The effect of pitch type on ground reaction forces in the baseball swing

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Abstract
Coaches have identified the batter’s weight shift as a critical component for promoting proper timing and balance in a baseball swing. Analysing the weight shift through maximum horizontal (Fx) and vertical (Fz) ground reaction forces (GRFs) of professional batters (N = 29; height = 185 ± 6 cm; mass = 92 ± 9 kg), the purpose of this study was to compare GRFs among swings against fastballs and changeups. General linear models were used to compare three conditions of interest: successful results against fastballs, successful results against changeups, and unsuccessful results against changeups. Batters had a similar loading mechanism and initial weight transfer from back foot to front foot regardless of pitch type, but peak front foot GRFx and GRFz occurred with significantly different magnitudes and at significantly different times, depending on the pitch type and hit result. Peak front foot GRFs were greater for successful swings against fastballs compared to both successful and unsuccessful swings against changeups. Peak front foot GRFs of unsuccessful swings against changeups occurred, on average, 15–20 ms earlier than successful swings against changeups and 30–35 ms earlier than successful swings against fastballs, quantifying how a changeup can disrupt the coordination of a hitter’s weight shift.

Keywords: Hitting, fastball, changeup, weight shift, timing

Introduction
The task of hitting a baseball has been labelled the hardest thing to do in sports (Williams & Underwood, 1986; Mihoces, 2003). A hitter generates the energy necessary for hitting a baseball by utilizing the kinetic chain (Race, 1961; DeRenne, 1993; Welch et al., 1995), transferring energy up from the ground through each successive body segment (i.e. feet—legs—pelvis—trunk—arms—bat). The ultimate goal is to precisely impact the ball with the greatest amount of energy possible to maximize the batted ball exit velocity (BEV). The coordinated energy generation begins with the batter’s feet pushing against the ground (DeRenne, 1993), creating ground reaction forces (GRFs). Many coaches believe that proper shifting of the body’s weight from back foot to front foot is necessary to successfully
hit the ball, as it promotes proper timing and dynamic balance in the batter’s swing (Lau & Glossbrenner, 1992; DeRenne, 1993; Gola & Monteleone, 2001; Mattingly & Rosenthal, 2007).

The most common approach in batting is to initially load the body’s weight (i.e. the centre of mass) towards the back foot (right foot for a right-handed hitter), often temporarily raising the front (left) foot off the ground. This is followed by a weight shift forward; the front foot strides out towards the pitcher, and the momentum of the body’s centre of mass is also driven in that direction. As the front foot hits the ground, the front leg and foot provide a firm base of support, stopping the body from continuing to move forward (DeRenne, 1993; Lund & Heefner, 2005). Several small studies have preliminarily investigated GRFs in baseball batting and have confirmed this general weight shift pattern (Mason, 1987; Marino, 1989; Welch et al., 1995; Lee & Eun, 2004; Katsumata, 2007; Fortenbaugh & Fleisig, 2008).

Hitting becomes exceedingly difficult in the context of a game, when a pitcher constantly alters the velocity, spin, and direction of the ball. The pitcher often throws the ball very fast to reduce the reaction time of the hitter, though the pitcher concomitantly takes on the risk that the batter, if successful, can hit a faster thrown ball with greater outgoing speed and distance than a slower one (Adair, 2002). With a simpler perspective, Hall of Fame pitcher Warren Spahn has famously been quoted as saying, ‘Hitting is timing. Pitching is upsetting timing.’ Katsumata (2007), in the only known GRF analysis of swings against pitches of different speeds, measured the vertical GRFs when six right-handed college hitters swung at pitches of two different speeds (32 and 20 m/s) of machine-pitched balls. The study identified a modulation in the weight shift pattern whereby batters adjusted to an off-speed pitch by increasing the amount of time between when the front foot touched back down and when the batter committed his weight forward. Katsumata was also interested in comparing successful and unsuccessful swings, but limitations in technology restricted the analysis to successful swings only.

