# Relationship between Ground Reaction Force Impulse and Throwing Arm Joint Kinetics in Collegiate Baseball Pitchers

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Abstract

Peak ground reaction force (GRF) is one variable that has been studied in the lower extremity to determine the amount of force generated by the drive leg and stride leg of the pitcher. Studies suggest that impulse can be used as a performance measure to determine rapid changes in displacement across a group of athletic individuals. The purpose of this study was to determine how peak GRF and GRF impulse of the drive and stride legs relate to ball speed and joint kinetics in collegiate baseball pitchers. It was hypothesized that collegiate baseball pitchers with peak GRF and GRF impulse at the stride leg will have peak internal rotational torque at the shoulder, peak valgus torque at the elbow, and ball speed. A sample of 20 collegiate pitchers were included in this retrospective study on data collected over the course of two baseball seasons. Ball speed was significantly influenced by stride leg horizontal GRF, stride leg vertical GRF, drive leg horizontal GRF, drive leg medio-lateral impulse, and stride leg medio-lateral impulse ($r^2 = 0.626$, $p = 0.024$), which accounted for 62.6% of variance in ball speed. The significant relationship found between medio-lateral impulse at the drive leg and stride leg and ball speed supports the idea that stabilization and balance in the lower extremity is essential for rotation to occur from the legs to the hips to the shoulder to produce a greater change in momentum for a greater ball speed. Further research can be conducted on this population to examine performance measures from the lower extremity to the upper extremity to correlate values with joint kinetics and ball speed and to understand mechanisms of injury using biomechanical variables such as peak GRF and impulse.

*Keywords:* throwing athletes, baseball, pitching mechanics, stride leg, drive leg, ground reaction forces, impulse, ball speed, injury risks, shoulder, elbow

## Injury Risks in Collegiate Baseball Pitchers and Pitching Biomechanics

Baseball pitching is a dynamic movement that requires the lower and upper extremity to perform in a manner that is efficient. This dynamic movement overtime creates overuse injuries of the musculoskeletal structures and tissues surrounding the throwing arm. Urbin et al. (2013) states that pitchers are particularly susceptible to overuse injuries because of the large forces and torques acting at and about the shoulder and elbow joints to achieve near-maximal to maximal ball speeds. In addition, Urbin et al. (2013) suggested that repeated application of high-magnitude kinetics can lead to progressive degeneration and eventual failure of the soft tissues. In one epidemiology study conducted on professional baseball players, Ciccotti et al. (2017) found that in Major League players, elbow injuries were the fourth most prevalent type of injury, behind upper leg (13.1%), shoulder (12.2%), and hand (9.1%). These same researchers found that in Minor Leaguers, elbow injuries were also the fourth most prevalent type, behind shoulder (15.2%), upper leg (11.4%), and hand (10.3%) (Ciccotti et al., 2017). Overuse injuries are prevalent in all levels of baseball pitchers. Oyama (2012) reported that pitchers are susceptible to upper extremity injuries as indicated by higher incidences of shoulder and elbow injury reported at high school, collegiate, and professional levels when compared to position players. Studies have been conducted to determine what variables can predict injury risk in this population at different age levels.

Joint kinetics such as maximum shoulder internal rotational (MIR) torque and maximum elbow valgus torque (MEV) are biomechanical variables that have been measured to determine risk factors and injury mechanisms in baseball pitchers at the shoulder and elbow. In one study, Fleisig et al. (1995) investigated the mechanisms of overuse injuries in elite adult baseball pitchers using joint kinetics at the shoulder and elbow to determine biomechanical variables with implications about injury mechanisms. Fleisig et al. (1995) identified two critical instants to measure joint kinetics and were identified as the following: first at the end of the arm cocking phase and second at the arm deceleration phase. In the first critical instant during the end of the arm cocking phase, Fleisig et al. (1995) found that large loads of 67 ± 11 N-m of internal rotation torque were produced at the shoulder. This kinetic data found at the shoulder suggested that the instant of maximum internal rotation torque during arm cocking and the instant of maximum compressive force during arm deceleration were two critical points for the shoulder, which supported the belief that most overuse injuries to the shoulder occur at these two instants or during the short time between them (Fleisig et al., 1995). In addition, Fleisig et al. (1995) found at the first critical instant during the arm cocking phase that a maximum varus torque of 64 ± 12 N·m was generated at the elbow and concluded that the maximum elbow varus torque, produced at the time of maximum shoulder internal rotation torque, which was identified as a critical load related to elbow injuries. According to Fleisig et al. (1995), these findings presented in their study support the idea that overuse injuries resulting from accumulated microtrauma developed during repetitive use are caused by the large forces and torques exerted at the shoulder and elbow during pitching. The findings presented in the study conducted by Fleisig et al. (1995) suggests that joint kinetics such as shoulder internal rotational torque and elbow valgus torque can be used to determine injury related risk factors at the shoulder and elbow in baseball pitchers.

