

Characteristic Ground-Reaction Forces in Baseball Pitching*

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ABSTRACT

Overhand throwing requires contributions from and interaction between all limb segments. Most previous investigations have concentrated on the throwing arm itself, yet poor mechanics at the arm may originate in the lower extremities. Multicomponent ground-reaction forces of both the push-off and landing limbs were measured in six collegiate and one high school level baseball pitchers. Full body kinematics were simultaneously recorded to correlate phases in the pitching cycle with the force data. Pitchers were found to generate shear forces of 0.35 body weight in the direction of the pitch with the push-off leg and to resist forces of 0.72 body weight with the landing leg. Wrist velocity was found to correlate highly with increased leg drive. This study validates the clinical impression that the lower extremity is an important contributor to the throwing motion. Based on this study, strengthening of the lower extremities could be inferred to be important both to enhance performance and to avoid injury.

Overhand throwing is a high-demand athletic skill involving fine coordination of all body segments.¹ Pappas et al.⁷ described baseball pitching as a sequential activation of body parts through a link segment beginning with the contralateral foot and progressing through the trunk to the rapidly accelerating upper extremity. Improper mechanics or injury that alter this complex chain of events will in turn produce additional stresses in other links of the chain. The upper extremity can be characterized as an open kinetic chain experiencing rapid acceleration and

deceleration. Because of the high forces generated from these kinetic events, soft tissues in the shoulder and elbow are highly vulnerable to injury.^{2,4,5,11} Although upper extremity injuries result in the most time lost from baseball, lower extremity injuries account for up to 60% of all injuries to baseball players in some studies.¹⁰

In a treatise on sequential motions of link segment models, Putnam⁸ has described the motion-dependent interaction and sequencing between segments, which proceed proximal to distal. He uses the example of overarm pitching and the various phases of windup, cocking, and release to illustrate the relationships between proximal and distal arm segments with force and moment interrelations and energy transfers. Because pitching involves all body segments, these principles can be extended to the lower extremities, which, following this argument, could influence arm mechanics at a relatively early stage of the cycle.

The role of the lower limbs in baseball pitching is a controversial topic among players, coaches, and trainers. House⁶ maintained that the pitcher should not drive toward the target, but rather initiate a "controlled fall"; Ryan and Torre⁹ emphasized the need to drive toward the target with maximal effort. In the only reported scientific study of ground-reaction forces in pitchers, Elliott et al.³ used a single force plate to measure forces of both fastball and curveball pitches from eight international pitchers. Only two force components, vertical and horizontal, were measured, and body positions were recorded with a single camera. Because there was only a single force plate, individual contributions of the legs could not be identified.

The purpose of the current study was to establish the ground-reaction force patterns of individual limbs and investigate the significance of these forces in pitching mechanics. We hypothesized that there were characteristic ground-reaction force patterns, and that variations in these force patterns would be reflected in measures of pitch outcome, namely throwing velocity. The relationship between throwing motion and lower extremity forces has significance for the participants (athletes and coaches) as

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well as health care professionals involved in the treatment and care of injuries in baseball players.

MATERIALS AND METHODS

Six collegiate pitchers and one high school pitcher participated in this study. All pitchers were right-handed. Kinematics were determined using reflective markers and a five-camera video analysis system (Motion Analysis Corporation, Santa Rosa, California). Individual markers were placed on bony landmarks at the ends of the midtoes, ankles (lateral malleoli), knees (lateral femoral condyles), hips (greater trochanters), shoulders (tips of the acromions), elbows (lateral humeral epicondyles), wrists, and sacrum. This marker set was chosen to minimize encumbrance and enable tracking during the complex, high-speed motion. Internal-external rotations of the hips and shoulders were calculated based on the position of the more distal segment and the assumption of a rigid, hinged connection between these segments. Ground-reaction forces were collected with two multicomponent force plates (Bertec, Worthington, Ohio) attached to the rigid steel frame of a custom-built pitching mound (Fig. 1A). This structure consisted of a horizontal section, where the pitching rubber was located, which abutted a sloped section that dropped 9 inches in height over its 108 inch length to simulate the sloped geometry of a regulation major league pitching mound. One force plate was set below the rubber to record push-off forces during the windup and initial portions of delivery, and a second force plate recorded the landing forces. The landing force plate was adjusted to each pitcher's stride length. Bolt holes in the steel frame and adjustable panels in the surrounding wood frame allowed this plate to be moved in 6-inch increments. A steel bar was mounted with bolts on the top back edge of the push-off force plate behind the rubber so that shear forces could be recorded and the pitching rubber would remain stationary. The rubber was positioned to abut with the steel bar, but was not otherwise fixed to the plate. Force plates were left uncovered, and pitchers wore rubber-soled sneakers. An adhesive spray was used to increase the friction on the plate if the pitcher felt any slippage or any was observed. Electronically synchronized video (200 Hz) and force plate (1000 Hz) data were collected for 3 seconds.

