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Association Between Lumbopelvic Stability During a Single-Legged Step Down and Elbow-Varus Torque During Baseball Pitching

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Context: During a baseball pitch, energy is transferred from the lower extremities through the lumbopelvic junction to the upper extremity. Reduced lumbopelvic stability has been associated with elbow injuries, but the mechanisms are unclear.

Objective: To characterize the predictive ability of lumbopelvic stability on elbow-varus torque during a baseball pitch.

Design: Cross-sectional study.

Setting: Facilities at National Collegiate Athletic Association Division I universities.

Patients or Other Participants: A total of 44 National Collegiate Athletic Association Division I baseball players (age = 19.6 ± 1.3 years, height = 190 ± 10 cm, mass = 90.1 ± 6.3 kg).

Main Outcome Measure(s): Pitchers completed a warm-up and then threw 10 fastballs from a mound to a catcher. During the pitches, elbow-varus torque was recorded using an inertial measurement unit, and ball velocity was recorded using a radar gun. Participants also completed a single-legged step-down (SLSD) task with and without a cognitive Stroop, and triplanar pelvic and trunk kinematics were recorded using inertial measurement units. Statistical analysis consisted of a cluster analysis, principal components analysis, and a multivariate logistic regression model.

Results: Cluster analysis identified 2 clusters: low torque–high velocity and high torque–low velocity. The principal components analysis identified 4 patterns of variability (principal components) during the SLSD: (1) sagittal plane, (2) transverse plane, (3) frontal-plane trail leg, and (4) frontal-plane lead leg. Logistic regression models indicated increased transverse-plane trunk (odds ratio = 2.9; 95% CI = 1.1, 8.0; *P* = .04) and increased pelvis motion (odds ratio = 2.5; 95% CI = 1.1, 6.0; *P* = .03) predicted higher odds of belonging to the high torque–low velocity cluster.

Conclusions: Lumbopelvic movement assessed during the SLSD can identify deficits that relate to high elbow torque–low ball velocity during the baseball pitch. Specifically, higher transverse-plane pelvis and trunk motion were independently associated with pitchers in the high torque–low velocity cluster. Our assessment of trunk and pelvis motion during an SLSD provides a method for coaches and clinicians to identify a potential risk factor related to increased elbow-varus torque and decreased ball velocity.

Key Words: ulnar collateral ligament, injury prevention, movement analysis, pitching mechanics, core stability

Key Points

- Higher elbow torque was separately associated with increased transverse-plane pelvis and trunk motion during a single-legged step-down (SLSD) task.
- The SLSD is a simple and repeatable test to estimate pitchers' risk of increased elbow-varus torque during pitching.
- Clinicians can assess trunk and pelvis kinematics during the SLSD to evaluate throwing-elbow injury risk and performance.

Ulnar collateral ligament (UCL) sprains of the elbow are common in baseball pitchers.[1] The UCL is a passive restraint stabilizing the medial elbow, resisting approximately 50% of elbow-valgus torque during pitching.[2,3] High (internal) elbow-varus torque during the pitch has been implicated in UCL injury.[4] One factor associated with increased elbow-varus torque during pitching is high ball velocity, but this relationship is inconsistent across pitchers.[5–7] Some pitchers can throw faster without a meaningful increase in elbow-varus torque, whereas others have a strong torque-velocity (T-V) relationship. Differences in physical capacities such as joint stability and control can mediate the T-V relationship, contributing to the increased variance observed among pitchers.[8]

The lumbopelvic junction is the intersection through which energy is transferred from the lower extremities to the trunk and then to the upper extremity during a baseball pitch.[9–11] A stable base at the lumbopelvic junction is important for both trunk and upper extremity motion during the pitch.[12] Increased stability and control at the lumbopelvic junction are thought to facilitate sequenced rotation of superior segments through improved segment-rotation timing and control of trunk rotation.[12,13] Lumbopelvic stability has been associated with the magnitude of elbow-varus torque and pitching performance.[8,14,15]

Deficits in lumbopelvic stability in baseball pitchers have been detected during dynamic single-legged tasks, such as the single-legged step-down (SLSD), single-legged squat, or single-legged balance task. Specifically, increased trunk lateral tilt and increased pelvic tilt in the sagittal plane can predict increases in elbow-varus torque, elbow injury rates, and associated time loss.[8,13,16] Observations during such tasks can predict kinematics during the pitch. For instance, increased trunk lean observed during the single-legged squat is associated with the same deviation during the baseball pitch.[17,18] However, the SLSD is a relatively simple task that, on its own, may not be challenging enough for trained, athletic participants to show differences in lumbopelvic stability. To address this concern, we aimed to advance previous research by using a Stroop condition during the SLSD to increase the ecological validity of the lumbopelvic stability assessment. A Stroop condition uses an auditory and cognitive element to mimic stimuli that demand external focus during the pitch. This condition may define more nuanced differences in lumbopelvic stability. It remains unclear whether lumbopelvic stability assessed during an SLSD predicts elbow-varus torque during pitching.

The primary purpose of our study was to determine the predictive ability of lumbopelvic stability assessed during the SLSD task on elbow-varus torque while controlling for ball velocity. We hypothesized that increased triplanar motion during an SLSD task would predict higher elbow-varus torque and lower ball velocity. To accomplish this, we first identified distinct clusters of pitchers characterized by elbow torque and ball velocity. Second, we determined how triplanar lumbopelvic kinematic variables during the SLSD (non-Stroop and Stroop) formed constructs of lumbopelvic stability. Third, we determined the relationship between lumbopelvic stability constructs and the pitcher clusters (subgroups). Characterizing how lumbopelvic stability relates to elbow torque can inform efforts aimed at reducing elbow injury during pitching.

METHODS

Participants

A total of 44 participants volunteered for this study. We included participants who were ≥18 years old and active pitchers on the roster of a National College Athletic Association Division I baseball team. We excluded volunteers who had an injury in their throwing elbow at the time of the study or any injury requiring ≥2 weeks of rest from playing in the 6 weeks before the study. All participants provided informed consent, and the study was approved by the Institutional Review Board of the University of Southern California, Los Angeles.

