Stride Leg Ground Reaction Forces Predict Throwing Velocity in Adult Recreational Baseball Pitchers

MICHAEL P. MCNALLY,[1,2] JOHN D. BORSTAD,[1,3] JAMES A. OÑATE,[1,4] AND AJIT M.W. CHAUDHARI[1,2,3]

[1]*School of Health and Rehabilitation Sciences, The Ohio State University, Columbus, Ohio;* [2]*Department of Orthopaedics, The Ohio State University Wexner Medical Center, Columbus, Ohio;* [3]*Division of Physical Therapy, The Ohio State University Wexner Medical Center, Columbus, Ohio; and* [4]*Division of Athletic Training, The Ohio State University Wexner Medical Center, Columbus, Ohio*

Abstract

McNally, MP, Borstad, JD, Oñate, JA, and Chaudhari, AMW. Stride leg ground reaction forces predict throwing velocity in adult recreational baseball pitchers. *J Strength Cond Res* 29(10): 2708–2715, 2015—Ground reaction forces produced during baseball pitching have a significant impact in the development of ball velocity. However, the measurement of only one leg and small sample sizes in these studies curb the understanding of ground reaction forces as they relate to pitching. This study aimed to further clarify the role ground reaction forces play in developing pitching velocity. Eighteen former competitive baseball players with previous high school or collegiate pitching experience threw 15 fastballs from a pitcher's mound instrumented to measure ground reaction forces under both the drive and stride legs. Peak ground reaction forces were recorded during each phase of the pitching cycle, between peak knee height and ball release, in the medial/lateral, anterior/posterior, and vertical directions, and the peak resultant ground reaction force. Stride leg ground reaction forces during the arm-cocking and arm-acceleration phases were strongly correlated with ball velocity ($r^2 = 0.45–0.61$), whereas drive leg ground reaction forces showed no significant correlations. Stepwise linear regression analysis found that peak stride leg ground reaction force during the arm-cocking phase was the best predictor of ball velocity ($r^2 = 0.61$) among drive and stride leg ground reaction forces. This study demonstrates the importance of ground reaction force development in pitching, with stride leg forces being strongly predictive of ball velocity. Further research is needed to further clarify the role of ground reaction forces in pitching and to develop training programs designed to improve upper extremity mechanics and pitching performance through effective force development.

KEY WORDS pitching, performance, biomechanics, kinetics

Introduction

Baseball pitching is one of the most dynamic motions in all of sports. During the pitching motion, the segments of the body work in a kinetic sequence from the ground up, beginning with the feet and ending with the hand, accelerate the baseball to maximum velocity while maintaining accuracy (13). Within this characterization of the pitching motion, the development of force from the lower extremities is critical for initiating the kinetic sequence. Previous studies in strength and conditioning have reported significant relationships between measures of lower body power and pitching performance. Lehman et al. (9) found that lateral hops, which closely mimic the striding action of the pitching motion, were consistently related to greater throwing velocity from both a stretch position and a shuffle throw. Similarly, Nakata et al. (12) investigated relationships between anthropometric and physical fitness characteristics to pitched ball kinetic energy in youth baseball players and found standing long jump and 10-m sprint time–along with age, body mass index, and grip strength–to be significant predictors of pitched ball kinetic energy. However, despite the evidence suggesting the importance of lower extremity power in pitching performance, the majority of performance and injury-related research in pitching relates to the upper half of the kinetic sequence, with few studies focusing on or quantifying lower extremity mechanics and forces.

Previous research investigating lower extremity mechanics suggest that force development by the lower extremity plays a significant role in both performance and injury prevention during pitching. In one of the first studies to describe the role of the lower extremity drive to pitching velocity, Elliott and Grove (4) found similar drive leg ground reaction forces between high-velocity and low-velocity groups. However,

Address correspondence to Michael P. McNally, Michael.mcnally@osumc.edu.

