THE ROLES AND MECHANISMS OF LINEAR AND ANGULAR IMPULSE GENERATION FOR BOTH LEGS IN BASEBALL PITCHING: A WHOLE-BODY PERSPECTIVE

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This study compared the role of each leg in generating linear and angular impulse during fastball pitches performed by professional pitchers (n=4). Participants were asked to pitch from an instrumented mound and 6-11 successful fastball pitches were used for the analysis. The results indicate that back leg generated forward linear impulse and the front leg generated backward linear impulse for all pitchers. Back leg ground reaction forces generated significantly larger angular impulse about a horizontal axis passing through the body center of mass from the mound to first base than the front leg in three of four pitchers. Additionally, the mechanisms of moment generation about the axis by each leg differed.

KEYWORDS: pitching, whole-body, ground reaction forces, impulse, rotation.

INTRODUCTION: Pitching is a full-body movement involving sequential rotation of body segments that results in a near maximum ball velocity at release (Pappas et al., 1985). The interaction between the body and the ground is crucial to pitching biomechanics (MacWilliams et al., 1998). Our aim in this study was to determine the role of each leg in generating linear and angular impulse before ball release.

The role of each leg in baseball pitching has been long-discussed. Elliot et al. (1988) suggested that the back leg drives the body forward while the front leg provides a stable base for the pelvis and the trunk to rotate over. MacWilliams et al. (1998) found that the front leg serves as “an anchor” for transforming the “forward and vertical momentum into rotational components”. Using energy flow analysis, Howenstein et al. (2020) suggested that that back leg propulsion kinetics help transfer linear power, whereas front leg braking kinetics create rotational power. Though peak ground reaction force (GRF) values have been associated with pitch velocities in studies prior (Elliot et al., 1988, McNally et al., 2015, MacWilliams et al., 1998), looking at GRF solely gives a limited view of ground interaction and how linear and angular momentum of the body is regulated during the pitch (McNally et al., 2015, Howenstein et al., 2020).

While segment rotation of pelvis and trunk is observed during pitching, the relative contributions of the back and front leg in generating angular impulse about the COM during the pitch on pitching is largely unknown. The angular momentum of the body about a vertical axis has been computed by Yanai et al. (2018). However, the implications on pitch biomechanics requires further interpretation.

Understanding how each leg contributes to the net linear impulse and net angular impulse is expected to provide meaningful insights of strategies individuals use to regulate linear and angular momentum during the pitch. We hypothesized that the back leg is responsible for generating forward linear impulse from mound to home plate and the front leg is responsible for generating backward linear impulse, with the net linear impulse producing an increase in the horizontal momentum of the body towards home plate. In contrast, we hypothesized that the GRFs generated by the front leg would contribute to greater angular impulse about a horizontal axis passing through the COM from mound to first base than the back leg.

METHODS: Professional pitchers at the Minor League level (n=4) volunteered for the study in accordance with the Institutional Review Board. They performed self-selected warmups before and after affixing markers from custom markerset allowing calculation of the body center of mass (COM) following de Leva (de Leva, 1996). Force plates (1000/1080 Hz, Bertec, OH, USA) were placed in an instrumented mound and were adjusted according to individual stride lengths to capture each foot's GRF. A pitching rubber was included. Friction tape strips were also added per pitcher preference. 3D kinematics were captured (250/360 fps, Optitrack, OR, USA). Participants pitched fastballs and we excluded trials that were rated poor/unrepresentative by pitchers, resulting in 6-11 successful fastball trials for each pitcher.
The orthogonal global axes were defined by an +X vector from the mound towards home plate ("forward"), a +Y axis from the mound towards first base, and an upward vertical axis (+Z). The variables of interest were the impulses generated by (1) the horizontal forward GRF (+GRF_X) directed toward home plate and (2) the moment applied about the global +Y vector passing through the body COM (+M_Y). The moment applied by the GRF of each leg about the COM by each leg was calculated by determining the cross product of the position vector (r_{COM}; from the COM to the center of pressure of the GRF by each leg) and the GRF. A positive M_Y acts to rotate the body forward in the X-Z plane. The linear impulse generated by the back and front leg GRF_X and the angular impulse generated by the back and front leg M_Y were determined by integrating GRF and M_Y from the last time GRF_Z decreased before increasing to its peak magnitude during the pitch and until the time of ball release. This signifies a pushing action of the back leg. The net impulses were found by adding the impulses of both legs. To characterize how the Y angular impulse was generated by M_Y, GRF magnitude, position vector length, and the orientation of the GRF in relation to the position vector (where θ=90° provides a maximum value of sin θ = 1) were quantified and compared (Zaferiou et al., 2016). The magnitude of the GRF and position vector length were calculated by finding their resultant vectors projected on the X-Z plane. The angle θ is the angle between these two projected resultant vectors onto X-Z plane. The results were normality distributed, thus two-tailed paired t-tests (α=0.05) were used to compare impulse generated by each leg within subject (Matlab).