Each pitcher went through a normal pregame warm-up period, then data from maximal effort pitches thrown to a catcher receiving throws at the regulation distance (60 feet, 6 inches) were collected. The pitcher continued to throw until data were collected on five pitches judged to be in the strike zone by the catcher. A single force component for one subject, landing F_x , was lost because of equipment malfunction. The landing forces for another subject had to be discarded because of incomplete contact with the landing force plate. The collected video data were tracked and processed using custom software to compute joint angles at each time frame.

The following normalization methods were used so that results could be averaged and compared. Time was normalized with pitch duration, defined as the time from

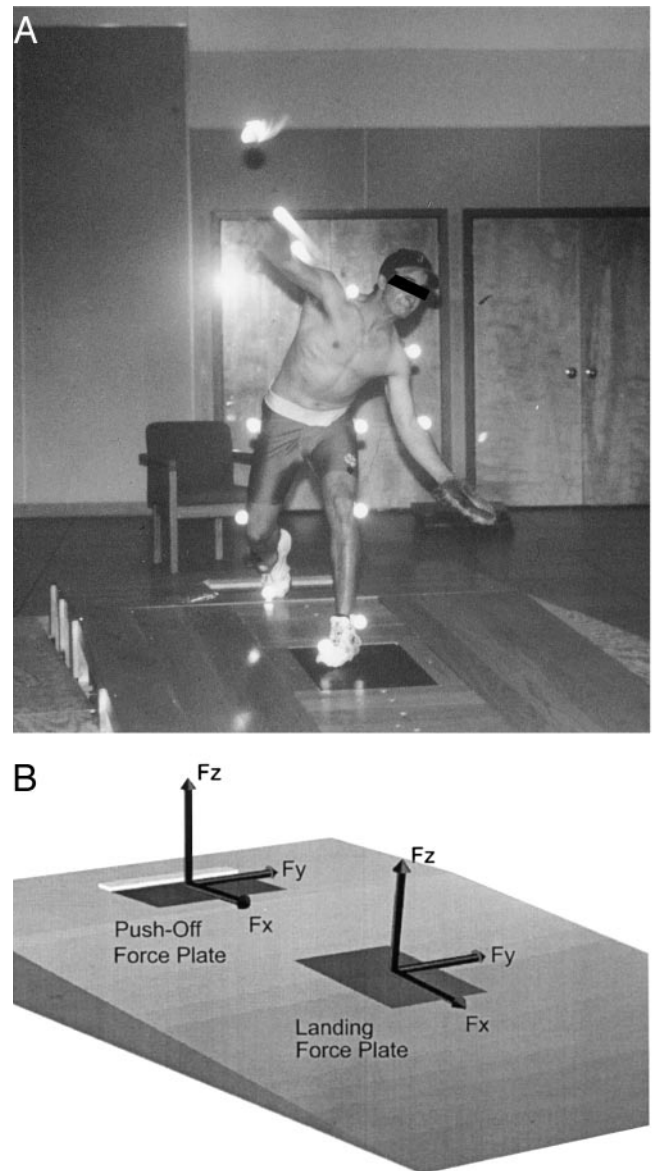


Figure 1. Instrumented pitching mound indicating force plate placement (A) and local coordinate system orientations (B).