Procedures

Participants completed 2 assessments within 48 hours of each other: an SLSD to assess lumbopelvic stability and a pitching bout to assess elbow-varus torque and ball velocity. For the pitching assessment, pitchers first completed their typical warm-up, which consisted of mobility, banded arm-care exercises, and long toss. Pitchers then threw 10 fastballs, 5 at 75% effort and 5 at 100% effort, from a regulation-size and -distance mound to a catcher. Elbow-varus torque was collected using a single inertial measurement unit secured to the ulna 2 finger widths distal to the medial humeral epicondyle with tape and self-adhering wrap (model PULSE; Driveline Baseball). Ball velocity was measured using a Stalker Sport 2 radar gun (Stalker Radar) positioned behind home plate. Test-retest reliability for elbow-varus torque was excellent (intraclass correlation coefficient [3,2] = 0.94), and error was low (standard error of the measurement = 3.4 N·m).

Pitchers performed an SLSD from a 20-cm box for lumbopelvic stability assessment. Six wireless inertial measurement units (MTw Awinda; Xsens) were secured to the participant using double-sided tape and hook-and-loop wraps on the following landmarks: bilaterally on the lateral border of the shank 2 finger widths below the tibial plateau, bilaterally on the lateral border of the thigh 4 finger widths above the lateral femoral epicondyle, on the sacrum between the posterior and superior iliac spines, and over the sternum on top of the xiphoid process (Figure 1). We ensured proper magnetometer function to enable sensor fusion correction. Sensors were calibrated with participants in a neutral posture and facing magnetic north, and the collection area was positioned 15 to 20 feet (4.6–6.1 m) from any other electronic devices to limit magnetic destabilization. The standardized neutral calibration position required participants to stand in line with an arrow while trunk position was standardized using the following command: “Slouch your upper body, now stand up tall like you are in the military, now relax by 10% and hold that position.” Standardized instructions for the SLSD and practice time were given to participants. For both normal and Stroop conditions, participants performed 1 set of 10 repetitions on each lower extremity. A repetition began with participants standing on the 20-cm box with their hands crossed over their shoulders and the noninvolved lower extremity hanging extended in front, off the box. Next, they stepped down until the opposite heel touched the floor, then returned to the original position (Figure 2). Additional instructions were provided before completion of the Stroop condition. An audio recording of a random combination of the words *high* and *low* was played, and the 2 words were played randomly at either a high pitch or low pitch. During the SLSD, participants had to orally indicate the pitch of the spoken word, regardless of the stated word. Participants practiced the SLSD with the auditory Stroop before data collection. To limit accelerometer and gyroscopic drift, we limited the duration of each data collection to approximately 5 minutes per participant. Test-retest reliability of lumbopelvic kinematics conducted during the SLSD indicated excellent reliability (intraclass correlation coefficient [3,2] = 0.83–0.99), with low error (standard error of the measurement = 0.25°–1.19°).

Data Processing

We retrieved kinematic data as Euler angles for each sensor from the manufacturer’s native software (MT Manager;