29(10)/2708–2715

Journal of Strength and Conditioning Research

further work by MacWilliams et al. (10) demonstrated strong relationships between linear wrist velocity and ground reaction forces on both the drive and stride legs in the vertical- and antero-posterior directions. The interpretation of results from these studies is limited however, as both populations include small sample sizes (Elliot and Grove 3 high-velocity and 3 low-velocity pitchers; MacWilliams et al. 7 pitchers total, 5 pitchers with stride leg data), and the results may be easily influenced by outliers in performance. Guido and Werner (7) identified correlations between stride leg ground reaction forces and upper extremity mechanics, which may be related to injury in collegiate baseball pitchers but did not report correlations between stride leg ground reaction forces and pitched ball velocity. Although these studies demonstrate that ground reaction forces likely influence pitching performance, the role of ground reaction forces in the development of ball velocity remains unclear. Because pitch velocity is one component of effective pitching and because velocity generation is emphasized in throwers of all ages, our research question is focused on determining if there are specific ground reaction forces that are related to pitch velocity. Specifically, we ask if drive leg and stance leg ground reaction forces differ in their contribution to pitch velocity.

Coaches and other pitching professionals commonly instruct players in the use of weight transfer to develop pitching velocity, coaching players to balance on the drive leg, push against the ground to drive their center of mass toward the target, and land with their full body weight supported on their stride leg. Understanding the role of ground reaction forces in pitching would guide strength coaches and other training professionals in the development of safe biomechanically based training programs to improve pitching velocity. Therefore, the purpose of this study was to investigate the role of ground reaction forces in pitching, specifically which components of ground reaction force best predict wrist velocity during pitching in adults with previous pitching experience. We tested the hypothesis that greater peak resultant, vertical and anterior-posterior ground reaction forces on the drive, and stride legs are each associated with increased wrist velocity.

Methods

Experimental Approach to the Problem

This study analyzed data originally collected during throwing as part of a broader study evaluating the effect of pitching fatigue on shoulder stiffness, strength, and motion. We used an observational design in a controlled laboratory setting to measure ground reaction forces simultaneously under the drive and stride legs during overhead baseball pitching.

Subjects

Eighteen healthy former competitive baseball players with previous pitching experience at high school or collegiate level were recruited to participate (age = 24.2 ± 2.5 years, height = 1.82 ± 0.06 m, mass = 83.3 ± 8.3 kg, 2–9 years out from competitive baseball). Six of the participants had been primarily pitchers, whereas the remaining 11 played primarily other positions but did have previous pitching experience. A power analysis was performed to estimate the sample size for the original study measuring changes in shoulder stiffness after throwing. To detect within-subject stiffness differences of 0.1 with power set at 0.8, a sample size of 17 subjects was estimated (15). This study was approved by The Ohio State University Institutional Review Board, and all subjects provided informed consent before testing.

Pitching Mound

A pitching mound was custom-built out of 4 isolated platforms bolted into 4 triaxial force plates (4060-10; Bertec Corp., Columbus, OH, USA) to measure three-dimensional ground reaction forces throughout the pitching motion (Figure 1). This approach to creating force platforms is inspired by similar designs that have been validated and used by others in investigations of stair climbing (1,14). A 15 cm long × 54.5 cm wide × 1.9 cm thick "pitching rubber" was bolted on top of a platform 25.4 cm above the ground to measure drive leg ground reaction forces, with the front edge of the rubber 15 cm from the start of the downslope. Beginning 15 cm in front of the pitching rubber, the mound slopes downward at 4.12°, which is consistent with major league pitching mound specifications (no greater than 25.4 cm above ground, slope beginning 15 cm in front of rubber, downward slope of 4.76°). When completely assembled, this provided a drive leg platform 55 cm wide × 15 cm long with an attached rubber and a stride leg platform 55 cm wide × 180 cm long. The mound was painted with an antislip additive, and adhesive spray was applied to the landing area to reduce slipping. Two noninstrumented wooden runners 305 cm long × 61 cm wide with a matching downslope were placed on each side of the instrumented section of the mound to allow room for participants to complete their natural pitching motion without falling off the structure.

Procedures

Before testing, each participant was allowed to warm-up outside and within the laboratory as much as desired to get accustomed to the pitcher's mound and prepare to pitch with maximal effort. When participants were ready, 54 retroreflective markers were placed bilaterally over the fifth and second metatarsal heads, posterior calcaneus, medial and lateral malleolus, lateral mid-shank, medial and lateral knee joint line, lateral mid-thigh, anterior superior iliac spine, posterior superior iliac spine, acromion process, lateral mid-upper arm, medial and lateral epicondyle of the elbow, mid-forearm, radial and ulnar styloid process, and second metacarpal joint. Additional markers were placed over the sternal notch, xyphoid process, seventh cervical vertebra, and 10th thoracic vertebra. An initial calibration was collected to define local segment coordinate systems of the body and measure each participant's static body weight.

