PELVIS ENERGY FLOW AND GROUND REACTION FORCE PREDICTORS OF ELBOW TORQUE IN HIGH SCHOOL AND COLLEGIATE BASEBALL PITCHERS

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High joint forces and torques are associated with injury risk in baseball pitching. Energy flow (EF) analyses have provided valuable information on how segment and joint powers influence the pitching motion but have not been used to investigate EF influence on elbow torque. The purpose of this study was to determine the relationship of pelvis EF and ground reaction force (GRF) with elbow valgus torque in a sample of high school and collegiate baseball pitchers using regularized regression and statistical parametric mapping. A set of 14 GRF and EF variables was found to be predictors of maximum elbow valgus torque. Both groups differed in pitch velocity and elbow torque but exhibited similar patterns of energy generation and transfer at the stride hip and L5S1 joints. These findings could translate to lower body strategies to reduce the injury risk of high school and collegiate pitchers.

KEYWORDS: overarm throwing; pitching biomechanics; joint kinetics; impulse

INTRODUCTION: Baseball pitching is a complex movement involving rotations of multiple body segments that are accelerated in sequential order through a kinetic chain (Scarborough et al., 2018). The high joint forces and torques associated with overarm throwing has been linked to pitching-related injuries (Chalmers et al., 2017), particularly at the elbow joint where valgus torques expose the joint to potential damage of the lateral and medial structures such as the ulnar collateral ligament (Anz et al., 2010). Energy demands of the throwing arm could lead to potentially detrimental torques at the elbow (Aguinaldo & Escamilla, 2019). Joint torques that accelerate the pelvis and trunk generate and transfer energy necessary to both minimize upper extremity demands and maximize pitch velocity (Aguinaldo & Nicholson, 2021; Kimura et al., 2020). Maximizing velocity while minimizing throwing arm kinetics is referred to as pitching efficiency. Evidence reported in the current literature suggests that proper timing of segmental rotations, mainly at the pelvis and trunk, could maximize pitching efficiency (Aguinaldo & Chambers, 2009). While previous energy flow (EF) analyses of baseball pitching have provided valuable information on how segment and joint powers influence the pitching motion, they have been limited to an examination of the energy predictors of pitch velocity (Aguinaldo & Nicholson, 2021), upper body contributions (Aguinaldo & Escamilla, 2019; Roach & Lieberman, 2014), or the energy flow patterns in youth pitchers (Wasserberger et al., 2021). We, therefore, aimed to estimate the influence of energy generation, absorption, and transfer through the pelvis along with ground reaction force (GRF) and impulse metrics on elbow valgus loading during pitching in high school and collegiate baseball players. Based on the EF analysis by Aguinaldo & Nicholson (2021), it was hypothesized that drive leg vertical impulse and hip transfer along with stride hip transfer would predict elbow torque. Furthermore, recent literature suggests high school and collegiate pitchers employ different pitching strategies (Nicholson et al, 2022a; Nicholson et al, 2022b), therefore a secondary aim was to compare these EF patterns throughout the pitching motion between the two groups.

METHODS: This retrospective study was approved by the university's institutional review board. Secondary analysis was performed on kinematic and kinetic data collected from 20 high school pitchers (age = 15.6 ± 1.2 years, height = 1.83 ± 0.07 m, mass = 75 ± 12 kg) and 20 collegiate pitchers (age = 20.1 ± 1.3 years, height = 1.86 ± 0.06 m, mass = 92 ± 9 kg) who each threw a sequence of fastball and off-speed pitches to a catcher at a regulation distance (18.4 m). One representative fastball was extracted for this study in which 3D motion data was collected using a 38 reflective marker set and a 12-camera motion analysis system (Qualisys,

