Influence of Lead Knee Extension on Ball Velocity and Elbow Varus Torque in Professional and High School Baseball Pitchers

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Background: When the lead leg of a pitcher contacts the ground, the knee braces and then rapidly extends, initiating energy transfer to begin pelvis and trunk rotation.

Purpose: To investigate the relationship of lead knee extension during the pitching delivery with peak lead knee extension velocity, ball velocity, and elbow varus torque in high school and professional pitchers.

Study Design: Descriptive laboratory study.

Methods: Data from 50 professional (PRO) and 50 high school (HS) pitcher groups were retrospectively analyzed. Pitchers threw 8 to 12 fastballs under 3-dimensional motion analysis (480 Hz). The groups were divided according to high or low lead knee extension: PRO-high (n = 18), PRO-low (n = 16), HS-high (n = 16), and HS-low (n = 17). Lead knee flexion, lead knee extension velocity, ball velocity, and elbow varus torque were analyzed between groups. Regression analyses were performed to quantify associations between lead knee extension and ball velocity and elbow varus torque for all pitchers.

Results: At foot contact, all pitchers landed with similar knee flexion. PRO-high and HS-high pitchers had significantly greater lead knee extension through remaining pitching time points compared with the PRO-low and HS-low pitchers. PRO-high pitchers had faster ball velocity than PRO-low pitchers (39.8 ± 1.1 vs 39.3 ± 1.3 m/s, respectively), and HS-high pitchers had faster ball velocity than HS-low pitchers (34.1 ± 2.6 vs 31.2 ± 1.8 m/s, respectively) ($P < .05$). PRO-high pitchers had decreased elbow varus torque compared with PRO-low pitchers (85.3 ± 10.7 vs 95.4 ± 13.3 N·m, respectively); conversely, HS-high pitchers had greater elbow varus torque than HS-low pitchers (64.2 ± 14.7 vs 56.3 ± 12.2 N·m, respectively). For every 1° increase in lead knee extension, ball velocity increased by 0.47 m/s ($P < .001$) and elbow varus torque increased by 0.27 N·m ($P = .025$).

Conclusion: Proper lead knee extension allowed efficient energy transfer through the kinetic chain to produce optimal ball velocity and minimize elbow varus torque in professional pitchers. Conversely, while proper lead knee extension improved ball velocity among high school pitchers, this did not minimize elbow varus torque.

Clinical Relevance: Professional pitchers can extend their lead knee with minimal impact at the elbow. In high school pitchers, cognizance of proper full-body pitching mechanics remains a priority over increased velocity.

Keywords: lead leg block; knee flexion; fastball; mechanics

The pitching motion consists of a coordinated sequence of body movement and muscular forces that work to transmit potential energy from the ground to a pitcher's throwing arm.[2,5,6,15] The lead leg initiates force development upon contact with the ground and facilitates energy transfer up the kinetic chain.[4,36,43] It is thought that lead leg block, or extension of the lead knee upon ground contact, induces favorable hip rotation and aids in effective energy transfer through the pelvis and trunk.[10-12] Conversely, flexion of the lead leg acts to dissipate ground-reaction force, leading to less efficient energy transfer and throwing mechanics.[12]

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Lead leg ground-reaction force has been shown to influence ball velocity in collegiate and professional pitchers.[21,26,30,31] Guido and Werner[19] found that collegiate pitchers with higher ball velocities demonstrated higher braking ground-reactive forces in the lead leg, which suggests that proper leg mechanics promote effective force transfer into the upper extremity for high-velocity pitching. Additionally, greater lead leg extension may be reliant on increased lower extremity strength and muscle mass in higher-level pitchers, which allows them to generate greater torque.[20] Training the lead leg to accept ground-reaction force at the appropriate time within the pitch delivery and efficiently transfer force through the kinetic chain is paramount.

Mistimed or inefficient lower body kinetics result in higher loading rates of the shoulder and elbow.[27,28,35,37,38] Lead knee extension is thought to decrease reliance on the arm to create energy through generating arm speed. Kibler and Chandler[23] reported that a 20% decrease in kinetic energy transfer from the hip and trunk requires a 34% increase in shoulder rotational velocity to produce an equivalent force of the throwing arm. As pitchers mature, the forces and torques sustained throughout the entire kinetic chain increase, as does the ability to achieve higher pitching velocities.[5,17,18,20] This implies that stress distribution and risk of injury vary among pitchers of different ages with compensatory throwing mechanics. For example, youth pitchers exhibit a common fault where trunk rotation precedes proper positioning of the shoulder and leads to increased elbow varus torque.[22] Kageyama et al[20] reported that adolescent pitchers do not develop hip and joint torques relative to their body size when compared with collegiate pitchers. Additionally, muscular weakness at the knee and hip have been identified as potential anatomic sites of disruption within the kinetic chain of youth pitchers.[3]