Pitching biomechanics have been studied in baseball pitchers to understand and measure potential injury risk. Different kinetic variables have been used to measure the performance output in pitchers from the lower extremity to the upper extremity. McNally et al. (2015) explains that 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. Peak ground reaction force (GRF) is one variable that has been studied in the lower extremity to determine the amount of force generated by the drive leg and stride leg of the pitcher. Such studies indicate that greater GRF are necessary to throw a ball at a greater velocity. However, Howenstein et al. (2020) argued that there is a limitation to examining GRF in relation to only release velocity because it does not provide much insight into how the GRF relates to joint-specific kinematics and kinetics during the pitching motion. The purpose of this study is to determine how peak GRF and GRF impulse of the drive and stride legs relate to ball speed and joint kinetics in collegiate baseball pitchers. It is hypothesized that collegiate baseball pitchers with peak GRF and GRF impulse at the stride leg will have peak internal rotational torque at the shoulder, peak valgus torque at the elbow, and ball speed.

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## Literature Overview

### Peak Vertical Ground-Reaction Forces on the Stride and Drive Legs in Baseball Pitchers

Overhead throwing is dynamic in nature and pitching biomechanics have been studied to determine what variables correlate with performance. Pitching biomechanics have been broken down into six phases. Erickson et al. (2016) state that while pitching is one continuous motion, the pitching mechanics consists of six phases that include the windup, early cocking, late cocking, acceleration, deceleration, and follow through. Throughout these phases kinetic and kinematic variables have been measured in the lower and upper extremity. Peak vertical GRF has been measured in the stride leg and the drive leg during the pitching phases. According to McNally et al. (2015) using GRF as a measure at the stride leg and drive leg during pitching correlates with a significant impact in the development of ball velocity. However, the amount of GRF used in the pitching motion has varied in research studies. In one study, MacWilliams et al.

(1998) found that collegiate and high school level baseball pitchers generated shear forces of 0.35 body weight in the direction of the pitch with the push-off leg (drive leg) and to resist forces of 0.72 body weight with the landing leg (stride leg).

In another study, Guido and Werner (2012) found in collegiate baseball pitchers that ground reaction forces were in excess of 200 % body weight were generated under the stride limb. In addition, Guido and Werner (2012) suggested that pitchers with the highest ball velocity also demonstrated higher braking GRF. These findings are supported by a previous study in which, Elliot et al. (1988) conducted a study on adult international pitchers and found that the ability to drive the body over a stabilized stride leg is a characteristic of high ball velocity pitchers. One study measured how GRF at the stride leg and drive leg correlated with low and high velocity pitches. In this study, Kageyama et al. (2014) found in collegiate baseball pitchers that high-ball-velocity pitchers are characterized by greater momentum of the lower limbs during pitching motion. These findings were supported by a study conducted in former competitive baseball pitchers at the high school or collegiate level, in which McNally et al. (2015) determined that the 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. These studies suggest that greater GRF are necessary to throw a ball at a greater velocity. While these studies suggest that greater GRF has an influence on pitching performance, further studies need to be conducted to determine GRF over time as a performance measure.

**Impulse-Momentum Relationship in Sports Performance**

Other studies have measured sports performance using peak GRF over time to determine impulse during movement. Some studies have found impulse-momentum as a useful variable to measure performance. Impulse-momentum has been studied in different movement activities. Hunter et al. (2005) reported significant ($p < .001$) correlations between relative net vertical impulse and sprint velocity ($r = .755$), as well as relative net horizontal impulse and sprint velocity ($r = .781$). In this study, Hunter et al. (2005) reported that high magnitudes of horizontal propulsion were likely to achieve high acceleration. Hunter et al. (2005) concluded that the results demonstrate the necessity for maximal relative net vertical or horizontal impulse to be produced during activities requiring rapid changes in displacement.

