Investigating the Influence of Modifiable Physical Measures on the Elbow Varus Torque – Ball Velocity Relationship in Collegiate Baseball Pitchers

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Background: The mechanism of ulnar collateral ligament (UCL) injury during pitching is excessive elbow varus torque (EVT). The EVT–ball velocity (T-V) relationship allows concurrent assessment of player performance and UCL injury risk. Modifiable physical capacities may underlie individual variation seen in the T-V relationship.

Purpose: To identify physical performance characteristics that impact the T-V relationship during pitching.

Study Design: Descriptive laboratory study.

Methods: A total of 87 National Collegiate Athletic Association Division I pitchers participated. Pitching collection involved measurement of EVT and ball velocity during 5 maximal effort fastballs thrown to a catcher. Physical measures collected were the following: shoulder and hip passive range of motion (ROM) and strength, shoulder rate of torque development (RTD), grip strength, and lumbopelvic stability. Physical measures were entered into univariate linear mixed models with ball velocity as a covariate to predict EVT. Variable reduction for multivariate models involved selection of physical measures based on random forest–derived variable importance and univariate relationship significance, rendering a 27-variable pool. Multivariate linear mixed models predicting EVT, adjusting for physical measures and other physical characteristics, were then created using backward elimination.

Results: In univariate analysis, for every 1 m/s (2.2 mph) increase in ball velocity, the mean EVT increased by 1.51 N·m (95% CI, 0.66-2.37 N·m; *P* = .001). In univariate analysis, hip abduction strength symmetry and bilateral lumbopelvic stability significantly increased EVT, while dominant-shoulder ROM, scaption RTD symmetry, and hip ROM significantly decreased EVT. Variables that increased EVT while controlling for ball velocity in the final model include grip strength symmetry, lead-leg lumbopelvic stability, and bodyweight. Increased dominant-shoulder internal rotation (IR) strength, dominant-shoulder flexion ROM, and scaption strength asymmetry decreased EVT as ball velocity increased.

Conclusion: Several modifiable physical measures affected EVT in the univariate analysis. In our final model, when controlling for ball velocity, EVT increased with increased grip strength symmetry, lead-leg lumbopelvic stability, and bodyweight and decreased with increased dominant-shoulder IR strength, dominant-shoulder flexion ROM, and scaption strength asymmetry.

Clinical Relevance: Defining the individual and multivariate effects of these physical capacities on EVT contextualizes their role in the T-V relationship and helps identify access points through which coaches and clinicians can optimize a pitcher's T-V relationship.

Keywords: elbow; baseball/softball; elbow varus torque; ball velocity; torque-velocity relationship; range of motion; pitching

The baseball pitch is a choreographed, full-body motion that requires generation and transfer of energy from the legs and torso, through the upper extremity, and

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ultimately into the ball.[19,51] The anterior band of the ulnar collateral ligament (UCL) is particularly susceptible to injury in baseball pitchers.[11,12] Recovery from UCL can be lengthy, and up to one-third of pitchers do not return to their former level of play.[55,58]

The mechanism of injury for the UCL is excessive elbow adductor (internal) torque during the late arm-cocking phase, commonly referred to as elbow varus torque (EVT).[22] The UCL provides approximately 50% of the resistance to EVT-imposed ulnohumeral joint gapping.[7] Accordingly, EVT is a proxy measure for UCL demand during pitching. When EVT increases, so does load on the UCL, which is also correlated with higher ball velocity.[5,61] This EVT–ball velocity (T-V) relationship is best described on an individual basis. Across pitchers, ball velocity is weakly associated with EVT.[37,43,50,53] The within-pitcher association is much stronger but with high variance, with some pitchers able to increase ball velocity without an increase in EVT.[37,50,53] It is unclear why the T-V relationship varies between pitchers and if or how this relationship is modifiable.

