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Peak Horizontal Ground Reaction Forces and Impulse Correlate with Segmental Energy Flow in Youth Baseball Pitchers

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Abstract
The purpose of this study was to determine associations between horizontal ground reaction force (GRF) kinetics and energy flow (EF) variables in youth baseball players. Twenty-four youth baseball players pitched fastballs in an indoor laboratory while motion capture and force plate data were collected. Horizontal GRF variables were extracted (peak GRF and GRF impulse) while EF was calculated by integrating magnitudes of mechanical powers transferred into and out of the pelvis, trunk, and arm segments via joint force power (JFP) and joint moment power (JMP) components. Peak propulsive GRF of the drive (back) leg correlated with EF into

proximal segments, whereas peak braking GRF of the stride (lead) leg correlated with EF into distal segments. Furthermore, peak GRF of the drive leg and GRF impulse of both legs correlated with the JFP components of EF into the pelvis and trunk segments. In contrast, peak GRF and GRF impulse of the stride leg both correlated with the JMP components of EF into the arm segment. These results suggest that horizontal GRF impulse from the drive and stride leg contribute to EF between major segments of the lower and upper extremity. In addition, these results also suggest that propulsion kinetics of the drive leg play a role in transferring linear power via the pelvis and trunk segments in the throwing direction of the pitch, whereas braking kinetics of the stride leg play a role in creating rotational power that is transferred between the trunk and arm segment via the shoulder joint.

Keywords
Sports**,** Biomechanics**,** Baseball**,** Pitching

1. Introduction
Shoulder and elbow injuries are prevalent in baseball players (Fleisig and Andrews, 2012). Unfortunately, overuse-related injuries in baseball pitchers in particular are beginning to appear at much younger ages (Olsen et al., 2006, Popchak et al., 2015), which suggests the need for biomechanical investigations at the youth level. Although previous studies have investigated upper body kinematics and kinetics in youth pitchers, not much research has focused on the lower body (Keeley et al., 2008, Sabick et al., 2004, Sabick et al., 2005). However, the pitching motion in baseball is characterized by forceful and dynamic actions of both legs. Throughout the pitching motion, a player generates kinetic energy at certain parts of the body and transfers it to other parts of the body in an effort to maximize pitch velocities (Chu et al., 2016, Seroyer et al., 2010). During the initial phases of the pitching motion the back (drive) leg creates forward motion of the entire body while the front (stride) leg creates a stable base about which the pelvis and trunk rotate during the arm cocking and acceleration phases of the pitch (Elliot et al., 1988). While the interaction between the body and the ground are considered to be fundamental to good pitching mechanics, little research has focused on how ground reaction forces (GRF) relate to pitching biomechanics.

A few studies have investigated the relationship between pitch velocity and the GRF created by the drive and stride leg, but with conflicting results (Elliot et al., 1988, MacWilliams et al., 1998, Guido and Werner, 2012, Kageyama et al., 2014, Kageyama et al., 2015). For example, McNally et al. (2015) found a significant relationship between peak propulsive and vertical GRF of the stride leg and ball velocity. However, the same authors found no relationship between the peak GRF of the drive leg force and ball velocity (McNally et al., 2015). Similarly, Oyama and Myers (2018) found that peak drive leg push off forces only weakly correlated with ball velocity. Most of these studies, however, have only examined peak GRF as independent variables (Elliot et al., 1988, MacWilliams et al., 1998, Guido and Werner, 2012, Kageyama et al., 2014, Kageyama et al., 2015). Although useful, looking at only the peak GRF gives a limited view about the interaction between the pitcher and the ground. In contrast, GRF impulse (i.e., the integral of force over time) provides information about the overall profile of the force–time curve, which may be more valuable. For one, the mechanical impulse that acts on a body is equal to the body's change in momentum, which may be especially relevant to baseball pitching as pitchers need to accelerate and decelerate their bodies very quickly during the pitching motion. Second, GRF impulse is a better key performance indicator for dynamic motions (e.g., squat jump) than peak GRF (McBride et al., 2010), which suggests that looking solely at the peak GRF does not provide adequate information about the performance profile of either leg.

