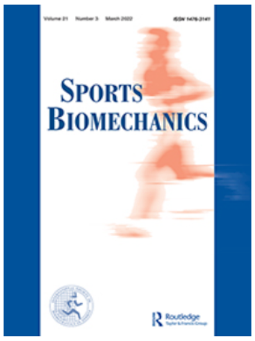

Sports Biomechanics

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rspb20

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To cite this article: Matthew J. Solomito, Erin J. Garibay, Andrew Cohen & Carl W. Nissen (2022): Lead knee flexion angle is associated with both ball velocity and upper extremity joint moments in collegiate baseball pitchers, Sports Biomechanics, DOI: 10.1080/14763141.2022.2046143

To link to this article: https://doi.org/10.1080/14763141.2022.2046143

Published online: 15 Mar 2022.

SPORTS BIOMECHANICS
https://doi.org/10.1080/14763141.2022.2046143

Lead knee flexion angle is associated with both ball velocity and upper extremity joint moments in collegiate baseball pitchers

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ABSTRACT

An important aspect of the pitching motion is the lead leg knee angle, from initial lead foot contact to ball release, which can influence pitching performance and injury potential. Understanding the implication of this angle is essential to appropriately coach baseball pitchers. Therefore, the purpose of this study was to determine the lead leg knee flexion influence on both ball velocity and the elbow varus moment. Kinematic and kinetic data were collected using standard optoelectronic motion capture methods from 121 collegiate pitchers and analysed using a random intercept, mixed effects regression model to evaluate the association between the knee angle on peak ball velocity and peak elbow varus moment, independently. Statistically significant associations between the knee flexion angle and ball velocity as well as with the elbow varus moment were noted. The data indicated that a 10° increase in knee flexion at ball was associated with a 2.1 Nm reduction in the peak elbow varus moment ($p = 0.021$, $r^2 = 0.12$) and a 0.2 m/s reduction in peak ball velocity ($p = 0.010$, $r^2 = 0.11$). This study provides scientific evidence that the lead knee flexion angle influences both upper extremity stresses and ball velocity.

ARTICLE HISTORY
Received 9 June 2021
Accepted 18 February 2022

KEYWORDS
Pitching mechanics; kinematics; kinetics

Introduction

The rate of pitching injuries has increased over the past three decades (Conte et al., 2016; Gugenheim et al., 1976; Lyman et al., 2001; Makhni et al., 2014), despite efforts to reduce injury risk such as pitch count limits, and continues to be prevalent in the sport (Conte et al., 2016; Fleisig et al., 2011). Recent epidemiological studies have projected that the number of ulnar collateral ligament (UCL) injuries in adolescent and collegiate pitchers will continue to rise through 2025 (AL Aguinaldo & Chambers, 2009). There is no one conclusive cause for this increased injury rate; rather many researchers believe the problem is multifactorial; caused in part by overuse, pitching prior to skeletal maturity, sports specialisation, and poor pitching mechanics (AL Aguinaldo & Chambers, 2009; Chalmers et al., 2017; Nissen et al., 2009; Werner et al., 1999). Therefore, there is a clear and present need to gain a better understanding of how variations in pitching mechanics may affect both injury risk and performance.

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UCL injuries are one of the more significant injuries encountered by baseball pitchers. This has inspired research focused on upper extremity mechanics and their relationship to upper extremity joint moments (Fortenbaugh et al., 2009; Nissen et al., 2009; Solomito et al., 2013; Stodden et al., 2005). Recently, there is a migration in investigations shifting from upper extremity centric studies towards full body dynamics to describe kinetic chain impacts (A Aguinaldo & Escamilla, 2019). To this end, there have been a number of recent publications detailing the role of the trunk on pitching mechanics (Aguinaldo et al., 2007; Cohen et al., 2019; Oyama et al., 2013, 2014; Solomito, Garibay, Nissen et al., 2018; Solomito et al., 2015), yet there remains a paucity of literature describing the contributions of the lower extremities on both upper extremity joint moments and ball velocity (Dun et al., 2007; Milewski et al., 2012; Stodden et al., 2005).