Physical capacities can often be modified with intervention, providing potential access points through which athletes, coaches, and clinicians may alter the T-V relationship. Several physical factors independently relate to EVT, ball velocity, or upper extremity injury. Of these, the most well studied is shoulder range of motion (ROM). Specifically, both shoulder rotational (external rotation [ER] and internal rotation [IR]) ROM and flexion ROM have been associated with increased EVT, throwing-arm demand, and injury.[8,10,26,28] Increases in shoulder ER, IR, and scaption strength have also been shown to relate to increases in ball velocity, upper extremity torques, or injury risk.[17,25,48] Grip strength, a measure of the flexor pronator muscle function, is associated with both protection of the medial elbow and maintenance of ball velocity.[46,57,60] Trunk and lower extremity mobility, strength, and stability can play an important role in modulating the T-V relationship. For example, increased hip strength, strength asymmetry, and ROM have been associated with increased ball velocity, EVT, and risk of injury.[3,4,38,47,64] Finally, deficits in lumbopelvic stability, defined as the ability to limit anterior-posterior or medial-lateral pelvic motion in unipedal stance, have also been associated with increased EVT and arm injury.[15,30,31] While these associations link modifiable physical factors with upper extremity demand and injury risk, most studies assessed these relationships in isolation.

In this study, we explored how physical capacities influence EVT in isolation while also seeking to better understand how several physical capacities may combine to influence EVT, controlling for ball velocity. The purpose of this study was to identify physical characteristics that impact the T-V relationship during pitching. We hypothesized that modifiable physical factors related to the capacity and control of the lumbopelvic, hip, shoulder, and forearm regions would impact EVT while controlling ball velocity.

METHODS

Participants

A total of 87 collegiate pitchers aged ≥18 years on a National Collegiate Athletic Association Division I roster were recruited for this study. Athletes with a current throwing elbow injury or injury in the last 6 months requiring ≥2 weeks of rest were excluded. This study was approved by the primary author's institutional review board (A.J.B., L.A.M.). All participants provided written informed consent before participation.

Procedures

Data were collected on 2 separate days as athletic schedules permitted, typically within 24 to 48 hours of one another. One day consisted of physical factor measurement, and the other day involved pitching collection. Test-retest reliability was conducted for all experimenters before data collection. An additional description of collection procedures and measurement reliability can be found in Supplemental Tables S1 and S2.

Pitching Collection. Before collection, pitchers completed their team-specific warm-up at their own pace. This typically included exercises, long-toss throws, and warm-up pitches. Participants were then instrumented with a single inertial measurement unit used to quantify EVT (PULSE; Driveline Baseball). The sensor was secured to the medial throwing forearm 2 finger-widths distal to the medial humeral epicondyle using tape and self-adhering wrap. Ball velocity was measured using a radar gun placed directly behind home plate (Stalker Sports). All pitches were thrown at regulation distance (18.4 m)

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from a mound to a catcher. Pitchers were allowed to throw as many warm-up pitches as they deemed necessary before throwing 5 maximal effort fastballs. The reliability of EVT was established as excellent (intraclass correlation coefficient [ICC] [3,2], 0.94; standard error of the mean [SEM], 24.3 N·m).

Shoulder Strength. Shoulder IR and ER strength were measured with participants in a seated position using a custom jig-secured handheld dynamometer (HHD) (Hoggan Scientific).[40] Scapular-plane elevation (scaption) strength was measured with the arm elevated to 90° and horizontally adducted 40° from the frontal plane. Two trials per arm were completed for each measure. In order to express strength as torque (N·m), ER and IR strength measures (N) were multiplied by forearm length (m), and scaption strength by arm length (m). Segment lengths were measured with a tape measure. Reliability was excellent (ICC[3,2], 0.94-0.98; SEM, 1.2-2.1 N·m). Three variables were computed using the maximum of 2 trials: peak strength on the dominant side, symmetry (absolute difference of dominant − nondominant), and rotational strength ratio (ER/IR).

Shoulder Rate of Torque Development. Shoulder rate of torque development (RTD) was measured concurrently with shoulder strength. Participants were instructed to push "as hard and as fast as possible" for 3 seconds while force and time data were recorded at 90 Hz (Myotest; Hoggan Scientific). Data were processed using a custom MATLAB code (MathWorks). Shoulder RTD was expressed in newton-meter per second by multiplying force over time (N/s) by dominant forearm length (m). Onset was defined as the time point when force increases by at least 1.4 N in consecutive frames. RTD was analyzed in 3 windows: peak (steepest slope of the force/time curve), mean slope in the first 100 milliseconds, and mean slope in the first 200 milliseconds.[33] Reliability was excellent across RTD windows (ICC[3,2], 0.92-0.97; SEM, 5.0-25.0 N/s). Three variables were computed for each measure (both ER and IR) and each RTD type using the maximum of 2 trials: RTD dominant side, symmetry (absolute difference of dominant – nondominant), and a ratio (ER/IR).

