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Original research

Using the single leg squat as an assessment of stride leg knee mechanics in adolescent baseball pitchers☆

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ABSTRACT

Objectives: Lack of control of the lower extremity or trunk during single leg tasks is often associated with pathomechanic adaptations during the pitching motion which may increase the risk of pain and injury to the upper extremity. The objectives of the study were to determine the amount of variability in stride knee mechanics accounted for by compensations during a common movement assessment, the single leg squat (SLS) and to establish the usefulness of SLS as a screening tool for at-risk athletes.
Design: Cross-sectional design.
Methods: Sixty-one adolescent baseball pitchers performed a SLS on each leg. Participants performed three fastball pitches to a catcher at a regulation distance. Kinematic data were collected at 100 Hz using an electromagnetic tracking device.
Results: MANOVAs with follow-up one-way ANOVAs were used to examine the amount of variance in pitching knee mechanics explained by SLS compensations. At stride foot contact, there was a significant effect of SLS valgus angle on knee valgus angle ($F_{1,51} = 23.16$, $p < 0.001$, $\eta_p^2 = 0.31$) and valgus moment ($F_{1,51} = 8.28$, $p = 0.006$, $\eta_p^2 = 0.14$). At ball release (BR), there was a significant effect of SLS valgus angle on flexion angle ($F_{1,51} = 9.37$, $p = 0.004$, $\eta_p^2 = 0.16$) and valgus angle ($F_{1,51} = 26.93$, $p < 0.001$, $\eta_p^2 = 0.35$). Examination of the average values occurring between SFC and BR, revealed a significant effect of SLS valgus angle on knee valgus angle ($F_{1,51} = 30.91$, $p < 0.001$, $\eta_p^2 = 0.38$).
Conclusions: SLS compensations are potentially a useful screening tool for stride knee mechanics in adolescent baseball pitchers.

Practical implications

- Adolescent pitchers who displayed greater single leg squat knee valgus also displayed greater stride knee collapse during the pitching motion.
- Adolescent pitchers who displayed greater single leg squat knee valgus also displayed greater stride knee flexion at ball release which could indicate suboptimal pitching performance.
- The single leg squat shows promise as a clinical assessment tool for stride knee mechanics during the pitching motion.

1. Introduction

The baseball pitch is a challenging, full-body task requiring the coordination of body segments to transmit forces from the lower extremity through the trunk, upper extremity, and into the ball. This force generation begins with the foot-ground interaction at the pitching event of stride foot contact (SFC) and proceeds sequentially through the kinetic chain in a proximal (lower extremity) to distal (upper extremity) manner.[1,2] If the lower extremity is inefficient in the absorption and transfer of forces generated during the early phases of the pitching motion, pitchers may compensate by increasing force production in the more distal aspects of the kinetic chain.[3] An inefficient lower extremity potentially increases susceptibility of pain and injury to more vulnerable structures in the upper extremity, such as the elbow and shoulder.[1]

A common inefficiency of the lower extremity during the pitching motion is the inability to control stride knee mechanics following SFC. This inefficiency has been demonstrated in an examination of high and low velocity pitchers which found that