Another movement activity in which there are rapid changes in displacement and has been measured using impulse is the vertical jump. Kirby et al. (2011) found that relative net vertical impulse during the propulsive phase of the vertical jump provided the most accurate way of explaining differences in jump performance across a group of college-aged subjects. These studies suggest that impulse can be used as a performance measure to determine rapid changes in displacement across a group of athletic individuals. For this reason, impulse momentum would be an appropriate performance measure in a dynamic sport such as baseball pitching. In their examination of peak GRF and impulse at the stride leg and drive leg in correlation with energy flow in youth pitchers, Howenstein et al. (2020) argued that using mechanical impulse as performance measure would be relevant to baseball pitching because pitchers need to accelerate and decelerate their bodies very quickly during the pitching motion. In addition, Howenstein et al. (2020) suggested that GRF impulse is a better key performance indicator for dynamic motions such as jump performance than peak GRF, which suggests that looking solely at the GRF at a discrete time point does not provide adequate information about the performance profile of either leg.

Howenstein et al. (2020) conducted a study on the lower and upper extremity in youth pitchers and used horizontal GRF impulse as one their variables to measure performance in their study. They found that for the drive leg, peak GRF correlated with energy flow (EF) into only the pelvis and trunk segments, whereas for drive leg GRF impulse correlated with EF into all segments (Howenstein et al., 2020). As for the stride leg, Howenstein et al. (2020) determined that the peak GRF correlated with EF into only the trunk and arm segments, whereas stride leg GRF impulse correlated with EF into all segments. Howenstein et al. (2020) state that based on their findings the results suggest that horizontal GRF impulse is a better predictor of EF across all segments than peak GRF.

## Relationship between Peak Horizontal GRF and Impulse, Ball Speed, and Joint Kinetics

Studies indicate that greater GRF are necessary to throw a ball at a greater velocity. McNally et al. (2015) determined that the stride leg ground reaction forces during the arm-cocking and arm-acceleration phases were strongly correlated with ball velocity, whereas drive leg ground reaction forces showed no significant correlations. While these studies suggest that greater GRF has an influence on pitching performance, further studies need to be conducted to determine GRF over time as a performance measure. Peak Horizontal GRF over time, impulse, has been studied as a performance measure in youth pitchers. Howenstein et al. (2020) determined that peak stride leg GRF in youth pitchers had the strongest relationship with EF from the trunk into the arm segment. In addition, Howenstein et al. (2020) found that EF through the shoulder joint is a strong predictor of pitching velocity, the correlation with peak GRF likely suggests an important role for the stride leg in preparing for the delivery phase of the pitching motion since these changes occur shortly after stride foot contact when the shoulder initiates the arm-cocking phase. The study conducted by Howenstein et al. (2020) establishes a foundation for the use of impulse to better understand performance measures in youth baseball pitchers and GRF data in the horizontal direction. However, other GRF components such as vertical or medio-lateral GRF components can be investigated to determine performance measures in pitchers to determine how these components relate to joint kinetics in adult pitchers. Pitching biomechanics has been studied using GRF components and recently impulse in youth pitchers to understand the performance measures and mechanics from the lower extremity to the upper extremity. Yet, pitching biomechanics using GRF components and impulse have not been studied in collegiate baseball pitchers. A baseline and foundation need to be established in collegiate baseball pitchers to determine mechanisms of injury in this population.

Forces surrounding the tissues and musculoskeletal structures in throwing arm have been studied to measure potential injury risks. Fleisig et al. (1995) conducted a quantitative descriptive study of the pitching biomechanics at the shoulder and elbow. They found that the instant of maximum internal rotation torque during arm cocking and the instance of maximum compressive force during arm deceleration were identified as two critical point for overuse injuries at the shoulder (Fleisig et al., 1995). In addition, Fleisig et al. (1995) found that maximum elbow varus torque, produced at the time of maximum shoulder internal rotation torque, was identified as a critical load related to elbow injuries. Injuries in the throwing arm have been related to a decrease in force generation of the external-rotator muscles or a low external-to-internal rotator strength ratio; and indicated the potential to lead to faulty humeral head migration, negatively affecting biomechanics of the pitching arm (Hurd & Kaufman, 2012). While joint kinetics such as GRF force and impulse have recently been studied in youth pitchers to understand the performance measures and pitching mechanics from the lower extremity to the upper extremity, these components have not been studied in collegiate baseball pitchers. A foundation needs to be established in collegiate baseball pitchers not only to determine performance measures, but to understand the mechanisms of injury using biomechanical components and joint kinetics in this population. For this reason, the importance of kinetic variables such as peak GRF and impulse can be used to examine performance measures from the lower extremity to the upper extremity to determine potential injury risks. Therefore, the purpose of this study is to determine how components in peak GRF and GRF impulse of the drive and stride legs relate to ball speed and joint kinetics in collegiate baseball pitchers. It is hypothesized that collegiate baseball pitchers with peak GRF and GRF impulse at the stride leg will have peak internal rotational torque at the shoulder, peak valgus torque at the elbow, and ball speed.