Another limitation to examining GRF in relation to only release velocity is that it does not provide much insight into how the GRF relates to joint-specific kinematics and kinetics during the pitching motion. One approach to investigate how GRF kinetics (i.e., peak GRF and GRF impulse), relate to the pitching mechanics would be to analyze these data in relation to the flow or transfer of mechanical energy between segments and across joints of the lower and upper body (Aguinaldo and Escamilla, 2019, Howenstein et al., 2019, Martin et al., 2014). Energy flow (EF) analysis is a method that allows researchers to quantify the transfer of mechanical energy between body segments, and thus provides some insight into the mechanics and efficiency of the body's "kinetic chain" (Martin et al., 2014). Recent research demonstrated the usefulness of EF for investigating pitching performance as well as shoulder and elbow loading (Aguinaldo and Escamilla, 2019, Howenstein et al., 2019). For example, EF between the arm and trunk segments through the shoulder joint is highly correlated with pitching velocity, and the total magnitude of EF into the trunk from the lower extremities is highly correlated with greater "joint load efficiency" (i.e., velocity-mass-height normalized net joint moments) for shoulder horizontal adduction and shoulder internal rotation moments (Howenstein et al., 2019). In addition, analysis of EF components, which arise from net joint force and net joint moment powers, provide additional insight into the respective contributions of linear and rotational kinetic energy transfer between segments and across joints. For example, the magnitude of EF through the hip into the trunk segment via linear joint powers is correlated with greater joint load efficiency for shoulder horizontal adduction, shoulder internal rotation, and elbow varus rotation (Howenstein et al., 2019). Knowledge about EF components and the relative contributions of linear and rotational energy of individual body segments to elbow and shoulder moments thus offers in-depth understanding of overall pitching biomechanics in relation to upper extremity loading.

Understanding how GRF kinetics (i.e., peak GRF and GRF impulse) of the drive and stride legs correlate with the magnitudes of EF and its components between segments and across joints could therefore provide important insight about the role of the lower extremities in relation to pitching performance and upper extremity loading. The purpose of this study was to investigate how peak GRF and GRF impulse of the drive and stride legs relate to the magnitude of EF and its components between the pelvis, trunk, and arm segments in youth pitchers. We hypothesized that (1) horizontal GRF impulse correlates better with EF variables than peak GRF, and that (2) horizontal GRF kinetics of the drive leg would correlate with EF variables across segments proximal to the throwing shoulder (i.e., pelvis & trunk), whereas GRF kinetics of the stride leg would correlate with EF variables across segments distal to the throwing shoulder (i.e., arm segments).

2. Methods

2.1. Participants

Twenty-four youth baseball pitchers (age: 11.1 ± 1.3 years; height: 1.549 ± 0.116 m; mass: 45.5 ± 11.9 kg) were recruited for this study. Inclusion criteria consisted of being between the ages of 9 and 13 year and having had at least one year of pitching experience. Exclusion criteria consisted of having any injury that affected one's ability to pitch or having an unorthodox throwing motion (e.g., side-arm delivery). Upon arrival at the laboratory, each participant and their guardians were asked to sign an informed assent and consent form. The study was approved by the Institutional Review Board at Marquette University.

2.2. Data collection procedures

Pitchers were first allowed an unlimited time to warm-up but were encouraged to do a warm-up similar to that used during a game. After the warmup, each pitcher was fitted with 32 individual skin-mounted markers and seven marker clusters (Fig. 1). The set of reflective markers used in this study combined an upper-extremity and trunk marker set consistent with ISB recommendations (Wu et al., 2005) with a lower-extremity marker set that was previously used (Graci et al., 2012). Briefly, individual tracking markers were placed on the trunk, pelvis, and feet, whereas ten markers were used solely for calibration. Marker clusters were attached bilaterally on the shanks and thighs, as well as on the upper arm, forearm, and hand of the throwing arm.