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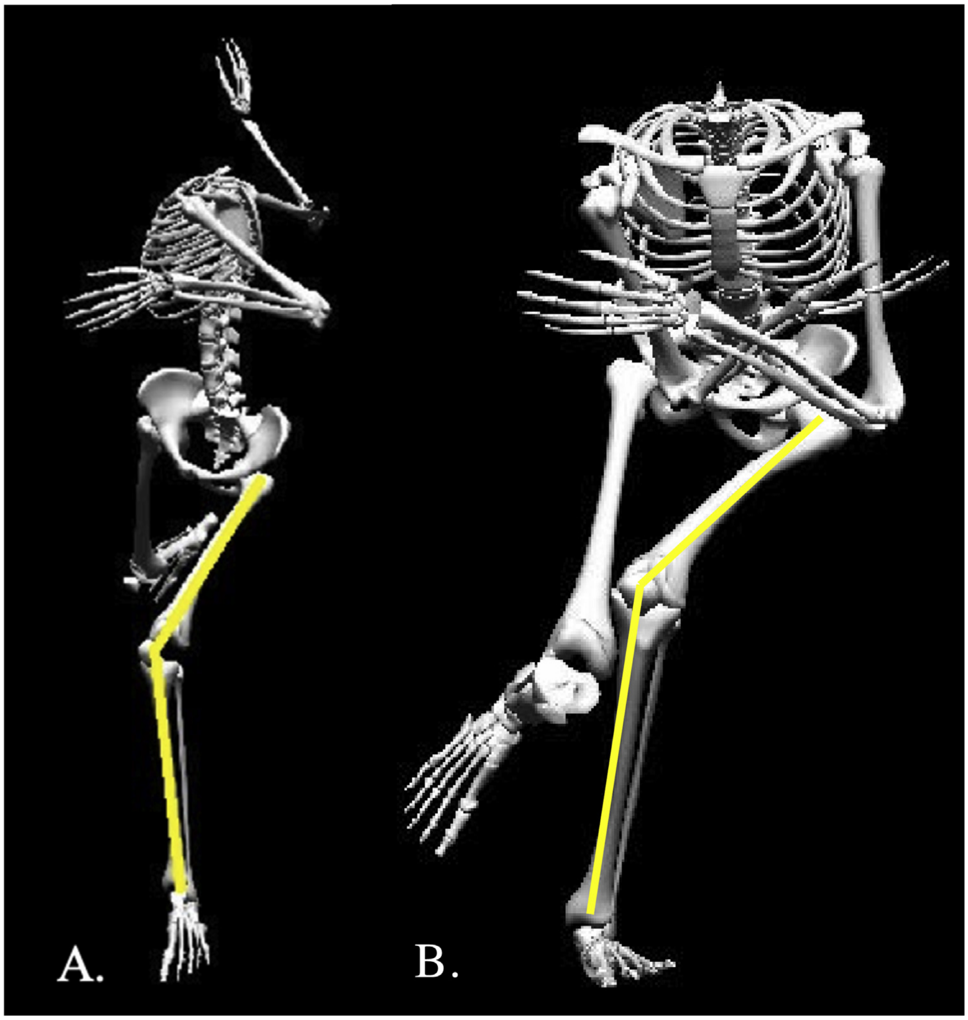

Fig. 1. (A) Dynamic knee valgus during the pitch. (B) Dynamic knee valgus during the single-leg squat.

high velocity pitchers displayed limited stride knee flexion after SFC and greater stride knee extension between SFC and ball release (BR) whereas low velocity pitchers displayed continued stride knee flexion after SFC and little to no stride knee extension between SFC and BR.[4] Cessation of stride knee flexion after SFC is colloquially referred to as 'front side bracing' and initiation of stride knee extension prior to BR is referred to 'front side recoiling'. Front side bracing and recoiling, as seen in high velocity pitchers, is thought to help stabilize the stride leg.[5] In agreement with proximal stability for distal mobility,[2] a more stable stride leg may enhance the ability of the trunk to rotate and drive the body forward over the stride leg as energy moves through the kinetic chain.[4]

Multi-planar stability is necessary for efficient joint movement. In the case of front side bracing and recoiling following SFC, knee stability may assist in the transfer of energy from the lower extremity into the trunk during the pitching motion. The importance of the multi-planar stride knee stability for proper transfer energy up the kinetic chain has been established in pitchers of multiple ages and ability levels.[5–8] Increased stride knee extension at maximum shoulder external rotation (MER) and BR has been associated with increased ball speed in adolescent pitchers, just as greater stride knee extension moments at MER and BR have been shown to differentiate collegiate from adolescent pitchers.[5,7] In addition to the documented importance between pitchers of different age and ability levels, the role of the stride knee has also been examined within individual pitchers as they approach fatigue. Kung et al. reported that adolescent pitchers experienced concomitant decreases in maximum stride knee extension angular velocity and ball speed during a simulated game.[9] Thus, it has been inferred that, as pitchers mature they are better able to control the stride knee flexion moment at SFC and successfully use their lower extremity and lumbopelvic-hip complex (LPHC) musculature to create knee extension.[5]