Stride length has been studied a great deal as researchers have attempted to find the ideal stride length for baseball pitchers (Crotin et al., 2015, 2014; Matsuo et al., 2001; Ramsey & Crotin, 2016; Ramsey et al., 2014; Solomito et al., 2020). More recently, foot placement at the instance of lead foot contact with the mound has also been explored (Slowik et al., 2021). However, the role of knee flexion at initial foot contact with the mound and throughout the remainder of the pitching cycle has received very little attention to date. Trigt et al. explored the influence of knee flexion on ball velocity and indicated that the magnitude of knee flexion during the acceleration phase of the pitch was associated with increased ball velocity, but was not associated with stride length (Van Trigt et al., 2018). Additionally, Werner et al. showed that increased knee flexion at initial foot contact decreased ball velocity (Werner et al., 1999). Dowling et al. investigated the difference between Japanese and American pitchers and showed significant differences in both knee flexion and ball velocity between the two groups, indicating that increased knee flexion may be associated with reduced ball velocity (Dowling et al., 2017). Therefore, the purpose of this study was to investigate the association between the knee flexion angle and both ball velocity and the elbow varus moment. It was hypothesised that increased knee flexion throughout the pitching motion would be associated with a decrease in both the elbow varus moment and in ball velocity.

Methods

This study was approved by the Institutional Review Boards at Connecticut Children's Medical Center and Hartford Hospital. All data were collected at Connecticut Children's Medical Center and data analysis was performed at Hartford HealthCare Bone and Joint Institute. All study participants signed informed consent prior to engaging in their pitching analysis. It is important to note that the results of this study were based on a subset of previously collected collegiate baseball pitchers involved in a separate prospective study. At the time of the evaluation, all participants were actively pitching for a National Collegiate Athletic Association (NCAA) Division I or Division III school. Additional inclusion criteria stated that all participants had to have at least 2 years of pitching experience. Participants were screened but excluded from the study if they had sustained a serious injury to their pitching arm (i.e., an injury that caused them to miss at least one game or practice) within the previous 6 months. Participants were also excluded from the study if they had undergone any surgical interventions to their pitching arm.

A total of 38 reflective markers were attached over specific bony landmarks to create a 16 segment biomechanical model as previously described (Nissen et al., 2007). Prior to the start of the data collection, anthropometric measures including height, weight, leg length, pelvic width, hip depth, and joint diameters were collected. These measures were taken to appropriately scale the inertial properties of the biomechanical model. Additional two markers were placed on the diameter of the ball to aid in the determination of ball release, the calculation of instantaneous ball velocity and the computation of joint kinetics. The addition of the markers on the ball is known to decrease the ball speed by 2.3 to 3.2 m/s (5 to 7mph; Solomito, Garibay, Golan et al., 2018). Prior to data collection, all participants were informed that the additional markers would reduce ball speed, and as a result, the participants were not provided feedback about their ball speed to ensure that they did not alter their pitching mechanics by throwing harder. All participants were provided as much time as they required to warm up and become comfortable pitching within the laboratory environment.

All participants pitched from a regulation, 25.4 cm tall pitching mound towards a pitching target with designated strike zone that was placed 18.4 m (60' 6") away. Participants were asked to only pitch the pitch types (i.e., fastball, curveball, slider, change-up, etc.) that they were comfortable pitching during a game setting. Each participant pitched a total of seven of each pitch type that they had selected prior to data collection, and pitches were thrown in random order to simulate a game setting. In total, each participant pitched between 21 and 28 pitches during data collection. It is important to note that participants indicating they pitched both a four seam and two seam fastball were instructed to pick the one they were most comfortable with and pitch only that pitch type. Motion data were collected at 250 Hz with a 12 camera Vicon 512 motion capture system (Vicon Motion Systems, Oxford, UK). The data presented in this paper is limited to the results of the fastball pitches only. Seven fastball pitches were collected, and data analysis was limited to the first three trials in which all marker data was present with complete marker trajectories. Trials were chosen regardless of outcome (i.e., ball or strike) to provide more generalisable data to a game setting.