# Methods

## Participants

A sample of 20 collegiate pitchers were included in this retrospective study on data collected over the course of two baseball seasons (Aguinaldo et al., 2020). Descriptive statistics were collected and analyzed for participant demographics that include age, anthropometrics, and years participating in sport.

## Research Design

Secondary analysis study

## Instrumentation

A set of 38 reflective markers for PitchTrak (Motion Analysis Corporation, Santa Rosa, California) were placed on the skin surface overlying specific anatomical landmarks to estimate joint locations and adjacent bone segments, which were defined to estimate joint kinematics and kinetics based on previously incorporated model specifications (Aguinaldo, Buttermore, & Chambers, 2007). During each movement, the 3D global locations of the markers were captured using a motion analysis system of ten visible-red cameras (Kestrel, Motion Analysis Corp., Santa Rosa, CA) integrated with the Cortex motion capture software at a sampling rate of 250 Hz. Ground reaction forces were collected with three multicomponent forces plates (AMTI, Watertown, Massachusetts) embedded in the Perfect Mound (Porta-Pro Mounds Inc, Sauget, Illinois) engineered at major league specification. The force plates were mounted on concrete poured to allow the force plate surfaces to be level with the fiberglass surface of the mound. One plate was positioned under the pitching rubber with the front edge 6 inches in front of the rubber. The other two plates were angled at 4.8° and covered the landing zone. Each plate was covered with 1 ¾ inch infilled artificial turf to match the rest of the mound. The center of the pitching rubber was defined as the origin of the global XYZ coordinate system with the X-direction defined as the vector to home plate, Z-direction vector was pointing vertically, and Y-direction vector was the parallel vector to the pitching rubber which is also the cross products of X and Z. Force plate data were collected at 1000 Hz. A Trackman device (Trackman, Scottsdale, Arizona) was used to record pitch velocity.

## Procedure

### *Biomechanics Measurements*

A set of 38 reflective markers for PitchTrak (Motion Analysis Corporation, Santa Rosa, California) were placed on the skin surface overlying specific anatomical landmarks to estimate joint locations and adjacent bone segments, which were defined to estimate joint kinematics and kinetics based on previously incorporated model specifications (Aguinaldo, Buttermore, & Chambers, 2007). The reflective markers were placed on the upper extremity of each participant. The markers were placed on the skin overlying the acromion process, spine of the scapula, inferior angle, lateral epicondyle, ulnar styloid, radial styloid, and the base of the fifth metacarpal and estimated joint centers will be defined using virtual markers for the glenohumeral, elbow, and wrist joints (Aguinaldo, Buttermore, & Chambers, 2007). During each movement, the 3D global locations of the markers were captured using a motion analysis system of ten visible-red cameras (Kestrel, Motion Analysis Corp., Santa Rosa, CA) integrated with the Cortex motion capture software at a sampling rate of 250 Hz. Each pitcher went through a normal pregame warm-up period, before pitching four fastballs, four breaking balls, and four change ups to a catcher receiving throws at a regulation distance. One representative fastball was reviewed for this study. Data were processed and variables were calculated with PitchTrak.

The peak vertical, propulsive, and medio-lateral ground reaction force data for the drive leg (rubber side) were extracted during the stride phase, defined from the time of maximum height of the stride knee (MKH) to stride foot contact. The stride leg GRF data were extracted during the arm-cocking and arm-acceleration phases, defined from foot contact to the moment of ball release. In addition, the resultant ground reaction force was calculated as the determinant of the vector from the three force components. All GRF data and joint torques were normalized by body weight (bw) and the product of body weight and height (h), respectively. Kinematic and kinetic points will be extracted from the time-series data for subsequent statistical analysis.