Previous biomechanical studies have laid some important groundwork in understanding the GRFs involved in baseball batting, though they have all had notable limitations in sample size, skill level, methodology, and/or technology. Additionally, while other studies have neglected to analyse trials in which the batter produced unsuccessful results (i.e. foul tips or misses), this decision may have discarded some important data. While addressing these limitations, the purpose of the current study was to compare GRFs among successful swings against fastballs and changeups as well as unsuccessful swings against changeups. Since the goal of an off-speed pitch is to upset a hitter’s timing and hitters are taught to prepare for every pitch to be a fastball, unsuccessful swings against changeups were suspected to be the result of a temporal problem in the swing mechanics, whereas the reasons for unsuccessful swings against fastballs were not believed to be directly related to timing and therefore beyond the scope of this study. The researchers hypothesized that peak GRFs occur earlier when a changeup is unsuccessfully hit as compared to successfully hit fastballs and changeups.

Methods

Participants

Ethics approval was obtained from the St. Vincent’s Hospital internal review board. Twenty-nine healthy AA-level minor league baseball players (13 left-handed and 16 right-handed batters) volunteered, representing seven different teams. All participants were asked to read and sign an informed consent form detailing the study’s procedures, as well as all risks and
consequences of the study. These players were 25 ± 2 years old with a height of 185 ± 6 cm and a mass of 92 ± 9 kg.

Procedure

The study was conducted during the middle of the baseball season so that players were in baseball-playing shape and regularly practicing their batting skills. Each participant reported to the biomechanics laboratory for testing at an assigned time. Hitters were asked to change into a baseball hat, snug fitting shorts, socks, and non-reflective shoes.

An eight-camera motion analysis system (Motion Analysis Corp., Santa Rosa, CA, USA) and a pair of force plates (Advanced Medical Technology Inc., Watertown, MA, USA) were used to capture the biomechanical data. Each day the motion capture system was calibrated as per the manufacturer’s recommendations with a static ‘seed’ and dynamic ‘wand’ calibration to within 0.5 mm residual error. The force plates, synchronized to the motion capture system, were ‘zeroed out’ before each participant’s batting session. The participant was allowed as many practice swings against the pitcher as desired to familiarize himself with the laboratory setting. The hitter was also allowed to perform any callisthenics or warm-up drills to prepare for the testing procedure.

The hitter took his stance in the middle of the cameras’ capture volume with one foot on each force plate. For each pitch, the motion capture system tracked the 3D locations of the baseball, which was covered with reflective tape to enable tracking, at a rate of 300 Hz while the force plates simultaneously recorded the GRFs also at a rate of 300 Hz. The X-axis pointed from home plate towards the pitcher, the Z-axis was vertical, and the Y-axis was their cross-product, \( Z \times X \). An experienced batting practice pitcher threw the baseballs to the hitter from a distance of approximately 13 m, a common distance used for throwing batting practice (Escamilla et al., 2009). The pitcher varied the pitches by speed and location to simulate the unpredictability of batting in game situations, with an approximate fastball to changeup ratio of 4:1. This ratio was chosen based on recommendations to pitchers given by pitching coaches (House, 2000). Each batter completed approximately 50 swings, though this study only incorporated those trials in which fastballs and changeups were thrown ‘down the middle’, resulting in approximately 10 swings for each pitch type, though the exact number of trials varied with each subject.