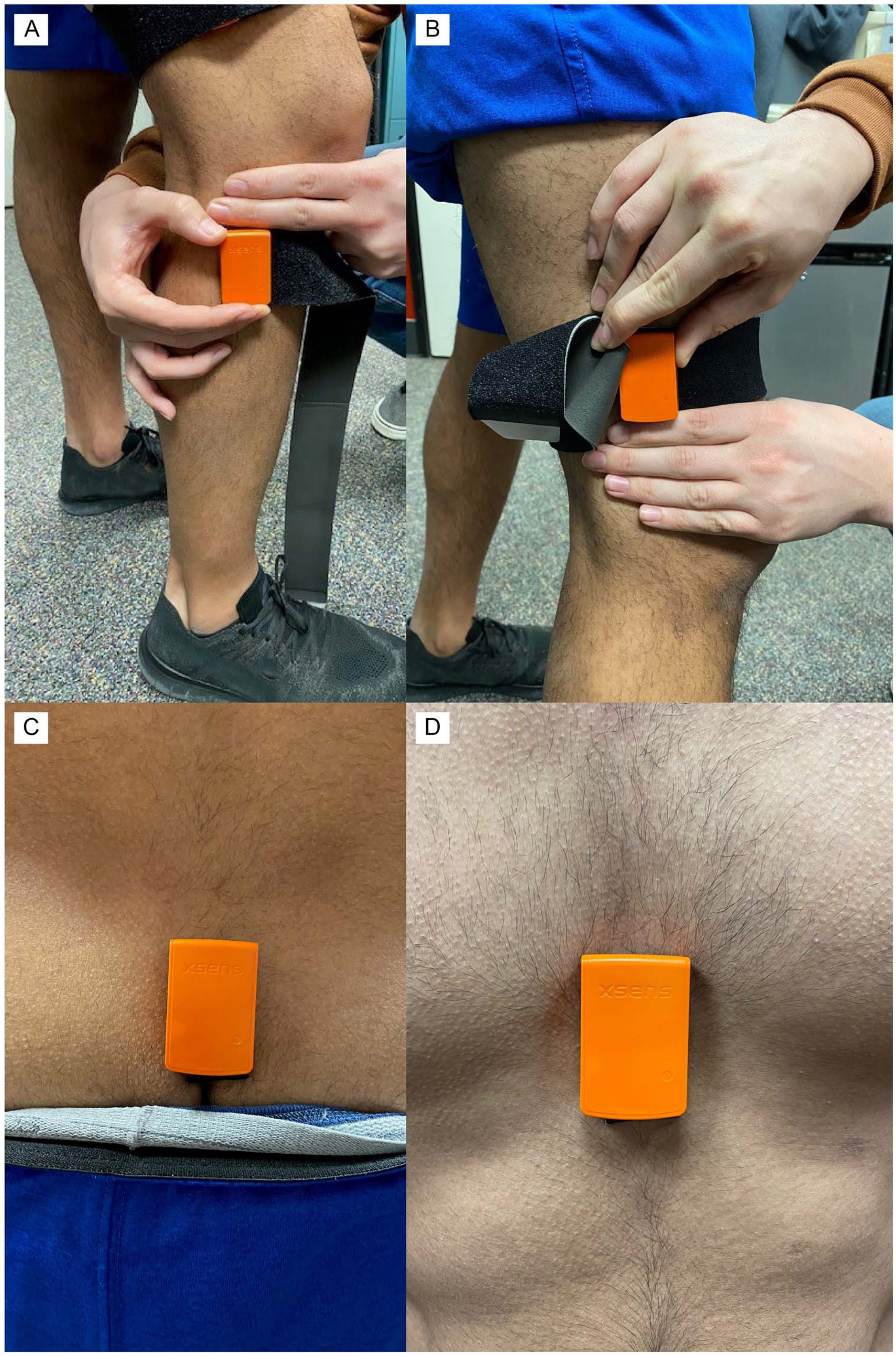

Figure 1. Inertial measurement units attached to participants using double-sided tape and secured with hook-and-loop straps on 6 different anatomic locations: A, bilaterally on the lateral border of the shank 2 finger widths below the tibial plateau; B, bilaterally on the lateral border of the thigh 4 finger widths above the lateral femoral epicondyle; C, on the sacrum between the posterior and superior iliac spines; and D, over the sternum on top of the xiphoid process.

Xsens). Next, we used a custom script (LabVIEW; National Instrument) to convert the Euler angles of each sensor to create rotational matrices, which we used to calculate Euler angles of one body segment with respect to another for all 3 planes of motion across the SLSD. We defined trunk and pelvis kinematics using the xiphoid process and sacral sensors relative to the laboratory, and the knee angle was defined using the shank sensor relative to the thigh sensor. We used a custom MATLAB script (version 2021a; MathWorks) to extract absolute values at peak knee-flexion angles for the trunk and pelvis in all 3 planes for both lead and trail legs. We omitted the first and last trials of each task from the mean calculation to control for ramp up and ramp down in completion of the SLSD task.

Figure 2. Single-legged step-down task on a 20-cm box.

Statistical Analysis

We performed a *k*-means cluster analysis to partition participants into mutually exclusive clusters (subgroups) using average ball velocity and average elbow-varus torque across 10 pitches. Given that clustering is sensitive to data order, the *best arrangement* (defined as the solution with the lowest total sum of point-to-centroid distances) of 100 random initializations was selected as the final solution. Before clustering, we standardized all variables to *z* scores to equalize the importance of each variable. We also checked data for extreme outliers (>5 SDs from the mean). We determined the optimal number of clusters by comparing 2- and 3-cluster solutions using the silhouette criterion to assess the quality of cluster separation while also considering the smallest sample size within the subgroups. The silhouette coefficient ranges from −1.0 to 1.0 and was interpreted as *good* (0.50–1.0), *fair* (0.20–0.49), or *poor* (−1.0–0.19).[19] For cluster interpretation, we used linear regression to assess differences between clusters of the underlying metrics (velocity and torque). We interpreted R^2 values as *strong* (≥0.50), *moderate* (0.25–0.49), *weak* (0.10–0.24), or *negligible* (0.0–0.09).[20]

We used principal components analysis (PCA) to reduce the 24 lumbopelvic kinematic variables during the SLSD (non-Stroop and Stroop) into constructs of meaningful PCs. We conducted PCA separately for the trunk and pelvis (12 variables each), using varimax rotations. Each set of 12 variables comprised 3 planes, 2 limbs (lead and trail), and 2 step-down types (Stroop and non-Stroop). We used the PCA to identify the kinematic domains related to plane of motion, limb, and step-down type. The number of components extracted for each PCA was limited to eigenvalues > 1.0 and/or components explaining at least 10% of the variance in the original dataset. We confirmed sample adequacy for each PCA using the Kaiser-Meyer-Olkin test (range, 0–1), with values <0.5 considered *unacceptable*. In addition, we used the Bartlett test of sphericity ($P < .05$) to confirm that the data were suitable for data reduction. We considered loadings of individual variables with a factor loading ≥0.6, without cross-loading of values ≤0.2. The factor scores (PCs) were saved via the regression method (ie, *z* scores with a mean of 0 and SD of 1).

Next, we used multivariate logistic regression models to determine the association between lumbopelvic stability (defined from the PCA) and T-V group membership (defined by the cluster analysis). Separate models were produced for the trunk and pelvis. The independent variables were the previously saved factor scores. After forced entry of the factor scores, we used a stepwise procedure to determine if height or mass was entered. To evaluate the overall accuracy of the logistic models, the Nagelkerke R^2 was reported. We performed all analyses using SPSS statistical software (version 28; IBM Corp) and a custom MATLAB script (version 2021a; MathWorks), with the α level set at .05.

RESULTS

A total of 44 male pitchers (age = 19.6 ± 1.3 years, height = 190 ± 10 cm, mass = 90.1 ± 6.3 kg) participated. Pitching torque or velocity variables were missing for 6 participants, leaving 38 participants for data analysis. We performed logistic regression on combined pitching and SLSD data. Mean torque was 55.6 ± 11.5 N·m, and mean ball velocity was 133.3 km/hr (82.9 ± 42.8 mph).

Cluster Analysis

A 2-cluster solution (silhouette criterion of 0.50) separated pitchers into 2 subgroups: cluster 1 (n = 17) and cluster 2 (n = 21) (Figures 3 and 4). Members of cluster 1 (low torque–high velocity) had a lower torque (48.3 ± 11.1 N·m vs 61.6 ± 8.3 N·m; $P < .001$) and higher ball velocity [136 + 3.2 km/hr (84.8 ± 2.0 mph vs 130.8 + 3.8 km/hr (81.3 ± 2.4 mph); $P < .001$] compared with members of cluster 2 (high torque–low velocity).