The pitching motion was divided by four events as previously described (Fleisig et al., 1995), starting with the instant of lead foot contact (FC) and ending with the instant of maximum internal rotation of the glenohumeral joint (MIR). The two intermediate events were the instant of maximum external rotation of the glenohumeral joint (MER) and ball release (BR). Joint angles were computed using Euler's equations of motion using Vicon Workstation and BodyBuilder (Vicon Motion Systems, Oxford, UK) as previously described (Milewski et al., 2012; Nissen et al., 2007). Joint kinetics were computed using custom Matlab code (Mathworks, Natick, MA) and are based on standard inverse dynamics techniques (Greenwood, 1988). All joint kinetics were calculated as internal moments, which reflects the body's response to the externally applied loads. Data were computed for all joints over the entirety of the pitching motion as previously discussed. However, this study focused on the lead knee flexion angle - termed knee angle throughout the remainder of this work. The knee angle was defined as the angle between the long axis of the femoral shaft and the long axis of the tibia, as previously defined by Milewski et al. (2012), and consistent with the knee flexion angle definition common in clinical gait analysis (Davis et al., 1991; Kadaba et al., 1990; Figure 1). Two additional variables were calculated for this study to describe the change in knee position between specific points within the pitching motion. The first variable

Figure 1. Illustration of the knee angle. Depicting 30° of flexion.

termed ΔFCMER was the change in the knee angle between foot contact and maximum external rotation of the glenohumeral joint. This variable was calculated simply as the difference in angular position between the two time points. The second variable, ΔMERBR, was calculated as the change in knee angle between maximum external rotation of the glenohumeral joint and ball release, again this variable described the difference in angular position between these two time points. All range of motion measures were calculated as the difference between the maximum joint angle and minimum joint angle within a specified time range (e.g., knee range of motion at FC to ball release would be calculated as the difference in maximum and minimum knee joint angles occurring between FC and ball release).

Descriptive statistics were computed for all variables of interest and means and standard deviations were presented throughout this work for all continuous normally distributed data. Prior to performing any statistical testing, all data were checked to determine if it was normally distributed using a Shapiro–Wilks Test. The variables of interest for this study included knee angle at foot contact, knee angle at MER, knee angle at BR and knee angle range of motion (ROM). The outcome variables for this study include ball velocity and the elbow varus moment. To determine the associations between the knee angle and the outcome variables a random intercept, mixed-effects regression model was used (Goldstein et al., 2002; Greenland, 2000). This model was chosen for the analysis method in this work as it takes into account repeated measures using all available trials, thus increasing model precision while accounting for variations in the standard error, as well as the fact that this model was consistent with other previously published works (Nissen et al., 2009; Solomito, Garibay, Golan et al., 2018; Solomito, Garibay, Nissen et al., 2018; Solomito et al., 2013, 2015). In this model, the random effects are the repeated measures on each participant, while the fixed effects are the independent variables and the participants. The model was run multiple times using a single predictor variable (above mentioned variables of interest), and a single outcome variable (either the

Table 1. Knee angle measures at specific point of the pitching motion.

Temporal Parameter	Knee Angle (°)
Foot Contact	42 ± 10
Maximum External Rotation	47 ± 14
Ball Release	44 ± 15
Maximum Knee Flexion	53 ± 10
Minimum Knee Flexion	31 ± 15
Δ FC to MER	6 ± 12
Δ MER to BR	−3 ± 3

FC: foot contact
MER: Maximum External rotation
BR: Ball Release
Δ: Difference from

peak ball velocity or the peak elbow varus moment). This methodology essentially makes the model analogous to a simple linear regression run a number of times. However, the advantage of this model is the fact that it includes and adjust for the repeated trials of each participant. A p-value of 0.05 or less was considered to be statistically significant association. All testing was performed using SAS 9.4 (SAS Institute Inc. Cary, NC, USA).

Results

A total of 121 male baseball pitchers were recruited for this study. The mean age for this study cohort was 20.1 ± 1.4 years old, mean height was 185.4 ± 6.5 cm, and mean weight was 89.1 ± 11.6 kg. The mean fastball speed for the study cohort was 32.3 ± 2.5 m/s and the mean elbow varus moment was 75.0 ± 15.4 Nm. The knee angle was similar across the study cohort and showed limited variation in movement throughout the pitching motion (Table 1 and Figure 2). Maximum knee flexion occurred at 42 ± 18% of the pitching motion and maximum knee extension occurred at 58 ± 47% of the pitching motion. The sagittal plane knee range of motion between foot contact and ball release was 22 ± 10°.