Previously, there have only been 2 biomechanical studies that have quantified total lead knee extension in pitchers.[11,12] Both studies reported that increased lead knee extension was associated with increased ball velocity. However, each of these studies sampled only adult (collegiate and professional) pitchers, with no high school pitchers included. It has been reported that high school pitchers adopt a different throwing pattern, whereby earlier trunk rotation starts the upward kinetic chain flow at comparable levels of elbow varus torque with professional pitchers but with a lower pitching velocity.[2]

The purpose of this study was to investigate differences in lead knee extension, peak lead knee extension velocity, ball velocity, and elbow varus torque in high school and professional pitchers. We hypothesized that professional pitchers would have greater lead knee extension and lead knee extension velocity compared with high school pitchers. Additionally, we hypothesized that professional pitchers with greater lead knee extension would have faster ball velocity but not increased elbow varus torque. In high school pitchers, we hypothesized that pitchers with less lead knee extension would have similar ball velocity but increased elbow varus torque.

METHODS

Participants

Data from 50 professional and 50 high school pitchers who were previously evaluated were included in this study. Inclusion criteria for professional pitchers were current status on a Major League Baseball or Minor League Baseball roster (Low A, High A, AA, or AAA team) with no prior record of severe injury (requiring >2 weeks of rest or rehabilitation) within the past 6 months. Inclusion criteria for the high school pitchers were active participation on a high school or club baseball team, no record of severe injury (requiring >2 weeks of rest or rehabilitation) within the past 6 months, and preparticipation clearance obtained from their primary care provider. All data were deidentified before distribution, and this study was determined as exempt from institutional review board approval under federal guidelines.

Data Collection

Pitching evaluations were conducted as previously described.[11,25] Pitchers reported to the test site, where they were administered a privacy waiver and provided informed consent. For pitchers younger than 18 years of age, the parent/legal guardian provided consent and the pitcher provided assent. Descriptive data were reported by the pitcher, including age, preferred throwing arm, experience level, and history of injury. Research staff measured and recorded the pitcher's height and mass. The pitcher was given unlimited time to warm up with his

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Figure 1. Time points of a pitch showing the change in lead knee flexion.

preferred routine for pitching at full effort. Once the pitcher indicated he was ready, 46 reflective markers were positioned on anatomic landmarks as previously defined.[11,25] Positional coordinate data of the reflective markers were collected using an 8-camera Raptor-E motion analysis system (Motion Analysis Corp) at 480 Hz. Before recording the pitches, we performed a single static calibration to align the pitcher with the laboratory coordinate system and define the local coordinate systems. The global coordinate system was established based on International Society of Biomechanics standards: Y was vertically upward, X was from the pitching rubber toward home plate, and Z was the cross-product of X and Y.[47]

Data for 8 to 12 fastballs were captured for each pitcher. All fastballs were pitched with gamelike effort from a regulation dirt mound to a catcher behind home plate at a regulation distance (18.4 m). Pitchers were allowed to pitch from either the stretch or windup deliveries as previous research has shown no difference between the 2 types in kinematics and kinetics.[13,38] They were instructed to pitch at their own pace but directed to aim for the middle of the strike zone. Ball velocity was collected with a radar gun (Stalker Sports Radar) behind the pitcher. The fastest pitch for each pitcher was used in the analysis to represent the best performance, as previous studies have reported.[25,32,33,41]

Outcome Evaluation

All data processing was performed using custom MATLAB scripts (The MathWorks) as previously described.[11,25] Data from the markers were filtered by a low-pass filter (fourth-order zero-lag Butterworth filter, 13.4-Hz cutoff frequency).[7] Full-body mechanics were calculated in order to establish key time points through the pitch: foot contact, maximum external rotation, ball release, and maximum internal rotation (Figure 1). Foot contact was identified as the first frame when the lead toe or heel in the Y-axis reached the ground surface. Maximum shoulder external rotation was the frame in which the throwing shoulder reached maximum external rotation relative to the trunk. Ball release was calculated as the instant 0.01 seconds after the wrist passed the elbow in the positive X direction. Maximum shoulder internal rotation was defined as the frame in which the throwing shoulder internally rotated the greatest amount after ball release. To establish a standardized pitch time, the pitch was calculated as a percentage of the pitch motion where foot contact represented time 0% and ball release represented time 100%. Additional kinematics calculated were lead knee extension, knee extension velocity, and elbow varus torque. Lead knee flexion was defined as 0° when straight. Total knee extension was defined as the difference in knee flexion angles between foot contact and ball release. A positive value indicated knee extension and a negative value indicated knee flexion. Peak elbow varus torque was reported as the absolute value occurring between foot contact and maximum internal rotation.

