Role of Pelvis and Trunk Biomechanics in Generating Ball Velocity in Baseball Pitching

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Abstract

Orishimo, KF, Kremenic, IJ, Mullaney, MJ, Fukunaga, T, Serio, N, and McHugh, MP. Role of pelvis and trunk biomechanics in generating ball velocity in baseball pitching. *J Strength Cond Res* XX(X): 000–000, 2022—The purpose of this study was to determine the impact of pelvis rotation velocity, trunk rotation velocity, and hip-shoulder separation on ball velocity during baseball pitching. Fastball pitching kinematics were recorded in 29 male pitchers (age 17 ± 2 years, 23 high school, 6 college). Pelvis and trunk angular velocities and hip-shoulder separation were calculated and averaged for the 3 fastest pitches. Associations between peak pelvis velocity, peak trunk velocity, hip-shoulder separation at foot contact, and ball velocity were assessed using Pearson correlation coefficients and multiple regression. The average ball velocity was $33.5 \pm 2.8\ \text{m}\cdot\text{s}^{-1}$. The average hip-shoulder separation at foot contact was $50 \pm 12^\circ$. The peak pelvis velocity ($596 \pm 88^\circ\cdot\text{s}^{-1}$) occurred at 12 ± 11% of the time from stride foot contact to ball release, with the peak trunk velocity ($959 \pm 120^\circ\cdot\text{s}^{-1}$) occurring at 36 ± 11%. Peak trunk velocity was predictive of ball velocity ($p = 0.002$), with 25% of the variability in ball velocity explained. No combination of factors further explained ball velocity. Hip-shoulder separation at foot contact (17%, $p = 0.027$), peak pelvis velocity (23%, $p = 0.008$), and the timing of peak pelvis velocity (16%, $p = 0.031$) individually predicted peak trunk velocity. The combination of peak pelvis velocity, hip-shoulder separation at foot contact, and the timing of peak trunk velocity explained 55% of the variability in trunk rotation velocity ($p < 0.001$). These data highlight the importance of interactions between pelvis and trunk for maximizing velocity in pitching. Training to improve pelvis-trunk axial dissociation may increase maximal trunk rotation velocity and thereby increase ball velocity without increasing training load on the shoulder and elbow.

Key Words: throwing, rotation, hip-shoulder separation, kinematics

Introduction

The baseball pitching motion is a complex movement that integrates both the upper and lower extremities to impart velocity to the ball. As pitchers who can throw the ball at higher velocities are generally more successful, there has been much research into biomechanical factors that influence ball velocity. Focusing on upper-extremity kinematics, previous research has shown that ball velocity is correlated with maximum shoulder external rotation, maximum elbow extension velocity, and maximum shoulder internal rotation velocity (11,15,26). Consequently, as faster, more powerful arm movements result in increased ball velocity, many resistance training programs have been developed to strengthen the upper extremity and shoulder muscles (2,6,7,27).

Weighted-ball training is a popular form of sport-specific training for pitchers. Using both underweight (<5 oz.) and overweight (>5 oz.) baseballs, this type of training is believed to increase shoulder and elbow velocity (9), as well as arm strength (5), thereby increasing throwing velocity. Although studies have shown this training method to have a beneficial effect on pitching velocity (3,21,28), there are concerns regarding the risk of injury associated with these types of training programs. Okoroha et al. found an increase in elbow medial torque with increasing ball weight in youth pitchers (17). In addition, Fleisig et al. found increased elbow loading during the flat-ground throwing exercises of a typical weighted-ball training program (10). Finally, Reinold et al., (21) in a randomized, controlled study, reported 2 injuries during the training period and an additional 2 injuries during the subsequent season in the weighted-ball training group compared with none in the control group. It is also worth noting that all 4 injuries reported by Reinold et al. involved the elbow.

Throwing-related shoulder and elbow injuries continue to rise, particularly at the youth, high-school and collegiate levels (4,14). Many of these injuries are attributable to overuse and lack of rest between bouts of throwing (13,19). Given the potential for components of weighted-ball programs (overweight balls and flat-ground throwing) to increase upper-extremity loading, the added throwing volume of about 40–80 pitches per week typically prescribed during this type of training (3,28), and the direct stress placed on the arm and shoulder during traditional strength training programs, an alternative method of training to increase ball velocity while reducing the training load on the arm and shoulder may be desirable. Over the course of development, pitchers must walk the fine line between accumulating the appropriate amount of throwing volume for competition and conditioning versus overstressing their arms. Reducing throwing volume during training while still achieving the desired increase in throwing velocity would be beneficial for both performance and injury risk. Before new training methods can be devised, biomechanical factors not related to the upper extremity that influence throwing velocity need to be identified.