The analysis indicated significant associations between the knee angle and both elbow varus moment and the ball velocity (Table 2). Results indicated that for every 10° increase in the knee flexion at the time of foot contact, MER, and ball release the peak elbow varus moment decreased by 2 Nm, 2.3 Nm, and 2.1 Nm, respectively ($p = 0.018$, $p = 0.023$, and $p = 0.023$, respectively). The knee flexion angle at both MER and ball release were significantly associated with peak ball velocity, the regression analysis indicated that for every 10° increase in knee flexion peak ball velocity decreased by 0.4 m/s and 0.8 m/s ($p = 0.010$, $p = 0.024$), respectively.

Discussion and implications

The purpose of this research was to explore the association between the lead knee flexion angle throughout the pitching motion and the peak elbow varus moment and peak ball velocity of collegiate baseball pitchers. Gaining a better understanding of the role the knee plays during pitching may provide valuable information to coaches, trainers, and medical staff members to correct mechanical flaws within the pitching motion.

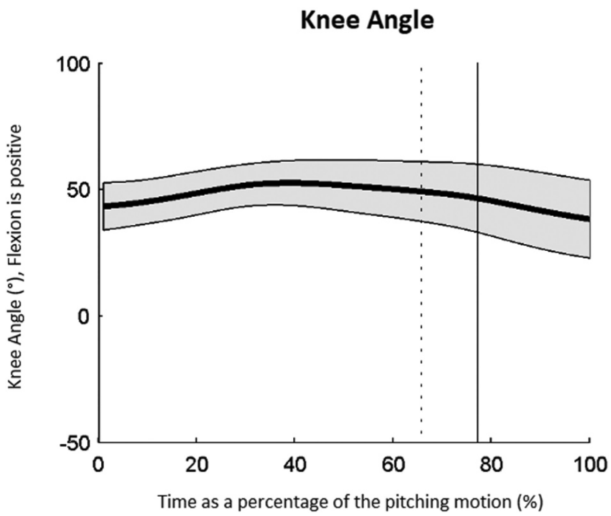

Figure 2. Knee angle over the course of the pitching motion from foot contact (0%) to maximum internal rotation of the glenohumeral joint (100%). Dotted vertical line represents maximum external rotation of the glenohumeral joint, the solid vertical line represents ball release. The bolded black line is the cohort mean and the shaded grey band represents ±1 standard deviation.

Table 2. Results of the regression analysis comparing knee flexion parameters to both ball velocity and the elbow varus moment.

	Ball Velocity			Elbow Varus Moment		
Predictor variable	p-value	r^2	Coefficient	p-value	r^2	Coefficient
Knee angle at FC	0.704	–	–	0.018	0.03	−0.2
Knee angle at MER	0.024	0.04	−0.04	0.023	0.04	−0.23
Knee angle at BR	0.010	0.11	−0.08	0.021	0.12	−0.21
Maximum knee flexion	0.001	0.03	−0.02	0.034	0.04	−0.29
Time of Maximum knee flexion	<0.001	0.09	−0.08	0.017	0.05	−0.17
Minimum knee flexion	0.005	0.02	−0.03	0.001	0.06	−0.24
Time of Minimum Knee Flexion	0.090	–	–	0.084	–	–
Knee Range of Motion	0.494	–	–	0.002	0.03	0.26
Δ FC to MER	0.004	0.15	−0.12	0.382	–	–
Δ MER to BR	0.182	–	–	0.182	–	–

FC: foot contact
MER: Maximum External rotation
BR: Ball Release
Δ: Difference from
r^2:Coefficent of determination
Coefficient: B—Regression coefficient/slope (unstandardised)

The majority of pitchers in this cohort landed in knee flexion, ranging between 32 and 52°, and within the cohort knee flexion remained relatively static through 60% of the pitching motion. From MER to MIR, there was a greater amount of variation in the knee angle, as noted by the standard deviation band depicted in Figure 2. Some pitchers continue to flex their knee and sink into the pitch as they released the ball while others began to extend their knee, these variations in knee position may be consistent with differences in pitching styles as described by Dowling et al. (2017) None of the pitchers in this cohort ever fully extended their knee and pitchers maintained at least 15° of flexion throughout the entire pitching motion. These findings are consistent with the previously published literature (Dowling et al., 2017; Dun et al., 2007; Milewski et al., 2012; Stodden et al., 2005; Werner et al., 1999). One reason for kinematic differences may be due to coaching philosophies such as standing tall and pitching, a Western/American strategy, versus dropping and dragging, an Eastern/Japanese strategy, as discussed by Dowling et al. (2017) Future work should explore these subtle differences in pitching style to further understand the implications of continuing to flex the lead knee or to extend the knee during the late acceleration phase of the pitching motion.