Data processing

A series of steps were completed to refine the data and prepare it for statistical analysis. First, to confirm the exact pitch speed, the motion analysis system tracked the ball’s flight path for approximately 5 m before contact with the bat. Next, the approximate frame of bat–ball contact was recorded for all trials in which the ball was actually contacted. This was determined by visually inspecting the 3D data display and documenting the frame immediately prior to the one in which the ball’s path deviated from its incoming trajectory. For the trials in which the batter swung at a changeup and completely missed the ball, the frame of bat–ball contact was estimated by averaging the X-position of the ball at bat–ball contact in successful swings against changeups for that batter. The frame of bat–ball contact was subsequently utilized in all temporal data analysis as a common reference point. In a similar fashion to the pitch speed, the BEV was computed directly from the motion capture data as the mean ball velocity for approximately 5 m after contact with the bat. Balls that were ‘swing and misses’ or ‘foul tips’ were noted as such and did not have a quantifiable BEV.
Any hit with a quantifiable BEV was operationally defined as a successful result and any foul or miss as an unsuccessful result.

The magnitude and the timing of GRFs were assessed during each swing. To help reduce the between-subject variability and to enable comparison of results to previous studies, the force values were normalized to per cent body weight (BW). Based on Katsumata (2007), one variable of interest was the moment of ‘weighting’, when the batter began to commit his weight forward. The current study used the time (relative to bat–ball contact) that the batter’s front foot vertical (Fz) GRFs surpassed 50% BW to capture this moment, which will be subsequently referred to as ‘weight shift commitment’. The other variables of interest were the magnitude and timing (relative to bat–ball contact) of peak horizontal (Fx) GRF and GRFz of both feet. For easier interpretation, these eight kinetic variables are described in the results and discussion sections as horizontal propulsive force (back foot GRFx), horizontal braking force (front foot GRFx), and vertical force (GRFz).

**Statistical analysis**

The data were analysed using Minitab 16 (Minitab Inc., State College, PA, USA) and compared three operationally defined ‘trial types’: successful results against fastballs, successful results against changeups, and unsuccessful results against changeups. Trial type differences in the time of weight shift commitment and the eight kinetic variables were analysed via general linear models (GLMs) with repeated measures to accommodate the unequal number of trials per trial type per subject and to incorporate within-subject as well as between-subject variability. The time of weight shift commitment (in milliseconds before bat–ball contact) and each of the kinetic variables were entered into separate GLM as the dependent variable; the trial type was entered as a within-subject factor with fixed effect; and the subject was entered as a factor with random effect to account for the fact that the batters were a sample from a larger population (i.e. all professional hitters) and the inference derived from these models would be directed to the overall population from which the subjects were selected. When a significant difference in the dependent variable across trial types was revealed, a Tukey post hoc comparison was conducted. For all tests, \( \alpha = 0.05 \). To help visualize the GRF patterns, Figures 1–4 represent average GRFx and GRFz for both feet for each of the three trial types (successful swings against fastballs, successful swings against changeups, and unsuccessful swings against changeups). These graphs were constructed by averaging all available trials for a subject for a given trial type (aligned by bat–ball contact frame) and then finally averaging all of the subjects to create one curve per trial type for each of the four GRFs.

To maximize the amount of information captured, all available trials were used in the statistical models, as opposed to averaging the trials and reducing the data to one value per participant per trial type. For the purpose of summarizing the data, however, means and standard deviations (weighted by the number of observations per subject) were used to accommodate the unequal number of trials for successfully hit fastballs and changeups across subjects. Unsuccessfully hit changeups often only had one or two trials per person, so for this trial type simple standard deviations were calculated as a conservative estimate of the variability.

**Results**

Fastballs were thrown with a speed of \( 24.9 \pm 0.6 \, \text{m/s} \). Changeups were thrown with a speed of \( 21.2 \pm 0.6 \, \text{m/s} \). Successful results against fastballs had a BEV of \( 37 \pm 3 \, \text{m/s} \) with a range of
Figure 1. Horizontal propulsive force over time.

Figure 2. Back foot vertical force over time.
Figure 3. Horizontal braking force over time.

Figure 4. Front foot vertical force over time.
26–46 m/s. Successful results against changeups had a BEV of 34 ± 6 m/s with a range of 18–44 m/s. By definition, unsuccessful results against changeups had no quantifiable BEV.