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Similar to other rotational athletic movements such as kicking or striking, pitching can be characterized by a proximal-to-distal sequence of motion. Generally, to achieve maximal velocity of the most distal segment, movement begins with the most proximal segment and progresses distally with the maximum velocity of each segment being greater than its predecessor (20). The progressive increases in segmental velocities are facilitated by the angular "separation" of adjacent segments. "Separation," or countermovement between adjacent segments, stretches the active muscles between segments and activates the stretch-shortening cycle. The release of elastic energy during the ensuing concentric contraction increases the force and power output of the muscle. As energy is transferred to the distal segment, momentum is conserved resulting in the increase in velocity. The importance of building velocity from proximal to distal and of segmental separation to sport performance has been demonstrated in the kinematic analysis of the golf swing. Previous studies have indicated that maximum trunk rotational velocity and the maximum angular separation between the hips and shoulders in the transverse plane (also known as X-factor) are predictive of performance metrics such as ball velocity and clubhead speed (12,16). In this context, a greater X-factor increases the eccentric load on the trunk musculature, which leads to a greater recoil and greater trunk rotational velocity, ultimately resulting in increased clubhead and ball velocities.

Applying these concepts to pitching, power generation is first initiated with movement of the pelvis and energy is then transferred sequentially to the trunk, upper arm, forearm, hand, and finally to the ball. Although associations have been made between ball velocity and upper-extremity kinematics (11,15,26), the exact contributions of the pelvis and trunk to ball velocity have not been studied extensively. Werner et al. found that peak trunk velocity was a factor in determining ball velocity in collegiate pitchers, although its individual contribution was not reported (26). In addition, Stodden et al. found that pelvis and trunk rotational velocities were individually associated with ball velocity, but did not examine the effect of hip-shoulder separation on pitching performance or any interactions between these factors (24). Finally, Bullock et al. did find significant relationships between hip-shoulder separation and peak trunk velocity and between peak trunk velocity and ball velocity, but did not provide prediction equations to quantify the degree of improvement in ball velocity for a given improvement in the other factors (1). Further understanding the interplay between these factors may provide useful insights into pitching performance. Therefore, the purpose of this study was to determine the impact of peak pelvis rotation velocity, peak trunk rotation velocity, hip-shoulder separation at foot contact, and the timing of these events on ball velocity during baseball pitching. It was hypothesized that pelvis velocity, trunk velocity, and hip-shoulder separation at foot contact would be positively correlated with ball velocity. Furthermore, as previous studies have highlighted the importance of trunk velocity to athletic performance (1,12,16,24,26), a secondary purpose of this study was to assess which factors, or combination of factors, most strongly influenced trunk velocity.

Methods

Experimental Approach to the Problem

A cross-sectional approach was used to explore the relationship between pitching biomechanics and ball velocity. Upper-extremity, trunk, and pelvis angles and velocities during fastball pitching, as well as kinematic sequencing, were measured from a group of baseball pitchers who were being examined as part of a preseason fitness evaluation. Regression analyses were used to determine which factor or combination of factors determine pitch velocity. Further analyses were performed to determine factors related to the primary factors found in the initial regression analysis.

Subjects

Twenty-nine pitchers (23 high school and 6 collegiate) participated in this study (age [mean ± SD]: 17 ± 2 year, height: 183 ± 7 cm, body mass: 82.2 ± 9.7 kg, right-handed pitchers = 24, and left-handed pitchers = 5). All pitchers were healthy and injury-free at the time of evaluation. This study was approved by the Northwell Health Institutional Review Board (Study# 21-0878), and each subject gave written informed consent to participate. The age range of the subjects was 15–20. Parental or guardian consent was obtained for pitchers who were younger than 18 years at the time of testing.