When considering the LPHC musculature and its ability to stabilize the lower extremity and trunk, clinicians and coaches often assess an athlete's capabilities through assessments such as the single leg squat (SLS).[10,11] The SLS has been shown to be a reliable assessment of lower body and LPHC strength,[11,12] plane-specific knee mechanics, sport performance prediction,[13,14] as well as lower extremity pain.[15] During the SLS, one must have adequate lower extremity strength and stability to complete the movement while maintaining one's center of mass over a reduced base of support. The reduced stability invoked by the SLS often results in compensatory mechanisms such as dynamic knee valgus, pelvic tilt, and trunk lean.[2] (Fig. 1).

Compensatory strategies during the SLS have been described in the literature.[10–12,14,15] A relationship has been demonstrated between pain level and kinematic compensations during the SLS, specifically the amount of knee valgus has been established.[15,16] The authors hypothesized that individuals who display greater knee valgus during the SLS may use a hip adductor dominant strategy throughout the movement instead of coactivation of the gluteal abductors and hip adductors.[15,16] While the previous studies did not specifically examine baseball athletes, it is reasonable to assume that adolescent pitchers with dysfunction in the coactivation between the hip adductors and the gluteal abductors may also be unable to stabilize the stride knee following SFC during the pitch. Inability to stabilize the stride knee may result in continued stride knee flexion and potentially excessive stride knee valgus as energy is transferred from the lower extremity to the trunk during the pitching motion. Therefore, compensations during a SLS assessment may be indicative of suboptimal lower body mechanics during dynamic tasks such as the baseball pitch.

Examining literature that has investigated the SLS and baseball pitching, Plummer et al. established a relationship between trunk lean during the SLS and trunk lean during the pitching motion.[14] Specifically, increased trunk lean during the SLS was associated with increased trunk lean during the pitch;[17] the latter of which has previously been associated with increased pitching upper extremity kinetics.[17] Furthermore, decreased anterior/posterior pelvic control while performing a single leg balance task has been associated with increased shoulder horizontal abduction and elbow valgus moment during the pitching motion[18] which have both, in turn, been associated with increased incidence of pain and injury in baseball pitchers.[1] Together, these studies provide evidence that a lack of control of the lower extremity, LPHC, or trunk during single leg tasks is often associated with pathomechanic pitching adaptations; increasing the risk of pain and injury to the upper extremity. A reliable clinical assessment of stride knee mechanics may prove useful for clinicians attempting to identify at-risk athletes. Thus, the purpose of this study was to determine the amount of variability in stride knee mechanics accounted for by compensations during the SLS in adolescent baseball pitchers. A secondary purpose was to determine whether the SLS may be used as a potential screening tool for at-risk athletes. It was hypothesized that greater degrees of compensation during the SLS would be indicative of inefficient stride leg knee mechanics. It was also hypothesized that the SLS would be able to clinically assess stride knee mechanics during the pitching motion.

2. Methods

The aim of this study was to determine the amount of variability in stride knee mechanics accounted for by compensations during the SLS. Single-leg squat compensations were assessed using select peak knee, hip, pelvis, and trunk angles achieved during the SLS task. Stride knee mechanics were assessed using flexion/extension angle, varus/valgus angle, flexion/extension angular velocity, flexion/extension moment, and varus/valgus moment between SFC and BR.