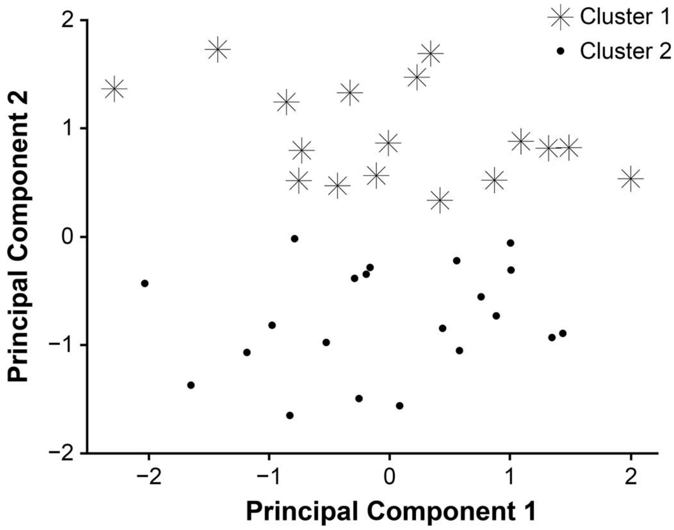

Figure 3. Visualization of *k*-means clustering output (*k* = 2) after principal components analysis. Principal component 1, 47.6% variance; principal component 2, 52.4% variance. Cluster 1, n = 17; cluster 2, n = 21.

Principal Components Analysis

We entered a total of 12 variables into each PCA: sagittal-plane lead-leg non-Stroop and Stroop, sagittal-plane trail-leg non-Stroop and Stroop, frontal-plane lead-leg non-Stroop and Stroop, frontal-plane trail-leg non-Stroop and Stroop, transverse-plane lead-leg non-Stroop and Stroop, and transverse-plane trail-leg non-Stroop and Stroop (Table 1). For both trunk and pelvis SLSD variables, sample adequacy using the Kaiser-Meyer-Olkin test (0.65 and 0.68, respectively) and suitability for data reduction using the Bartlett test of sphericity (all $P < .001$) were confirmed. For the trunk, only 4 components were extracted, for a total explained 85.4% variance (Table 2): (1) PC 1: sagittal plane (eigenvalue = 4.0, 33.7% variance, 4 variables), (2) PC 2: transverse plane (eigenvalue = 3.5, 29.3% variance, 4 variables), (3) PC 3: frontal-plane trail leg (eigenvalue = 1.5, 12.1% variance, 2 variables), and (4) PC 4: frontal-plane lead leg (eigenvalue = 1.2, 10.2% variance, 2 variables). Factor scores consisted of items loading at $\geq$0.820 on a component (Table 3), with all 12 trunk SLSD variables included in the final PCA solution. For the pelvis SLSD variables, only 4 components were extracted and, in total, explained 90.0% of the variance (Table 2): (1) PC 1: sagittal plane (eigenvalue = 5.2, 43.6% variance, 4 variables), (2) PC 2: transverse plane (eigenvalue = 2.1, 17.5% variance, 4 variables), (3) PC 3: frontal-plane trail leg (eigenvalue = 1.9, 16.2% variance, 2 variables),

Table 1. Descriptive Data for Single-Legged Step Down (Mean ± SD)[a]

	Non-Stroop	Stroop	Combined
Trunk			
Sagittal-plane lead, °	12.8 ± 8.6	12.8 ± 8.1	12.8 ± 8.3
Sagittal-plane trail, °	14.3 ± 8.5	13.0 ± 8.2	13.7 ± 8.3
Frontal-plane lead, °	2.8 ± 2.0	3.2 ± 1.8	3.0 ± 1.9
Frontal-plane trail, °	2.7 ± 2.0	3.3 ± 2.2	3.0 ± 2.1
Transverse-plane lead, °	28.0 ± 19.8	28.5 ± 20.1	28.2 ± 19.8
Transverse-plane trail, °	21.4 ± 16.1	23.0 ± 16.7	22.2 ± 16.3
Pelvis			
Sagittal-plane lead, °	9.3 ± 7.8	8.2 ± 7.6	8.8 ± 7.7
Sagittal-plane trail, °	9.5 ± 7.7	8.4 ± 7.3	9.0 ± 7.5
Frontal-plane lead, °	4.2 ± 2.3	4.3 ± 2.2	4.3 ± 2.2
Frontal-plane trail, °	4.5 ± 2.9	4.7 ± 2.9	4.6 ± 2.9
Transverse-plane lead, °	20.1 ± 15.7	20.4 ± 17.2	20.3 ± 16.4
Transverse-plane trail, °	16.7 ± 12.7	17.9 ± 13.1	17.3 ± 12.8

[a] All variables represent the value at peak knee flexion (absolute value), represented as the mean over the middle single-legged step-down trials (ie, all except the first and last repetition).

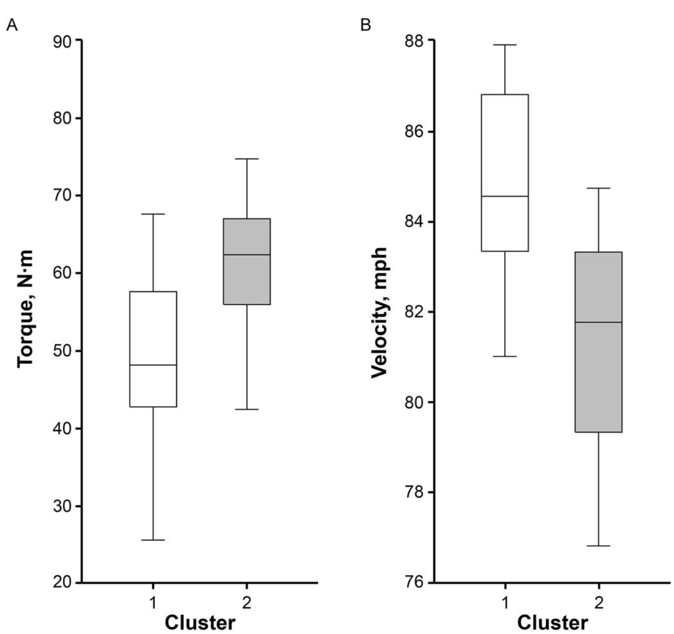

Figure 4. Cluster characteristics in male pitchers. The *k*-means clustering (k = 2) was performed with 2 variables of torque (N·m) and velocity (mph). Cluster 1, low torque–high velocity (n = 17). Cluster 2, high torque–low velocity (n = 21).