RESULTS:
Exemplary GRF_X and M_Y graphs are shown in Figure 1. We found that the back leg generated positive X (forward) linear impulse, and the front leg generated negative X (backward) linear impulse that was smaller, resulting in a net positive X linear impulse for all pitchers (Figure 2A).

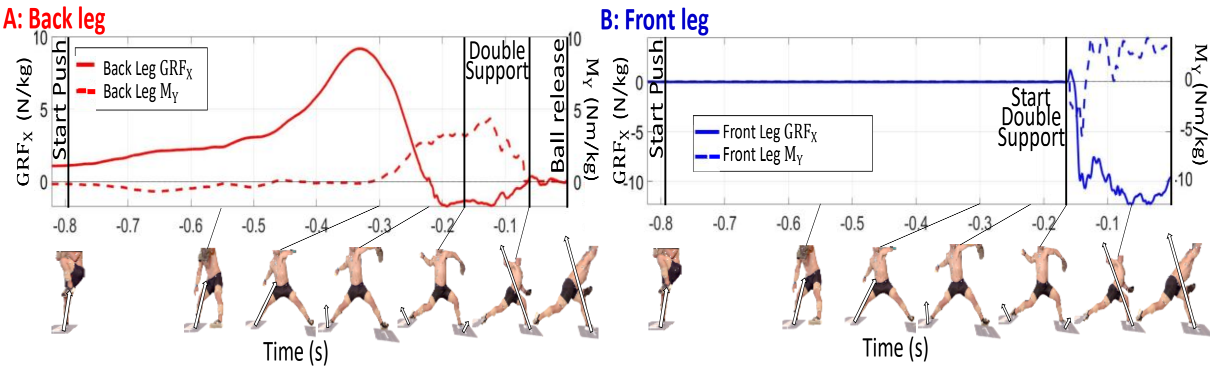

Figure 1: Exemplar GRF_X (solid line) and M_Y (dashed line) vs. time applied by the (A) back and (B) front legs (Subject 1).

We also found that both legs generated positive Y angular impulse during the pitch which resulted in a positive change in angular momentum of the body in X-Z plane (Figure 2B). The back leg generated more positive Y angular impulse than did the front leg, statistically so in three of four pitchers and ranging from 10% to 90% more average Y angular impulse across pitchers. For the back leg, M_Y first became positive (Figure 3A) as θ became positive when the GRF was directed behind the COM. The increase of M_Y to its peak value (Figure 3B) was attributed to increases of θ to 75-85° and position vector length despite the decrease of GRF magnitude. The decrease of M_Y was due to a further decrease of GRF magnitude as the back foot drags off the force plate. For the front leg, M_Y first became positive as angle θ became positive (Figure 3A) when the GRF was directed behind the COM. The maintenance of high M_Y (Figure 3C) until ball release is attributed to high GRF values, despite θ hovering around a small positive value (~8-17°) and the position vector length decreasing as the COM moves towards the front foot.

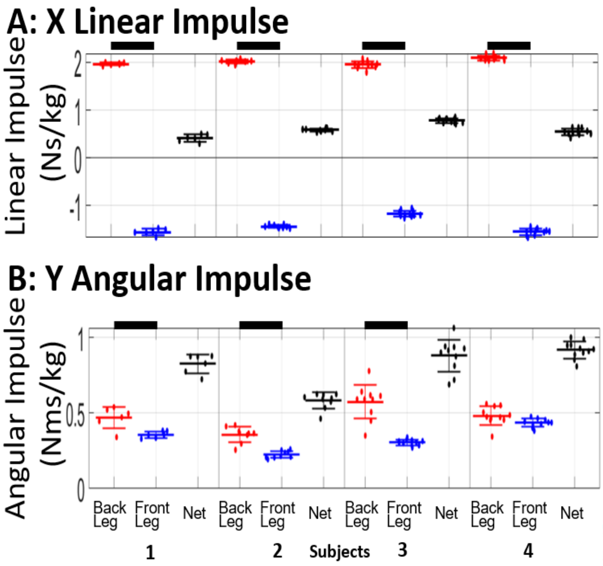

Figure 2: (A) X linear impulse and (B) Y angular impulse for the back leg (red), front leg (blue), and net (black) during fastballs for all subjects. Bold horizontal lines indicate rejecting the null hypothesis (α=0.05).

