researcher encouraged participants to "rotate fast and hard" for three seconds to assess RFD and Fmax. Five test trials were performed to collect Fmax and RFD for both shoulder IR and ER, respectively, totaling 10 trials. Participants were allowed 1-minute rest between trials. Trials were recorded using the manufacturer provided software and saved in raw form for later analysis.

Following strength testing, participants warmed-up for the throwing velocity assessment, by jogging, skipping, and dynamic stretching followed by submaximal throws with a standard baseball. When ready, the subject performed five throws from the stretch in an indoor throwing lane. Peak throwing velocity was measured by radar gun mounted 0.9 m behind the target. Participants were allotted 30 s between trials. Radar gun settings were selected to display peak velocity which was recorded into a spreadsheet.

2.4. Data analysis

Raw, unfiltered force–time data from the strain gauge were uploaded into MATLAB (version: 2019B, The MathWorks, Inc., MA USA), with trials inspected and irregularities (i.e., failure to maintain pretension) discarded. The start of the trial was manually selected as first point of increase from resting force pre-contraction. Subsequently, Fmax was defined as the instantaneous peak across the entire trial and RFD as the average force value over the 120-milliseconds succeeding force onset. For Fmax and RFD IR and ER, and throwing velocity, all five trials were averaged for the final analysis. The data underlying the subsequent statistical analysis is available in Supplementary files.

2.5. Statistical analysis

All statistical analyses were performed in JASP (JASP, 2024). Outlier analysis and normality testing preceded statistical analyses. Descriptive data are presented as means and standard deviations, representing centrality and spread of data. To address the first aim, a series of independent samples t-tests were used to measure differences in anthropometrics, strength and throwing velocity between the HS and college pitchers. To address the second aim two multiple linear regression models with stepwise selection criteria were built with raw force values and forearm length. This analysis was performed on pooled data (i.e., both cohorts) to both increase statistical power, and due to a lack of clear between group differences. Separate models were built for IR and ER due to different roles of the shoulder rotators while throwing, and include Fmax, RFD and forearm length for IR and ER, respectively. Inclusion and exclusion criteria for predictors were set at $p < 0.05$ and $p > 0.1$, respectively. To assess overall model fit, adjusted R^2 and comparison to the null model (using the p-value and F-statistic) were reported. To assess model contribution, unstandardized coefficients and 95 % confidence intervals were reported, alongside standardized coefficients. Finally, the association between strength metrics within IR and ER (Fmax vs. RFD, for IR and ER each) and between (IR vs. ER, for Fmax and RFD each) was assessed using Pearson's correlation coefficient (*r*). The magnitudes of the correlation coefficients were interpreted using Cohen's scale (Cohen, 2013): <0.10, trivial; 0.10–0.29, small; 0.30–0.49, moderate; ≥0.50, large. For all tests, the significance level set to $p < 0.05$.

3. Results

There were differences in age ($p < 0.001$), and forearm length ($p < 0.05$) between HS and college pitchers, however, there were no other differences ($p > 0.05$) between the cohorts (see Table 1). The similarity in throwing velocity between groups is evident (Fig. 2), and in combination with the non-statistically significant between-group differences in shoulder rotator strength ($p > 0.05$) led to the pooling of participants for subsequent analyses.

In both IR and ER stepwise linear regression models, Fmax was the only variable retained; RFD and forearm length were removed (see Table 2). A positive association was observed in both models where a 30 N increase in IR Fmax resulted in a 0.51 m/s increase in throwing velocity (throwing velocity = 32.710 + 0.017 × IR Fmax; Fig. 3), and a 30 N increase in ER Fmax resulted in a 0.72 m/s increase in throwing velocity (throwing velocity = 31.649 + 0.024 × ER Fmax; Fig. 4).

Pairwise correlations were statistically significant between shoulder IR and ER for Fmax ($r = 0.63$, $p < 0.001$) and RFD ($r = 0.71$, $p < 0.001$). Similarly, the correlations between Fmax and RFD were also statistically significant for IR ($r = 0.725$, $p < 0.001$) and ER ($r = 0.549$, $p = 0.004$).