**Statistical Analysis**

Simple linear regressions were used to investigate the correlations between independent and dependent variables. For the first analysis, the independent variables consisted of the following: braking and propulsive forces, horizontal, vertical, and medio-lateral GRF kinetic variables (i.e., peak GRF and GRF impulse) while the dependent variables consisted of ball speed and joint kinetics (i.e., shoulder internal rotational torque and elbow valgus torque). The criterion for statistical significance of the correlations was set at a level of 0.05. All statistical analyses were performed in SPSS 21.0 (IBM Corporation, Armonk, NY, USA). Descriptive statistics were collected and analyzed for participant demographics that include age, years participating in sport, and anthropometrics (height, body mass, and body mass index [BMI]). IBM SPSS Statistics (version 19.0 IBM Corporation, Armonk, NY) will be used to analyze the statistics.

**Results**

As shown in Table 1, the multiple regression analysis demonstrated that the maximum elbow valgus torque (MEV) was significantly influenced by the drive leg vertical impulse ($r^2 = 0.308$, $p = 0.011$), which accounted for 30.8 % of variance in MEV. The descriptive statistics for the

MEV regression analysis model were n = 20; Mean ± SD = 106.9 ± 67.5 N·m. In Table 2, the multiple regression analysis model for maximum shoulder internal rotational torque (MIR) determined that MIR was significantly associated with two variables, drive leg medio-lateral GRF ($p$ = 0.020) and stride leg horizontal impulse ($p$ = 0.038). However, while this regression model explained 64.8% of the variance in MIR in the current sample ($r^2$ = 0.648), it was not statistically significant ($p$ = 0.078). The descriptive statistics for the MIR regression analysis model were n = 20; Mean ± SD = 62.7 ± 13.6 N·m. The multiple regression analysis showed that ball speed was significantly influenced by stride leg horizontal GRF, stride leg vertical GRF, drive leg horizontal GRF, drive leg medio-lateral impulse, and stride leg medio-lateral impulse ($r^2$ = 0.626, $p$ = 0.024), which accounted for 62.6% of variance in ball speed (Table 3). The descriptive statistics for the ball speed regression analysis model were n = 20; Mean ± SD = 87.9 ± 2.7 mph.

Table 1. Variables Included in MEV Multiple Regression Analysis (n = 20; Mean ± SD = 106.9 ± 67.5 N·m)

| | *B | **β | *p*-Value |
|---|---|---|---|
| Intercept | 28.139 | | |
| Impulse | | | |
| Drive Leg Vertical | 0.068 | 0.024 | 0.011 |

**B, standardized regression coefficient; **β, unstandardized regression coefficient.*

Table 2. Variables Included in MIR Multiple Regression Analysis (n = 20; Mean ± SD = 62.7 ± 13.6 N·m)

| | *B | **β | *p*-Value |
|---|---|---|---|
| Intercept | 232.090 | | |
| GRF | | | |
| Stride Leg Medio-lateral | -0.258 | 0.144 | 0.100 |
| Stride Leg Vertical | -0.092 | 0.064 | 0.180 |
| Drive Leg Medio-lateral | -0.977 | 0.359 | 0.020 |

| | | | |
|---|---|---|---|
| Drive Leg Vertical | 0.275 | 0.125 | 0.050 |
| Impulse | | | |
| Drive Leg Horizontal | 1.96 | 1.27 | 0.149 |
| Drive Leg Medio-lateral | 2.28 | 1.19 | 0.083 |
| Drive Leg Vertical | -0.279 | 0.196 | 0.183 |
| Stride Leg Horizontal | -3.40 | 1.44 | 0.038 |

**B, standardized regression coefficient; **β, unstandardized regression coefficient.*

Table 3. Variables Included in Ball Speed Multiple Regression Analysis (n = 20; Mean $\pm$ SD = 87.9 $\pm$ 2.7 mph)

| | *B | **β | *p*-Value |
|---|---|---|---|
| Intercept | | | |
| | 81.079 | | |
| GRF | | | |
| Stride Leg Horizontal | -0.037 | 0.010 | 0.003 |
| Stride Leg Medio-lateral | 0.009 | 0.005 | 0.122 |
| Stride Leg Vertical | 0.009 | 0.003 | 0.007 |
| Drive Leg Horizontal | -0.048 | 0.021 | 0.040 |
| Impulse | | | |
| Drive Leg Medio-lateral | 0.043 | 0.016 | 0.021 |
| Stride Leg Medio-lateral | 0.057 | 0.024 | 0.034 |