Passive Shoulder ROM. For both arms, passive IR, ER, and flexion ROM were measured with the participant supine. For IR and ER, the arm was in 90° of abduction and elbow flexion. The elbow was fully extended for shoulder flexion.[52] The examiner moved the arm to end range, and measurement was made using an Acumar inclinometer (Lafayette Instrument Company). Reliability was good to excellent (ICC[3,2], 0.79-0.95; SEM, 1.3°-3.6°). For shoulder flexion measurement, 2 variables were calculated using the mean of 2 trials: dominant-side ROM and symmetry (dominant – nondominant). For IR and ER, we also calculated dominant-side ROM, symmetry (dominant − nondominant), total ROM (TROM) on the dominant side (IR ROM + ER ROM), and TROM symmetry (dominant – nondominant).

Dominant-side ER and IR ROM were also expressed by adjusting for humeral torsion, measured using ultrasound as previously described.[41,44] Reliability was good (ICC[3,2], 0.77; SEM, 1.3°). We controlled for humeral torsion by subtracting the humeral torsion angle from ER ROM and adding the humeral torsion angle to IR ROM. These values were also used to calculate the symmetry indices (dominant − nondominant) adjusted for humeral torsion for ER, IR, and TROM.

Grip Strength. Grip strength was measured using a JAMAR grip dynamometer (Lafayette Instruments) with the participants in a seated position and their arm in 90° of abduction, ER, and elbow flexion. Two trials were performed on each hand. Reliability was excellent (ICC[3,2], 0.96; SEM, 56.7 N). Two variables were calculated from the grip strength measurement using the maximum of 2 trials: peak strength on the dominant side and symmetry (absolute difference of dominant − nondominant).

Hip Abduction Strength. Hip abduction strength was measured with the participants side lying and the test leg at 0° of abduction.[47,65] One strap secured an HHD 5 cm proximally to the lateral femoral condyle of the test (top) leg, while a second was secured just above the iliac crests for stabilization. Hip strength was expressed as torque by multiplying hip abduction force (N) by leg length (m) measured using a tape measure. Two trials were performed on each leg. Reliability was excellent (ICC[3,2], 0.95; SEM, 3.9 N·m). Three variables were computed for each measurement using the maximum of 2 trials: peak abduction strength for both legs and symmetry (absolute difference of lead − trail).

Hip ROM. With the athlete prone and knees flexed to 90°, the examiner moved the leg into hip IR and ER. Measurements were taken using a digital inclinometer for 2 trials (Lafayette Instruments). Reliability was excellent (ICC[3,2], 0.99; SEM, 0.7°-1.1°). The following variables were calculated using the mean of 2 trials for both IR and ER: ROM for both trail and lead legs, symmetry (absolute difference between sides: lead − trail), TROM for both the trail and lead legs, and TROM symmetry (absolute difference between sides: lead − trail).

Lumbopelvic Stability. Lumbopelvic stability was measured using a single-leg hip bridge endurance test. The testing position was achieved by raising the hips such that the body was in a straight line and straightening the knee of the noninvolved leg. Transverse plane stability was measured using a dual-axis digital protractor fixed to a belt across the anterior pelvis with hook-and-loop fasteners. Sagittal plane stability was measured using a protractor fixed to the dorsal surface of the stance leg thigh. One trial was performed per leg, recording time (in seconds) from initiation until failure (fatigue or technique failure). The hold time for both legs and symmetry (absolute difference between sides) were calculated for analysis. Reliability was excellent (ICC[3,2], 0.76; SEM, 9.3 seconds).

Statistical Analysis

Demographic and physical measure variables are described using mean with standard deviation and median with interquartile range for continuous variables. Categorical variables are described using frequency and percentage. Sample size estimation for a linear regression model with 5 predictors (α = .05, β = 0.8, $R^2 \geq 0.16$) indicated a minimum sample size of 80 participants was needed.