4. Discussion

The focus of this research was to understand the differences between

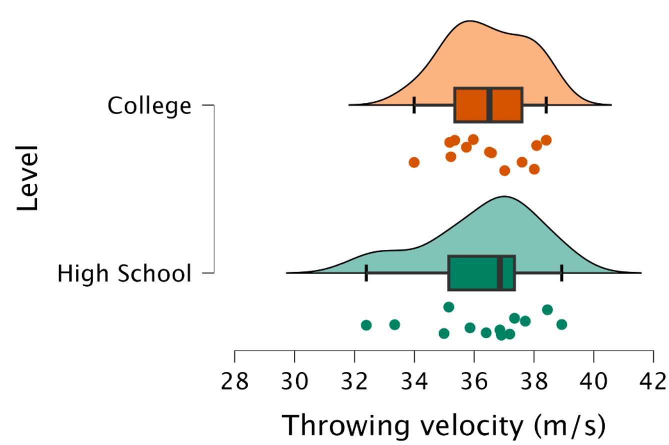

Fig. 2. Comparisons in throwing velocity between HS and college pitchers.

Table 2
Association between shoulder strength and throwing velocity for internal and external rotation.

Variable	Coefficient (95 % CI)	Standardized Coefficient	p	Variable	Coefficient (95 % CI)	Standardized Coefficient	p
External rotation [(1)]				Internal rotation [(2)]			
Intercept	31.649 (27.201, 36.098)	—	0 < 0.001	Intercept	32.710 (29.079, 36.340)	—	0 < 0.001
Fmax	0.024 (0.002, 0.046)	0.410	0.037	Fmax	0.017 (3.047×10^{-4}, 0.033)	0.394	0.046
RFD	—	—	—	RFD	—	—	—
Forearm length	—	—	—	Forearm length	—	—	—

[(1)] , $F(1,24) = 4.855$, $p = 0.037$.
[(2)] , $F(1,24) = 4.418$, $p = 0.046$; CI, confidence intervals; ER, external rotation; IR, internal rotation; Fmax, peak force; RFD, rate of force development; —, variable dropped from stepwise model.

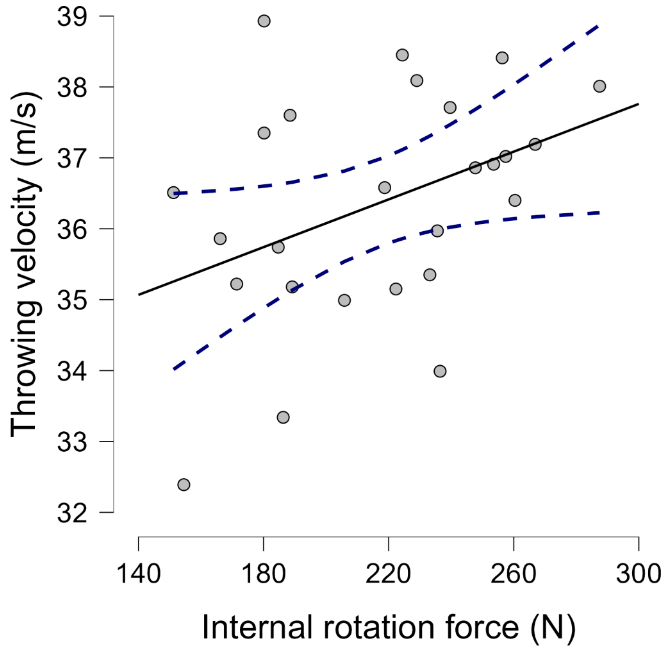

Fig. 3. Relationship between shoulder IR Fmax and throwing velocity with 95 % confidence intervals (linear fit = black line, confidence intervals = dashed lines, points = individual data).