initial lead foot contact to ball release. Time scales were synchronized by offsetting the data so that $t = 0$ was the point of initial lead foot contact. Force values were normalized with the subject's body weight. Forces were reported in the local coordinate system of each force plate with the x -axis toward home plate, the y -axis toward first base, and the z -axis the upward normal to each plate (Fig. 1B). Because of the slope of the mound, the landing plate was tilted forward 4.8° about the y -axis relative to the push-off plate. All force results reported were the measured reaction forces as applied by the foot, not the force on the foot, at the center of pressure of foot contact as determined by the moments about the x - and y -axes. Forces could be transformed into local anatomic coordinates based on position of the foot, but we believed that this

would make results more difficult to interpret. Reaction moments (moments about the z -axis at the center of pressure) were also recorded and studied but are not presented here.

The normalized data were transformed into the frequency domain via fast Fourier transform, and the first 32 harmonics coefficients (real and imaginary components) were used for statistical analysis. A power spectrum analysis indicated that higher frequencies did not contribute significantly to the signal. Means and standard deviations in the time domain were based on the recomposed signals of the means and standard deviations of these coefficients. This procedure was used to enable pitchers with various delivery durations to be compared.

RESULTS

Characteristic patterns in both push-off and landing force patterns were identified. For individual subjects, means and standard deviations were obtained using the number of available trials for each subject ($N = 2$ [1 subject], 3 [1 subject], 4 [2 subjects], or 5 [3 subjects], the number of recorded pitches successfully tracked). Standard deviations within subjects were small (the largest standard deviation of a single force component at any time was 8.0% body weight [BW]).

Because variations within individual subjects were small, statistical analysis of the subject population based on individual means was possible. The standard deviations based on the mean values of the seven subjects were calculated. Means and standard deviations of all force components and the resultant force magnitudes are shown in Figure 2. Standard deviations of the group were small, indicating that there was a characteristic pattern of ground-reaction forces among the pitchers tested.

Anterior-Posterior Shear

The force component F_x is in the general direction of the pitch and can be interpreted throughout most of the pitching cycle as an anterior-posterior (AP) directed force referenced to the general sense of the body. On average, F_x for the push-off limb exhibits a gradual increase until just before foot contact, reaching a maximum of -0.35 BW. The reaction force has a negative sense, indicating it is opposite of the ball direction, and thereby produces body forces in the direction of the pitch. After foot contact, AP shear rapidly dissipates on the push-off limb as weight is increasingly borne by the lead leg. Landing AP shear increases rapidly after foot contact and reaches a maximum of 0.72 BW just before ball release. This force is at all times positive, indicating that throughout the pitch cycle, the lead foot anchors the body to balance forces generated in the upper extremities.

Medial-Lateral Shear

The force F_y is directed toward first base (or to the left) for a right-handed pitcher, and its general anatomic sense is oriented medially for push-off forces and laterally for landing. This force component is small, accounting for less