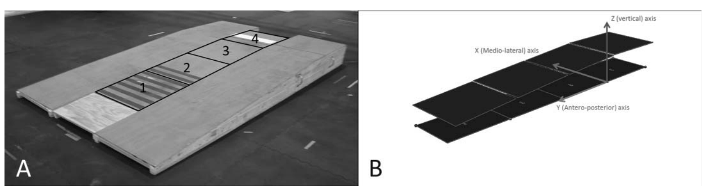

Figure 1. A) Image of custom-built pitcher's mound. B) Platforms 1–4 are bolted to in ground-embedded force plates to measure stride leg (platforms 1–3) and drive leg (platform 4) ground reaction forces. Ground reaction forces are reported in reference to the laboratory coordinate system.

For all pitching trials, three-dimensional marker locations were recorded at 300 Hz using 10 Vicon MX-F40 motion capture cameras (Vicon Inc., Oxford, United Kingdom) and synchronized with analog ground reaction force signals collected at 1,500 Hz using Vicon Nexus software. Each participant threw 15 fastballs from an instrumented pitcher's mound into a net placed approximately 9 m down the target line (approximately half that of a regulation field pitching mound to home plate distance). Participants started from their preferred pitching position (15 from wind-up, 2 from stretch), so when they reached their balance position, their drive leg was within the width of the pitching rubber, consequently ensuring they were in contact with the drive leg force platform. Each pitcher was encouraged to throw with his natural motion, so one pitcher had to be omitted from data analysis because of placement of the stride foot lateral of the instrumented section. Although accuracy is a key component to pitching performance, it was not considered within this study because of equipment limitations.

Ground reaction forces from the 2 force structures within the landing zone were summed to calculate the force that was applied to the mound by the stride foot. Because of high-frequency ringing within the aluminum structures of the instrumented sections, ground reaction force signals were filtered using a fourth order low-pass Butterworth filter with a cutoff frequency of 50 Hz, which eliminated ringing from the force signal, while maintaining the physiological signal.

Each participant threw 7 sets of 15 pitches for the main investigation on throwing fatigue, with data from the first set of 15 pitches used in this analysis. The final 5 pitches of this set of 15 throws were analyzed, ensuring that participants were fully acclimated to the mound and the laboratory setting, but not yet affected by fatigue. An upper extremity biomechanical model was defined using three-dimensional marker trajectories, consistent with that

Table 1. Descriptive statistics (mean, *SD*, 95% confidence intervals) and reliability statistics (mean coefficient of variation and intraclass correlation coefficients [3–1]) for peak wrist velocity and each of the peak ground reaction force variables measured during the drive leg stance, arm-cocking, and arm-acceleration phases.*†

				95% confidence interval			
Phase	Measure	Mean	*SD*	Lower	Upper	Mean CV	ICC (3,1)
	Wrist velocity	18.0	1.32	17.9	18.7	0.018	0.947
Drive leg stance	Resultant	1.28	0.15	1.20	1.36	0.027	0.939
	Lateral (to stride)	−0.07	0.02	−0.08	−0.05	−0.181	0.782
	Medial (to stride)	0.16	0.04	0.14	0.18	0.079	0.913
	Anterior	0.52	0.08	0.48	0.56	0.052	0.897
	Vertical	1.21	0.14	1.14	1.28	0.026	0.941
Arm cocking	Resultant	1.55	0.25	1.42	1.68	0.074	0.747
	Lateral (to stride)	−0.19	0.03	−0.21	−0.17	−0.166	0.321
	Medial (to stride)	0.05	0.04	0.03	0.07	0.824	0.486
	Posterior	0.66	0.12	0.72	0.60	−0.090	0.699
	Vertical	1.4	0.23	1.29	1.52	0.077	0.737
Arm acceleration	Resultant	1.59	0.25	1.46	1.72	0.047	0.894
	Lateral (to stride)	−0.01	0.06	−0.04	0.02	0.375	0.683
	Medial (to stride)	0.13	0.07	0.09	0.17	0.339	0.833
	Posterior	0.65	0.12	0.71	0.59	−0.066	0.873
	Vertical	1.46	0.22	1.34	1.57	0.047	0.882

*CV = coefficient of variation; ICC = intraclass correlation coefficient.
†All ground reaction forces are expressed as percentage of body weight.