Regression analysis indicated that there were a number of statistically significant associations between the magnitude of knee flexion and the elbow varus moment. The results using the above described analysis method, for every pitcher and for every trial included in the study, demonstrated a pattern that indicated that the more a pitcher flexes their knee from foot contact through ball release they have a significant reduction in the elbow varus moment. Essentially, a 10° increase in knee flexion was associated with a reduction in the elbow varus by 2.1 Nm. While 2.1 Nm may seem trivial, results of previous work have noted that pitchers during a pitch typically load their UCL to nearly the same magnitude as the UCL failure threshold (Morrey & An, 1983); therefore, the argument can be made that any reduction in joint moments can be protective for the pitcher. These findings suggest that the Eastern style of pitching has substantially greater knee flexion angles when compared to Western style pitchers (Dowling et al., 2017), but experience reduced joint loads. Yet, the regression coefficient indicated that the independent variables alone do not explain more than 12% of the change in the elbow varus moment. Thus this finding may be statistically significant but may not be clinically relevant. The lack of clinical significance for the association between the elbow varus moment and knee angle is also supported by the fact that the knee flexion angle does not create a 10% change in the elbow varus moment, which has been previously stated as indicating clinical significance (Nissen et al., 2013).

Results also indicated that increased knee flexion reduced ball velocity. Pitchers that had a greater amount of knee flexion at MER and ball release, as well as greater maximum knee flexion angles were noted to have a nearly 0.8 m/s (1.8 mph) reduction in ball speed, which is consistent with previously published studies (Dowling et al., 2017; Werner et al., 1999). This finding was inconsistent with the work by Trigt et al. which indicated that greater knee flexion at the time of MER and ball release increased ball velocity (Van Trigt et al., 2018). However, this difference may be attributed to the fact that Trigt et al. utilised high speed cameras rather than computerised motion analysis which may have introduced some positional bias that affected the angle measures. Additionally, the Trigt et al. study was conducted on youth baseball pitchers rather than collegiate or professional pitchers. Pitchers that reached their peak knee flexion closer to ball release were noted to have a significant decrease in ball speed. Therefore, there appears that there is a tradeoff between decreased ball speed and decreased joint moments. The results of this study indicate that a 10° increase in knee flexion was associated with a nearly 3% decrease in the elbow varus moment; however, it also associated with a 2.4% decrease in ball velocity. Similar to the results of the elbow varus moment, the r^2 values did not indicate that the knee flexion angle alone could significantly predict the ball velocity. Although a change of nearly 0.8 m/s (1.8 mph) in ball velocity could have significant ramifications for upper level (i.e., collegiate and professional) pitchers, the findings may not have substantial clinical implications. Future work needs to be directed towards finding an optimal knee flexion angle for baseball pitchers that can minimise joint moments while maximising ball velocity. These findings also suggest that coaches may be able to instruct pitchers returning from an injury, or who have mentioned that they experience pain while throwing to flex their lead knee more to reduce joint loads. Regression analysis also indicated that for every 10° increase in sagittal plane knee range of motion was associated with a 2.6 Nm increase in the peak elbow varus moment, but was not associated with ball velocity. Limiting knee range of motion over the course of the pitching motion takes a great deal of strength and neuromuscular control. Future work focused on understanding the relationship between both neuromuscular control and lower extremity and core strength with pitching performance would be extremely beneficial to coaches and trainers.

This study is not without limitations. First, this is a laboratory-based study, and pitching performance may have been affected by pitching in a controlled environment. Efforts were made to simulate actual pitching conditions, including the use of a regulation mound in a full length pitching space and the allowance for an adequate warm-up period. Another limitation is that the markers placed on the ball during data collection slow the pitch, resulting in a mean velocity lower than typically reported; however, all pitchers pitched with the same instrumented ball; therefore, the reduction in ball velocity is consistent across all study participants. Finally, the results and conclusions of this work are based on data collected on collegiate pitchers and, consequently, may not apply to younger or older age groups.