Statistical Analysis

The professional and high school pitchers were divided into separate groups (PRO and HS groups, respectively). In addition, pitchers in each group were subdivided into a "high" lead knee extension and a "low" lead knee extension group based on the individual mean lead knee extension being $>$0.5 SD or $<$0.5 SD from the entire group mean: PRO-high (n = 18), PRO-low (n = 16), HS-high (n = 16), or HS-low (n = 17). In order to further compare the differences between the groupings, a 2-way mixed-factorial analysis of variance (ANOVA) was performed (group [HS-high, HS-low, PRO-high, PRO-low] vs phase [foot contact, maximum external rotation, maximum internal rotation]). For pitch characteristics, 3 separate 1-way ANOVAs were used to assess between-group differences (Table 1). Three separate 2-way ANOVAs were used to analyze group (HS vs PRO) $\times$ level (high vs low) interactions for lead knee extension velocity, ball velocity, and elbow varus torque. When necessary, follow-up analysis included repeated-measures ANOVA and Bonferroni-corrected dependent-samples and independent-samples t tests. Correlation coefficients were utilized to quantify the degree of correlation between lead knee extension and ball velocity and elbow varus torque for all pitchers (N = 100). The change scores (mean $\pm$ standard error) were calculated and reported to describe group lead knee extensions across phases. For all analyses, statistical significance was set at $P < .05$. All data analyses were performed using SPSS Statistics (Version 23; IBM Corp).

TABLE 1
Characteristics of High School and Professional Pitchers Grouped by Low and High Lead Knee Extension During a Pitch[a]

	HS-Low (n = 17)	HS-High (n = 16)	PRO-Low (n = 16)	PRO-High (n = 18)	Significance[b]
Age, y	16.4 ± 1.6	16.8 ± 1.3	21.8 ± 1.9	22.4 ± 1.2	a, b, c, d
Height, cm	180.4 ± 9.8	181.9 ± 6.7	189.8 ± 6.2	187.5 ± 4.1	a, b, c, d
Weight, kg	74.9 ± 9.5	76.7 ± 10.5	97.9 ± 8.4	92.2 ± 5.3	a, b, c, d

[a]Data are reported as mean ± SD. HS, high school; PRO, professional.
[b]Significant differences ($P < .05$) between (a) HS-low and PRO-low, (b) HS-low and PRO-high, (c) HS-high and PRO-low, and (d) HS-high and PRO-low.

RESULTS

Table 1 shows the comparison of pitcher characteristics (age, height, and weight) across study groups. There were no significant differences within the HS or PRO groups regarding these characteristics. However, there were significant differences between the PRO and HS groups in all 3 variables ($P < .05$).

With regard to lead knee flexion, there was a significant group × phase interaction ($P < .001$; partial $\eta^2 = 0.670$). Post hoc analyses revealed that there were no significant differences among groups in lead knee flexion at foot contact; however, as the phases progressed, PRO-high and HS-high lead knee flexion decreased steadily (into knee extension), whereas PRO-low and HS-low first increased further into knee flexion as they progressed to maximum shoulder external rotation, and then knee flexion decreased through ball release and maximum internal shoulder rotation (Figure 2).

There were significant group × level interactions for lead knee extension velocity ($P = .017$; partial $\eta^2 = 0.086$), ball velocity ($P = .008$; partial $\eta^2 = 0.107$), and elbow varus torque ($P = .005$; partial $\eta^2 = 0.118$) (Figure 3). Pitching kinematic and kinetic data for each group are displayed in Table 2.

Values that derived significance from the 4 groups for lead knee extension were analyzed with regression correlation coefficients. For every 1° increase in lead knee extension, ball velocity increased by 0.47 m/s (1.06 mph) ($R^2 = 0.22$; $\beta = 0.472$; $P < .001$). For every 1° increase in lead knee extension, elbow varus torque increased by 0.27 N·m ($R^2 = 0.075$; $\beta = 0.274$; $P = .025$).