Göteborg, Sweden) at a sampling rate of 400 Hz. Ground reaction forces (GRF) were collected at 1200 Hz using three force platforms (AMTI, Watertown, MA) embedded in the Perfect Mound (Porta-Pro Mounds Inc, Sauget, IL) according to Major League Baseball (MLB) specification. Ball speed was recorded with a ball tracking system (Trackman, Scottsdale, AZ).
Joint kinematic and kinetic data were calculated with a 14-segment, 26 degrees-of freedom (DOF) full-body model configured in Visual3D (C-Motion, Germantown, MD) as previously described by Aguinaldo & Nicholson (2021). The kinetic variable of interest was the elbow valgus torque, defined as the bending moment about the joint's anterior-posterior axis that places the lateral side under compression and the medial side under tension.
The joint force powers (JFP), segment torque powers (STP), and the joint torque powers (JTP) at the drive hip, stride hip, and lumbosacral joints were calculated as previously detailed elsewhere (Aguinaldo & Nicholson, 2021; Robertson & Winter, 1980). Positive and negative joint torque power indicate the rates of energy generation and absorption, respectively, by the joint torque. If the segments are rotating in the same direction, the joint torque can also transfer energy between segments at the rate of the slower moving segment (ET) with the direction of transfer determined by the polarity and magnitudes of the proximal and distal STP (Robertson & Winter, 1980):

$$ET = \frac{|STP_p| + |STP_d| - |JTP|}{2}$$

JFP and ET were then summed to yield the rate of net energy transfer across a joint.
Four phases in the pitching motion were defined temporally by the instances of maximum knee height (MKH) of the stride limb, stride foot contact (SFC), maximum external rotation (MER) of the throwing shoulder, ball release (BR), and maximum internal rotation (MIR) of the throwing shoulder: stride phase (MKH to SFC), arm-cocking (SFC to MER), arm-acceleration (MER to BR), and follow-through (BR to MIR). Energy generation (or absorption) and transfer at the drive hip joint were computed by integrating the JTP and ET, respectively, in the stride phase. Likewise, energy generation (or absorption) and transfer at the stride hip and lumbosacral joints were computed by integrating the JTP and ET, respectively, in the arm-cocking, arm-acceleration, and follow-through phases.
We extracted the maximum elbow valgus torque (MEVT) normalized by body weight and height. A set of 35 discrete variables that includes all components of the peak GRF, impulse, and energy terms for the drive and stride legs as well as a categorical variable (high school, collegiate) was 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=27) of our sample and a 10-fold cross-validation in a process aimed to filter out variables that are not closely related to MEVT. The performance of the model was assessed with the root mean square error (RMSE) and the coefficient of determination (R^2) based on a multiple regression of the reduced dataset. All regression analyses were performed in RStudio (version 1.2) using the *tidyverse* and *glmnet* packages. To determine differences in JTP and transfer time-series curves between the two groups, statistical parametric mapping *t* tests (SPM{t}) were performed in Python (version 3.7) using *Spyder* (version 3.3) and the *spm1d* package (Pataky, Robinson, & Vanrenterghem, 2013). Random field theory was employed to determine the critical threshold at which the *t* statistic would cross in 5% (α = .05) of observed clusters of smooth, random data throughout the temporal field of the pitching motion (SFC-MIR).

RESULTS: The mean normalized MEVT was higher in high school pitchers (5.6 ± 1.4% BW-H) than it was in collegiate pitchers (3.6 ± 0.6% BW-H, $p < .001$), and the pitch velocities were slower in the high school group (34.8 ± 1.7 m/s) compared to the collegiate group (39.3 ± 1.7 m/s, $p < .001$). LASSO regression reduced the number of potential predictor variables of normalized MEVT from 35 to 14, the linear combination of which was found to predict MEVT with a RMSE of 0.5% BW-H and a strong model fit ($R^2 = 0.95$, $p < .001$). Table 1 lists the variables selected by LASSO and identified as statistically significant by multiple regression. Both high school and collegiate pitchers exhibited a distal energy transfer at the stride hip starting midway through the arm-cocking phase and only differed by the rate of ET ($|t| > 3.31$, $p = .022$) in the late arm-acceleration period (56%-62%) of the pitching motion (Figure 1).