Table 2. Summary of Variables Captured by Principal Components Analysis for the Trunk and Pelvis

Principal Component	Variable	Variance Explained, %: Trunk Analysis	Variance Explained, %: Pelvis Analysis
1: Sagittal plane	Sagittal-plane lead leg non-Stroop Sagittal-plane lead leg Stroop Sagittal-plane trail leg non-Stroop Sagittal-plane trail leg Stroop	33.7	43.6
2: Transverse plane	Transverse-plane lead leg non-Stroop Transverse-plane lead leg Stroop Transverse-plane trail leg non-Stroop Transverse-plane trail leg Stroop	29.3	17.5
3: Frontal-plane trail leg	Frontal-plane trail leg non-Stroop Frontal-plane trail leg Stroop	12.1	16.2
4: Frontal-plane lead leg	Frontal-plane trail leg non-Stroop Frontal-plane trail leg Stroop	10.2	12.7

Table 3. Trunk Principal Components (PC) Analysis Loading Matrix for Single-Legged Step-Down Kinematics

	PC 1	PC 2	PC 3	PC 4
Sagittal plane				
Lead leg non-Stroop	0.909[a]	−0.020	0.162	−0.014
Lead leg Stroop	0.930[a]	−0.032	0.080	0.017
Trail leg non-Stroop	0.942[a]	0.056	−0.061	0.010
Trail leg Stroop	0.955[a]	−0.019	0.041	0.025
Transverse plane				
Lead leg non-Stroop	−0.021	0.937[a]	−0.050	0.150
Lead leg Stroop	−0.003	0.940[a]	−0.009	0.163
Trail leg non-Stroop	0.033	0.872[a]	0.377	0.042
Trail leg Stroop	−0.022	0.833[a]	0.361	0.059
Frontal plane				
Lead leg non-Stroop	−0.062	0.214	0.177	0.820[a]
Lead leg Stroop	0.079	0.073	0.061	0.884[a]
Trail leg non-Stroop	0.051	0.102	0.877[a]	0.145
Trail leg Stroop	0.119	0.222	0.856[a]	0.094

[a] Variable captured by the PC.

and (4) PC 4: frontal-plane lead leg (eigenvalue = 1.5, 12.7% variance, 2 variables). Factor scores consisted of items loading at ≥0.867 on a component (Table 4). We included all 12 pelvis SLSD variables (Table 1) in the final PCA solution (Table 2). In summary, based on the PCA findings, we developed a classification system for the SLSD based on the plane of motion and limb type (relevant for the frontal plane only). This system revealed 4 dominant patterns of variability in pitchers' performance on the SLSD: transverse plane, sagittal plane, frontal-plane trail leg, and frontal-plane lead leg.

Logistic Regression

Logistic models predicted the high torque–low velocity cluster using the SLSD kinematic variables' PCs (Tables 5 and 6). For the trunk variables, only PC 2: transverse plane was different (odds ratio [OR] = 2.9; 95% CI = 1.1, 7.7; $P = .03$), with higher PC 2: transverse plane values for the trunk predicting higher odds of belonging to the high torque–low velocity pitcher cluster subgroup. Higher PC 2: transverse plane values for the trunk corresponded to higher transverse-plane motion for all underlying metrics (Figure 5). Therefore, higher transverse-plane motion for the lead and trail legs (Stroop and non-Stroop conditions) for the trunk predicted higher odds of belonging to the high torque–low velocity pitcher cluster subgroup. The overall fit (R^2) was 26% (model 1 in Table 5). After the stepwise procedure, we entered weight, which increased the model fit to 42%. With the inclusion of weight, PC 2: transverse plane remained different (OR = 2.9; 95% CI = 1.1, 8.0; $P = .04$) (model 2 in Table 5).

For the pelvis variables, only PC 2: transverse plane was different (OR = 2.2; 95% CI = 1.0, 4.8; $P = .049$), with higher PC 2: transverse plane pelvis values predicting higher odds of belonging to the high torque–low velocity pitcher cluster. Higher PC 2: transverse plane values for the pelvis corresponded to higher transverse-plane motion for all underlying metrics (Figure 6). Therefore, higher transverse-plane motion for the lead and trail legs (Stroop

Table 4. Pelvis Principal Components (PC) Analysis Loading Matrix for Single-Legged Step-Down Kinematics

	PC 1	PC 2	PC 3	PC 4
Sagittal plane				
Lead leg non-Stroop	0.956[a]	0.221	0.085	−0.014
Lead leg Stroop	0.938[a]	0.140	0.091	−0.035
Trail leg non-Stroop	0.893[a]	0.277	0.192	−0.045
Trail leg Stroop	0.934[a]	0.222	0.130	0.019
Transverse plane				
Lead leg non-Stroop	0.204	0.890[a]	0.094	−0.141
Lead leg Stroop	0.165	0.878[a]	0.104	−0.003
Trail leg non-Stroop	0.198	0.875[a]	−0.005	0.096
Trail leg Stroop	0.212	0.867[a]	−0.004	0.051
Frontal plane				
Lead leg non-Stroop	−0.014	0.031	0.162	0.950[a]
Lead leg Stroop	−0.032	−0.019	−0.076	0.963[a]
Trail leg non-Stroop	0.144	0.039	0.964[a]	0.028
Trail leg Stroop	0.184	0.085	0.959[a]	0.055

[a] Variable captured by the PC.

