ENERGY FLOW AND GROUND REACTION FORCE PREDICTORS OF BAT SWING SPEED DURING PITCHED BALL BATTING IN PROFESSIONAL BASEBALL PLAYERS

Jason Hashimoto[1], D. Taylor La Salle[1], Avery Takata[1], Arnel Aguinaldo[1], Kyle Wasserberger[2]

Kinesiology, Point Loma Nazarene University, San Diego, CA[1]
Driveline Baseball, Kent, WA[2]

The purposes of this study are to determine how mechanical energy is absorbed, generated, and transferred during baseball hitting for professional athletes. This study also aims to identify which ground reaction force and energy flow variables influence bat speed. The findings of this study suggest that energy flows from the trunk to the lead leg as the pelvis rotates towards the pitcher. The results of this study emphasize the crucial role of the back leg and trunk during acceleration as well as eccentric contraction of muscles in the lead leg and trunk to decelerate during follow-through. Training strategies that improve muscular strength and mobility of the trunk and hips can be implemented to potentially increase bat speed.

KEYWORDS: kinetics, impulse, baseball hitting, energy transfer

INTRODUCTION: Baseball hitting is a high velocity dynamic motion in which all segments of the body absorb, generate, and transfer energy (energy flow) to produce a fast and accurate swing. Energy flow analysis shows that the pelvis acts as the “root” of energy transfer during baseball hitting, transferring energy to both the torso and lower limbs (Horiuchi et al., 2021; Takata & Aguinaldo, 2022). However, no study to date has investigated energy flow (EF) in professional baseball hitters. Furthermore, previous research has often been limited to hitting off a batting tee rather than utilizing pitched ball data, which better mimics in-game performance (Ae et al., 2017; Horiuchi et al., 2021). Therefore, the purpose of this study was to examine energy generation, absorption, and transfer through the lead and back hips and the lumbosacral (L5S1) joint, as well as identify which GRF and EF variables influence bat speed in professional baseball hitters reacting to pitched balls. It was hypothesized that energy will transfer ‘down the chain’ from the L5S1 joint into the pelvis as the lead foot plants, and that L5S1 energy absorption and transfer in the acceleration phase, front and back leg impulse, and lead hip energy absorption in follow-through will correlate with bat speed.

METHODS: Eleven professional baseball players (age = 22.7 ± 2.9 years, height = 1.82 ± 0.06 m, mass = 88.3 ± 7.0 kg) participated in this study. Prior to participation, individuals signed an informed consent, which was approved by an institutional review board and were cleared by a physical therapist. Athletes performed a self selected warm-up, and were instructed to perform 2 rounds of 8 maximum intent swings with 1 minute rest in between. During collection, a pitching machine (Spinball Sports, Mt Vernon, IL, USA) was set to 65 mph at a distance of 40 feet. A Blast Motion sensor (Blast Motion, San Marcos, CA, USA) was fixed to the handle of the bat to record bat speed for all swings. Forty-seven reflective markers (9 mm DIA) were placed on the skin surface overlying specific anatomical landmarks to estimate joint locations and adjacent bone segments, which are defined to estimate joint kinematics and kinetics based on previously incorporated model specifications (Marsh et al., 2018). During each swing, the 3D global locations of the markers and GRFs were captured using a motion analysis system of 17 OptiTrack Prime17 Cameras (NaturalPoint/Optitrack, Corvallis, OR, USA) and two force platforms (Bertec Corporation, Columbus, OH, USA) at a sampling rate of 360 Hz and 1080 Hz, respectively. Biomechanical metrics were extracted from a total of 69 swings for EF, GRF, and impulse analysis using a 14-segment, 26 degrees-of freedom (DOF) full-body model configured in

Visual3D (C-Motion, Germantown, MD). Hitting motion events were identified as foot-on (FO), maximum trunk rotation (MTR), ball impact (BI), and swing finish (SF). Discrete variables were analyzed by phases of the hitting motion; transition (FO to MTR), acceleration (MTR to BI), and follow-through (BI to SF). Rates of energy generation, absorption, and transfer were time-integrated within each phase to output the respective energies using previously reported methods (Aguinaldo & Nicholson, 2021; Horiuchi et al., 2021). Thirty-one discrete variables were extracted from each swing, which included peak GRF, impulse, and energy flow terms for the lead and back hip, and the L5S1 joint. These variables were then entered into a regularized regression model based on the least absolute shrinkage and selection operator (LASSO), which is a machine learning approach frequently used to reduce high-dimensional data (Tibshirani, 1996). The model was trained using a subgroup (N=46) of our sample and a 10-fold cross-validation in a process aimed to filter out variables that are not closely related to bat speed. Model performance was assessed using the root mean square error (RMSE) in units of m/s and an ordinary least squares (OLS) regression coefficient of determination (R^2). The descriptive statistical and regression analyses were performed in RStudio (version 1.2.10) using the *tidyverse* and *glmnet* packages.