Mixed-effects linear regression was performed to univariately assess the relationship of ball velocity and 57 available modifiable physical measure variables on EVT. Variables were retained in the pool if their random forest–derived variable importance score exceeded 0.69 or they were significantly associated with EVT in univariate analysis ($P < .05$). Three additional, nonmodifiable physical factors, previous elbow injury, throwing handedness, and bodyweight, were included based on prior evidence of a relationship with elbow injury or EVT, resulting in a reduced set of 27 variables.[1,56,62] Mixed-effects linear regression models using backward elimination were used to model the reduced bank of 27 variables. Collinearity was evaluated by screening model inputs to ensure that similar physical measures were not included in the same model. Theoretical rationale was used to select the most relevant input. For example, a model would not be permitted to be run if the list of variable inputs included shoulder ER RTD at both 100- and 200-millisecond analysis windows because of high collinearity ($r > 0.70$). For all models, participant bodyweight was included as a covariate in lieu of ratio normalization.[23] Models containing a history of previous elbow injury and throwing handedness were removed from consideration given the small samples of left-handed and previously injured pitchers and lack of association with EVT. In total, 7 models demonstrated reduced out-of-bag error compared with the 27-variable full model and were retained for final comparison. The final model included variables with a P value of $\leq .1$ and were theoretically and clinically relevant based on the significance of the variables in the model AIC (akaike information criterion), BIC (bayesian information criterion), and expert opinion.

Results are described using beta coefficients, with associated 95% confidence intervals and P values. Statistical tests were 2-sided with type 1 error at 0.05. All statistical analyses were performed using Stata 17/SE (StataCorp).

RESULTS

Descriptive statistics for demographic, anthropometric, pitching, and physical measure data for 87 pitchers are reported in Table 1.

In univariate analysis (Table 2), for every 1 m/s (2.2 mph) increase in ball velocity, the mean EVT increased by 1.51 N·m (95% CI, 0.66 to 2.37 N·m; P = .001). Other variables significantly associated with EVT included dominant-shoulder flexion ROM, dominant-shoulder TROM, scaption RTD symmetry, hip abduction strength symmetry, both lead and trail leg ER ROM and TROM, and unilateral hip bridge time for both legs ($P < .05$). No grip strength variables were significantly associated with EVT in univariate analysis. All variables used in the univariate analysis are described in Supplemental Table S2.

Variables included in the final regression model after variable reduction are shown in Table 3. Ball velocity remained significantly associated with EVT after adjusting for modifiable physical measures. Increased grip strength asymmetry, lumbopelvic stability on the lead leg, and bodyweight were significantly associated with increased EVT, controlling for ball velocity ($P < .05$). Increased dominant-shoulder IR strength, dominant shoulderflexion ROM, and scaption strength asymmetry were associated with decreased EVT, controlling for ball velocity ($P < .1$). No ROM measures in either univariate analysis or our final model were adjusted for humeral torsion.

TABLE 1
Descriptive Statistics, Demographics, and Variables in Final Model[a]

Variable	Summary Statistics
Mean age, y	19.6 (2.5)
Mean height, m	1.9 (0.1)
Mean weight, kg	90.6 (7.3)
Ethnicity	
Hispanic	10 (11.5%)
Non-Hispanic	77 (88.5%)
Race	
White	70 (80.5%)
Black	2 (2.3%)
Asian	1 (1.1%)
Multiple races	1 (1.1%)
Unknown/other	13 (14.9%)
Mean elbow varus torque, N·m	58.63 (12.64)
Mean ball velocity, m/s; mph	37.87 (1.55); 84.83 (3.47)
Median grip strength symmetry, N	552.3 (497.4-596.5)
Median shoulder IR strength peak dominant side, N·m	61.6 (53.8-73.4)
Mean shoulder flexion ROM dominant side, degrees	173.9 (11.1)
Median shoulder scaption strength symmetry, N·m	3.6 (1.4-5.7)
Mean unilateral hip bridge, lead leg, s	74.6 (34.7)

[a]Data are presented as n (%), mean (SD), or median (interquartile range). IR, internal rotation; ROM, range of motion.

DISCUSSION

Modifiable physical measures related to the capacity and control of the lumbopelvic, hip, shoulder, and forearm regions affect the T-V relationship. Identifying the physical factors that affect the T-V relationship is critical, given the epidemic rise in UCL injuries in pitchers.[34] Several physical measures were shown to be related to the EVT univariate analyses but were not retained in the final model (Supplemental Table S3). In the multivariate final model, 3 physical measures were associated with increased EVT in addition to ball velocity: increased mean grip strength asymmetry, lead-leg lumbopelvic stability, and bodyweight. On the other hand, increases in mean dominant-shoulder IR strength, dominant-shoulder flexion ROM, and scaption strength asymmetry were associated with decreased EVT. We used a univariate analysis to define the relationship between a single physical factor and EVT; however, that association changed when