Table 1: Regression model ($R^2 = 0.95$, $p < .001$) of the dataset reduced by LASSO regularization with significant predictor variables of normalized MEVT

Predictor Variable	*B*	*SE B*	*p*
Intercept	4.45***	0.69	< .001
Level Group (HS)	1.32***	0.22	< .001
Stride Leg Medial Impulse	-5.68*	2.59	.039
Stride Phase			
Drive Leg Propulsive GRF	-9.45*	3.75	.019
Drive Leg Medial Impulse	-3.83**	1.12	.002
Arm-Cocking Phase			
Stride Hip Absorption	-0.93***	0.14	< .001
Lumbosacral Distal Transfer	-0.65***	0.10	< .001
Arm-Acceleration Phase			
Stride Hip Generation	-3.16***	0.81	<.001
Follow-Through Phase			
Stride Hip Generation	0.67*	0.30	.032

*B = unstandardized coefficient; SE B = standard error of coefficient. *p < .05. **p < .01. ***p < .001*

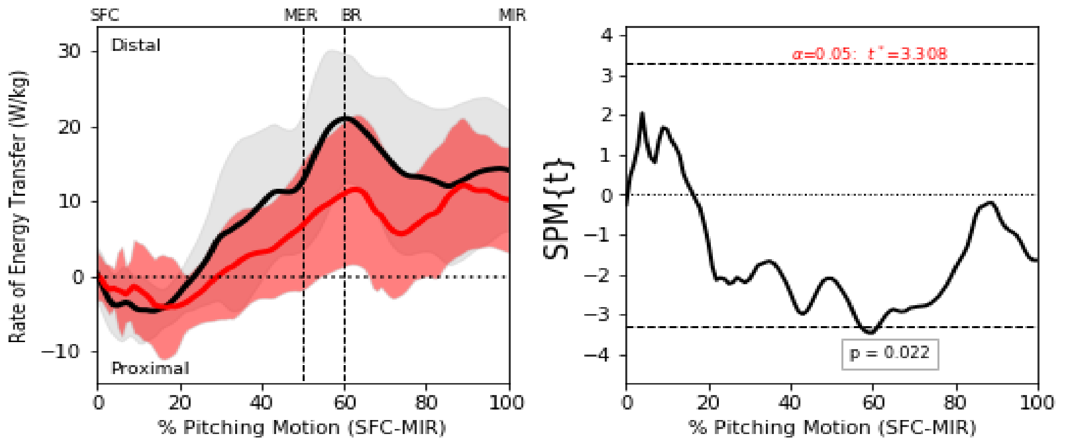

Figure 1: Stride hip energy transfer (left) for high school (red) and collegiate (black) pitchers. SPM{t} scalar field (right) showing a suprathreshold region in the arm-acceleration phase. SFC = stride foot contact; MER = maximum shoulder external rotation; BR = ball release; MIR = maximum shoulder internal rotation.

DISCUSSION: Although it's been previously reported that drive leg impulse and energy transfer through the pelvis predict pitch velocity (Aguinaldo & Nicholson, 2021), the current study aimed to employ a similar approach to predict elbow valgus loading. The LASSO regression model showed that among all of the GRF variables, the drive leg medial impulse prior to SFC and stride medial impulse were found to be predictors of MEVT. Pelvis rotation starts in the stride phase and peaks early in the arm-cocking phase in both adolescent and adult pitchers (Aguinaldo & Escamilla, 2019) so the medial impulse on both legs could indicate the change in angular momentum of the pelvis. This action is also demonstrated at the stride hip and lumbosacral joints, which generate and transfer energy distal to the pelvis and appear to also play an important role in elbow valgus loading. The finding that both groups of pitchers exhibit distal energy transfer at the stride hip further reinforces the notion that the stride leg provides a stable foundation on which the pelvis and trunk can rotate throughout the pitching motion in what is commonly referred to as "lead leg block" in the baseball community. Overall, the pelvis energy predictors of elbow valgus loading found in this study underscore the importance of optimizing the muscular strength and flexibility of the lower trunk and hips in potentially improving pitching performance and reducing injury risk (Zipser et al., 2021). It is hoped that this study may provide the basis on which future energy flow research and lower body training strategies can be developed and implemented in all levels of baseball pitchers.

CONCLUSION: Elbow valgus torque was related to bilateral medial impulse as well as to generation and distal transfer at the stride hip and lumbosacral joints. High school and collegiate pitchers exhibit similar distal energy transfer at the stride hip. These findings could translate to lower body strategies to reduce the injury risk of high school and collegiate pitchers.

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