Table 5. Trunk Principal Components (PC) Order by Odds Ratios for Multivariate Logistic Regression to Predict High Torque–Low Velocity Cluster Membership

Model	Predictor	Odds Ratio (95% CI)	*P* Value	Nagelkerke R^2, %
1	PC 2: Transverse plane	2.9 (1.1, 7.7)	.03[a]	Total: 26
	PC 3: Frontal-plane trail leg	1.4 (0.5, 3.5)	.50	
	PC 1: Sagittal plane	0.9 (0.3, 2.3)	.81	
	PC 4: Frontal-plane lead leg	0.8 (0.3, 2.5)	.77	
2	PC 2: Transverse plane	2.9 (1.1, 8.0)	.04[a]	
	PC 3: Frontal-plane trail leg	2.0 (0.7, 6.3)	.22	
	PC 1: Sagittal plane	0.9 (0.3, 2.5)	.86	
	PC 4: Frontal-plane lead leg	0.6 (0.2, 2.1)	.39	
Weight, N		1.0 (1.0, 1.0)	.044[a]	Weight: 16 Total: 42

[a] Different ($P < .05$).

Table 6. Pelvis Principal Components (PC) Order by Odds Ratios for Multivariate Logistic Regression to Predict High Torque–Low Velocity Cluster Membership

Model	Predictor	Odds Ratio (95% CI)	*P* Value	Nagelkerke R^2, %
1	PC 2: Transverse plane	2.2 (1.0, 4.8)	.049[a]	Total: 25
	PC 3: Frontal-plane trail leg	1.6 (0.8, 3.4)	.20	
	PC 1: Sagittal plane	1.0 (0.5, 2.1)	.97	
	PC 4: Frontal-plane lead leg	0.7 (0.3, 1.7)	.40	
2	PC 2: Transverse plane	2.5 (1.1, 6.0)	.03[a]	
	PC 3: Frontal-plane trail leg	1.8 (0.8, 4.1)	.17	
	PC 1: Sagittal plane	0.8 (0.3, 2.0)	.67	
	PC 4: Frontal-plane lead leg	0.6 (0.2, 1.5)	.29	
Weight, N		1.0 (1.0, 1.0)	.048[a]	Weight: 14 Total: 39

[a] Different ($P < .05$).

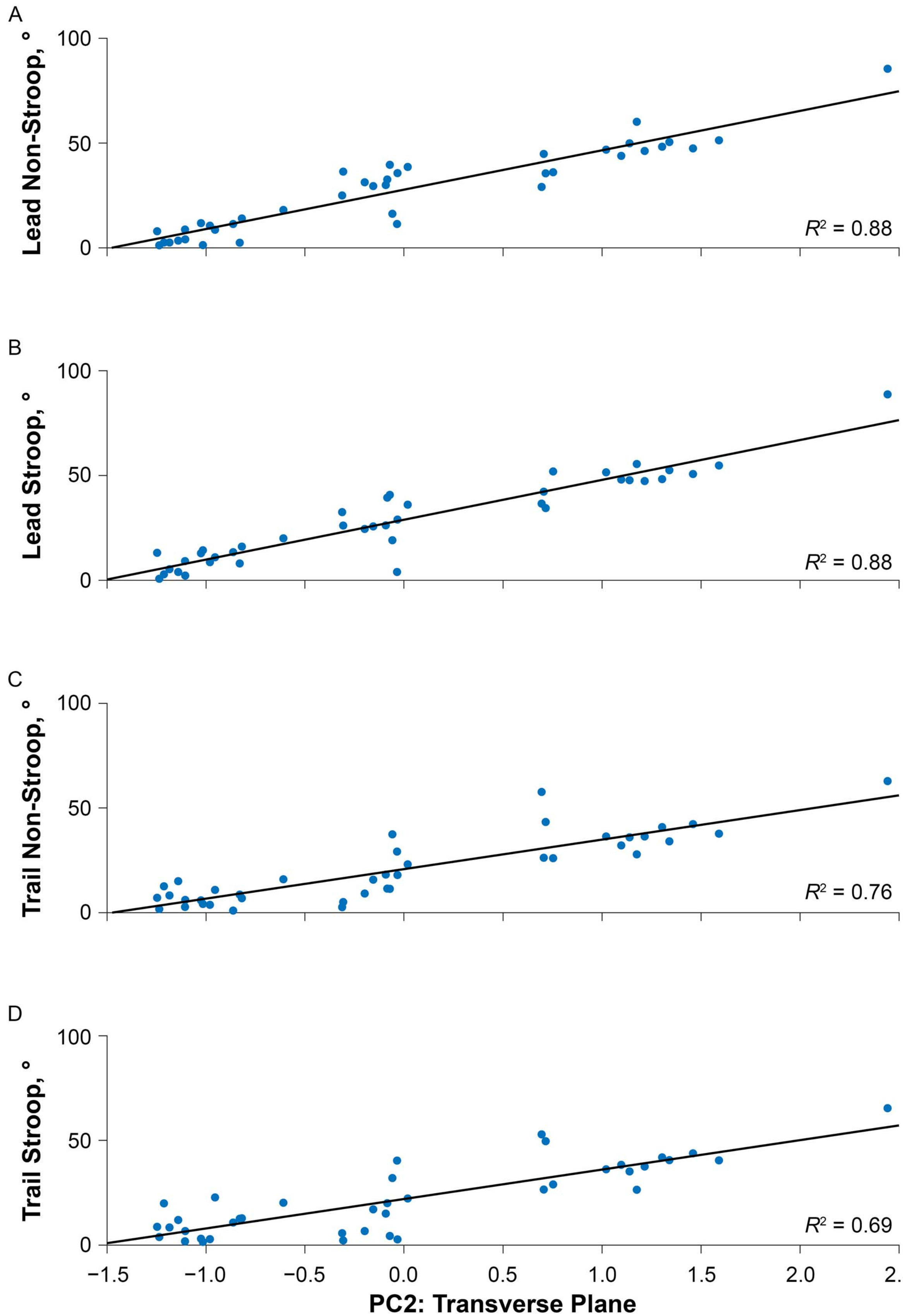

Figure 5. Regression analysis demonstrating a positive relationship between principal components for the trunk and the underlying transverse-plane metrics. A, Lead leg non-Stroop. B, Lead leg Stroop. C, Trail leg non-Stroop. D, Trail leg Stroop.