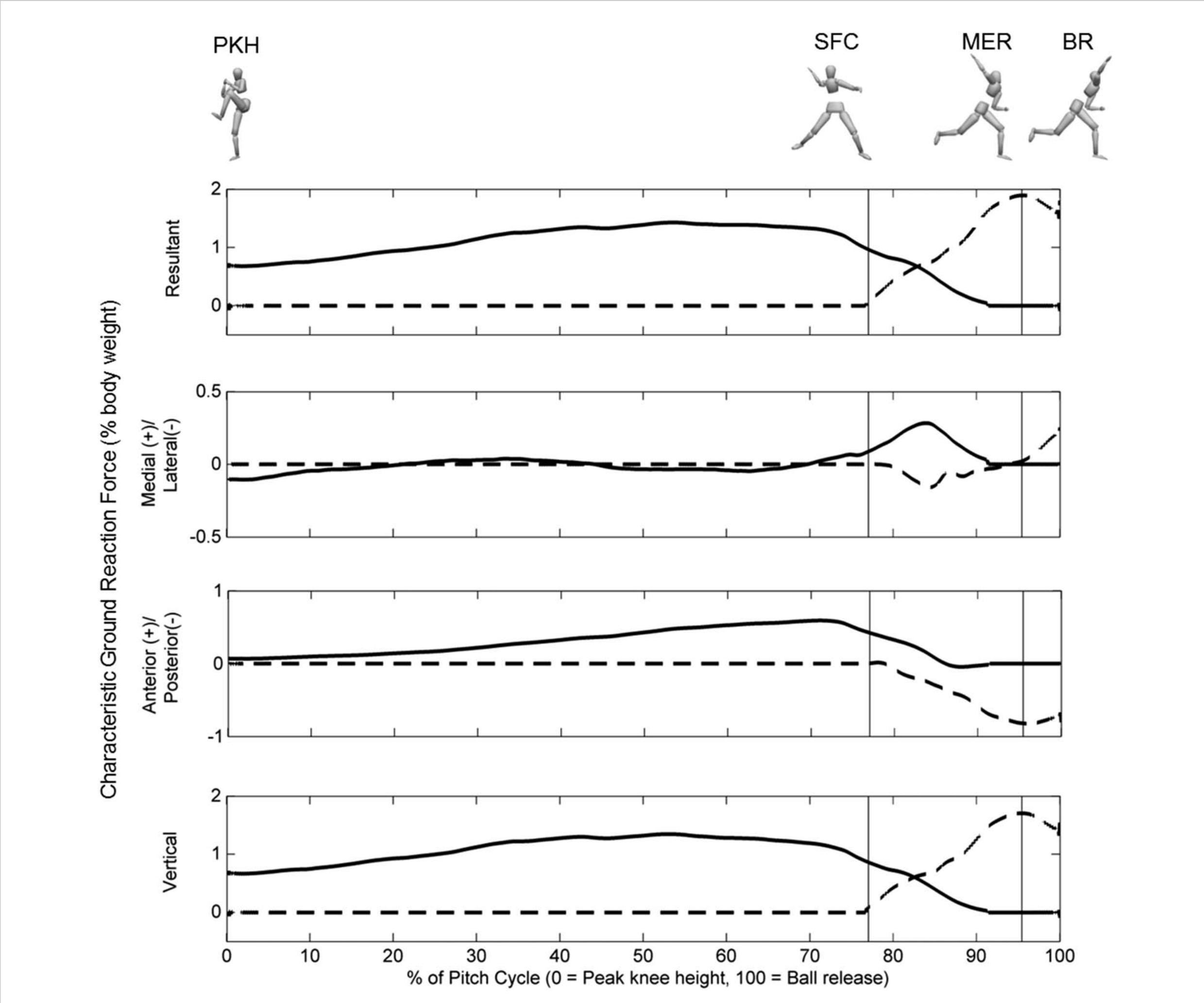

Figure 2. Characteristic ground reaction force profile of the resultant, medial/lateral, anterior/posterior, and vertical ground reaction forces for the drive (solid) and stride (dashed) legs from peak knee height (0%) to ball release (100%). PKH = peak knee height; SFC = stride foot contact; MER = maximum glenohumeral external rotation; BR = ball release.