There was a significant difference in the timing of the weight shift commitment ($p < 0.001$). Post hoc comparison revealed that the commitment occurred significantly closer to bat–ball contact against fastballs with successful results (-172 ± 9 ms) than against changeups with both successful results (-201 ± 20 ms) and unsuccessful results (-213 ± 36 ms), with no difference between the swings against changeups with successful or unsuccessful results.

Group means and standard deviations for GRF peak magnitudes for each trial type are displayed in Table I (in %BW). Based on GLM results, no significant differences were seen in either peak horizontal propulsive force ($p = 0.056$) or peak back foot vertical force ($p = 0.931$) across trial types. However, significant differences were seen in peak horizontal braking force ($p < 0.001$) and peak front foot vertical force ($p < 0.001$). Post hoc comparisons showed that horizontal braking force was greater against fastballs with successful results than against changeups with successful results or unsuccessful results, with no statistical difference between swings against changeups with successful or unsuccessful results. The same pattern was observed for peak front foot vertical force.

Group means and standard deviations for the timing of peak GRF magnitudes for each trial type are given in Table II (in milliseconds relative to bat–ball contact). Based on GLM results, there were significant differences in the timing of the peak horizontal propulsive force ($p < 0.001$) and the peak back foot vertical force ($p < 0.001$). Post hoc comparisons demonstrated for both of these timing variables that, like the weight shift commitment, swings against fastballs with successful results exhibited peak back foot forces significantly closer to the time of bat–ball contact than swings against changeups with either successful or unsuccessful results, with no differences between successful and unsuccessful results against changeups. Significant differences were also seen in the timing of the peak horizontal braking force ($p < 0.001$) and the peak front foot vertical force ($p < 0.001$). Post hoc comparisons revealed significantly different timing patterns among the three trial types for both the peak

### Table I. Average peak GRFs magnitude comparison of trial types.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Fastballs – successful</th>
<th>Changeups – successful</th>
<th>Changeups – unsuccessful</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal propulsive force (%BW)</td>
<td>25 ± 2</td>
<td>25 ± 2</td>
<td>24 ± 5</td>
</tr>
<tr>
<td>Back foot vertical force (%BW)</td>
<td>97 ± 2</td>
<td>97 ± 3</td>
<td>97 ± 7</td>
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<tr>
<td>Horizontal braking force (%BW)*</td>
<td>-57 ± 5</td>
<td>-51 ± 7</td>
<td>-52 ± 14</td>
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<tr>
<td>Front foot vertical force (%BW)*</td>
<td>150 ± 13</td>
<td>140 ± 18</td>
<td>134 ± 24</td>
</tr>
</tbody>
</table>

*Significant difference ($p < 0.05$) between successful fastballs and changeup conditions.

### Table II. Average time (relative to bat–ball contact) of peak GRFs magnitude of trial types.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Fastballs – successful</th>
<th>Changeups – successful</th>
<th>Changeups – unsuccessful</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal propulsive force (ms)*</td>
<td>-466 ± 49</td>
<td>-504 ± 58</td>
<td>-529 ± 106</td>
</tr>
<tr>
<td>Back foot vertical force (ms)*</td>
<td>-514 ± 53</td>
<td>-566 ± 71</td>
<td>-611 ± 98</td>
</tr>
<tr>
<td>Horizontal braking force (ms)**</td>
<td>-90 ± 17</td>
<td>-100 ± 21</td>
<td>-117 ± 27</td>
</tr>
<tr>
<td>Front foot vertical force (ms)**</td>
<td>-92 ± 20</td>
<td>-108 ± 25</td>
<td>-126 ± 30</td>
</tr>
</tbody>
</table>

*Significant difference ($p < 0.05$) between successful fastballs and changeup conditions.; ** Significant difference ($p < 0.05$) among all trial types.
horizontal braking force and the peak front foot vertical force. The peak front foot forces against fastballs with successful results occurred closest to bat–ball contact, with peaks for swings against changeups with successful results occurring a bit earlier and peaks for swings against changeups with unsuccessful results occurring earlier still.