TABLE 2
Significant Variables in Univariate Mixed-Effects Models Analysis to Predict Non-normalized Elbow-Varus Torque ($p < 0.05$)[a]

Physical Measure	N	β Coefficient	95% CI	P	+X Beyond Mean/Median IV → Y Effect on Mean EVT
Shoulder ROM, deg; mean of 2 trials					
Shoulder flexion ROM					
Dominant side	87	−0.27	−0.50 to −0.03	.025	+1° → −0.27 N·m EVT
Shoulder Total ROM (TROM)					
Dominant side	87	−0.16	−0.31 to −0.004	.045	+1° → −0.16 N·m EVT
Shoulder RTD, N·m/s; max of 2 trials					
Shoulder scaption RTD					
Symmetry, peak	87	−0.06	−0.11 to −0.001	.046	+1 N·m/s asymmetry → −0.06 N·m EVT
Hip strength, N·m; max of 2 trials					
Hip abduction strength					
Symmetry, absolute	87	0.3	0.11 to 0.49	.002	+1 N·m asymmetry → +0.3 N·m EVT
Hip ROM, deg; mean of 2 trials					
Hip ER ROM					
Lead leg	87	−0.21	−0.37 to −0.05	.012	+1° → −0.21 N·m EVT
Trail leg	87	−0.17	−0.34 to −0.01	.043	+1° → −0.17 N·m EVT
Hip Total ROM (TROM)					
Lead leg	87	−0.13	−0.25 to −0.02	.023	+1° → −0.13 N·m EVT
Trail leg	87	−0.13	−0.25 to −0.01	.029	+1° → −0.13 N·m EVT
Unilateral hip bridge, s; max of 2 trials					
Lead leg	85	0.11	0.03 to 0.18	.005	+1 s → +0.11 N·m EVT
Trail leg	86	0.07	0.001 to 0.143	.048	+1 s → +0.07 N·m EVT

[a]ER, external rotation; EVT, elbow varus torque; max, maximum; ROM, range of motion; RTD, rate of torque development; TROM, total range of motion. IV, independent variable.

TABLE 3
Final Multivariate Linear Mixed-Effects Model Predicting EVT[a]

Independent Variable	β Coefficient	95% CI	P	Effect on Mean EVT
Velocity, m/s	1.85	1.03 to 2.68	<.0001	+1 m/s (2.2 mph) → +1.85 N·m EVT
Grip strength symmetry, N	0.27	0.07 to 0.48	.008	+1 N asymmetry → +0.27 N·m EVT
Shoulder IR strength, dominant side, N·m[b]	−0.93	−1.80 to −0.05	.039	+6.16 N·m → −0.93 N·m EVT
Shoulder flexion ROM, dominant side, deg	−0.35	−0.53 to −0.16	<.0001	+1° → −0.35 N·m EVT
Shoulder scaption strength symmetry, N·m[b]	−0.14	−0.30 to 0.02	.094	+0.36 N·m asymmetry → −0.14 N·m EVT
Unilateral hip bridge, lead leg, s	0.07	0.01 to 0.13	.024	+1 s → +0.07 N·m EVT
Bodyweight, kg	0.87	0.6 to 1.14	<.0001	+1 kg → +0.87 N·m EVT

[a]AIC = 2478.6; BIC = 2518.8. EVT, elbow varus torque; IR, internal rotation; ROM, range of motion.
[b]Variable is analyzed in log scale, and it is interpreted as every 10% increase (or decrease) in the variable, mean torque changed by the beta coefficient.

considered alongside other factors in a multivariate analysis. While both univariate and multi-variate analyses have their place, the multivariate approach controls for associations between physical factors and thus provides how these factors together are related to ball velocity and EVT. To our knowledge, this is the first study to quantify the impact of modifiable physical measures on EVT while controlling for ball velocity in collegiate pitchers. Our results can inform the selection of physical measures to assess and guide intervention to optimize a pitcher's T-V relationship.