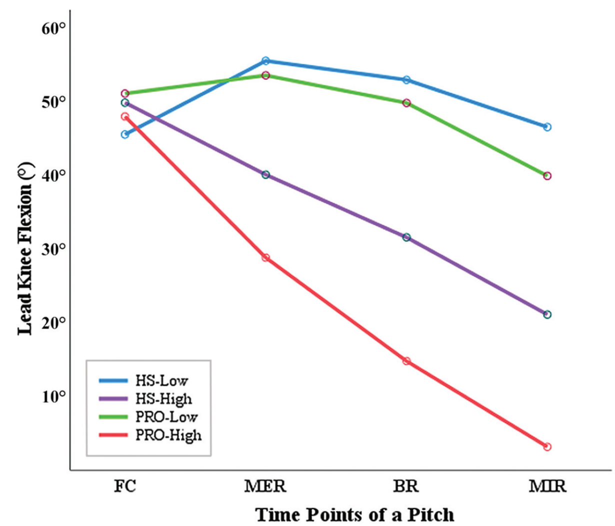

Figure 2. Lead knee flexion at different points of the pitch for professional (PRO) and high school (HS) pitchers grouped by amount of lead knee extension: high (>0.5 SD from the group mean) or low (<0.5 SD from the group mean). BR, ball release; FC, foot contact; MER, maximum external rotation; MIR, maximum internal rotation.

DISCUSSION

The lower extremities are fundamental to efficient pitching mechanics, as they are responsible for initial energy creation and subsequent energy transfer up the kinetic chain to drive the pitching motion forward. A stable base created by the lead leg allows for the pelvis and trunk to rotate, allowing for the throwing arm to follow. The purpose of this study was to investigate the relationship of lead knee extension motion during the pitching delivery with peak lead knee extension velocity, ball velocity, and elbow varus torque in high school and professional pitchers. Our hypotheses were confirmed, as professional pitchers had greater lead knee extension, lead knee extension velocity, and ball velocity compared with high school pitchers. Professional pitchers with greater lead knee extension (PRO-high) had faster ball velocity and decreased elbow varus torque compared with professional pitchers with lower lead knee extension (PRO-low). High school pitchers with greater lead knee extension (HS-high) had faster ball velocity and increased elbow varus torque compared with high school pitchers with less knee extension (HS-low).

All pitchers landed with similar knee flexion at foot contact. This has been established in previous research investigating professional pitchers separated by high and low velocity,[12] high and low accuracy,[29] and high and low pelvic rotation at foot contact.[10] Dowling et al[12] provided the range of lead knee flexion for youth, high school, collegiate, and professional pitchers from previously reported studies; while a meta-analysis was not performed, a narrow range

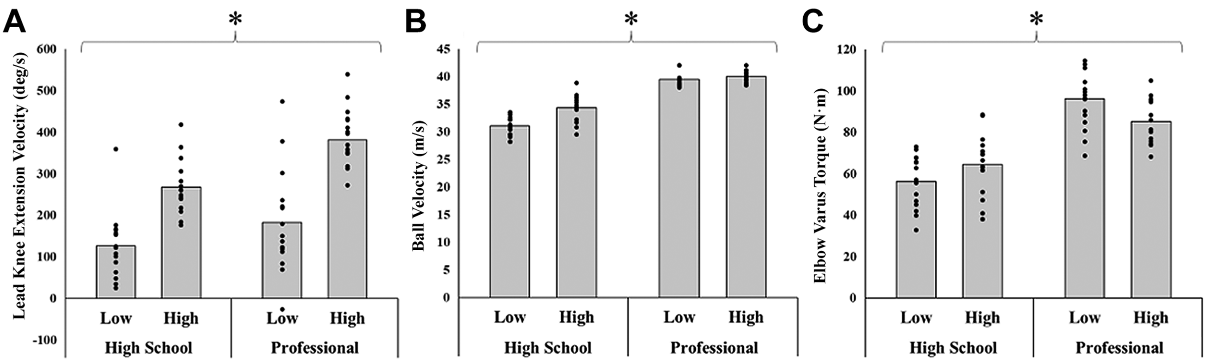

Figure 3. Group (professional vs high school) × level (low vs high) comparisons for (A) lead knee extension velocity, (B) ball velocity, and (C) elbow varus torque. *Significant group × level interaction ($P < .05$).