**Discussion and implications**

The comparison of trial types provided important insights into how GRF values are associated with pitch type and batting success. Both peak back foot GRF magnitudes were statistically the same for all three trial types, and, as seen in Table II, the difference in the timing of these events between fastballs and changeups (irrespective of result) was around 50–100 ms. This time difference can be accounted for by estimating the travelling time of the ball from the pitcher’s hand to bat–ball contact using the pitching distance and the difference in mean pitch speeds of fastballs and changeups. This means that a professional batter likely undertakes the same initial loading mechanism for every pitch. It is unlikely that pitch recognition occurred before the peak back foot forces since, according to calculations, the peak back foot forces seemingly occurred near the time the ball was released from the pitcher’s hand. A discrepancy in timing between fastballs and changeups (irrespective of result) continued through weight shift commitment with a mean difference around 30–40 ms. This is quite interesting because with about 200 ms before bat–ball contact and the ball a little over 4 m away (based on incoming pitch speed), the batter has begun to shift his weight forward to his front foot without manifesting any changes in GRF patterning to accommodate different pitch types. Future motor control and neurophysiology studies would be useful in linking the actions of the body to the perceptions of the mind during batting to determine exactly when the batter identifies a pitch and how long it takes before his body begins to process that information and appropriately react.

The heart of the differences lies in the peak GRF of the front foot. As seen in Table II, the peak horizontal braking force and vertical force occur approximately 90 ms before bat–ball contact during a successful swing against a fastball. Batters appeared to be ‘fooled’ slightly even when successfully hitting a changeup, as the peak horizontal braking force occurred (based on confidence intervals) between 7 and 17 ms earlier than for fastballs, and the peak front foot vertical force occurred between 10 and 21 ms earlier. Batters were seemingly fooled even more when a swing against a changeup had an unsuccessful result. The peak horizontal braking force and the front foot vertical force occurred 5–22 and 7–26 ms earlier, respectively, than when the changeup was hit successfully. The differences between successfully hit fastballs and unsuccessful swings against changeups, obviously, were even larger. Unsuccessful swings against changeups had the peak horizontal braking forces 17–34 ms earlier and the peak front foot vertical forces 22–41 ms earlier than successful swings against fastballs. This disruption in the timing pattern of batters is undoubtedly what pitchers are seeking to effect by changing pitch speeds. Significantly more peak front foot force magnitudes were detected for fastballs than changeups (irrespective of result), though the exact reason for this is unclear. One theory is that when the batter is fooled by the changeup it causes a brief hesitation in his movements which, in turn, dissipates some of the force.

The results of the current study compared favourably with most available previous research (Mason, 1987; Katsumata, 2007; Fortenbaugh & Fleisig, 2008), though a few distinct differences can be seen. Table III summarizes the findings of the comparable previous research and the successful hits against fastballs from the current study. A variety of reasons may explain some of the differences among the findings. All three studies with
comparable data used amateur players, whose performances are likely to differ from more experienced professional players, both in terms of group mean values and variability within subjects and groups. Fortenbaugh and Fleisig and Katsumata also severely limited the realism for the batters, testing them on swings off of a batting tee and pitching machine, respectively, as opposed to facing a live pitcher. While it is often speculated by the casual observer that pitching machines and live pitching are virtually the same, Jinji and Sakura (2006) showed differences in ball flight physics between the two. Lastly, the extremely low sample size in each of the previous studies negatively affects the generalizability and reproducibility of the studies’ results.