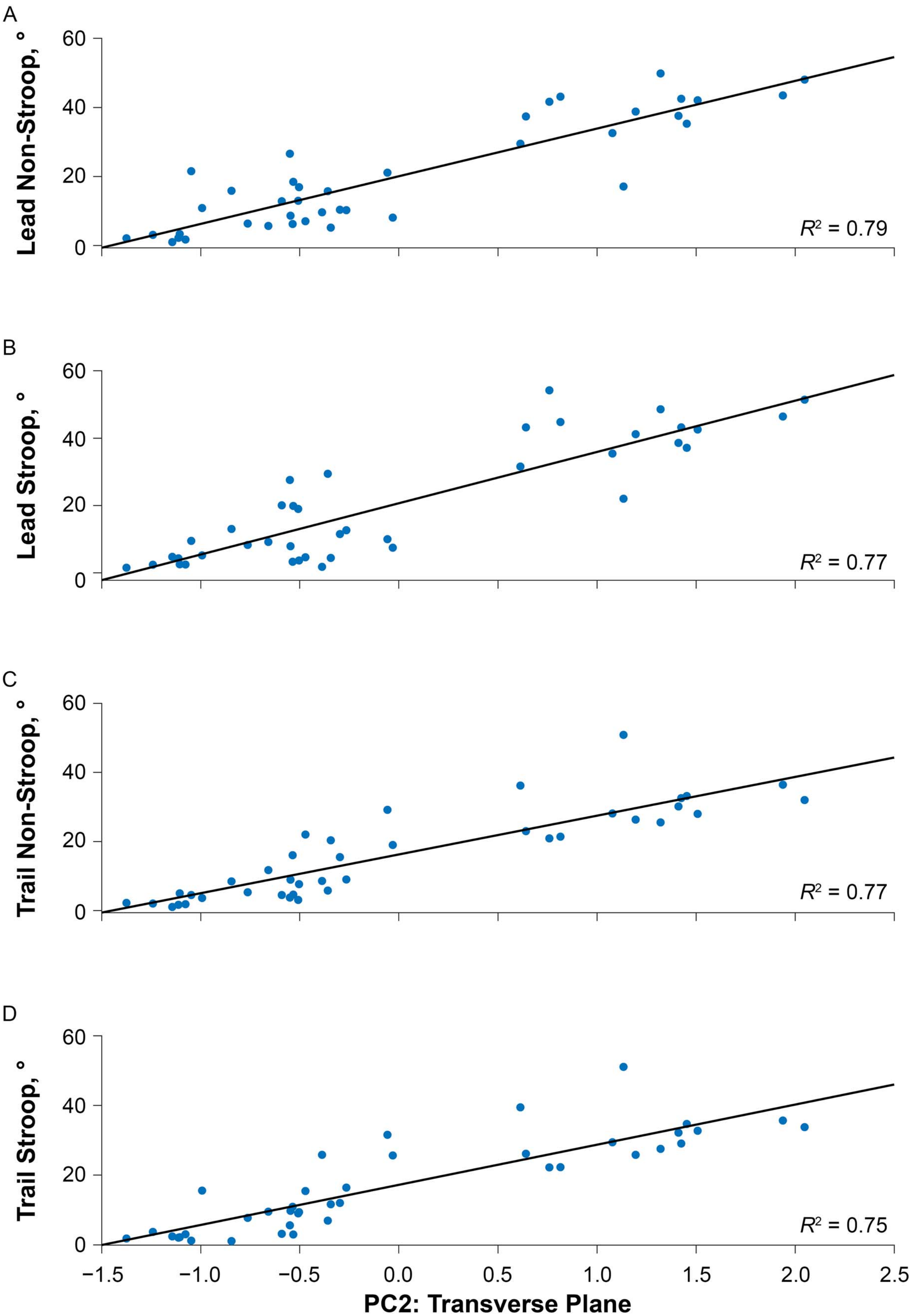

Figure 6. Regression analysis demonstrating a positive relationship between principal components for the pelvis and the underlying transverse-plane metrics. A, Lead leg non-Stroop. B, Lead leg Stroop. C, Trail leg non-Stroop. D, Trail leg Stroop.

and non-Stroop conditions) for the pelvis predicted higher odds of belonging to the high torque–low velocity pitcher cluster subgroup. The overall model fit (R^2) was 25% (model 1 in Table 6). After the stepwise procedure, we also entered weight, increasing the model fit to 39%. With the inclusion of weight, PC 2: transverse plane remained different (OR = 2.5; 95% CI = 1.1, 6.0; $P = .03$) (model 2 in Table 6).

DISCUSSION

Proximal stability is generally considered to improve distal mobility.[12] Within the framework of pitching, the ability to minimize unwanted lumbopelvic movement is thought to facilitate sequenced rotation of superior segments through improved segment rotation timing.[12,13] Increased lumbopelvic stability in pitchers has been associated with decreased upper extremity demand, lower UCL injury risk, and improved pitching performance.[8,13,14,16] In this study, we aimed to determine if lumbopelvic stability during the SLSD could predict elbow-varus torque while controlling for ball velocity. Our results partially confirmed our hypothesis that triplanar kinematics would predict the T-V relationship. Specifically, increased transverse-plane trunk and pelvis motion during the SLSD separately predicted membership in the high torque–low velocity cluster subgroup. To the best of our knowledge, we are the first to use unsupervised methods to identify clusters within the T-V relationship, as well as the first to quantify dynamic lumbopelvic-stability–associated T-V clusters in baseball pitchers. By clarifying the elements of lumbopelvic stability in an SLSD task that best differentiate the cluster subgroups of low torque–high velocity versus high torque–low velocity, this research provides knowledge that can inform efforts to reduce UCL injury.

We are the first to successfully use unsupervised methods to identify subgroups in the T-V relationship. Due to limited subgroup sizes, we were limited to testing 2- and 3-subgroup solutions. However, the 2-cluster solution achieved a silhouette criterion of 0.50 (good), indicating well-matched and tightly fit groups. Members of the high torque–low velocity group had higher elbow-varus torque and lower ball velocity compared with members in the low-torque–high-velocity group (Figure 4). Given a larger sample size, different subgroups may emerge. Future work should be done to independently validate the cluster groups.