Sixty-one (164 ± 15.8 cm; 57.9 ± 14.5 kg; 12.6 ± 2.1yrs) male adolescent baseball pitchers were recruited to participate in this study. Inclusion criteria included no lower or upper extremity injuries in the past 6 months and no history of surgery to the upper or lower extremity. The Institutional Review Board of Auburn University approved all testing protocols. Prior to data collection, all testing procedures were explained to each participant and informed assent and parental consent were obtained.

On the day of testing, participants reported to the Sports Medicine and Movement Laboratory prior to engaging in any throwing or vigorous physical activity that day. After an overview of testing procedures was given, 13 electromagnetic sensors (Flock of Birds; Ascension Technologies Inc., Burlington, VT, USA) were affixed to the skin at the following locations: (1) posterior aspect of the trunk at the first thoracic vertebrae (T1) spinous process; (2) posterior aspect of the pelvis at the first sacral vertebrae (S1); (3–4) flat broad portion of the acromion on the bilateral scapula; (5–6) lateral aspect of the bilateral upper arm at the deltoid tuberosity; (7–8) posterior aspect of the distal bilateral forearm, approximately halfway between the radial and ulnar styloid processes; (9) dorsal aspect of the throwing-side hand, approximately halfway along the third metacarpal, (9–10) lateral aspect of the bilateral thigh, approximately halfway between the greater trochanter and lateral condyle of the knee; (11–12) lateral aspect of the bilateral shank, approximately halfway between the lateral condyle of the knee and lateral malleolus; (13) dorsal aspect of the non-throwing side foot, approximately halfway along the second metatarsal. A 14th sensor was attached to a moveable plexiglass stylus for the digitization of bony landmarks.

Lower extremity segment reference frames were defined using International Society of Biomechanics recommendations.[24] Hip joint centers were calculated from femur movement relative to the sacrum using the rotation method.[25] Joint centers for the ankle and knee were calculated as the midpoint of medial and lateral bony landmarks.[24] Motions for hip and knee were defined by Euler angles of rotation of the distal segment relative to proximal segment reference frame using a Z, X',Y" decomposition sequence. The first rotation defined the degree of flexion/extension about the Z-axis, the second rotation defined the amount of abduction/adduction about the X-axis, and the third rotation defined the amount of axial rotation about the Y-axis.[24] Kinetic data were calculated using inverse dynamics equations from The MotionMonitor software.

After sensor attachment and digitization, participants performed a SLS on each leg.[14] Participants were instructed to cross their arms over chest, flex the non-testing knee to 90°, and to squat as low as they could while maintaining balance and an upright trunk. After reaching peak depth, participants ascended to the starting position without letting their non-testing foot touch the ground and without letting their non-testing leg touch the testing leg.[12,14] A failed trial consisted of the non-testing leg touching the ground or resting on the testing leg. Cadence for the SLS was self-selected by the participant.[12,14] Participants were allowed to practice the task until they were comfortable performing a correct SLS.

Following the SLS, participants were allotted an unlimited amount of time to prepare for full-effort pitching. Individual pregame routines were allowed to ensure that each participant could most closely mimic in-game effort levels.[26] Once participants indicated they were ready, they performed three, full-effort fastball pitches to a catcher at an age-appropriate regulation distance (14.0–18.4 m).

Kinematic data were collected at 100 Hz using an electromagnetic tracking device (trakSTAR™, Ascension Technologies Inc.; Burlington, VT, USA) synchronized with The MotionMonitor software (Innovative Sports Training; Chicago, IL, USA). Previous reported root mean square error for similar systems is 1.8 mm for position and 0.5° for orientation.[19] Research has shown good to excellent test-retest reliability of 3D knee kinematics using electromagnetic motion capture technologies;[20,21] suggesting examination of frontal plane mechanics using the current methodology was reasonable. Furthermore, electromagnetic tracking systems have previously been used to examine lower extremity mechanics during dynamic athletic tasks.[22,23]