suggested by the International Society of Biomechanics (18). The drive leg was only analyzed during the "drive phase," defined as the time from peak height of the stride leg lateral knee trajectory to toe off of the drive leg (vertical force fell below 10 N). The stride leg was analyzed during the arm-cocking and arm-acceleration phases of the pitching motion, defined in accordance with previous literature (2). The arm-cocking phase was defined from stride foot contact ([SFC], vertical ground reaction force exceeds 10 N) to maximum shoulder external rotation, and arm acceleration was defined from maximum shoulder external rotation to ball release (BR). Ball release was determined from kinematic data using an automated method (5), which defines BR as 10 ms after the radial styloid of the wrist passes the lateral epicondyle of the elbow in the global Y direction (from the pitching rubber to the target). Ground reaction forces occurring after BR are not able to contribute to the generation of ball velocity and were not analyzed for this study. Wrist position was determined as a landmark located between the medial and lateral wrist markers, and linear wrist velocity was calculated as the first derivative of wrist position over time. Peak wrist velocity was found between maximum external rotation and BR, which has been used in previous studies as a strong correlate of ball velocity ($r^2 = 0.97$) (10).

Ground reaction forces were reported relative to the laboratory coordinate system (Figure 1B) with the anterior-posterior axis representing a line from the middle of the pitching rubber to the center of the target, the vertical axis-oriented straight-up (as opposed to relative to the slope of the mound), and the medial-lateral axis-oriented normal to the anterior-posterior and vertical

TABLE 2. Correlations between wrist velocity and peak ground reaction forces by phase.

Phase	Measure	Correlation to wrist velocity	95% confidence interval		p
			Lower	Upper	
Drive leg stance	Resultant	0.04	−0.45	0.51	0.870
	Lateral (to stride)	0.27	−0.24	0.66	0.292
	Medial (to stride)	0.21	−0.30	0.63	0.410
	Anterior	0.36	−0.15	0.72	0.156
	Vertical	0.03	−0.46	0.50	0.921
Arm cocking	Resultant	0.75**	0.42	0.90	0.001
	Lateral (to stride)	0.16	−0.35	0.59	0.530
	Medial (to stride)	0.15	−0.36	0.59	0.553
	Posterior	0.79**	0.50	0.92	<0.001
	Vertical	0.73**	0.39	0.90	0.001
Arm acceleration	Resultant	0.71**	0.35	0.89	0.001
	Lateral (to stride)	−0.32	−0.69	0.19	0.208
	Medial (to stride)	0.59*	0.15	0.83	0.014
	Posterior	0.79**	0.50	0.92	<0.001
	Vertical	0.68**	0.30	0.87	0.003

*$p \leq 0.05$.
$p \leq 0.01$.

axes, pointing to the right (toward third base). Resultant ground reaction force was calculated as the combined magnitude of the force vector from each of the 3 force components. Peak resultant, vertical, anterior-posterior, and medial-lateral ground reaction forces normalized to body weight were found throughout the drive and stride phases and during individual phases of the pitch cycle. Pitch-to-pitch repeatability for each of these measurements calculated from the 5 pitches analyzed within each subject is displayed in Table 1.

Statistical Analyses

A Shapiro-Wilk test was used to test the normality of distribution for each variable. Peak medial force on the stride leg (directed medially about the stride leg toward throwing arm side) was the only nonnormally distributed variable, so its relationship with peak wrist velocity was calculated using a Spearman's rank correlation. Pearson product correlations were performed between all other peak ground reaction force variables and peak wrist velocity with significant correlations set a priori at $p \leq 0.05$. A stepwise regression analysis beginning with forward selection followed by bidirectional elimination (3) was used to determine which factors were independently predictive of peak wrist velocity. Included in the stepwise regression as potential predictors were peak ground reaction forces in the medial, lateral, anterior/posterior, and vertical directions from the drive leg during the drive leg stance phase and from the stride leg during the arm-cocking and arm-acceleration phases. Variables were entered into the final model with a $p \leq 0.05$ and removed from the model if $p > 0.10$.