More than half of the variables in the final model were associated with increases in EVT. Ball velocity was significantly associated with EVT in both the univariate analysis and our final model. Specifically, a 1-m/s (2.2 mph) increase in mean ball velocity increased EVT by 1.51 N·m in univaraite analysis, and by 1.85 N·m in the final multivariate model. Previous studies have similarly shown that the stabilization demand of the medial elbow increases with ball velocity across pitchers.[37,50,53] When controlling for the effect of ball velocity on EVT, 2 physical factors increased EVT in our final model. Grip strength symmetry had a positive association with EVT (+0.27 N·m EVT per +1 N mean grip strength asymmetry) (Table 3) when controlling for ball velocity. Our mean dominant arm grip strength in our sample was comparable to that in other studies reporting grip strength in collegiate pitchers.[18,54] The flexor pronator muscles contribute to the dynamic stability of the medial elbow by limiting ulnohumeral gapping with increased medial elbow stiffness, which may help to mitigate increased EVT.[29,49,57,60] The relevance of grip strength on the nondominant arm is unclear, making interpretation difficult. Grip strength for individual arms was not significant in univariate analysis, nor was it entered into the multivariate final model. The entry of grip strength symmetry into the final model without individual arm grip strength may mean that symmetry is the most meaningful expression of grip strength in our sample. The second physical measure associated with increased EVT when controlling for ball velocity was lead-leg lumbopelvic stability (+0.07 N·m EVT per +1-second mean unilateral hip bridge hold time) (Table 3). The ability to maintain pelvic alignment in a single-leg hip bridge is driven by hip extensors and trunk strength, as well as muscular endurance. The lead-leg gluteal muscles are particularly important in the production of large extensor and abductor moments, which decelerate the center of mass and provide a stable base for the rotation of the superior segments after lead foot contact.[2,45] Lead-leg lumbopelvic stability may impact the T-V relationship by facilitating trunk rotation, which has been shown to increase ball velocity without increased EVT.[42] The final measure associated with increased EVT was participant bodyweight (+0.87 N·m EVT per +1 kg mean bodyweight). This was expected as bodyweight is used to scale mean anthropometric parameters to determine forearm moment of inertia and therefore EVT.

Of the 5 physical measures entered in our final model, 3 were associated with decreased EVT when controlling for ball velocity. Dominant-shoulder IR strength was associated with a 0.93 N·m decrease in EVT per 6.16 N·m increase in mean dominant-shoulder IR strength. Our results differ from those of Hurd and Kaufman,[26] who showed that isometric IR strength was not correlated with EVT. These differences may be generally attributed to differences in testing position (prone vs seated), lack of fixation of the HHD, and EVT normalization method. Other studies tested associations between shoulder IR strength and injury, but their broad definitions of injury make comparison difficult.[9,54] During arm cocking, the shoulder internal rotators have high levels of activity as they work eccentrically to decelerate throwing-arm ER.[20] Although we measured shoulder strength isometrically, there is a strong correlation between isometric and eccentric isokinetic strength ($R^2 = 0.95$; $P < .001$).[24] It is conceivable that pitchers exhibiting greater isometric shoulder IR strength have greater muscular capacity to decelerate the forearm as it moves into end-range ER during late arm cocking. An increase in dominant-shoulder flexion ROM was associated with the decreased EVT in our final model and was significant in the univariate analysis. For each degree of flexion ROM beyond the 174° mean, EVT decreased by 0.35 N·m. Our mean flexion ROM was comparable to that in professional pitchers (177° ± 4.6°).[63] The association between EVT and flexion ROM was small but significant, agreeing with prior studies indicating that shoulder flexion ROM plays an important role in mitigating EVT and elbow injury risk.[10,63] The third and final modifiable physical factor associated with decreased EVT when controlling for ball velocity was scaption strength asymmetry. When mean scapular strength asymmetry increased by 0.36 N·m, EVT decreased by 0.14 N·m when controlling for ball velocity. Shoulder elevation strength is important to help pitchers achieve and maintain a stable, abducted arm posture during arm cocking and arm acceleration.[20] If these muscles lack the capacity to support the humeral head in the glenoid, injury risk has been shown to increase, especially for the throwing shoulder.[20,39,59] Scaption strength symmetry may represent increased importance of relative scaption strength or indicate that within-pitcher relationships are more important than the mean.