Data were processed by MatLab (version R2013b; The Math Works Inc.; Natick, MA, USA) and analyzed using SPSS 21 for Windows (SPSS, Chicago, IL, USA). Kinematic and kinetic parameters for the three fastballs were averaged for analysis. Only the SLS of the leg contralateral to the throwing arm (stride leg) was used for analysis. The SLS was event marked at the start and finish of the exercise as indicated by initiation and cessation of testing leg knee flexion. The pitching motion was event marked at SFC and BR. For each pitch, BR was marked as the midpoint between MER and maximal shoulder internal rotation (MIR).[26] Variables were examined at the events of SFC and BR.

Table 1
Select stride knee kinematic and kinetic variables at pitching events of foot contact, ball release, and average between events[a].

	Mean (SD)		
	Foot contact	Ball release	Average
Flexion/Extension θ	−44.3 (9.37)	−33.9 (15.5)	−44.0 (9.89)
Varus/Valgus θ	−4.17 (7.80)	2.49 (9.05)	−0.62 (7.84)
Flexion/Extension Angular Velocity	−23.9 (98.1)	169 (119)	57.0 (82.6)
Flexion/Extension Moment	−0.04 (0.29)	0.77 (1.02)	0.32 (0.83)
Varus/Valgus Moment	−0.25 (0.27)	0.44 (0.71)	−0.003 (0.61)

[a] Flexion/extension θ:flexion = negative; varus/valgus θ:valgus = negative; flexion/extension angular velocity: flexion = negative; flexion/extension moment: flexion = negative; varus/valgus moment: valgus = negative; angles are expressed in degrees; angular velocities are expressed in degrees per second; moments are mass normalized and expressed in N*m/kg.

Table 2
Zero-order correlations between SLS valgus angle and stride knee mechancis[a].

	Correlation Coefficient	Sig
SFC		
Varus/Valgus θ	0.69	<0.001
Varus/Valgus Moment	0.26	0.041
BR		
Varus/Valgus θ	0.65	<0.001
Flexion/Extension θ	0.27	0.032
Average		
Varus/Valgus θ	0.70	<0.001

[a] SLS = single leg squat; SFC = stride foot contact; BR = ball release; Average = average value between SFC and BR.

To examine the amount of variance in pitching knee mechanics explained by SLS compensations, multivariate analysis of variance (MANOVA) was used. Three separate multivariate models were used to examine pitching parameters at SFC, BR, and the average values between events with SLS kinematics representing the independent variables and stride knee parameters during the pitch representing the dependent variables. Testwise error was set *a priori* at $\alpha = 0.05$. Where significant multivariate effects were present, follow-up one-way ANOVAs were used to determine how SLS kinematic effects differed among stride knee flexion/extension angle, varus/valgus angle, flexion/extension angular velocity, flexion/extension moment, and varus/valgus moment. To minimize the effects of type 1 error, Bonferroni corrections were applied to all follow-up ANOVAs ($\alpha = 0.01$). Where significant univariate effects were present, pearson product-moment correlations were used to determine the directionality of the relationships between SLS compensations and stride knee mechanics during the pitch.

3. Results

Descriptive statistics for flexion/extension angle, varus/valgus angle, flexion/extension angular velocity, flexion/extension moment, and varus/valgus moment during the pitching motion can be found in Table 1. Average fastball velocity for the pitchers in this study was approximately 24 m per second (54 miles per hour). The only SLS parameter that accounted for significant variability in stride knee mechanics was knee valgus angle. The average SLS valgus angle in our study was $9^\circ \pm 8^\circ$.