RESULTS: The measured bat speed for professional baseball players was 32.3 ± 1.5 m/s. The LASSO model predicted bat speed with a RMSE of 2.47 mph (R^2 = 0.420, p < .001) and included Peak Back Leg Vertical GRF, Back Leg Medial-Lateral Impulse, L5S1 Generation (AA), Lead Hip Net (FT), L5S1 Generation (FT), L5S1 Net (FT), and Total Back Hip Net (Table 1). The rates of energy generation-absorption and transfer during pitched ball batting are plotted in Figures 1 and 2, respectively.

Table 1: Energy flow, ground reaction force, and impulse variables identified by the LASSO regularization to be most related to bat speed (R^2 = 0.420, RMSE = 2.47, p < .001).

Variable	*Mean ± SD*	*B*	*p*
Bat Speed	72.2 ± 3.3	-	-
Peak Back Leg Vertical GRF (N)	886.5 ± 90.5	0.01	.566
Back Leg Medial-Lateral Impulse (N/s)	-11.2 ± 22.7	-0.03*	.041
L5S1 Generation (AA)	1.5 ± 2.5	-0.26	.155
Lead Hip Net (FT)	18.2 ± 11.4	0.03	.714
L5S1 Generation (FT)	8.9 ± 10.5	0.01	.757
L5S1 Net (FT)	8.6 ± 18.5	0.01	.262
Total Back Hip Net	21.3 ± 31.7	-0.01	.351

*AA = arm-acceleration, FT = follow-through, *p < .05.*

Figure 1: Mean and standard deviation joint torque powers (JTP), representing the rates of energy generation and absorption in the lead hip, back hip, and L5S1 joint during the swing. Vertical lines represent maximum trunk rotation (MTR) and ball impact (BI).

Lead Hip JTP | Back Hip JTP | L5S1 JTP

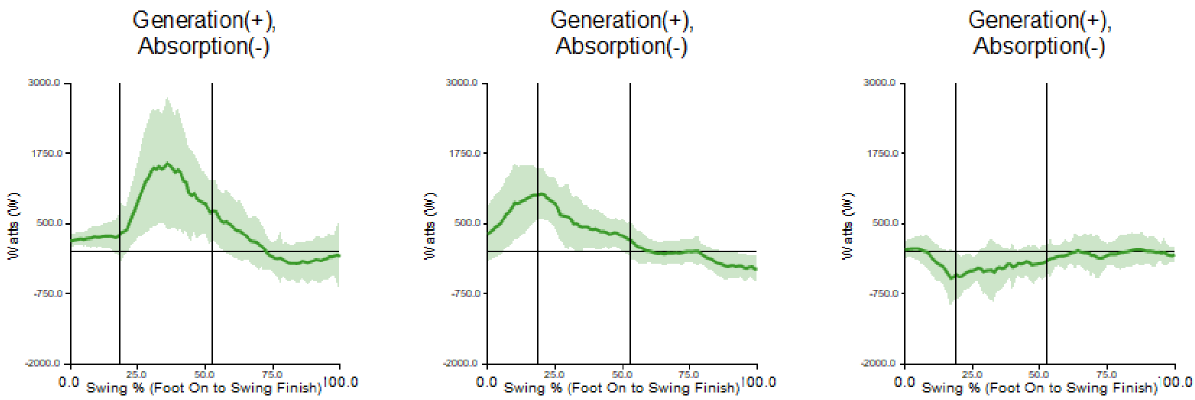
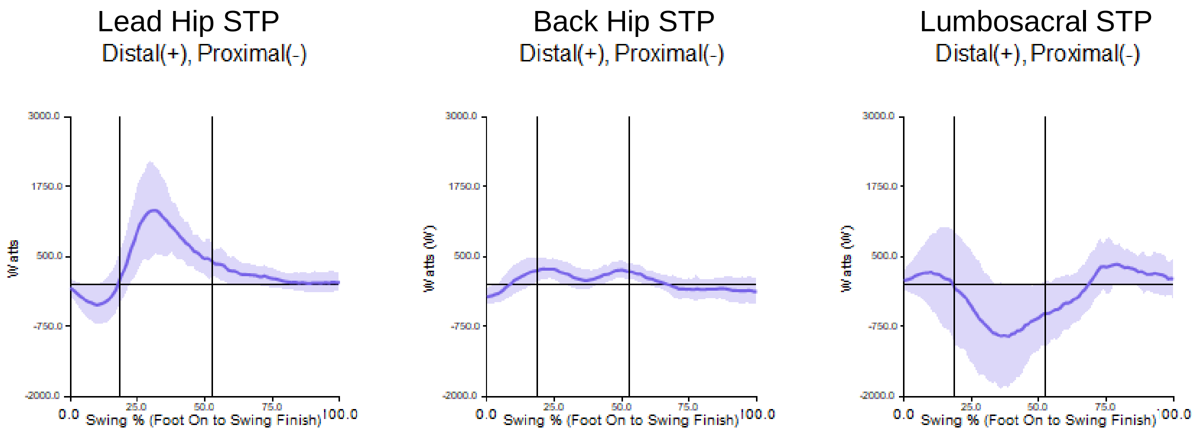