RESULTS

A characteristic ground reaction force curve with each event of the pitching cycle is shown in Figure 2. Descriptive statistics and reliability for all recorded measures are shown in Table 1, and correlations between peak wrist velocity and peak ground reaction forces on both the drive and stride legs are presented in Table 2. Peak ground reaction forces imparted by the drive leg were not significantly related to peak wrist velocity. Stride leg ground reaction forces in the vertical and posterior directions, as well as the resultant ground reaction force, were strongly correlated to peak wrist velocity during both the arm-cocking and arm-acceleration phases ($r = 0.68$–0.79). Peak stride leg medial ground reaction force was significantly correlated to wrist velocity during the arm-acceleration phase ($R = 0.59$).

Stepwise regression analysis resulted in peak stride leg posterior ground reaction force occurring within the arm-cocking phase being the only significant predictor of peak wrist velocity ($\beta = -8.672$; 95% confidence interval = $[-12.380, -4.965]$; $SE = 1.739$). The final model yielded an R^2 of 0.62 with an SEE of 0.84 $m \cdot s^{-1}$ (1.9 mph), with the final equation:

$$Wrist_{vel} = 12.273 - 8.672(PeakPostGRF_{AC}).$$

DISCUSSION

Force imparted by the stride leg acting against the direction of the throw appears to contribute strongly to achieving maximum throwing velocity, explaining 61% of the variance in wrist velocity. Although stride leg ground reaction forces in the posterior, medial, and vertical directions were strongly correlated to wrist velocity during both the arm cocking and acceleration, the action of posterior-directed ground reaction force during the arm-cocking phase was most predictive of wrist velocity. The observed association of stride leg mechanics to wrist velocity is in agreement with previous studies, which have found decreased stride leg knee flexion velocity during stride leg stance and increased stride leg knee extension velocity at BR, to be positively associated with both pitch velocity (11,16) and javelin throwing distance (17).

Force imparted by the stride leg may be at least in part because of the stride leg knee joint resisting flexion and moving into extension, which has been suggested to play an important role in maximizing throw velocity and distance (11,17). Peak stride leg posterior ground reaction force occurs near maximum shoulder external rotation (Figure 2), and within subjects can occur either during the arm-cocking phase (67.9% of all trials) or during the arm-acceleration phase (32.1% of all trials). However, the correlation between peak posterior ground reaction force during arm cocking and wrist velocity is still greater than the relationship between peak posterior ground reaction force during the entire stance phase and wrist velocity ($r^2 = 0.61$ vs. 0.59), indicating that the generation of posterior ground reaction force is most critical during the arm-cocking phase. After the arm-cocking phase, the influence of ground reaction forces on ball velocity are less clear, but they are likely to have missed the window of opportunity to assist in the development of pitching velocity. However, stride leg ground reaction forces may still play an important role in providing lower body stability to maximize control of body position. This could have particularly important implications for fielding performance and risk of injury during the deceleration phase of pitching, because an inability of the muscles to dissipate the forces produced during pitching may place additional strain on other soft tissues (such as tendons and ligaments). An inability to dissipate the forces after BR may also impact the time it takes for pitchers to finish the motion and get into a fielding position, limiting their ability to react to balls hit back in their direction.

In contrast to the study by MacWilliams et al., we found no relationship between drive leg ground reaction forces and wrist velocity. Differences in sample population (former pitchers vs. collegiate and high school) or sample size (5 vs. 17) may help to explain the differences in findings. Although our results suggest that force produced by the stride leg is more critical to the development of wrist velocity, drive leg forces may still be of importance for the initial generation of momentum in the direction of the throw and the force-coupling relationship, which initiates transverse rotation of the body. The lack of relationship between drive leg ground reaction forces and wrist velocity may be indicative of different strategies for generating linear momentum towards the direction of the throw. This finding suggests that the strategy used to generate momentum may not be as important to the development of pitching velocity as the strategy of generating stride leg posterior forces during the cocking phase. Additionally, the total impulse generated during each of these phases (a representation of the overall effort during each phase) should be investigated further, as the peak forces investigated in this study may only explain part of the relationship between ball velocity and ground reaction force, particularly regarding the drive leg and its ability to generate linear momentum.