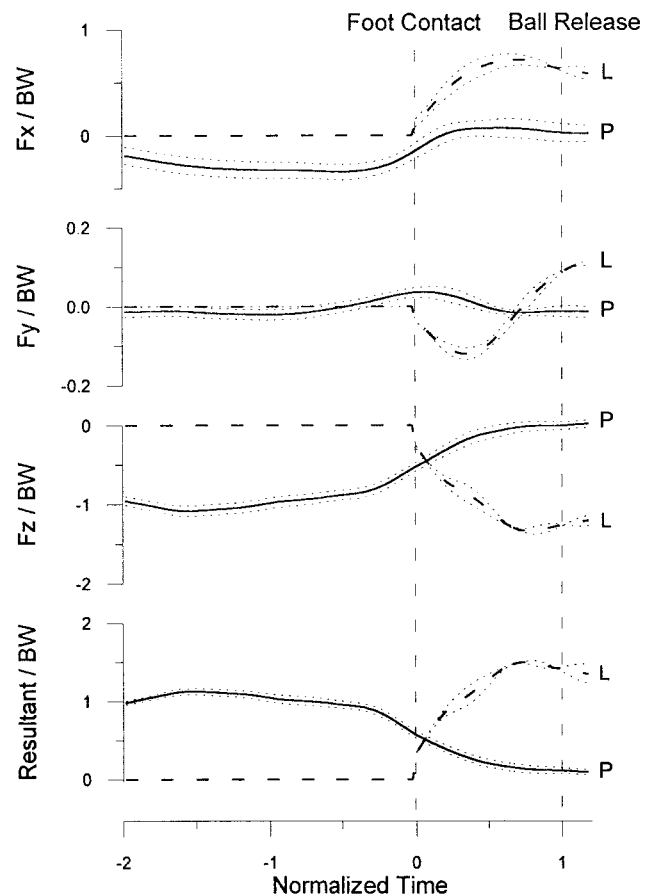


Figure 2. Push-off (P, thick solid line) and landing (L, dashed line) plate forces and standard deviations (dotted lines) based on the mean values of the seven subjects. Force data are normalized with body weight.

than 10% of the resultant force at all times. Push-off medial-lateral (ML) shears are negligible, indicating that push-off forces are concentrated in the plane of the pitch. Landing forces reflect the rotational motion of the trunk and torso. Initially, after foot contact, a medially directed force is applied to halt the rotation of the landing leg, it then changes to a lateral direction as weight is fully transferred to the lead leg and the arm is coming forward, reaching a maximum of about 0.1 BW at ball release.

Vertical

The vertical force component reflects body weight support. Push-off vertical forces are fairly constant, with peak magnitudes of slightly more than 1.0 BW occurring early in the pitch cycle. Landing vertical forces are gradually built up after foot contact to approximately 1.5 BW, peaking just before ball release.

Resultant Forces

Vector summation of the three force components F_x , F_y , and F_z yielded a resultant force (R) that, from examina-

tion of the individual components, was primarily directed in the plane of the pitch for both push-off and landing. The push-off resultant was relatively constant at about 1.0 BW until just before foot contact. Landing resultants increased gradually from foot contact to just before ball release, reaching a maximum of about 1.75 BW.

Correlations to Throwing Velocity

To demonstrate the relationship between ground-reaction force data and kinematic data, five events in the pitching cycle are specified (Fig. 3). In the order of occurrence these points were push-off maximal AP shear, landing leg foot contact, maximal shoulder external rotation, ball release, and follow-through (defined as 0.03 seconds after ball release). In the figure, body force vectors, equal and opposite to the measured ground-reaction forces, from one representative trial are shown.

The theory that the forceful leg drive observed in "power" pitchers is related to the velocity with which these individual pitchers are able to throw a baseball was tested by correlating wrist linear velocity to ground-reaction forces. Although ball velocity itself was not measured in this group of subjects, using sample data from a single subject throwing with maximal effort, the linear wrist velocity was shown to have a high correlation ($r^2 = 0.97$, $N = 5$ trials) with ball velocity measured with the motion-analysis system. Linear wrist velocity at ball release correlated highly with maximal push-off AP shear force (Fig. 4), with vertical and resultant push-off force at the time of maximal anterior push-off force, and also with landing AP shear, vertical, and resultant forces at ball release.

Elliot et al.³ found that pitchers with slower ball velocities tended to have peak ground-reaction forces occur earlier in the cycle than pitchers with faster velocities. To check this observation, phases of the pitching cycle at which the peak landing forces (F_x , F_z , R) occurred were correlated with wrist velocities. Although trends in the data of all three variables indicated that pitchers with slower wrist velocities had earlier peaks, the coefficients of correlation were weak ($r^2 = 0.53$, 0.13, and 0.35, respectively).

DISCUSSION

This study is the first to document ground-reaction forces for both lower extremities in baseball pitchers, and this information helps to further delineate the exact mechanics of the throwing motion. Push-off forces were gradually built up during the windup, and peaked before foot contact. After foot contact, the lead foot applied an anterior shear, or "braking," force to slow the motions of the lower limbs. This energy is transferred to the trunk and arms as described by Putnam.⁸ At the point of maximal external rotation of the arm in cocking, the peak vertical forces (1.5 BW) and peak braking forces (nearly 0.75 BW) were generated. These forces gradually diminished through the remainder of the pitching cycle. These findings indicate that the ground-reaction forces were primarily concen-