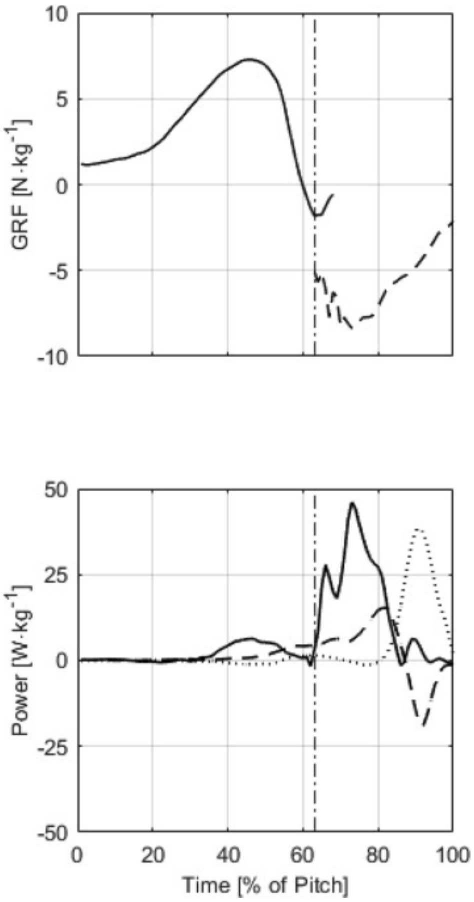

Fig. 1. Sample horizontal ground reaction forces (N·kg^{-1}) for the drive/back (solid line) and stride/lead (dashed line) leg (top panel) and segment power (W·kg^{-1}) time-series data for the pelvis (solid line), trunk (dashed line), and arm (dotted line) segments (bottom panel) from one pitch. **Note:** Positive GRF represent propulsion forces and negative GRF represent braking forces. Energy flow into each respective segment is calculated as the integral of positive power. Vertical dash-dot line identifies stride leg contact.

The three-dimensional position data of the reflective markers were recorded with a 14-camera motion capture system (Vicon, Oxford, UK) at 250 Hz. GRF data were recorded at 1000 Hz with two force plates (Kistler, Winterthur, Switzerland) that were imbedded into a custom-built pitching mound; one plate was placed under the pitching rubber and one under the landing area, which could be adjusted based on the pitcher's natural stride length.

After attachment of the markers, pitchers performed two calibration trials while standing on the pitching mound. For the first trial, the pitchers stood motionless in neutral anatomical position with both the tracking and calibration markers attached. For the second calibration trial, the pitchers stood in the same position but performed small forward arm circles. The pitchers were then instructed to throw practice pitches from the mound in the laboratory until they felt comfortable with the markers and experimental set-up. Each pitcher then threw up to 15 maximum effort fastballs at a hanging strike zone that was located 14 m (46 ft) from the pitching rubber. The fastest three strikes were chosen for analysis.

2.3. Data processing procedures

Kinematic data were filtered with a fourth-order low-pass Butterworth filter at 14 Hz and the force plate data were filtered with a fourth order, low-pass Butterworth filter at 300 Hz. The upper-extremity and trunk coordinate systems as well as the respective degrees of freedoms of each joint were established using ISB recommendations (Wu et al., 2005). The pelvis coordinate system was defined according to the CODA pelvis (Charnwood Dynamics Ldt., UK) and the lower limb coordinate systems were defined with a previously used lower-extremity model (Graci et al., 2012). The rotation sequences for all but the shoulder joint were based on X – Y – Z Cardan sequences. A Z – Y – Z Euler rotation sequence was used for the shoulder joint. In each case the rotation of the distal segment was expressed relative to the proximal segment. A more detailed description of the biomechanical model used in the current study is published elsewhere (Howenstein et al., 2019).

Joint forces and moments were calculated with Visual3D software (C-Motion, Germantown, MD). Energy flow was calculated with a segment power analysis for the pelvis, trunk, and throwing arm segments (Robertson and Winter, 1980). Specifically, the rate of work done on each segment by the net joint forces (JFP; Eq. (1)) and net joint moments (JMP; Eq. (2)) were calculated at the proximal and distal ends of each segment (Martin et al., 2014, Robertson and Winter, 1980). Eqs. (1), (2) used the dot product to multiply the respective generalized vectors of each variable in computing the JFP and JMP. The total segment power (SP) was calculated as the sum of the JFP and JMP at each end of the segment (Eq. (3)). Integrating SP over a specific period (e.g., pitch duration) gives the magnitude of energy transferred into or out of the segment due to interactions with neighboring segments during that time interval (Fig. 1). Examining the rate of energy transfer, and determining whether a segment gains or loses energy over a specific time interval, thus provides information about energy transfer or flow between segments for that duration. In addition, the integration of either JFP or JMP at the proximal or distal ends of a segment can be used to calculate the energy transferred via the respective joint force or moment contributions at the specific joint. The individual components of each power variable were integrated over the period that they were either positive to calculate the energy that was gained by the segment or negative to calculate the energy that was lost by the segment (Fig. 2). The calculation of EF during the pitch began when the pitcher’s stride leg reached its maximum height at the beginning of the pitching motion, and ended when the ball was released. The primary EF variables that were calculated included EF into the pelvis, EF into the trunk, EF into the arm. In addition, the components of the total EF produced by JFP and JMP were also calculated for the pelvis, trunk, and arm.