This study supports the hypothesis that ground reaction forces likely play a critical role in the development of maximum pitching velocity. This is in line with previous studies, which have suggested that ground reaction forces are strongly related to ball velocity (4,10) and upper extremity biomechanics (7). The magnitude of ground reaction forces normalized to body weight was similar between this study and those reported by Elliott and Grove and MacWilliams et al., adding to the validity of these results. Further research is needed, however, to establish the reliability of ground reaction force measurements and variability within subjects. Intraclass correlation coefficients were calculated to give indications of the pitch-to-pitch repeatability within individual participants of the measures analyzed in this study. These intraclass correlation coefficients (ICCs) were generally high (>0.8), but some low values did exist (i.e., peak medial and lateral forces during arm cocking, ICC = 0.486 and 0.321). Coefficients of variation were also generally low, except in peak medial and lateral forces where the mean was closer to zero. Further work is needed to explore the reliability across multiple sessions to further validate ground reaction force measurements in pitching.

The results of this study should be considered in light of some limitations. Wrist velocity was used in place of ball velocity during this study because of inconsistent readings from a radar gun used in the laboratory during data collections. Additional pitch velocity may be attained by the wrist and fingers; however, previous research suggests that this effect is minimal (8), and other research has reported a high correlation ($r^2 = 0.97$) between linear wrist velocity and ball velocity (10). Accuracy of ball placement in the strike zone by the pitcher was not assessed in this study because of equipment limitations but should also be considered as an important aspect in pitching performance. Pitchers within this study threw from their preferred starting position (wind-up or stretch position) that could potentially alter the magnitude of the ground reaction force. However, the effect of starting position and the effect of throwing from a nonpreferred starting position are unknown and require further research to determine relationships to performance. Additionally, pitchers in a game situation may alter their mechanics in favor of more control or different pitch types as opposed to throwing maximum velocity fastballs as performed in this study. Similarly, different styles of pitching mechanics (i.e., short vs. long stride length) may also affect the force needed to be produced by the stride leg. Further work should investigate the trade-off between ball velocity and accuracy, the effect of different pitching mechanics and pitch types on ground reaction forces and in particular how ground reaction forces can help to moderate ball velocity, accuracy, and overall pitch effectiveness by influencing more distal kinematics. Finally, although the sample size of this study was larger than previous research, the sample population explored in this study may not be representative of the athletes who compete in baseball at other levels. Additional work is needed to determine if these results are similar across baseball pitchers of other ages and populations (e.g., youth, high school, collegiate, and professional pitchers). For future studies, based on the R^2 of 0.62 found in the stepwise regression analysis, a sample size of 25 would be required to achieve 80% power in a future study using the same stepwise approach in different pitching populations (6).

This study demonstrated that stride leg ground reaction force is a strong independent predictor of a pitcher's ability to generate ball velocity when pitching from a mound, whereas drive leg ground reaction force is not. Of particular importance is the stride leg posterior ground reaction force during the arm-cocking phase, which has been posited to provide a stable base for transfer of energy to the trunk and upper extremity (11,17). Other factors likely affect the development of ball velocity in this dynamic motion; so, further investigation is needed into the complete role of ground reaction forces, particularly in relation to the stride leg, and how these forces act to control the most proximal ends of the kinetic chain, the legs, and pelvis. Additionally, work is needed to determine how training programs focused on the lower extremities may affect ball velocity and injury risk biomechanics of the upper extremity. Quantifying the link between ground reaction forces and ball velocity further demonstrates that pitching is a full body kinetic chain motion beginning from the foot-ground interaction, and training more proximal aspects of the kinetic chain may help in the generation of maximum throwing velocity.

Practical Applications

Based on these results, coaches and trainers interested in generating pitch velocity should place a greater emphasis on addressing stride leg ground reaction force generation and timing. Mechanics aimed at improving force producing capabilities of the lower extremities, particularly eccentric loading through the stride leg, will benefit pitchers by enabling the athlete to more effectively use the legs in developing ball velocity. In particular, generation of posterior ground reaction force during the arm-cocking phase ("slamming on the brakes") may be an effective way to improve pitching velocity. Improved control of the forces developed by the stride leg to be directed posteriorly to the target, as opposed to medially or laterally, may also affect kinematics and kinetics related to injury risk (7). Plyometric exercises particularly focused on generation of force acting posteriorly (i.e., single-leg landing from a forward hop and backwards hops), and pitching drills focused on the stride leg and transfer of energy (i.e., throwing from a kneeling position, extending knee to standing upon release) may help to develop the strength and neuromuscular efficiency to more effectively use the lower extremities and improve performance. Improving eccentric knee flexion control through single-leg exercises, such as Bulgarian squats and skater jumps, may allow the athlete to better manage the high-reaction forces that are needed immediately after SFC. Finally, to ensure transfer of learning, focused practice on controlling stride leg motion and generating increased posterior ground reaction force by the stride leg during the cocking phase of pitching is recommended.