Figure 2: Mean and standard deviation segment torque powers (STP), representing the rates of energy transfer in the lead hip, back hip, and lumbosacral joints during the swing. Vertical lines represent maximum trunk rotation (MTR) and ball impact (BI).



DISCUSSION: The current study aimed to investigate the relationship between mechanical energy flow, ground reaction force, and bat swing speed in professional baseball hitters reacting to a pitched ball. The LASSO regression model identified 5 EF, 1 GRF, and 1 impulse variable. Peak vertical GRF in the back leg as well as medial-lateral impulse of the back leg were identified by the model as influencing factors for bat speed. Conversely, previous research has found that stride foot GRF and impulse correlates with bat speed (Horiuchi & Nakashima, 2023). Further research is necessary to gain a deeper understanding of the contribution of GRFs and impulse in pitched ball batting, specifically the roles of the lead and back leg. As the hitter reaches MTR, the back hip starts to rotate and generates a large amount of energy to propel the pelvis forwards towards the pitcher (Ae et al., 2017, Horiuchi et al., 2021). Our results affirm this principle and demonstrate that the back hip generates the most energy at MTR, and then gradually absorbs energy throughout the rest of the swing (Figure 1). Our model confirms the significance of the back hip, as net energy flow at the back hip was found to be a predictor of bat speed. The energy generated by the L5S1 joint during the acceleration phase was also found by the model as a predictor of bat speed, which aligns with research previously reported (Horiuchi et al., 2021). Three EF variables were identified by the model in the FT phase; lead hip net, L5S1 generation, and L5S1 net. Our results show that the lead hip and the L5S1 joint are both absorbing and transferring energy towards the pelvis after BI, indicating that the hitter must decelerate during FT. As a result, the hitter is slowing himself down through eccentric contraction of the muscle groups surrounding the lead hip and torso (Welch et al., 1995, Horiuchi & Nakashima, 2022). However, it is unclear if this relationship applies to pitched ball batting. Our findings confirmed the notion that energy is not propagating up the kinetic chain as has been documented in previous research (Ae et al., 2017, Horiuchi et al., 2021), but rather that as the hitter reaches MTR and the pelvis is rotating towards the pitcher, energy transfers proximally through the L5S1 joint and into the pelvis (Figure 2). Furthermore, the lead hip transfers energy distally away from the pelvis at MTR (Figure 2), detailing the importance of hip abduction and knee extension in the stride leg and its contribution to the lower trunk adjustments made when hitting a pitched ball (Ae et al., 2018). Both hip joints generated and transferred larger amounts of energy when compared to previous studies that evaluated energy flow, likely due to the population and pitched ball condition (Ae et al., 2017, Takata & Aguinaldo, 2022). Thus, this study reinforces the belief that strengthening the muscles that extend, adduct, and rotate the hip joints could improve batting performance (Takata & Aguinaldo, 2022, Zipser et al., 2021). Of the variables identified in our hypothesis, only back leg impulse was identified by the LASSO model to predict bat speed. While the importance of the variables may not translate into bat speed, further research is needed to better understand how energy flow, GRF, and impulse produce a swing.

CONCLUSION: This study provides more insight into the different factors that predict bat speed during pitched ball batting in an elite hitting population. Vertical GRF in the lead leg, medial-lateral impulse in the back leg, net energy flow in the back leg, trunk generation during acceleration, as well as lead leg and trunk energy flow during follow-through were predictors of bat speed. This study emphasizes the crucial role of the back leg and trunk during acceleration as well as eccentric contraction of muscles in the lead leg and trunk to decelerate during follow-through. Thus, training strategies that improve muscular fitness of the trunk and hips may improve bat speed.

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ACKNOWLEDGEMENTS: We thank Driveline Baseball, Inc. and the baseball players who participated in this study

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