(1)

$$\mathrm{JFP} = (\mathrm{netjointreactionforce}) \cdot (\mathrm{linearjointvelocity})$$

(2)

$$\mathrm{JMP} = (\mathrm{netjointmoment}) \cdot (\mathrm{segmentangularvelocity})$$

(3)

$$\mathrm{SP} = \mathrm{JFP}_{\mathrm{Proximal}} + \mathrm{JMP}_{\mathrm{Proximal}} + \mathrm{JFP}_{\mathrm{Distal}} + \mathrm{JMP}_{\mathrm{Distal}}$$

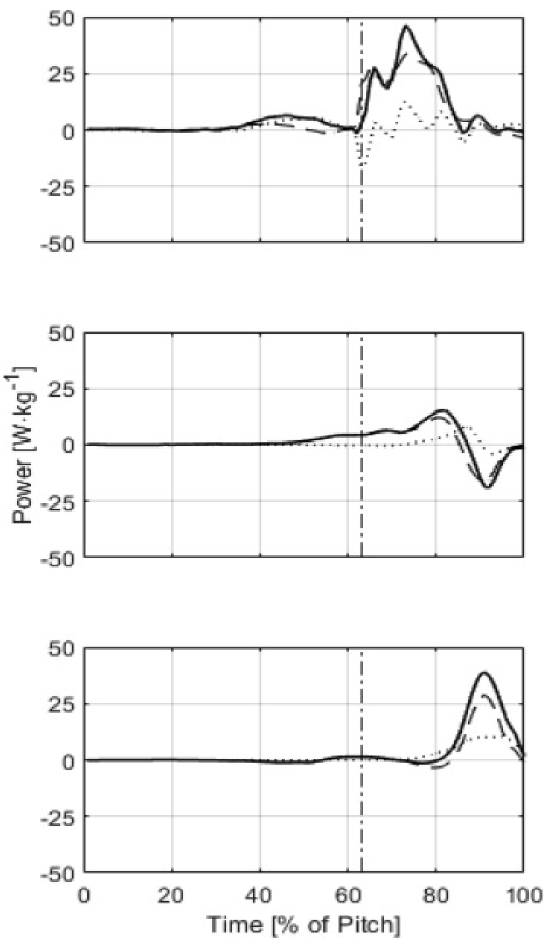

Fig. 2. Sample segment (solid line), joint force (dashed line), and joint moment (dotted line) powers (W·kg^{-1}) time-series data for the pelvis (top panel), trunk (middle panel), and arm (bottom panel) segments from one pitch. **Note:** Energy flow into each respective segment is calculated as the integral of positive power. Vertical dash-dot line identifies stride leg contact.

The GRF data from both force plates were extracted and used to calculate the peak propulsive GRF from the drive leg (i.e., force in the direction of the pitch – $^{+}$Y in the global lab coordinate system) and peak braking forces from the stride leg (i.e., force in the direction opposite of the pitch – $^{-}$Y in the global lab coordinate system) (Fig. 1). The mechanical impulse was calculated as the integral of GRF over time for the propulsive and braking GRF's of the respective legs. For the drive leg, the time interval for integration lasted from peak knee height to stride foot contact. For the stride leg, the time interval for integration lasted from stride leg foot contact to ball release. All kinetic data were normalized to the body mass of each pitcher.

2.4. Statistical analysis

For the purpose of the statistical analysis, stride leg data were multiplied by negative one so that the direction of any correlations would be consistent between both legs. The normality of the distributions of each variable were analyzed with Q – Q plots and the Shapiro-Wilk test. Simple linear regressions were used to investigate the correlations between independent and dependent variables. For the first analysis, the independent variables consisted of the horizontal GRF kinetic variables (i.e., peak GRF and GRF impulse) while the dependent variables consisted of the three segmental EF variables (i.e., EF into the pelvis, trunk, and arm). The second analysis used the same independent variables, but the dependent variables consisted of the two components that contribute to each of the three EF variables (i.e., JFP and JMP components of EF into the pelvis, trunk, and arm). The criterion for statistical significance of the correlations was set at an α level of 0.05. All statistical analyses were performed in SPSS 24.0 (IBM Corporation, Somers, NY, USA).