Procedures

Thirty-two retroreflective markers were placed on the lower extremities, arms, trunk, and head. The marker locations were as follows: C7 vertebra, right and left acromia, right and left lateral elbow, right and left medial elbow, right and left ulnar styloid, right and left distal radius, right and left anterior superior iliac spine [ASIS], right and left greater trochanter, sacrum, right and left lateral femoral condyle, right and left medial femoral condyle, right and left lateral malleolus, right and left medial malleolus, right and left base of the fifth metatarsal, and head of the third metacarpal on the throwing hand. Four additional markers were placed on the pitcher's baseball cap on the front, top, and bilateral sides of the head. Kinematic data were recorded with a 10-camera motion capture system at 500 Hz (BTS Bioengineering, Quincy, MA). After a self-directed warm-up, which included stretching of the upper and lower extremities, light tossing into the net, and a gradual increase to maximal effort pitching, each pitcher threw 5 fastball pitches into a net positioned approximately 20 feet from a portable indoor turf pitcher's mound (ProMounds, Braintree, MA). Ball velocity was measured with a radar gun (Pocket Radar Inc., Santa Rosa, CA).

Starting with the pelvis, the proximal-to-distal sequence of segmental rotations (uncoiling) toward the target typically begins around the time of stride foot contact, and all of the energy generated must be transferred to the ball by the time of release. Therefore, peak pelvis rotation velocity, peak trunk rotation velocity, and peak elbow extension velocity were determined between the events of stride foot contact to ball release. Hip-shoulder separation was measured at foot contact, and shoulder internal rotation velocity was assessed at ball release. In addition, the timings of these peak values were expressed as percentages of the time between stride foot contact and ball release. Rotational velocities were expressed in degrees per second ($°\cdot s^{-1}$), and hip-shoulder separation at foot contact was expressed in degrees. Average ball velocity and kinematic metrics were calculated for the 3 highest velocity pitches for each subject.

Statistical Analyses

The associations between ball velocity and individual kinematic measurements were assessed using Pearson correlation

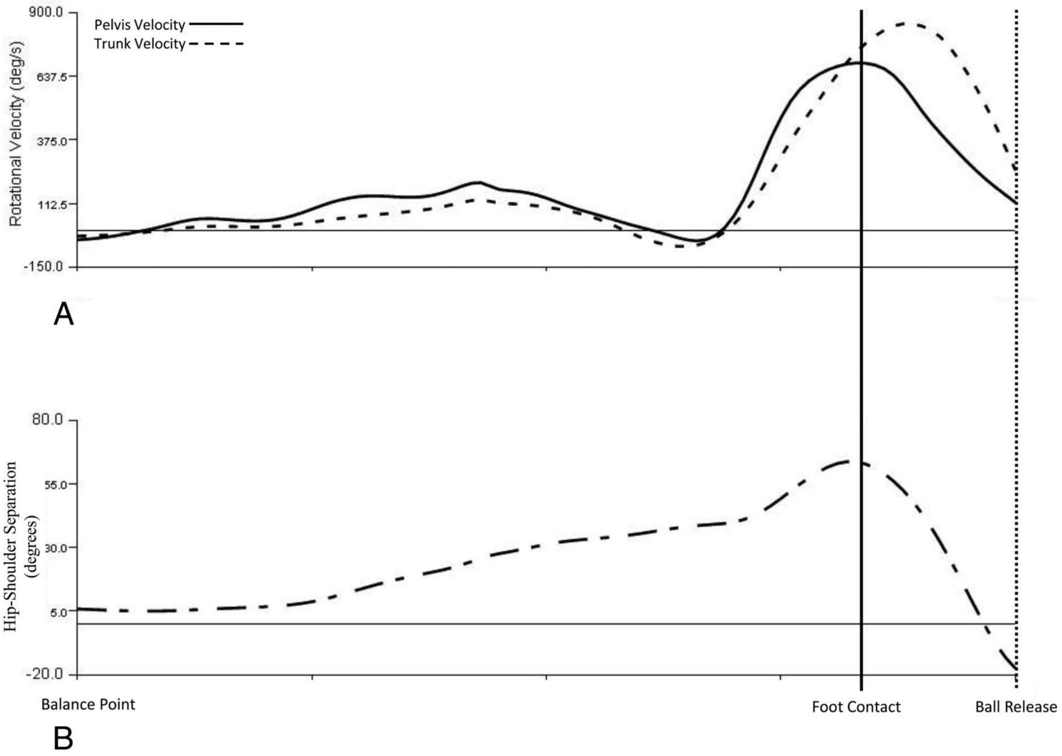

Figure 1. Kinematic variables from balance point to ball release of a representative subject. A) Rotational velocities of the pelvis and trunk (degrees/sec) and (B) hip-shoulder separation. Solid vertical line indicates foot contact, and the dotted vertical line indicates ball release.