Conclusion

This study demonstrated that knee flexion angle throughout the pitching motion is important for both pitching performance and injury risk reduction. The data indicates that although an increase in the knee flexion angle may reduce the elbow varus moment, a similar decrease in ball velocity was also seen. Ultimately, this indicates that additional work is required to find an optimal knee flexion angle that would maintain ball velocity while still reducing the elbow varus moment

Acknowledgments

We would like to acknowledge Sylvia Ounpuu and the entire team at the Center for Motion Analysis at Connecticut Children's medical center for their assistance in data collection.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The author(s) reported there is no funding associated with the work featured in this article.

References

Aguinaldo, A. L., Buttermore, J., & Chambers, H. (2007). Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various levels. *Journal of Applied Biomechanics*, *23*(1), 42–51. https://doi.org/10.1123/jab.23.1.42

Aguinaldo, A. L., & Chambers, H. (2009). Correlation of throwing mechanics with elbow valgus load in adult baseball pitchers. *The American Journal of Sports Medicine*, *37*(10), 2043–2048. https://doi.org/10.1177/0363546509336721

Aguinaldo, A., & Escamilla, R. (2019). Segmental power analysis of sequential body motion and elbow valgus loading during baseball pitching: comparison between professional and high school baseball players. *Orthopedic Journal of Sports Medicine*, *7*(2), 2325967119827924. https://doi.org/10.1177/2325967119827924

Chalmers, P. N., Wimmer, M. A., Verma, N. N., Cole, B. J., & Romeo, A. A. (2017). The relationship between pitching mechanics and injury: A review of current concepts. *Sports Health*, *9*(3), 216–221. https://doi.org/10.1177/1941738116686545

Cohen, A. D., Garibay, E. J., & Solomito, M. J. (2019). The association among trunk rotation, ball velocity, and the elbow varus moment in collegiate-level baseball pitchers. *The American Journal of Sports Medicine*, *47*(12), 2816–2820. https://doi.org/10.1177/0363546519867934

Conte, S., Camp, C., & Dines, J. (2016). Injury trends in Major League Baseball over 18 seasons: 1998-2015. *American Journal of Orthopedics (Belle Mead, N.J.)*, *45*(3), 116–123.

Crotin, R. L., Bhan, S., & Ramsey, D. K. (2015). An inferential investigation into how stride length influences temporal parameters within the baseball pitching delivery. *Human Movement Science*, *41*, 127–135. https://doi.org/10.1016/j.humov.2015.03.005

Crotin, R. L., Kozlowski, K., Horvath, P., & Ramsey, D. K. (2014). Altered stride length in response to increasing exertion among baseball pitchers. *Medicine & Science in Sports & Exercise*, *46*(3), 565–571. https://doi.org/10.1249/MSS.0b013e3182a79cd9

Davis, R. B., Ounpuu, S., Tyburski, D., & Gage, J. (1991). A gait analysis data collection and reduction technique. *Human Movement Science*, *10*(5), 575–587. https://doi.org/10.1016/0167-9457(91)90046-Z

Dowling, B., Owen, C. P., Laughlin, W. T., & Fleisig, G. S. (2017). Kinetmatic and kinetic comparison between American and Japanese college pitchers. *ISBS Proceeding Architecture*, *1* (59), 556–559. https://doi.org/10.1177/2325967119825625

Dun, S., Fleisig, G. S., Loftice, J., Kingsley, D., & Andrews, J. R. (2007). The relationship between age and baseball pitching kinematics in professional baseball pitchers. *Journal of Biomechanics*, *40*(2), 265–270. https://doi.org/10.1016/j.jbiomech.2006.01.008

Fleisig, G. S., Andrews, J. R., Cutter, G. R., Weber, A., Loftice, J., McMichael, C., Hassell, N., & Lyman, S. (2011). Risk of serious injury for young baseball pitchers: A 10-year prospective study. *The American Journal of Sports Medicine*, *39*(2), 253–257. https://doi.org/10.1177/0363546510384224