Our combined univariate and multivariate analyses highlight the impact modeling approaches can have on the associations between physical measures and EVT. Physical measures with a strong univariate influence on EVT may not maintain that association in multivariate analysis. Our analysis identified several such variables, 2 of which were associated with increased EVT in univariate analysis but were not selected in the final model. The first was absolute hip abduction strength symmetry, which increased EVT by 0.3 N·m for each additional newton-meter of hip abduction asymmetry (Table 2). The legs work to generate and transfer energy proximally early in the pitch and then later provide a stable base for the rotation of the superior segments. Increased side-to-side asymmetry may elicit upstream compensations and increase the risk of sustaining a shoulder or elbow injury.[47] The second variable associated with increased EVT in univariate analysis alone was increased trail hip lumbopelvic stability, which increased EVT by 0.07 N·m for each second beyond the mean hold time (Table 2). The increased gluteal strength and motor control required for increased trail hip lumbopelvic stability may facilitate greater power generation, transfer, and eventually ball velocity.[19,27] We also identified 6 variables that decreased EVT in univariate analyses but were not included in our final model. Dominant-shoulder TROM decreased EVT by 0.16 N·m (Table 2, Supplemental Table S3). Shoulder TROM, especially its ER component, is thought to increase the range over which the pitcher is able to generate ball velocity during arm acceleration.[8] Increased asymmetry in scaption RTD also decreased EVT. For each 1-N·m/s gain in the dominant shoulder compared with the nondominant shoulder, EVT decreased by 0.06 N·m. The rate at which muscles produce force can be crucial in shoulder stabilization during rapid motion of the pitch. Our univariate analyses indicated that pitchers able to access torque more readily in the muscles producing scapular elevation (like the supraspinatus and deltoid) are better able to mitigate increased EVT. As with scaption strength symmetry, scaption RTD symmetry may owe its effect to better and more prompt stabilization of the humeral head within the glenoid during arm cocking and acceleration. The final 4 measures decreasing EVT in univariate analyses were components of hip ROM, specifically bilateral hip ER ROM and TROM. On the trail leg, each additional degree of hip ER ROM and TROM decreased EVT by 0.17 N·m and 0.13 N·m, respectively (Table 2). On the stride leg, each additional degree of hip ER ROM and TROM decreased EVT by 0.21 N·m and 0.13 N·m, respectively (Table 2). Increased ER ROM and TROM in the hips are necessary for increased stride length, which has been associated with increased ball velocity without a corresponding increase in EVT in professional pitchers.[36] The resultant EVT is the product of total body capacities.

Although univariate analysis is undoubtedly important in determining which physical measures may affect EVT, single-variable analysis can only capture a small part of the picture. The multivariate model addresses this shortcoming by demonstrating how various physical capacities work together to explain larger amounts of variance in EVT.

Limitations

Our study is not without limitations. We quantified EVT using the PULSE sensor. Sensor reliability, including ours, has been established as good to excellent.[6,14,32,35] Studies support use of the PULSE sensor with a moderate to strong relationship between EVT calculation and motion capture.[6,14] However, validation studies have shown that this sensor can underestimate EVT magnitude compared with optical motion capture, indicating that comparison of values derived from the 2 methods is not recommended.[6,13] Therefore, we have not compared EVT values from our study with others derived from motion capture. Pitchers only threw fastballs, which limits generalizability across pitch types. Previous studies have shown that EVT can vary by pitch type, in addition to natural variation in ball velocity inherent in pitch type.[21] The RTD measures were collected at 90 Hz, which is lower than the recommended 1000-Hz minimum for collecting RTD, although bias has been shown to be dependent on the sampling window used.[16,33] Our sample was predominantly White and non-Hispanic. Pitchers from different geographic regions can have different shoulder strength profiles, which may affect the T-V relationship.[40] The relationship between the physical measures and EVT was evaluated using regression analysis. Specifically, we reported unstandardized beta coefficients representing each physical measure's per-unit effect on EVT. The magnitude of the betas for each physical measure represents the relative effect on EVT but cannot be compared with each other. Finally, alteration of physical capacities likely influences pitching mechanics, resulting in changes to EVT and/or ball velocity. If 2 pitchers alter one of their physical capacities by the same amount, there may be different degrees of consequential change in their mechanics. It is important to be mindful of changes in mechanics when attempting to modify the T-V relationship to prevent unintended consequences.

CONCLUSION

The T-V relationship allows concurrent assessment of player performance and UCL injury risk. Our results indicated that modifiable physical measures confound the T-V relationship. Increases in ball velocity, grip strength symmetry, lumbopelvic stability on the lead leg, and bodyweight all increased EVT. On the other hand, increases in dominant-shoulder IR strength, dominant-shoulder flexion ROM, and scaption strength asymmetry decreased EVT. Our model identified appropriate physical characteristics through which clinicians, coaches, and athletes may alter the expected EVT (and therefore T-V relationship) for a given fastball. Future studies should continue to identify the explanatory combinations of modifiable physical factors that predict variance in the T-V relationship.

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