coefficients. Multiple regression was used to determine whether combinations of variables improved the prediction of ball velocity beyond any single predictive variable. A second analysis assessed the associations between trunk velocity and other kinematic measurements using Pearson correlation coefficients. Multiple regression was used to determine whether combinations of variables improved the prediction of trunk velocity beyond any single predictive variable. The r^2 and R^2 values are reported and represent the percentage of the variability in the dependent variable (ball velocity or trunk velocity) explained by independent variables (r^2) or combinations of variables (R^2). For multiple regression analyses, variables that had a bivariate relationship with the dependent variable with a p value of <0.100 were included as factors in the multiple regression in a stepwise manner.

Results

The average ball velocity across all subjects was 33.5 ± 2.8 m·s^{-1}. The peak pelvis velocity occurred at 12 ± 11% of the time between stride foot contact and ball release, followed by peak trunk velocity, which occurred at 36% ± 11% (Figure 1 and Table 1).

Peak trunk velocity accounted for 25% of the variability in ball velocity ($p = 0.006$), with peak pelvis velocity and shoulder internal rotation velocity at ball release having nonsignificant contributions (8%, $p = 0.061$ and 13%, $p = 0.055$, respectively). Hip-shoulder separation at foot contact, peak elbow extension velocity, and any of the timing variables did not predict ball velocity (Table 2). The combinations of peak trunk and pelvis velocities, as well as peak trunk, peak pelvis, and shoulder IR velocities, were entered into a multiple regression analysis (based on their independent relationships to ball velocity having a p value < 0.100), but neither combination improved the prediction of ball velocity beyond what peak trunk velocity predicted on its own ($R^2 = 27\%$ and $R^2 = 28\%$, respectively).

Hip-shoulder separation at foot contact, peak pelvis velocity, and the timing of peak pelvis velocity were all individually positively correlated with peak trunk velocity ($r^2 = 17, 23$, and 16%, respectively). Furthermore, hip-shoulder separation at foot contact and peak pelvis velocity combined to explain 40% of the variability in trunk velocity. Finally, the combination of hip-shoulder separation at foot contact, peak pelvis velocity, and the timing of peak trunk velocity explained 55% of the trunk velocity variability (Table 3).

An additional correlation between hip-shoulder separation at foot contact and peak pelvis velocity was performed and found no association between these variables ($r = 0.01$, $p = 0.961$).

Discussion

The main findings of this study were that peak trunk rotation velocity has a moderate effect on ball velocity and that a greater hip-shoulder separation, plus a higher peak pelvis velocity, plus a longer delay from foot contact to peak trunk velocity had the combined effect of maximizing trunk velocity. In addition, none of the upper-extremity kinematic variables (i.e., peak elbow extension velocity, the timing of peak elbow extension velocity, or shoulder IR velocity at ball release) were found to significantly affect ball velocity. These results imply that it is possible to increase ball velocity without intentionally modifying upper-extremity mechanics. Based on the mean data

Table 1

Kinematic pitch metrics and occurrence during the pitching cycle.

	Mean ± SD	Timing (% foot contact to ball release) (*SD*)
Hip-shoulder separation at foot contact (°)	50 ± 12	0
Peak pelvis velocity (°/s)	596 ± 88	12 (11)
Peak trunk velocity (°/s)	959 ± 120	36 (11)
Peak elbow extension velocity (°/s)	3,089 ± 911	93 (2)
Shoulder IR velocity at ball release (°/s)	5,346 ± 730	100
Ball velocity (m·s^{-1})	33.5 ± 2.8	100

and the regression equation, a 10% increase in trunk velocity would result in a 5% increase in ball velocity. Furthermore, when taken together, a 10% increase in hip-shoulder separation at foot strike, peak pelvis velocity, and time from foot strike to peak trunk velocity would increase trunk velocity by 8%.

It is also important to note that although all subjects exhibited proper proximal-to-distal kinematic sequences, none of the timing variables (i.e., timing of peak pelvis and trunk or elbow velocity) significantly influenced ball velocity. This finding corroborates the results of Fleisig et al. (8) who found no differences in the timing of peak rotational velocities across levels of development (i.e., youth, high school, collegiate, or professional) despite significant increases in ball velocity from one level to the next. Taken together, the results of these studies imply that the proximal-to-distal kinematic sequence is an essential component to the pitching motion, but may not significantly affect ball velocity. In addition, previous research by Oyama et al. and Scarborough et al. demonstrated that kinematic sequencing is related to upper-extremity forces and torques, which implies that these timing variables may be important factors related to pitching injuries, rather than performance (18,23).