The current study was able to address quite a number of concerns that have arisen from previous work, but there were still some additional limitations not yet discussed that future research may be able to investigate. Even though every effort was made to reproduce a game-like situation and players do routinely take batting practice in indoor batting cages against live pitching, the batters were in a laboratory setting, limiting the realism of facing a pitcher in an actual game from regulation distance. The white baseballs were covered in grey reflective tape in order to track their position, making the balls more difficult for the batters to see. Still, the fact that batters were able to hit both fastballs and changeups with similar ranges of success indicates that they were able to adapt to the testing conditions and nearly did replicate game-like BEV (Sherwood et al., 2000). GRFs represent an important initial movement of the baseball swing, the weight shift, but they are hardly a complete description of the swing. The development of a more robust model including kinematic data in addition to GRFs should give a much more accurate depiction of the kinetic chain in action during the baseball swing and how it is modulated by pitch types.

The findings of this research are a good initial step for scientists and practitioners in understanding some of the underlying mechanisms of the weight shift in baseball batting. This study provides biomechanical evidence that an effective off-speed pitch, as postulated, upsets a hitter’s timing. The data in this study also support the claim of the difficulty of hitting a baseball well, as literally just tiny fractions of a second separated the successful and unsuccessful swings. While a properly coordinated weight shift may not guarantee successful results every time, gaining a better understanding of a fundamental component of such a challenging task as hitting a baseball may reduce the skill’s perceived complexity and allow for better skill development by hitters.

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### Table III. Comparison of previous and current findings of average GRFs during successful swings against a fastball.

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of subjects</td>
<td>29</td>
<td>n/a</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Skill level of subjects</td>
<td>Pro</td>
<td>Amateur</td>
<td>College</td>
<td>College</td>
</tr>
<tr>
<td>Horizontal propulsive force (%BW)</td>
<td>25</td>
<td>40</td>
<td>n/a</td>
<td>16</td>
</tr>
<tr>
<td>Back foot vertical force (%BW)</td>
<td>97</td>
<td>65</td>
<td>100</td>
<td>n/a</td>
</tr>
<tr>
<td>Horizontal braking force (%BW)</td>
<td>57</td>
<td>90</td>
<td>n/a</td>
<td>39</td>
</tr>
<tr>
<td>Front foot vertical force (%BW)</td>
<td>150</td>
<td>225</td>
<td>130</td>
<td>126</td>
</tr>
<tr>
<td>Horizontal propulsive force (ms)</td>
<td>-466</td>
<td>-250</td>
<td>n/a</td>
<td>-407</td>
</tr>
<tr>
<td>Back foot vertical force (ms)</td>
<td>-514</td>
<td>-600</td>
<td>-750</td>
<td>n/a</td>
</tr>
<tr>
<td>Horizontal braking force (ms)</td>
<td>-90</td>
<td>-250</td>
<td>n/a</td>
<td>-81</td>
</tr>
<tr>
<td>Front foot vertical force (ms)</td>
<td>-92</td>
<td>-100</td>
<td>-150</td>
<td>-81</td>
</tr>
</tbody>
</table>

* Average values based on reported ranges.; ** Estimated values based on reported graphs.
Conclusion

This was the first known biomechanical investigation of professional baseball batters taking swings against a live pitcher throwing fastballs and changeups while in a typical indoor batting practice session. The focus was to assess the relationship between the weight shift and the batting performance as modulated by different pitch types.

Each batter had a very similar initial loading mechanism for both pitch types with respect to back foot GRFs. The batter’s uniform approach to the swing seemingly continued as the weight shifted from the back foot to the front foot. However, distinctions could clearly be made among the three conditions when peak front foot GRFs were ultimately applied. The batter applied maximum vertical and horizontal braking forces earlier for a successfully hit changeup than a successfully hit fastball, and even earlier for an unsuccessful swing against a changeup. This may be an indication that the batter is fooled a little when successfully recognizing a changeup in adequate time and fooled quite a bit more on unsuccessful swings when this recognition occurs too late.

References

Mihoce, G. (2003, March 3). 10 hardest things to do in sports. USA Today, p. 3C.