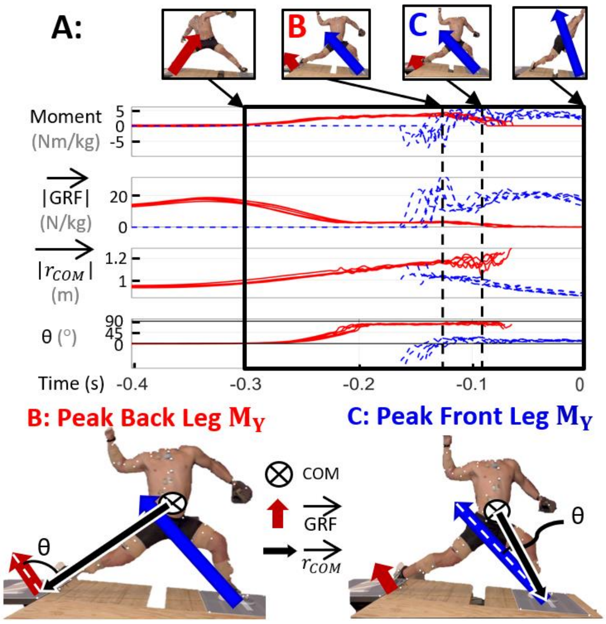

Figure 3: (A) Exemplar moment generated during six trials for the back (red solid line) and front (blue dashed line) legs until ball release at t=0 s (Subject 1). Moment components at peak M_Y of the (B) back and (C) front legs.

DISCUSSION: The purpose of this study was to examine the roles of both legs in generating linear and angular impulse. The results supported the hypothesis that the back leg generated forward linear impulse from mound to home plate and the front leg generated backward linear impulse. However, we found that, surprisingly, the back leg generated more positive angular impulse about the horizontal axis from mound to first base than the front leg despite the notion that the front leg is thought to generate rotation. The interpretation that the front leg facilitates the transfer of rotational power (Howenstein et al., 2020) is not incorrect, though the substantial role of the back leg in contributing to the generation of whole-body rotation should be noted.

The role of each leg in generating linear impulses followed closely from the previous analysis of GRF values (MacWilliams et al., 1998, Howenstein et al., 2020). For the back leg, there were periods of negative GRF_X as the foot dragged along the force plate despite the overall forward linear impulse. For the front leg, for three of four pitchers, there were period of positive GRF_X at ground contact. We suspect that this may be due to hamstring and calf muscles co-contracting to protect and stabilize the knee joint (Chimera et al., 2004), and/or to protect from slipping down the mound. This certainly warrants further investigation.

Initially, the back leg extended and pushed the body forward as indicated by the increase of GRF_X. The increase of M_Y from negative to positive for the back leg occurred only when the GRF_X started to decrease after reaching its peak and was oriented behind the COM (θ being positive). This indicated that the role of the back leg transitioned from linear propulsion to rotation generation. Then, the back foot turned over and started dragging along the force plate and GRF_X was directed backwards. GRF_X and GRF_Z during dragging oriented θ near 90° and was applied at a great distance from the COM, leading to a large M_Y despite the relatively small GRF magnitude. The role of dragging of the foot for Y angular impulse generation also coincided with the priority that pitching coaches place in "reading the drag line".

For the front leg, M_Y was driven by a high GRF magnitude and the small positive θ between 8-17°. When the front leg first contacted the ground, there were always periods of negative M_Y

which may coincide with the flexing of the front knee and hip at initial contact. The front leg M_Y became positive when the GRF was directed behind the COM. From the video, we observed that this occurs when the front knee was holding an isometric position. This is aided by the forward translation of the COM through front leg bending and trunk rotating forward, allowing θ to become positive despite the reduction in position vector length.

There are several limitations to this study. First, the sample size is small, containing only four professional pitchers, and different strategies may be uncovered with more pitchers. Second, we have only included X linear and Y angular impulse in detail due to the paper length. Third, the back foot frequently continued dragging on the ground beyond the force plate area, though this would likely increase the overall back leg angular impulse, which does not take away from the key findings of this study. Fourth, there were occasional gaps in the GRF data due to measurement system error (maximum gap size of ~20 ms) that were filled using a conservative cubic spline (though no further filtering of the GRF data was performed). Relatedly, during the front leg initial contact, the instrumented mound vibrated with an oscillation of approximately 2 mm, which resulted in an oscillating GRF within the first 40 ms of initial contact. This study was performed within a lab, so the pitching distance was less than realistic (27 ft). In the future, we will include more pitchers, use realistic distances, and study the other rotational planes.

CONCLUSION: This study reinforced that the back leg generated forward linear impulse and the front leg generated backward linear impulse. We also uncovered the back leg's contribution towards the generation of whole-body angular impulse about the horizontal axis from mound to first base as well as the different strategies used by each leg to do so. Collectively, these results contribute to the understanding of pitching biomechanics on a whole-body control level.

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