Previous studies have also found an association between peak trunk rotation velocity and ball velocity. Werner et al. found that peak trunk velocity was among 10 biomechanical variables that explained nearly 70% of the variance in ball velocity in collegiate pitchers. However, its individual contribution was not reported (26). More recently, Bullock et al. reported that peak trunk velocity, alone, explained 23% of the variance in ball velocity in a group of high-school pitchers (1), which is very comparable to the 25% in the current study. The fact that similar associations between pitching kinematics and ball velocity have been found in homogeneous groups of pitchers, as well as the mixed group of high-school and collegiate pitchers included in the current study, seems to indicate that being able to generate high trunk rotation velocity is an important component to the ability to pitch a ball at high velocities.

In addition, similar to the study by Bullock et al. (1), the current study found a significant positive correlation between peak trunk velocity and hip-shoulder separation at foot contact but no association between hip-shoulder separation at foot contact and peak pelvis velocity. These results further reinforce the notion that the ability of a pitcher to "separate" the hips and shoulders seems to be essential in the generation of high trunk velocity. Greater separation between the pelvis and trunk produces greater stretch of the abdominal muscles and storage of elastic energy. The elastic energy produced by this eccentric contraction is released through the stretch-shortening cycle causing the trunk to rotate at a high velocity. Although it was not found to be directly associated with ball velocity, hip-shoulder separation may represent a potentially modifiable factor that could influence ball velocity. Although the authors of the current study are not aware of any study demonstrating that increasing hip-shoulder separation range of motion increases trunk velocity or ball velocity during pitching, Stodden et al. showed that the hip-shoulder separation range of motion during seated trunk rotations with elastic resistance, as well as medicine ball rotational throws, was similar to that during the pitching motion (25). These authors speculated that, although these training exercises may not increase a pitcher's hip-shoulder separation ability, training for strength and power within a range that is similar to that of the pitching motion may be beneficial to performance. Further studies are warranted to investigate the effects of increasing hip-shoulder separation range of motion on changes in pitching performance.

Although weighted-ball throwing programs represent a highly sport-specific form of training for pitchers and have the potential to improve ball velocity, the risk of injury associated with these programs is high. Although they reported a 3.3% increase in ball velocity after weighted-ball training, Reinold et al. also found a 24% (4 of 17) injury rate in the weighted-ball training group versus 0% in the control group (21). In addition, the total training volume for the subjects in the weighted-ball training program increased by 35 throws per week. A subsequent study by these authors demonstrated acute increases in throwing shoulder external rotation range of motion of 2.5 and 6.5%, respectively, after a single weighted-ball throwing session with overweight and "extreme" overweight balls (22). It was speculated that these increases in motion and the increased throwing volume may lead to increased injury rates. The results of the current study illustrate that motion of the trunk is moderately correlated with ball velocity and could

Table 2

Predictors of ball velocity.

Factor	Correlation coeff.	% Explained	*p*	Regression equation
Hip-shoulder separation at foot contact	0.29	$r^2 = 8\%$	0.128	
Peak pelvis velocity	0.35	$r^2 = 12\%$	0.061	
Peak trunk velocity	0.50	$r^2 = 25\%$	**0.006**	**y = 0.012x + 22.4**
Peak elbow extension velocity	0.19	$r^2 = 3.5\%$	0.327	
Shoulder IR velocity at ball release	0.36	$r^2 = 13\%$	0.055	
Timing peak pelvis velocity	0.05	$r^2 < 1\%$	0.807	
Timing peak trunk velocity	0.05	$r^2 < 1\%$	0.790	
Timing peak elbow ext. Velocity	−0.09	$r^2 < 1\%$	0.644	

Bolded to highlight the significant *p*-value associated with the regression equation

Table 3

Predictors of peak trunk velocity.