When examining stride knee mechanics at SFC, there was a significant effect of SLS valgus angle on the dependent variables ($\lambda = 0.644$; $F_{5,47} = 5.12$, $p < 0.001$; $\eta_p^2 = 0.36$). Follow up one-way ANOVA indicated a significant effect of SLS valgus angle on SFC valgus angle and SFC valgus moment (valgus angle: $F_{1,51} = 23.16$, $p < 0.001$, $\eta_p^2 = 0.31$; valgus moment: $F_{1,51} = 8.28$, $p = 0.006$, $\eta_p^2 = 0.14$). At BR, there was a significant effect of SLS valgus angle on the dependent variables ($\lambda = 0.622$; $F_{5,47} = 5.71$, $p < 0.001$; $\eta_p^2 = 0.38$). Follow-up one-way ANOVA indicated a significant effect of SLS valgus angle on BR flexion angle and BR valgus angle (flexion angle: $F_{1,51} = 9.37$, $p = 0.004$, $\eta_p^2 = 0.16$; valgus angle: $F_{1,51} = 26.93$, $p < 0.001$, $\eta_p^2 = 0.35$). When looking at the average values between SFC and BR, there was a significant effect of SLS knee valgus angle on the dependent variables ($\lambda = 0.585$; $F_{5,47} = 6.67$, $p < 0.001$; $\eta_p^2 = 0.42$). Follow-up one-way ANOVA indicated a significant effect of SLS valgus angle on average valgus angle between SFC and BR ($F_{1,51} = 30.91$, $p < 0.001$, $\eta_p^2 = 0.38$). Results from follow-up correlation analysis can be found in Table 2.

4. Discussion

The purpose of the present study was to determine the amount of variability in stride knee mechanics accounted for by compensations during the SLS. Since the stride leg is largely responsible for converting the linear momentum generated during the early phases of the pitch into angular motion after SFC, stride knee mechanics are an important link in the kinetic chain during the baseball pitching motion.[6] This energy transfer places large demands on the musculature surrounding the stride knee. A reliable clinical assessment of sagittal and frontal plane knee mechanics would allow coaches, clinicians, and sports medicine personnel to better identify at-risk athletes, thereby improving the ability to proactively guard against future injury. The most important finding of this study is that the SLS accounted for significant variability in stride knee mechanics; indicating it is a potentially useful clinical assessment of lower extremity mechanics in adolescent baseball pitchers.

Lower extremity parameters during the pitch in this study were similar to those reported for this age group in previous pitching research. Fleisig et al. reported average knee flexion angles of 48° and 39° in 13 year old pitchers at SFC and BR, respectively.[8] In addition, Kageyama et al. reported knee flexion angles of 40° at SFC and 31° at BR in their adolescent population.[5] The average knee flexion angles in the current study were 44.3° and 33.9° at SFC and BR, respectively (Table 1). Knee flexion/extension angular velocity and moment patterns were also similar to previously reported values for adolescent pitchers.[5]

In the present study, pitchers who displayed greater knee valgus during the SLS also displayed greater knee flexion at BR during the baseball pitch. In a comparison of low and high velocity pitchers, Kageyama and colleagues found that higher velocity pitchers displayed less knee flexion at BR when compared with similarly-aged, low velocity pitchers.[27] This suggests that less knee flexion at BR may be indicative of increased pitching performance. It then follows that pitchers with decreased SLS valgus compensation may also display better stride knee mechanics during the pitching motion. Conversely, Fleisig et al. found no difference in knee flexion angle at SFC when comparing pitchers across various levels of development.[28] Differences in findings between Kageyama et al. and those of Fleisig et al.[28] may be due to differences of the participant cohorts. Specifically, Kageyama et al. cross-sectionally investigated adolescent pitchers whereas Fleisig et al. investigated youth, high school, collegiate, and professional pitchers.[28] Given the conflicting literature regarding knee flexion and extension kinematics during the pitching motion, additional studies, particularly of longitudinal nature, are needed before optimal sagittal plane stride knee mechanics may be determined and whether SLS performance can be used as a screening tool in the sagittal plane for baseball pitchers.