Fleisig, G. S., Andrews, J. R., Dillman, C., & Escamilla, R. F. (1995). Kinetics of baseball pitching with implications about injury mechanisms. *The American Journal of Sports Medicine*, *23*(2), 233–239. https://doi.org/10.1177/036354659502300218

Fortenbaugh, D., Fleisig, G. S., & Andrews, J. R. (2009). Baseball pitching biomechanics in relation to injury risk and performance. *Sports Health*, *1*(4), 314–320. https://doi.org/10.1177/1941738109338546

Goldstein, H., Browne, W., & Rasbash, J. (2002). Multilevel modelling of medical data. *Statistics in Medicine*, *21*(21), 3291–3315. https://doi.org/10.1002/sim.1264

Greenland, S. (2000). Principles of multilevel modelling. *International Journal of Epidemiology*, *29* (1), 158–167. https://doi.org/10.1093/ije/29.1.158

Greenwood, D. T. (1988). *Principles of dynamics* (2nd ed.). Prentice-Hall Inc.

Gugenheim, J., Stanley, R. F., Woods, G. W., & Tullos, H. S. (1976). Little league survey : The Houston study. *The American Journal of Sports Medicine*, *4*(5), 189–200. https://doi.org/10.1177/036354657600400501

Kadaba, M. P., Ramakrishnan, H. K., & Wooten, M. E. (1990). Measurement of lower extremity kinematics during level walking. *Journal of Orthopaedic Research*, *8*(3), 383–392. https://doi.org/10.1002/jor.1100080310

Lyman, S., Fleisig, G. S., Waterbor, J. W., Funkhouser, E. M., Pulley, L., Andrews, J. R., Osinski, E. D., & Roseman, J. M. (2001). Longitudinal study of elbow and shoulder pain in youth baseball pitchers. *Medicine and Science in Sports and Exercise*, *33*(11), 1803–1810. https://doi.org/10.1097/00005768-200111000-00002

Mahure, S. A., Brent, M., Shamah, S., Kwon, Y., & Rokito, A. (2016). Disproportionate trends in ulnar collateral ligament reconstruction: Projections through 2025 and a literature review. *Journal of Shoulder and Elbow Surgery*, *25*(6), 1005–1012. https://doi.org/10.1016/j.jse.2016.02.036

Makhni, E., Morrow, Z., Luchetti, T., Mishra-Kalyani, P. S., Gualtieri, A. P., Lee, R. W., & Ahmad, C. S. (2014). Arm pain in youth baseball players: A survey of healthy players. *The American Journal of Sports Medicine*, *43*(1), 41–46. https://doi.org/10.1177/0363546514555506

Matsuo, T., Escamilla, R. F., Fleisig, G. S., Barrentine, S. W., & Andrews, J. R. (2001). Comparison of kinematic and temporal parameters between different pitch velocity groups. *Journal of Applied Biomechanics*, *17*(1), 1–13. https://doi.org/10.1123/jab.17.1.1

Milewski, M. D., Ounpuu, S., Solomito, M. J., Westwell, M., & Nissen, C. W. (2012). Adolescent baseball pitching technique: Lower extremity biomechanical analysis. *Journal of Applied Biomechanics*, *28*(5), 491–501. https://doi.org/10.1123/jab.28.5.491

Morrey, B. F., & An, K. (1983). Articular and ligamentous contributions to the stability of the elbow joint. *Am J Sp*, *11*(5), 315–319. https://doi.org/10.1177/036354658301100506

Nissen, C. W., Solomito, M. J., Garibay, E. J., Ounpuu, S., & Westwell, M. (2013). A biomechanical comparison of pitching from a mound versus flat ground in adolescent baseball pitchers. *Sports Health*, *5*(6), 530–536. https://doi.org/10.1177/1941738113502918

Nissen, C. W., Westwell, M., Õunpuu, S., Patel, M., Solomito, M. J., & Tate, J. (2009). A biomechanical comparison of the fastball and curveball in adolescent baseball pitchers. *The American Journal of Sports Medicine*, *37*(8), 1492–1498. https://doi.org/10.1177/0363546509333264