Factors	Correlation coeff.	% Explained	p	Regression equation
Hip-shoulder separation at foot contact	0.411	$r^2 = 17\%$	**0.027**	$\mathbf{y = 4.14x + 751}$
Peak pelvis velocity	0.481	$r^2 = 23\%$	**0.008**	$\mathbf{y = 0.657x + 567}$
Timing peak pelvis velocity	0.401	$r^2 = 16\%$	**0.031**	$\mathbf{y = 4.29x + 909}$
Timing peak trunk velocity	0.366	$r^2 = 13\%$	0.051	
Hip-shoulder separation + pelvis velocity	0.629	$R^2 = 40\%$	**0.001**	$\mathbf{y = 4.09\, x_1 + 0.652x_2 + 365}$
Hip-shoulder separation + pelvis velocity + trunk timing	0.741	$R^2 = 55\%$	**<0.001**	$\mathbf{y = 4.33x_1 + 0.651x_2 + 4.42x_3 + 365}$

Entries are bolded to highlight the significant *p*-value associated with the regression equation

represent a modifiable target for training that is not related to the throwing arm. Although the influence on ball velocity seems small, focusing on improving this factor may allow a pitcher to still benefit from training while providing rest and recovery time for the throwing arm.

Although the current study highlights the contributions of the trunk and pelvis in generating ball velocity, there are a few limitations that need to be mentioned. First, although the speed of each pitch was measured by a radar gun, the accuracy of each pitch (i.e., whether a pitch was thrown for a strike) could not be determined because of the limited distance from the mound to the net (about 20 vs. 60.5 feet). Therefore, the laboratory conditions were not truly reflective of the on-field conditions that a pitcher typically encounters. Second, the study group was limited to a small population of collegiate and high-school pitchers and the results may not be generalizable to professional or youth pitchers. Establishing similar relationships between pelvis and trunk kinematics and ball velocity across a larger range of skill levels may aid in the development of training programs that can be used by pitchers at all levels of development. Finally, although the focus of this study was to determine kinematic factors related to ball velocity, it did not explore the possible relationships between upper-body and lower-body kinematics during the pitching motion. Understanding the effects of altering lower-body kinematics on the movements of the shoulder and elbow would further aid the development of training programs that target the lower body without significantly changing upper-body mechanics. Future studies should be performed to further understand these relationships.

Practical Applications

This study highlights the importance of targeting the trunk in training interventions for the pitcher to increase ball velocity and decrease training stress in the throwing arm. Based on the results of the current study, pelvis velocity and hip-shoulder separation are likely the most modifiable factors that were correlated with trunk velocity. To that end, strength and power training for the hips and lower extremities may help in increasing the rotational velocity of the pelvis during the pitching motion. In addition, safely increasing a pitcher's ability to dissociate the pelvis and trunk, along with training to efficiently use that increased range of motion in the form of a progression from static stability to dynamic stability and then to more explosive drills may also yield improvements in trunk kinematics. Future research should investigate how such training affects pitching biomechanics and ball velocity.

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REFERENCES

1. Bullock GS, Strahm J, Hulburt TC, et al. The relationship of range of motion, hip shoulder separation, and pitching kinematics. *Int J Sports Phys Ther* 15: 1119–1128, 2020.
2. Carter AB, Kaminski TW, Douex AT Jr, Knight CA, Richards JG. Effects of high volume upper extremity plyometric training on throwing velocity and functional strength ratios of the shoulder rotators in collegiate baseball players. *J Strength Cond Res* 21: 208–215, 2007.
3. DeRenne C, Buxton BP, Hetzler RK, Ho KW. Effects of under- and overweighted implement training on pitching velocity. *J Strength Cond Res* 8: 247–250, 1994.
4. Erickson BJ, Harris JD, Chalmers PN, et al. Ulnar collateral ligament reconstruction: Anatomy, indications, techniques, and outcomes. *Sports Health* 7: 511–517, 2015.
5. Escamilla RF, Speer KP, Fleisig GS, Barrentine SW, Andrews JR. Effects of throwing overweight and underweight baseballs on throwing velocity and accuracy. *Sports Med* 29: 259–272, 2000.
6. Escamilla RF, Fleisig GS, Yamashiro K, et al. Effects of a 4-week youth baseball conditioning program on throwing velocity. *J Strength Cond Res* 24: 3247–3254, 2010.
7. Escamilla RF, Ionno M, deMahy MS, et al. Comparison of three baseball-specific 6-week training programs on throwing velocity in high school baseball players. *J Strength Cond Res* 26: 1767–1781, 2012.
8. Fleisig GS, Barrentine SW, Zheng N, Escamilla RF, Andrews JR. Kinematic and kinetic comparison of baseball pitching among various levels of development. *J Biomech* 32: 1371–1375, 1999.
9. Fleisig GS, Phillips R, Shatley A, et al. Kinematics and kinetics of youth baseball pitching with standard and lightweight balls. *Sports Eng* 9: 155–163, 2006.
10. Fleisig GS, Diffendaffer AZ, Aune KT, Ivey B, Laughlin WA. Biomechanical analysis of weighted-ball exercises for baseball pitchers. *Sports Health* 9: 210–215, 2017.
11. Fortenbaugh D, Fleisig GS, Andrews JR. Baseball pitching biomechanics in relation to injury risk and performance. *Sports Health* 1: 314–320, 2009.
12. Joyce C. The most important "factor" in producing clubhead speed in golf. *Hum Mov Sci* 55: 138–144, 2017.
13. Lyman S, Fleisig GS, Andrews JR, Osinski ED. Effect of pitch type, pitch count, and pitching mechanics on risk of elbow and shoulder pain in youth baseball pitchers. *Am J Sports Med* 30: 463–468, 2002.
14. Mahure SA, Mollon B, Shamah SD, Kwon YW, Rokito AS. Disproportionate trends in ulnar collateral ligament reconstruction: Projections through 2025 and a literature review. *J Shoulder Elbow Surg* 25: 1005–1012, 2016.