**B, standardized regression coefficient; **β, unstandardized regression coefficient.*

## Discussion

The purpose of this study was to determine how components in peak GRF and GRF impulse of the drive and stride legs relate to ball speed and joint kinetics in collegiate baseball pitchers. It was hypothesized that collegiate baseball pitchers with peak GRF and GRF impulse at the stride leg would have a peak internal rotational torque at the shoulder, peak valgus torque at the elbow, and ball speed. The results partially supported the hypothesis in that the regression analysis for ball speed demonstrated that there was a significant relationship between the kinematic and kinetic predictors and ball speed. The kinematic and kinetic predictors found to be significant in the ball speed regression model were stride leg horizontal GRF, stride leg vertical GRF, drive leg horizontal GRF, drive leg medio-lateral impulse, and stride leg medio-lateral impulse. Based on the ball speed regression model, the findings supported the hypothesis that collegiate baseball pitchers with peak GRF and GRF impulse at the stride leg would have a statistically significant relationship with ball speed. However, the findings for the MEV regression model did not support the hypothesis that the stride leg would correlate with peak GRF and impulse because the drive leg vertical impulse was determined to be the predictor that was statistically significant with MEV and not the stride leg. In addition, the findings for MIR did not support the hypothesis that MIR was directly related with peak GRF and GRF impulse at the stride leg. While the regression model for MIR found the variables, drive leg medio-lateral GRF and stride leg horizontal impulse to be significant predictors, the entire model was not statistically significant.

The components in peak GRF and GRF impulse of the drive and stride legs were found to have a significant relationship with ball speed. Ball speed was significantly influenced by stride leg horizontal GRF, stride leg vertical GRF, drive leg horizontal GRF, drive leg medio-lateral impulse, and stride leg medio-lateral impulse. These results are supported by other studies in which the drive leg and stride leg have been found to correlate with ball speed. In one study, Elliot et al. (1988) measured GRF in the drive and stride legs of adult international pitchers and found that the ability to drive the body over a stabilized stride leg is a characteristic of high ball velocity pitchers. Similarly, Kageyama et al. (2014) found in collegiate baseball pitchers that high-ball-velocity pitchers are characterized by greater momentum of the lower limbs during pitching motion. In another study, McNally et al. (2015) determined that the stride leg ground reaction forces during the arm-cocking and arm-acceleration phases were strongly correlated with ball velocity whereas drive leg ground reaction forces showed no significant correlations. The findings in these studies support the results that peak GRF in the lower limbs correlates with ball speed.

GRF impulse was another variable measured in this study and the regression model determined that GRF impulse along with peak GRF were significant predictors of ball speed. These findings are supported by a study conducted by Howenstein et al. (2020) where both peak GRF and impulse were measured, and the findings determined that peak stride leg GRF in youth pitchers had the strongest relationship with energy flow (EF) from the trunk into the arm segment. In addition, Howenstein et al. (2020) found that EF through the shoulder joint is a strong predictor of pitching velocity, the correlation with peak GRF likely suggests an important role for the stride leg in preparing for the delivery phase of the pitching motion since these changes occur shortly after stride foot contact when the shoulder initiates the arm-cocking phase. While Howenstein's et al. (2020) study measured impulse as a performance measure and found that the drive leg and stride leg influence ball speed, the kinetic and kinematic variables were measured only in the horizontal direction.

Other GRF components such as vertical and medio-lateral peak GRF and GRF impulse were investigated in this study to determine if there was a significant relationship between these components, joint kinetics, and ball speed in adult pitchers. MEV was significantly influenced by the drive leg vertical impulse and ball speed was significantly influenced by stride leg vertical GRF. These findings have been supported by other research studies, where Aguinaldo and Nicholson (2021) measured energy distribution among the joints and segments of the drive limb, stride limb, pelvis, and trunk in collegiate baseball pitchers. Aguinaldo and Nicholson (2021) found that the energy generated at the stride hip joint and the braking impulse of the stride leg were found to be predictors of ball speed along with the vertical GRF, impulse, and hip joint transfer on the drive leg. This study supports the findings of this current study in that Peak GRF and GRF impulse on the drive leg and stride leg influence ball speed in the vertical direction.