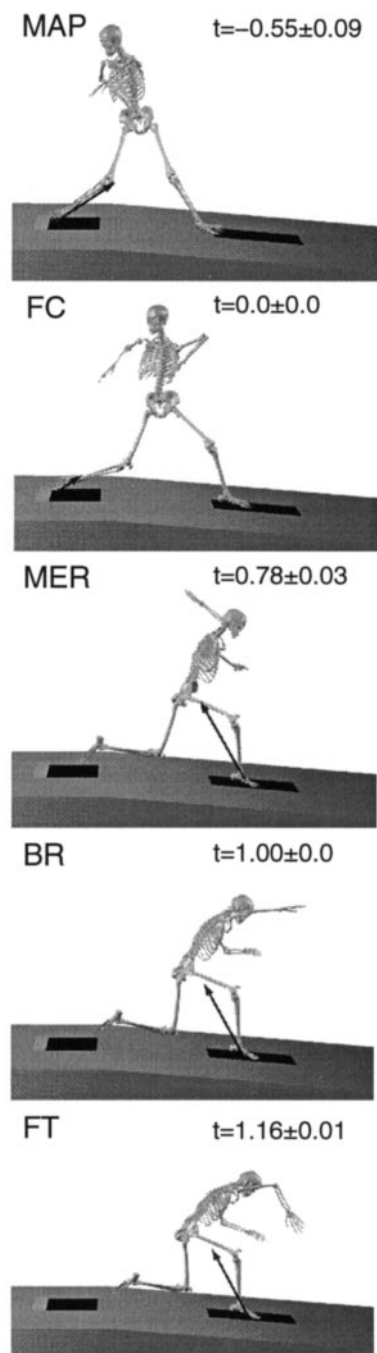


Figure 3. Phases of the pitching cycle as they correlate to kinematics and ground-reaction forces: maximal anterior push-off force (MAP), initial foot contact (FC), maximal external shoulder rotation (MER), ball release (BR), and follow-through (FT). Means and standard deviations of the normalized times, t , at which these events occur are listed. Scaled vectors representing opposite-sensed ground-reaction forces (or forces on the body) are shown. The corresponding magnitudes are indicated in Figure 2.