Nissen, C. W., Westwell, M., Õunpuu, S., Patel, M., Tate, J. P., Pierz, K., Burns, J. P., & Bicos, J. (2007). Adolescent baseball pitching technique: A detailed three-dimensional biomechanical analysis. *Medicine & Science in Sports & Exercise*, *39*(8), 1347–1357. https://doi.org/10.1249/mss.0b013e318064c88e

Oyama, S., Yu, B., Blackburn, J. T., Padua, D. A., Li, L., & Myers, J. B. (2013). Effect of excessive contralateral trunk tilt on pitching biomechanics and performance in high school baseball pitchers. *The American Journal of Sports Medicine*, *41*(10), 2430–2438. https://doi.org/10.1177/0363546513496547

Oyama, S., Yu, B., Blackburn, J. T., Padua, D. A., Li, L., & Myers, J. B. (2014). Improper trunk rotation sequence is associated with increased maximal shoulder external rotation angle and shoulder joint force in high school baseball pitchers. *The American Journal of Sports Medicine*, *42*(9), 2089–2094. https://doi.org/10.1177/0363546514536871

Ramsey, D. K., & Crotin, R. L. (2016). Effect of stride length on overarm throwing delivery : Part II : An angular momentum response. *Human Movement Science*, *46*, 30–38. https://doi.org/10.1016/j.humov.2015.11.021

Ramsey, D. K., Crotin, R. L., & White, S. (2014). Effect of stride length on overarm throwing delivery : A linear momentum response. *Human Movement Science*, *38*, 185–196. https://doi.org/10.1016/j.humov.2014.08.012

Slowik, J. S., Diffendaffer, A. Z., Crotin, R. L., Stewart, M. S., Hart, K., & Fleisig, G. S. (2021). Biomechanical effects of foot placement during pitching. *Sports Biomechanics*, 1–10. https://doi.org/10.1080/14763141.2021.1898668

Solomito, M. J., Cohen, A. D., & Garibay, E. J. (2020, September). Influence of stride length on upper extremity joint moments and ball velocity in collegiate baseball pitchers. *Sport Biomechanical*, *10*, 1–10. https://doi.org/10.1080/14763141.2020.1809698

Solomito, M. J., Garibay, E. J., Golan, E., & Nissen, C. W. (2018). Elbow flexion post ball release is associated with the elbow varus deceleration moments in baseball pitching. *Sport Biomechanical*, *1*, 1–10. https://doi.org/10.1080/14763141.2018.1560495

Solomito, M. J., Garibay, E. J., & Nissen, C. W. (2018). Sagittal plane trunk tilt is associated with upper extremity joint moments and ball velocity in collegiate baseball pitchers. *Anthropology Journal of Sport Medicine*, *6*(10), 1–10. https://doi.org/10.1177/2325967118800240

Solomito, M. J., Garibay, E. J., Ounpuu, S., Tate, J. P., & Nissen, C. W. (2013). A biomechanical evaluation of the kinetics for multiple pitching techniques in college-aged pitchers. *Orthopedic Journal of Sport Medicine*, *1*(5), 2325967113508255. https://doi.org/10.1177/2325967113508255

Solomito, M. J., Garibay, E. J., Woods, J. R., Õunpuu, S., & Nissen, C. W. (2015). Lateral trunk lean in pitchers affects both ball velocity and upper extremity joint moments. *The American Journal of Sports Medicine*, *43*(5), 1235–1240. https://doi.org/10.1177/0363546515574060

Stodden, D., Fleisig, G., McLean, S., & Andrews, J. (2005). Relationship of biomechanical factors to baseball pitching velocity: Within pitcher variation. *Journal of Applied Biomechanics*, *21*(1), 44–56. https://doi.org/10.1123/jab.21.1.44

Van Trigt, B., Schallig, W., Van Der Graaff, E., Hoozeman, M., & Veeger, D. (2018). Knee Angle and stride length in association with ball speed in youth baseball pitchers. *Sports*, *6*(51), 1–10. https://doi.org/10.3390/sports6020051

Werner, S. L., Murray, T. A., Hawkins, R. J., & Gill, T. J. (1999). Relationship between throwing mechanics and elbow valgus in professional baseball pitchers. *Journal of Shoulder and Elbow Surgery*, *11*(2), 151–155. https://doi.org/10.1067/mse.2002.121481