Acknowledgments

The authors would like to thank Tom Stoughton and Jay Young for their assistance in the collection and processing of motion capture data. Results of this study do not constitute endorsement of the product by the authors or the National Strength and Conditioning Association.

References

1. Della Croce, U and Bonato, P. A novel design for an instrumented stairway. *J Biomech* 40: 702–704, 2007.
2. Dillman, CJ, Fleisig, GS, and Andrews, JR. Biomechanics of pitching with emphasis upon shoulder kinematics. *J Orthop Sports Phys Ther* 18: 402–408, 1993.
3. Draper, NR and Smith, H. *Applied Regression Analysis.* Hoboken, NJ: Wiley Interscience, 1998.
4. Elliott, B and Grove, JR. Timing of the lower limb drive and throwing limb movement in baseball pitching. *Int J Sports Biomech* 4: 10, 1988.
5. Escamilla, RF, Fleisig, GS, Barrentine, SW, Zheng, N, and Andrews, JR. Kinematic comparisons of throwing different types of baseball pitches. *J Appl Biomech* 14: 23, 1998.
6. Faul, F, Erdfelder, E, Buchner, A, and Lang, AG. Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behav Res Methods* 41: 1149–1160, 2009.
7. Guido, JA Jr and Werner, SL. Lower-extremity ground reaction forces in collegiate baseball pitchers. *J Strength Cond Res* 26: 1782–1785, 2012.
8. Hore, J, Watts, S, and Martin, J. Finger flexion does not contribute to ball speed in overarm throws. *J Sports Sci* 14: 335–342, 1996.
9. Lehman, G, Drinkwater, EJ, and Behm, DG. Correlation of throwing velocity to the results of lower-body field tests in male college baseball players. *J Strength Cond Res* 27: 902–908, 2013.
10. MacWilliams, BA, Choi, T, Perezous, MK, Chao, EY, and McFarland, EG. Characteristic ground-reaction forces in baseball pitching. *Am J Sports Med* 26: 66–71, 1998.
11. Matsuo, T, Escamilla, RF, Fleisig, GS, Barrentine, SW, and Andrews, JR. Comparison of kinematic and temporal parameters between different pitch velocity groups. *J Appl Biomech* 17: 14, 2001.
12. Nakata, H, Nagami, T, Higuchi, T, Sakamoto, K, and Kanosue, K. Relationship between performance variables and baseball ability in youth baseball players. *J Strength Cond Res* 27: 2887–2897, 2013.

13. Pappas, AM, Zawacki, RM, and Sullivan, TJ. Biomechanics of baseball pitching. A preliminary report. *Am J Sports Med* 13: 216–222, 1985.

14. Thoma, LM, Flanigan, DC, Chaudhari, AM, Siston, RA, Best, TM, and Schmitt, LC. Quadriceps femoris strength and sagittal-plane knee biomechanics during stair ascent in individuals with articular cartilage defects in the knee. *J Sport Rehabil* 23: 259–269, 2014.

15. Thomas, SJ, Swanik, CB, Higginson, JS, Kaminski, TW, Swanik, KA, Kelly, JD, and Nazarian, LN. Neuromuscular and stiffness adaptations in division I collegiate baseball players. *J Electromyogr Kinesiol* 23: 102–109, 2013.

16. Werner, SL, Suri, M, Guido, JA Jr, Meister, K, and Jones, DG. Relationships between ball velocity and throwing mechanics in collegiate baseball pitchers. *J Shoulder Elbow Surg* 17: 905–908, 2008.

17. Whiting, WC, Gregor, RJ, and Halushka, M. Body segment and release parameter contributions to new-rules javelin throwing. *Int J Sport Biomech* 7: 111–124, 1991.

18. Wu, G, van der Helm, FC, Veeger, HE, Makhsous, M, Van Roy, P, Anglin, C, Nagels, J, Karduna, AR, McQuade, K, Wang, X, Werner, FW, and Buchholz, B. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion–Part II: Shoulder, elbow, wrist and hand. *J Biomech* 38: 981–992, 2005.