Clinical paradigms are often used at the expense of ecological validity to measure physical capacities such as lumbopelvic stability. The relative simplicity of these tasks facilitates clearer, more specific findings about the physical capacity in question. Despite their decreased ecological validity, findings from clinical paradigms like the SLSD are often reflected in the mechanics of athletic movement outside of the task itself, and pitching is no exception.[17,18,21] These simpler movements can be paired with dual-tasking paradigms to improve the ecological validity of a task by mimicking the in-game cognitive demands of the sport, increasing the difficulty and consequently movement variability.[22] Separate PCAs for the pelvis and trunk identified 4 domains within the kinematic data across the non-Stroop and Stroop conditions: (1) sagittal-plane kinematics, (2) transverse-plane kinematics, (3) frontal-plane kinematics for the trail leg, (4) and frontal-plane kinematics for the lead leg. Interestingly, only increased transverse-plane trunk and pelvis rotation during the SLSD were separate predictors of high-torque–low-velocity cluster membership. Specifically, pitchers with increased transverse-plane trunk movement were 2.9 times more likely to be a member of the high-torque–low-velocity group after accounting for body weight. Increased transverse-plane pelvis movement similarly increased high-torque–low-velocity membership likelihood by 2.5 times after accounting for body weight. Although transverse-plane trunk and pelvis motion during the SLSD are generally considered to be compensatory mechanics, they can also be a byproduct of SLSD task performance.[23] Participants were not told how to complete the test; rather, they were instructed to lower themselves to the ground until the opposite heel touched the floor. Increased transverse-plane trunk and pelvis rotation, as well as increased frontal-plane leg movement, may reflect a strategy to achieve heel contact with the floor rather than true compensatory movement.

Gluteal muscle performance controls multiplanar pelvis stability and thus may underlie the increased transverse-plane motion seen in the high-torque–low-velocity group. During the baseball pitch, trail-leg gluteal muscles influence transverse-plane pelvis rotation and trunk-pelvis dissociation, in addition to stabilizing extraplanar movement.[9,11,24] The lead-leg gluteal muscles are tasked with stabilizing the pelvis during the late arm-cocking and arm-acceleration phases. Immediately after lead-foot contact, the lead-leg gluteus maximus and medius experience high levels of activity as they absorb energy to keep the pelvis level and decelerate the anterior and inferior translation of the center of mass in unipedal stance.[25] Both the gluteus maximus and medius work to provide lumbopelvic stability through resistance to hip flexion, internal rotation, and pelvis lateral tilt during arm acceleration.[26] The SLSD offers similar lumbopelvic stabilization demands in that proper execution of the task requires minimization of unwanted, extraplanar movement while descending in single-legged stance. Researchers have demonstrated that individuals with sufficient gluteal muscle strength and coordination have decreased pelvis movement, variability, and compensatory kinematics in the trunk and lower extremities during pitching.[27,28]

The core muscles function at the lumbopelvic junction, the anatomic link between the pelvis and trunk. During the pitch, the core and gluteal muscles stabilize the pelvis and control trunk axial rotation, affecting ball velocity and upper extremity moments that include elbow-varus torque.[11] Although we analyzed the trunk and pelvis separately, Lewis et al, analyzing SLSD kinematics, showed that transverse-plane pelvis and trunk rotation tend to occur in the same direction.[23] These aligned and concurrent rotations suggest trunk kinematics are related to proximal stability at the pelvis. During the baseball pitch, sequential transverse-plane rotations of the pelvis and trunk form the primary energy delivery mechanism between the lower and upper extremities.[29] A pelvis that is not adequately stabilized or rotated may compromise energy transfer to the trunk. Lumbopelvic stability may be improved with increased gluteal and core muscle performance and thus convert a high-torque–low-velocity pitcher who displays poor transverse-plane trunk and pelvis control during an SLSD into a low-torque–high-velocity pitcher.

Limitations of our results include the use of a single inertial sensor to measure elbow-varus torque and the need for validation of our clustering approach. Although the Motus pulse IMU (inertial measurement unit) has demonstrated good to excellent reliability,[30-33] and research supports the use of the Motus pulse IMU for measuring elbow kinetics, with authors reporting a moderate to strong relationship between IMU-derived elbow torque and motion-capture–derived elbow torque,[30,31] validation studies indicate that the IMU can underestimate the magnitude of elbow-varus torque compared to motion-capture methods.[30,34] Therefore, comparison of values derived from these 2 methods is not recommended. Hence, we have not compared elbow-varus torque values from our study with others derived from motion capture. Additionally, while we defined a 2-cluster solution to group the T-V relationship as high or low torque, these clusters and definitions need to be validated in other samples of pitchers to ensure their robustness. Despite these limitations, our results provide coaches and clinicians with a clinical paradigm of the SLSD to assess lumbopelvic stability and gauge a pitcher's risk of increased elbow-varus torque for a given ball velocity. Pitching biomechanics have been related to SLSD mechanics,[17,35] but the underlying mechanisms of this relationship have not been identified. We identified that increased transverse-plane trunk and pelvis kinematics during an SLSD were separately related to pitchers with high elbow torque during a baseball pitch.

CONCLUSIONS

Lumbopelvic stability during the SLSD can predict elbow-varus torque while controlling for ball velocity during a baseball pitch. Specifically, increased transverse-plane trunk and pelvis motion, while controlling for body weight, separately predicted membership in the high torque–low velocity group. The T-V clusters of high torque–low velocity and low torque–high velocity were identified using unsupervised learning. Plane of motion, rather than SLSD condition (non-Stroop versus Stroop), described variance in SLSD kinematics. Pitchers with increased transverse-plane pelvis or increased trunk motion during an SLSD are at higher risk for higher elbow-varus torque and concurrent lower ball velocity during the baseball pitch. These results afford clinicians with simple criteria for assessing trunk and pelvis kinematics during the SLSD, with implications for throwing-elbow injury risk and performance.

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