15. Matsuo T, Escamilla RF, Fleisig GS, Barrentine SW, Andrews JR. Comparison of kinematic and temporal parameters between different pitch velocity groups. *J Appl Biomech* 17: 1–13, 2001.
16. Myers J, Lephart S, Yung-Shen T, et al. The role of upper torso and pelvis rotation in driving performance during the golf swing. *J Sports Sci* 26: 181–188, 2008.
17. Okoroha KR, Meldau JE, Jildeh TR, et al. Impact of ball weight on medial elbow torque in youth baseball pitchers. *J Shoulder Elbow Surg* 28: 1484–1489, 2019.
18. Oyama S, Yu B, Blackburn JT, et al. Improper trunk rotation sequence is associated with increased maximal shoulder external rotation angle and shoulder joint force in high school baseball pitchers. *Am J Sports Med* 42: 2089–2094, 2014.
19. Parks ED, Ray TR. Prevention of overuse injuries in young baseball pitchers. *Sports Health* 1: 514–517, 2009.
20. Putnam C. Sequential motions of body segments in striking and throwing skills: Descriptions and explanations. *J Biomech* 26(Suppl): 125–135, 1993.
21. Reinold MM, Macrina LC, Fleisig GS, Aune K, Andrews JR. Effect of a 6-week weighted baseball throwing program on pitch velocity, pitching arm biomechanics, passive range of motion, and injury rates. *Sports Health* 10: 327–333, 2018.
22. Reinold MM, Macrina LC, Fleisig GS, Drogosz M, Andrews JR. Acute effects of weighted baseball throwing programs on shoulder range of motion. *Sports Health* 12: 488–494, 2020.
23. Scarborough DM, Linderman SE, Sanchez JE, Berkson EM. Kinematic sequence classification and the relationship to pitching limb torques. *Med Sci Sports Exerc* 53: 351–359, 2021.
24. Stodden DF, Fleisig GS, McLean SP, Lyman SL, Andrews JR. Relationship of pelvis and upper torso kinematics to pitched baseball velocity. *J App Biomech* 17: 164–172, 2001.
25. Stodden DF, Campbell BM, Moyer TM. Comparison of trunk kinematics in trunk training exercises and throwing. *J Strength Cond Res* 22: 112–118, 2008.
26. Werner SL, Suri M, Guido JA Jr, Meister K, Jones DG. Relationship between ball velocity and throwing mechanics in collegiate baseball pitchers. *J Shoulder Elbow Surg* 17: 905–908, 2008.
27. Wooden MJ, Greenfield B, Johanson M, et al. Effects of strength training on throwing velocity and shoulder muscle performance in teenage baseball players. *J Orthop Sports Phys Ther* 15: 223–228, 1992.
28. Yang WW, Liu YC, Lu LC, et al. Performance enhancement among adolescent players after 10 weeks of pitching training with appropriate baseball weights. *J Strength Cond Res* 27: 3245–3251, 2013.