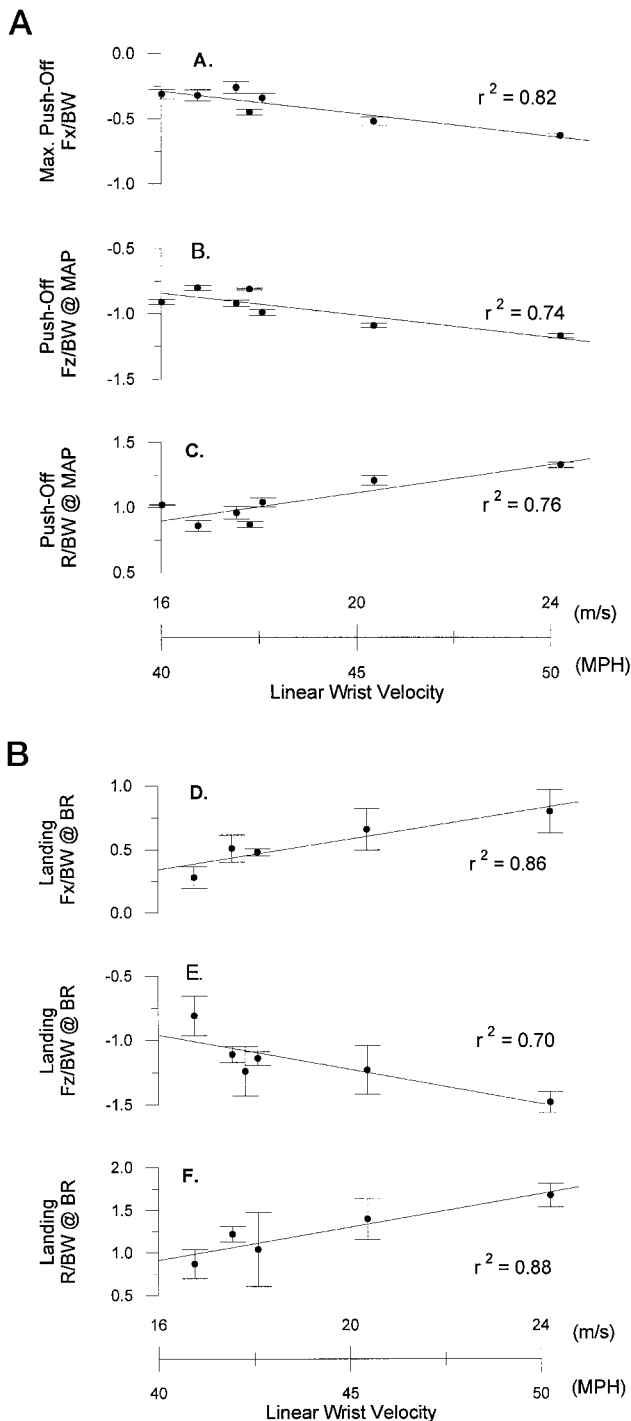


Figure 4. Linear wrist velocities at ball release correlate highly ($r^2 = 0.82$) with maximal posterior push-off shear force, a representation of “leg drive,” indicating that forces generated early in the pitching cycle with the lower extremities contribute to the throwing velocity. Linear wrist velocity also correlated highly with vertical push-off force at MAP ($r^2 = 0.74$), push-off resultant force at MAP ($r^2 = 0.76$), landing anterior shear force at BR ($r^2 = 0.86$), landing vertical force at BR ($r^2 = 0.70$), and landing resultant force at BR ($r^2 = 0.88$).

trated within the plane defined by the path of the ball and the vertical axis.

Forces generated in the plane of the pitch were shown to be related to linear wrist velocity when the players were studied as a group. However, correlations between forces and wrist velocity within individual pitchers varied. Some players exhibited trends similar to the group, with wrist velocity increasing with increasing forces. Others demonstrated an opposite trend, with higher forces correlating with diminished velocities. This difference suggests that there may be an effect of attempting to overthrow, with loss of velocity resulting from attempts to generate unnaturally high push-off forces. This anecdotal information suggests that pitchers should train to develop powerful leg drives as a normal part of the throwing motion, but they should not attempt to overpush to gain extra velocity.

The tendency of all pitchers in the study to develop high levels of force in the direction of the pitch, combined with the finding that pitchers who developed the largest forces (normalized to body weight) threw fastest, seems to contradict the theory that pitching is a “controlled fall.” The pitching motion depends on significant contributions from the lower limbs to create forward impetus. The exact contributions of each segment to the pitching motion will require further study using a complex multisegmental dynamic model.

Based on this study, we hypothesize that the push-off forces in the direction of the pitch (AP shear) initiate the forward momentum of the entire body. The greater this magnitude, the more kinetic energy there is in the direction of the pitch. Similarly, the vertical push-off component can be used to generate potential energy, which can be transformed into kinetic energy at later stages. The landing leg serves as an anchor in transforming the forward and vertical momentum into rotational components; posteriorly directed forces at the landing foot reflect an overall balance of the inertial forces of the body moving forward to create ball velocities.

This information is important when training and developing efficient delivery to home plate. The high ground-reaction forces generated in the throwing motion also support the concept that rehabilitation of pitchers with lower extremity dysfunction should be performed on level ground before returning to the mound. Further study of the relationship of these ground-reaction forces to the kinematics and kinetics of pitchers throwing other pitches would be beneficial. These studies may someday delineate those patterns that predispose an athlete to injury.

CONCLUSION

Ground-reaction forces from the pitchers are highly repeatable within trials of the same subject, and characteristic patterns in a group of pitchers can be identified. Forces were concentrated in the plane defined by the direction of the pitch and the vertical axis. Both push-off forces from the cocking phase and landing forces at the time of ball release correlated with wrist velocity. These data indicate that leg drive is an important aspect of the overarm throwing motion. This study verifies that leg

drive influences arm velocity. These findings are in agreement with those of other authors who speculate that lower extremity strength is an important aspect of the baseball pitch.

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