TABLE 2
Kinematic and Kinetic Differences Between High School and Professional Pitchers Grouped by Low and High Lead Knee Extension During a Pitch[a]

	HS-Low (n = 17)	HS-High (n = 16)	PRO-Low (n = 16)	PRO-High (n = 18)	Significance[b]
Lead knee extension, deg	–7 ± 5	18 ± 6	1 ± 8	33 ± 7	a, b, c, d, e, f
Lead knee extension velocity, deg/s	124 ± 77	270 ± 65	187 ± 122	409 ± 76	a, b, c, d, e, f
Extension velocity timing, %	57 ± 31	65 ± 24	47 ± 29	61 ± 28	
Ball velocity, m/s	31.2 ± 1.8	34.1 ± 2.6	39.3 ± 1.3	39.8 ± 1.1	a, b, c, d, e, f
Elbow varus torque, N·m	56.3 ± 12.2	64.2 ± 14.7	95.4 ± 13.3	85.3 ± 10.7	a, b, c, d, e, f

[a]Data are reported as mean ± SD. Negative lead knee extension represents knee flexion. HS, high school; PRO, professional.
[b]Significant differences ($P < .05$) between (a) HS-low and HS-high, (b) PRO-low and PRO-high, (c) HS-low and PRO-low, (d) HS-low and PRO-high, (e) HS-high and PRO-low, and (f) HS-high and PRO-low.

of lead knee flexion at foot contact between all the groups (43° to 50°) was reported. As the pitch delivery progressed, differences in lead knee flexion between age groups became more evident. Solomito et al[39] confirmed this point, as the knee flexion of collegiate pitchers was similar at foot contact but became more variable as the pitch delivery progressed from maximum external rotation through maximum internal rotation. In the current study, the PRO-high and HS-high groups were able to extend their lead knee immediately after foot contact through ball release and into maximum internal rotation. However, the PRO-high group was able to extend the knee through 55% more extension compared with the HS-high group. Pitchers in the HS-low group continued to flex their knee into greater flexion after foot contact and at ball release, as these pitchers were at lower knee flexion than at foot contact (–1° extension).

In both the HS and PRO groups, pitchers with greater lead knee extension (the high groups) displayed significantly greater ball velocity compared with the pitchers with lower lead extension (difference between groups: HS, 2.9 m/s [6.5 mph]; PRO, 0.5 m/s [1.1 mph]). This is consistent with previous research in professional pitchers where lead knee extension and lead knee extension velocity were statistically significant predictors of ball velocity.[12,14,30] Similarly in collegiate baseball pitchers, Werner et al[45] reported that increased lead knee extension at both foot contact and ball release was associated with increased ball velocity. In youth pitchers, van Trigt et al[44] reported similar findings, that ball velocity increased by 1 mph as lead knee extension increased by 18° at maximum external rotation and 19.5° at ball release. However, these values reported by van Trigt et al were large changes in knee angles, especially when compared with those observed in the current study where the HS-high and PRO-high groups were extending a total of 18° and 33°, respectively, and these values might not be physically attainable in the HS groups. When comparing all pitchers, for every 1° increase in lead knee extension there was a 0.47-m/s (1.05-mph) increase in ball velocity. The difference in ball velocity between the HS groups was large; however, the difference was much smaller between the PRO-high and PRO-low groups. It is plausible that younger pitchers have greater variability in mechanics that ultimately influences ball velocity, as compared with more accomplished pitchers who have refined their mechanics by the time they advance to the professional level.[40]

The correlation between lead knee extension and ball velocity identified in this study for both high school and professional pitchers holds direct relevance to sports performance and sports medicine. Improved lead knee extension in younger pitchers may point toward an overall more efficient motion. We posit that increasing knee extension after foot contact may be a modifiable parameter that pitchers and coaches may target to increase ball velocity. Among high school pitchers, deficits throughout the kinetic chain likely also need to be addressed to achieve a comparable pitching motion that mitigates the increased elbow varus torque identified in our study population. Given the complex, synchronous movement patterns that define the pitching motion, close monitoring with tools such as video camera or motion capture data is necessary to ensure that increasing lead knee extension is accomplished without disrupting the temporal relationship between the constituent movements of the lower and upper extremities during the pitch.