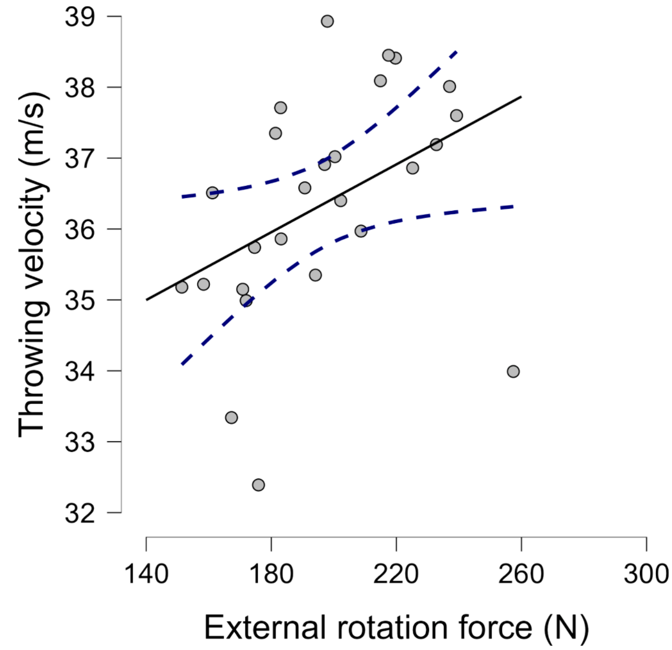

Fig. 4. Relationship between shoulder ER Fmax and throwing velocity with 95 % confidence intervals (linear fit = black line, confidence intervals = dashed lines, points = individual data).

HS and collegiate pitchers, the relationship of shoulder rotator strength with throwing velocity, and the relationship of strength measures to each other. The main findings were: 1) in our sample, HS and collegiate pitchers did not differ from each other in the principal variables of interest; 2) IR and ER Fmax appeared positively associated with throwing velocity, where RFD was not; and 3) finally, large correlations ($r \geq 0.50$; $p < 0.001$) were observed between the IR and ER force measures, and between Fmax and RFD capabilities for both IR and ER.

It was hypothesized that collegiate compared to HS pitchers would be stronger and throw faster, however, this was unsupported. Differences in age (19.6 %, $p < 0.001$) and forearm length (4.8 %, $p < 0.05$) did not discern throwing velocity between skill levels within these pitchers. Albeit statistically significant, the difference in forearm length is likely not meaningful. Collegiate pitchers in this study were primarily from the Division III level with similar throwing velocity to previous research (36.4 m/s versus 34.3–36.6 m/s, respectively) (Cross et al., 2023; Fleisig et al., 2009; Fleisig et al., 1999; Stodden et al., 2005). The HS pitchers in this study were better trained compared to existing research with greater throwing velocities (36.3 m/s versus 29.1–33.0 m/s, respectively) (Fleisig et al., 2009; Fleisig et al., 1999; Scarborough et al., 2021), which may explain the similarities between groups. Furthermore, heightened awareness of rotator strength importance and an emphasis on training these muscles earlier in a competitive career might explain the non-significant differences in throwing velocity. This contention somewhat supported as the shoulder rotator Fmax of the HS pitchers in this study were greater (IR = 214.5 ± 38.1 N, ER = 192.8 ± 21.5 N) compared to similar cohorts (IR = 127.2–203.6 N, ER = 120.1–138.4 N) (Hurd and Kaufman, 2012; Hurd et al., 2011; Shitara et al., 2017; Tyler et al., 2014), albeit with differing methodologies. Furthermore, if training protocols are improving and becoming more common, the influence of shoulder rotator strength on throwing velocity across different competition levels may decrease.

Our hypotheses were supported regarding the influence of rotator strength on throwing velocity. The only variable entered into the regression models was Fmax which accounted for 12.0 % ($p = 0.046$) and 13.4 % ($p = 0.037$) shared variance for the IR and ER models, respectively. Previous researchers have reported higher common variance between throwing velocity and isometric IR peak torque (35.0–46.0 %) and isometric ER peak torque (32.1–70.2 %), although with smaller sample sizes ($n = 12$–18) of HS and collegiate pitchers (Clements et al., 2001; Cross et al., 2023; Higgins, 2019). Comparing common variance among studies is difficult due to varying equipment, testing positions and sample sizes (Job et al., 2024a).