3. Results

The average velocity of the three fastest strikes was 23.5 ± 3.3 m·s^{-1} (52.6 ± 7.3 mph). Several GRF kinetic variables correlated with EF into the pelvis, trunk, and arm segments (Table 1). For the drive leg, peak GRF correlated with EF into only the pelvis and trunk segments, whereas for drive leg GRF impulse correlated with EF into all segments. For the stride leg, peak GRF correlated with EF into only the trunk and arm segments, whereas stride leg GRF impulse correlated with EF into all segments.

Table 1. Pearson correlation coefficients (*r*) between ground reaction force (GRF) variables for the drive and stride leg and energy flow (EF) variables.

	Drive Leg				**Stride Leg**			
	Peak GRF		**GRF Impulse**		**Peak GRF**		**GRF Impulse**	
	r	***p***	***r***	***p***	***r***	***p***	***r***	***p***
EF into Pelvis	**0.544**	**0.006**	**0.772**	**0.001**	0.253	0.253	**0.660**	**0.001**
EF into Trunk	**0.619**	**0.001**	**0.667**	**0.001**	**0.550**	**0.005**	**0.671**	**0.001**
EF into Arm	0.377	0.069	**0.430**	**0.036**	**0.629**	**0.001**	**0.472**	**0.020**

Note: Significant ($p < 0.05$) *r* and *p*-values are highlighted in **bold**.

Several GRF kinetic variables correlated with the JFP and JMP components of EF into the pelvis, trunk, and arm segments (Table 2). For the drive leg, peak GRF correlated with the JFP components of EF into the pelvis, trunk, and arm segments, whereas drive leg impulse correlated with the JFP components of EF into the pelvis and trunk segments as well as the JMP component of EF into the arm segment. For the stride leg, peak GRF correlated with JMP components of EF into the trunk and arm segments as well as the JFP and JMP components of EF into the arm segment. Stride leg impulse correlated with JFP components of EF into the all segments, and the JFP component of EF into the arm segment.

Table 2. Pearson correlation coefficients (*r*) between ground reaction force (GRF) variables for the drive and stride leg and energy flow (EF) components (JFP: joint force power; JMP: joint moment power).

	Drive Leg				**Stride Leg**			
	Peak GRF		**GRF Impulse**		**Peak GRF**		**GRF Impulse**	
	r	***p***	***r***	***p***	***r***	***p***	***r***	***p***
EF into Pelvis by JFP	**0.514**	**0.010**	**0.789**	**0.001**	0.290	0.169	**0.711**	**0.001**
EF into Pelvis by JMP	0.230	0.279	0.009	0.968	0.038	0.859	0.029	0.893
EF into Trunk by JFP	**0.614**	**0.001**	**0.660**	**0.001**	0.367	0.078	**0.676**	**0.001**
EF into Trunk by JMP	0.239	0.261	0.261	0.218	**0.554**	**0.005**	0.240	0.259
EF into Arm by JFP	**0.521**	**0.009**	0.372	0.074	**0.541**	**0.006**	**0.457**	**0.025**
EF into Arm by JMP	0.154	0.472	**0.420**	**0.041**	**0.616**	**0.001**	**0.406**	**0.049**

Note: Significant ($p < 0.05$) *r* and *p*-values are highlighted in **bold**.

4. Discussion

The purpose of this study was to investigate how peak GRF and GRF impulse of the drive and stride legs relate to the magnitude of EF and its components between the pelvis, trunk, and arm segments in youth pitchers. The results partially supported our hypothesis in that numerous GRF kinetic variables correlated with EF variables, and the GRF impulse correlated with more EF variables than peak GRF. Further, GRF impulse generated by the drive and stride leg appeared to be important contributors to EF between segments, and across major joints, of the lower and upper extremity. Specifically, detailed analysis and interpretation of the correlational analysis between GRF kinetics and EF suggest that the kinetics of the drive leg appeared to play a major role in transferring linear power via the pelvis and trunk segments in the direction of the pitch, whereas the kinetics of the stride leg played a larger role in creating and transferring rotational power between the trunk and arm segments via the shoulder joint. The novel contributions of these findings suggest that kinetics of the drive and stride legs have unique roles with respect to mechanical EF during fastball pitching in youth baseball players.