Drive leg medio-lateral impulse and stride leg medio-lateral impulse were also found to be significant predictors related to ball speed. The relationship between peak GRF and GRF impulse in the medio-lateral direction at the drive leg and stride leg in pitchers could relate to ball speed because of the dynamic stability at the hips necessary to maintain balance during the pitching cycle. Kageyama et al. (2014) suggest that stabilization of the lower limbs is related high-pitched-ball velocity because the hip adduction torque of the stride leg at stride foot contact is important to control and stabilize the stride leg to increase the rotation and forward motion of the trunk during the pitching cycle. The significant relationship found between medio-lateral impulse at the drive leg and stride leg and ball speed supports the idea that stabilization and balance in the lower extremity is an essential part of pitching performance.

In addition, stabilization and balance at the legs serves as a foundation for rotation to occur from the hips to the shoulder to produce a greater change in momentum which influences ball speed. Hip strength is an important component in pitching because maximal ball speed is achieved through sequential movements in which the lower extremity transfers forces and generates a change in momentum to the upper extremity. Yanagisawa et al. (2019) state that hip adduction strength in the drive leg helps stabilize the pelvis and lengthen the stride by preventing downward tilt of the contralateral pelvis during the windup and early cocking phases of baseball pitching. Yanagisawa et al. (2019) add that the hip flexion and adduction strength in the drive leg are also important physical factors that support translation motion with a unilateral stance during the early cocking phase of baseball pitching. Similarly, Yanagisawa et al. (2019) argue that greater hip adduction strength in the stride leg may be particularly a prerequisite for increasing ball velocity, and that the hip flexors and abductors in the stride leg also may contribute to the control and stabilization of the stride leg after stride foot contact.

Movement pattern deficiencies in the lower extremity have been related to upper extremity injuries in baseball pitchers. Oliver et al. (2015) state that for normal shoulder movement to occur during the pitching phase, there must be stability at both the pelvis and scapula, as abnormalities in the pelvic or hip motion can lead to kinetic chain alterations. Oliver et al. (2015) studied the gluteus medius and scapula muscle activations in youth baseball pitchers. They found that decreases in hip abduction have been seen in 49% of athletes with arthroscopically diagnosed posterior superior labral tears (Oliver et al., 2015). In addition, Oliver et al. (2015) state that pitchers have decreased hip abduction strength and internal rotation in their ipsilateral stride leg compared with position players and that these alterations in motions may lead to breakdowns in the kinetic chain and increase the risk of upper and lower extremity injuries. Hip strength, stability, and mobility are components of the kinetic chain that influence the upper extremity and ball speed in baseball pitching. Further research needs to be conducted in collegiate baseball pitchers to quantify peak GRF and GRF impulse at the drive leg and stride leg in the horizontal, medio-lateral, and vertical direction to determine how much force and change in momentum correlates with joint kinetics and ball speed. Furthermore, the importance of kinetic variables such as peak GRF and GRF impulse can be used to examine performance measures from the lower extremity to the upper extremity to determine potential injury risks. Determining these potential injury risks at the hip and shoulder in collegiate baseball pitchers can lead practitioners to develop training programs to improve movement patterns and muscle strength for optimal performance.

**Conclusion**

The results partially supported the hypothesis in that the regression analysis for ball speed demonstrated that there was a significant relationship between the kinematic and kinetic predictors and ball speed. MEV was significantly influenced by the drive leg vertical impulse and ball speed was significantly influenced by stride leg vertical GRF.  Drive leg medio-lateral impulse and stride leg medio-lateral impulse were also found to be significant predictors related to ball speed.  The significant relationship found between medio-lateral impulse at the drive leg and stride leg and ball speed supports the idea that stabilization and balance in the lower extremity is essential for rotation to occur from the legs to the hips to the shoulder to produce a greater change in momentum for a greater ball speed.  Further research can be conducted on this population to examine performance measures from the lower extremity to the upper extremity to correlate values with joint kinetics and ball speed and to understand mechanisms of injury using biomechanical variables such as peak GRF and impulse.

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