To the authors' knowledge, this is the first study to examine stride knee valgus angle during the baseball pitch. In the present study, pitchers who were able to minimize knee valgus angle during the SLS also displayed less knee valgus at SFC, BR, and between SFC and BR during the baseball pitch. Given the associations between LPHC stability, knee valgus, and musculoskeletal injury in other sports,[29] minimizing knee valgus during the baseball pitch could prove novel in reducing pain and injury risk and increasing the mechanical efficiency of the lower extremity. By minimizing knee valgus, a baseball pitcher may better transfer the energy generated by the lower extremity up the kinetic chain. Results from the present study indicate that the SLS could possibly serve as a screening tool for frontal plane knee mechanics during the baseball pitch. Future studies should focus on establishing normative standards and injury risk thresholds regarding frontal plane knee motion for adolescent baseball athletes.

Dispite work from Kageyama et al. and Matsuo et al. that revealed greater knee extension angular velocity at BR in more skilled pitchers,[4,27] the present study revealed no relationships between SLS compensations and knee extension angular velocity during the pitch. However, both aforementioned studies examined collegiate pitchers whereas the present study examined only adolescent pitchers. Differences between lower extremity mechanics of adolescent and collegiate pitchers may be explained by the increased ability of more physically developed pitchers to use their lower body musculature to generate and transfer energy up the kinetic chain.[5,28] It may be the case that the increased muscle mass of collegiate pitchers allowed for more noticeable differences in knee extension to appear.

No relationships between SLS compensations and stride knee extension moment at FC, BR, or when averaged between FC and BR were found in the present study. We attempted to relate moments of the stride knee during a baseball pitch to the SLS, which is a movement assessment used to determine overall strength and stability of the LPHC. It is possible that the inability of the SLS to assess sagittal plane knee moments may be due to the more ballistic nature of the baseball pitch in comparison to the SLS. A more ballistic clinical assessment, such as a drop jump task, may better mimic the force absorption and transmission demands placed on the lower extremity during the baseball pitch. The lack of significance regarding extension moments agrees with previous work examining stride knee extension moments that revealed no differences between more skilled and less skilled pitchers of similar ages.[27] Though, in an examination of collegiate and adolescent pitchers, it was found that collegiate pitchers have greater knee extension moments at BR when compared with their adolescent counterparts.[5] It was postulated that the differences between adolescent and collegiate stride knee mechanics may be due to the increased muscular strength and stability gained through maturation and time spent training.[5] It follows that no significance was found in our sample since they were exclusively adolescent pitchers.

While several studies have investigated sagittal plane stride knee mechanics,[4,5,27] no studies, to the authors' knowledge, have examined frontal plane stride knee kinetics during the baseball pitch. The present study indicates that pitchers who display greater SLS valgus also display greater stride knee valgus moment at SFC. Increased stride knee valgus moments during the pitch may increase the risk of injury to the lower extremity and negatively affect energy transfer from the lower extremity to the trunk during the pitching motion. Future work should examine the effects of stride knee valgus on segmental power generation during the pitching motion.

Despite the insights provided by the present study, limitations of our work must be addressed. First, given the conflicting reports regarding lower extremity mechanics between adolescent and mature pitchers, the current results may not be generalizable to more physically developed athletes, such as collegiate or professional pitchers. Only healthy adolescent baseball pitchers, with no history of injury, participated. It is possible that adolescent pitchers with a history of injury may exhibit different kinematic associations between the SLS and the pitching motion. Additionally, the cross-sectional nature of the present study limits our ability to establish trends as pitchers mature. Future studies should focus on tracking adolescent pitchers over time to observe lower extremity mechanical changes throughout development as well as investigating whether these changes differ between pitchers with and without injury.

5. Conclusion

In the adolescent pitcher, an athlete's SLS performance translates into stride knee mechanics during the pitching motion. Future studies should consider defining what constitutes excessive stride leg knee valgus during pitching and consider its implications on lower and upper extremity injuries of the adolescent baseball pitcher.

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