4.1. GRF kinetics & EF magnitudes

Numerous GRF kinetic variables correlated with the magnitudes of EF across the pelvis, trunk, and arm segments in the little league pitchers of the current study. Specifically, for the drive leg, peak GRF correlated with EF across the pelvis and trunk segments, whereas GRF impulse correlated with all EF variables. The results differed slightly for the stride leg in that peak GRF correlated with EF across the trunk and arm segments. However, GRF impulse of the stride leg still correlated with all EF variables. In general, these results suggest that horizontal GRF impulse is a better predictor of EF across all segments than peak GRF. When compared to other studies, some of our findings are similar to those by McNally et al. (2015) who reported a significant relationship between peak stride leg GRF and ball velocity. However, McNally et al. (2015) found no relationship between the peak drive leg GRF and pitch velocity, which may reflect the current finding that peak drive leg GRF had no significant correlation to EF into the arm, since that is a primary determinant of pitch velocity.

Peak stride leg GRF had the strongest relationship with EF from the trunk into the arm segment. Given that EF through the shoulder joint is a strong predictor of pitching velocity (Howenstein et al., 2019), 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 peak occurs shortly after stride foot contact when the shoulder initiates the arm-cocking phase. While peak stride leg GRF was the strongest predictor of EF into the arm, it only explained about 40% of the variance of EF into the arm segment. Other factors, such as trunk forward and lateral motions or the generation of velocity-dependent likely account for parts of the remaining variance in EF into the arm segment (Hirashima et al., 2008). Regardless, GRF impulse of the stride leg was also correlated with EF into the pelvis segment, which may reflect the role of the stride leg in decelerating a pitcher's center of mass and providing a stable base about which to rotate during the delivery phase. Similarly, the significant correlation between peak drive leg GRF and EF into proximal segments (e.g., pelvis and trunk) likely reflects the role of the drive leg in initiating the pitching motion and accelerating the pitcher toward their target.

4.2. GRF kinetics & EF components

Several of the GRF kinetic variables correlated with the JFP and JMP components of EF between the pelvis, trunk, and arm segments. Specifically, peak propulsive GRF and GRF impulse of the drive leg correlated with the JFP components of EF into the pelvis and trunk segment. Furthermore, braking GRF impulse of the stride leg correlated with the JFP components of EF into the pelvis and trunk segments. These results suggest that propulsion GRF kinetics produced by the drive leg play a role in transferring linear power via the pelvis and trunk segments in the throwing direction of the pitch.

With respect to the JMP, peak braking GRF and GRF impulse of the stride leg both correlated with the joint moment components of EF into the arm segment, which likely indicates that braking kinetics of the stride leg play an important role in creating rotational moments and transferring the mechanical power generated by these moments between the trunk and arm segments through the shoulder joint. Since peak braking GRF of the stride leg had a stronger correlation with EF into the arm than GRF impulse, it appears that the production of large GRF are important to effectively transfer energy along the 'kinetic chain' (Seroyer et al., 2010). Previous research suggests that EF from the trunk into the arm is the strongest predictor of pitching velocity (Howenstein et al., 2019). These findings may therefore have significant practical implications because these results suggest that large braking forces of the stride leg immediately after foot contact provide a counter force to the propulsive action of the drive leg, and may allow the lateral aspect of the pelvis of the back leg an opportunity to rotate before trunk rotation in a proximal to distal sequence.

4.3. Limitation

There are several limitations to the current study. First, the children in the current study were between 9 and 13 years old, and varied greatly in size, skill, and pitching experience. However, these variations may also enhance the generalizability of the current results to broader populations. Second, data were collected in a laboratory and an instrumented pitching mound. Although the strike zone was hung at regulation distance away from the pitching mound, pitching mechanics may differ from those outside and/or during an actual game. Third, the power and energy flow analysis used in the current study may not adequately account for energy transfer from bi-articular muscles between non-adjacent segments (Robertson and Winter, 1980). Lastly, only GRF data in the horizontal direction were considered in the current study. Future research could thus also investigate the vertical or medio-lateral GRF components or examine the angles between these GRF components.

5. Conclusion

The results of the current study suggest that horizontal GRF kinetics of the drive and stride leg are important contributors to EF across the pelvis, trunk, and arm segments. Moreover, these results also indicate that the horizontal GRF kinetics of the drive leg play a role in transferring joint force power via the pelvis and trunk segments in the throwing direction of the pitch, whereas the horizontal GRF kinetics of the stride leg play a role in creating joint moment power that is transferred between the trunk and arm segment via the shoulder joint. Collectively, these results contribute to our understanding of overall pitching biomechanics.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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