RFD was excluded from the models, which was somewhat surprising given the extraordinary arm speeds reported while throwing (Fleisig et al., 1999) seemingly indicating a necessity to develop and brake force quickly. One explanation might be that isometric RFD has little correspondence to the dynamic RFD needed for pitching (James et al., 2023). While isometric testing is simple and efficient, it does lack the stretch shortening cycle which contributes to RFD in dynamic actions. Another contention is that timing, muscle activation and force production increases of the shoulder rotators during the preceding phases influence arm acceleration, consequently making RFD less important (Escamilla and Andrews, 2009). Additionally, submaximal shoulder rotator muscle activity during the deceleration phase and/or a gradual rise in force production from the preceding kinetic sequence (Escamilla and Andrews, 2009) may influence the importance of RFD. It would seem of the two variables, Fmax is more important than RFD in characterizing throwing velocity.

It was thought that pitchers with high IR strength would have similarly high ER strength. Large correlations (≥.50; $p < 0.001$) were observed between the IR and ER strength measures. Intuitively, it makes sense that if you have strong throwing accelerators, or IRs, you need matching strength in the throwing decelerators, or ERs. Although the correlations were large, there was some unexplained variance between measures, suggesting cause to assess and monitor both. Given that preseason shoulder ER weakness and disparate ER:IR ratios have been associated with throwing arm injuries requiring surgery (Byram et al., 2010), regularly incorporating shoulder rotator strength assessment may provide value to athletes and coaches. A portable device, such as the one used in this study, could be used throughout the competitive season to individualize training based on athlete needs. For example, if an athlete's ER Fmax declines, coaches could modify training to specifically target the ER musculature.

Large correlations were also observed between Fmax and RFD for IR and ER. Fmax and RFD seem to share similar strength qualities but also offer different insight into force capability, especially for ER RFD. The large correlations between Fmax and RFD were not surprising given that maximal strength (i.e., Fmax) is usually the cornerstone of most rehabilitation and sport performance programs, and explosive strength (i.e., RFD) is typically prescribed following maximal strength. However, it has been reported in the literature that the two measures are somewhat independent strength qualities and therefore the need to be assessed and probably trained independently (Maffiuletti et al., 2016; Taber et al., 2016). Perhaps explosive rotator strength training is needed in this cohort to delineate more clearly between the two measures. The specific importance of RFD to the accelerators and decelerators of the arm for throwers seems negligible but further research should be considered.

In this cohort, HS and lower ranking collegiate level pitchers showed no differences ($p > 0.05$) in throwing velocity and shoulder strength. We speculated that this was due to better trained HS pitchers with greater shoulder rotator strength and pitching velocity in this cohort compared to similar cohorts previously reported. However, future research should aim to replicate these results in other athlete cohorts, and with larger samples. Indeed, increased power might uncover smaller but potentially interesting associations with other force metrics underlying throwing velocity. Shoulder IR and ER Fmax were associated with throwing velocity, albeit seemingly minorly, which might be explained by the cohort's homogeneity. Nonetheless, a 30 N increase in IR Fmax predicted a 0.51 m/s increase in throwing velocity, similarly a 30 N increase in ER Fmax projected a 0.72 m/s increase. RFD and forearm length were not clearly associated with throwing velocity. Although there is shared variance between shoulder IR and ER, it is likely important to specifically target each action for strengthening separately from throwing. Such improvements on shoulder IR and ER Fmax capability could have positive outcomes on throwing performance. Finally, monitoring shoulder rotator strength via simple, efficient isometric testing could be a method of workload monitoring for pitchers to maximize performance.

CRediT authorship contribution statement

Trey D.W. Job: . **Matthew R. Cross:** Writing – review & editing, Methodology, Formal analysis. **John B. Cronin:** Writing – review & editing, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: John Cronin is an inventor and shareholder in the strain gauge technology used in this study. The results of the present study do not constitute endorsement of the product by authors.

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Appendix A. Supplementary data

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