Increased lead leg extension was also related to increased lead knee extension velocity in both the HS and PRO groups, where the HS-high and PRO-high pitchers had faster lead knee extension velocity. Actively extending the knee once the front foot touches the ground causes the leg to brace and results in a braking effect. The braking effect then allows for the pelvis to rotate over the hip and requires less muscle power of the knee extensors in an extended knee (rather than a flexed knee) because of the shorter moment arm.[44] This braking effect aids in the proper sequence of the kinetic chain and has been found to aid in the transfer of momentum through the trunk to the throwing arm, ultimately producing greater ball velocities.[21,24] Increased segment velocities are essential to developing optimal ball velocity. In a recent study of professional pitchers, proper kinetic chain sequencing led to faster lead knee extension velocity and faster ball velocity with no concomitant increase in elbow varus torque.[28] The authors of that study suggested that the lead knee extension and lead knee extension velocity may be a key determinant in pitchers' ability to increase ball velocity while minimizing elbow varus torque. In collegiate and professional pitchers divided into low and high ball velocity groups, the high-velocity group had faster lead knee extension velocity (260 deg/s) compared with the low-velocity group (161 deg/s).[30] Conversely, Kageyama et al[20] reported no difference in lead knee extension velocity between adolescent and collegiate pitchers. However, these authors reported that collegiate pitchers had greater maximum lead knee extension torque (relative to body size) and concluded that this allows for greater control and stabilization of the lead knee. Muscular weakness in the knee and hip has been implicated as a potential area for a break in the kinetic chain.[3] In the current study, the professional pitchers more than likely had greater lower limb strength and muscle mass than high school pitchers, along with increased lower extremity momentum, resulting in increased ball velocity.

Elbow varus torque is an important area of study, as the mechanics that produce it may be modified to minimize the risk of medial-sided elbow pain and injury in baseball players.[8,16] We hypothesized that increased knee extension would be related to decreased elbow varus torque. This was confirmed in the PRO group, as the PRO-low pitchers had increased elbow varus torque compared with the PRO-high group. However, in the HS group, the pitchers with increased knee extension (HS-high) also had increased elbow varus torque. We believe that pitchers in the HS group had greater variability in throwing mechanics beyond lead knee extension that may have influenced the magnitude of elbow varus torque. Previous studies in both high school and professional pitchers have identified biomechanical predictors for elbow varus torque during pitching, such as greater maximum shoulder external rotation, early onset of trunk rotation, greater shoulder abduction at foot contact, and lateral trunk flexion at maximum external rotation.[1,2,7,9,34,38,42,46] There remains a gap in the literature regarding the influence of lower extremity mechanics on elbow varus torque. According to a recent study of 107 high school pitchers, increased wrist extension, elbow pronation, lead knee flexion, back knee extension, and upward displacement of the body's center of mass at foot contact significantly correlated with decreased elbow varus torque.[42] Tanaka et al[42] reported that 38% of the variance in peak elbow varus torque was explained by a combination of those 5 kinetic variables. In the current study, we found that for every 1° of lead knee extension there was a 0.27-N·m increase in elbow varus torque when comparing all pitchers. While this was significant, this was a weak correlation with only 7.5% of the variance being explained by the model. We investigated lead knee extension in isolation and recognize the possibility that we may be neglecting other links to elbow varus torque in these players, especially the high school pitchers. Moreover, further investigation is needed to evaluate what happens when a pitcher is instructed to change his lead knee extension (eg, flexion or increased extension) and how this intervention could influence elbow varus torque and ball velocity within an individual player.

Limitations

This study has limitations that warrant discussion. First, pitchers were asked to throw only fastballs, and these findings may not be applicable to other pitch types. While pitchers were instructed to pitch with gamelike effort and threw from a dirt mound, this controlled setting was atypical from practice and competition. This may cause pitchers to reduce effort and inadvertently cause reduction in lead knee extension as well as ball velocity. However, the setting was the same for all pitchers, and this type of environment allows for this type of research. Professional and high school pitchers were evaluated in this study, and the results are not generalizable to pitchers participating in various levels of competition. Investigating collegiate players would help bridge the gap between the 2 groups in the current study and might help us understand the change in utilizing the lead leg block from the high school to professional level. Moreover, potentially confounding variables related to handedness, trunk and throwing arm kinematics, prior injury, and workload were not accounted for in our analyses and could influence the findings. We did not investigate within-pitcher effects of lead knee extension, and changes within a pitcher might result in different outcomes.

CONCLUSION

Proper lead knee extension allowed efficient energy transfer through the kinetic chain to produce optimal ball velocity and minimize elbow varus torque in professional pitchers. Instructing professional pitchers to improve lead knee extension may contribute to faster ball velocity with minimal impact on elbow varus torque. Conversely, while proper lead knee extension improved ball velocity among high school pitchers, this did not minimize elbow varus torque in professional pitchers.

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