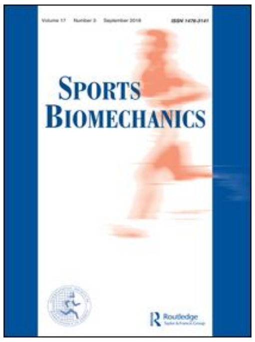

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Energy generation, absorption, and transfer at the shoulder and elbow in youth baseball pitchers

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ABSTRACT

Performance during the baseball pitch is dependent on the flow of mechanical energy through the kinetic chain. Little is known about energy flow during the pitching motion and it is not known whether patterns of energy flow are related to pitching performance and injury risk. Therefore, the purpose of this study was to quantify energy generation, absorption, and transfer across the shoulder and elbow during the baseball pitch and explore the associations between these energetic measures, pitch speed, and traditional measures of upper extremity joint loading. The kinematics of 40 youth baseball pitchers were measured in a controlled laboratory setting. Energy flow between the thorax, humerus, and forearm was calculated using a segmental power analysis. Regression analyses revealed that pitch speed was best predicted by arm cocking phase shoulder energy transfer to the humerus and peak elbow valgus torque was best predicted by arm acceleration-phase elbow energy transfer to the forearm. Additionally, energy transfer across the shoulder and elbow generally exhibited the strongest correlations to pitch speed and upper extremity joint loads. These data reinforce the importance of energy transfer through the kinetic chain for producing high pitch speeds and provide descriptive data for energy flow during baseball pitching not previously found in the literature.

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KEYWORDS
Elbow valgus; energy flow; injury; kinetic chain; performance; segment power

Introduction

Baseball pitching performance is predicated on the generation and transfer of mechanical energy from larger proximal segments, such as the lower extremities and thorax, to smaller distal segments. Due to the pitching motion's ballistic nature, the upper extremity musculature and passive restraints are subjected to large amounts of tensile stress as energy is funnelled from the thorax through the pitching arm (Fleisig et al., 1995). Ultimately, the goal is to pass as much of this energy as possible into the baseball before ball release (BR) to propel the ball at maximal speed towards home plate. Following BR, the remaining energy is dissipated as the throwing arm decelerates during the pitcher's follow-through, subjecting the posterior shoulder musculature to substantial eccentric stress as it attempts to control humeral distraction, internal rotation, and horizontal adduction (Escamilla & Andrews, 2009; Laudner et al., 2012).

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Despite extensive research into pitching mechanics at the youth level, pitching arm injuries continue to occur at alarming rates (Melugin et al., 2018; Zaremski & Krabak, 2012). Overuse injuries to the shoulder and elbow are of particular concern to coaches and clinicians as they are among the most common injuries and pitchers typically require extensive time away from practice and competition to heal (Wong et al., 2017; Zaremski & Krabak, 2012). Common shoulder and elbow overuse injuries in youth pitchers include Little League elbow, Osteochondritis Dissecans, biceps and rotator cuff tendonitis, and internal impingement (Wong et al., 2017; Zaremski & Krabak, 2012).

Traditionally, the loads placed on the shoulder and elbow during pitching have been described using individual orthogonal components of the net joint force or torque (Fleisig et al., 1995, 2018). The external rotation torque at the shoulder and valgus torque at the elbow have garnered much of the attention in previous research due to their anatomical relevance to commonly injured structures at the shoulder and elbow (i.e., glenoid labrum and ulnar collateral ligament) (Chalmers et al., 2017). However, despite their extensive description and application, individual kinetic measures have yet to show a significant ability to help identify pitchers at greater risk of injury (Agresta et al., 2019). Moreover, kinematic changes related to decreases in shoulder and elbow joint loading are also often associated with decreases in pitch speed, limiting their clinical applicability to coaches and players (Howenstein et al., 2019).

Examination of mechanical energy flow between body segments has recently gained popularity as a technique for further investigation of the associations between pitching mechanics, performance, and injury risk (A. Aguinaldo & Escamilla, 2019; A. L. Aguinaldo & Escamilla, 2020; Howenstein et al., 2019; Kimura et al., 2020). Studies have shown associations between various thorax and pitching arm energy flow measures with pitch speed and normalised joint loads, indicating a potential to complement traditional biomechanical analyses (A. Aguinaldo & Escamilla, 2019; Howenstein et al., 2019). However, prior energy flow examinations have focused on more aggregate measures such as peak segment power or segmental inflow and outflow at the whole segment level. Because energy can be simultaneously exchanged at both of a segment's endpoints, whole segment energy flow analyses may miss crucial energy flow patterns at individual segment ends and underestimate the magnitudes of proximal and distal energy flow within individual segments. Additionally, the examination of energy inflow and outflow over time does not indicate whether energy is being transferred to/from the adjacent segment or generated/absorbed by structures surrounding the joints.

Examination of proximal and distal energy flow within individual segments and separation of energy flow into its transfer, generation, and absorption components may provide additional insight into the associations between pitching mechanics, performance, and injury risk. Additionally, differentiating between energy generation, absorption, and transfer during the baseball pitch has not been attempted to date and could increase understanding of the stresses experienced by the structures surrounding the shoulder and elbow joints. Therefore, the purpose of our study was to quantify how much and at what rates energy is generated, absorbed, and transferred across the shoulder and elbow during the pitching motion and explore the associations between these energetic measures, pitch speed, and common measures of upper extremity joint loading in a sample of youth baseball pitchers. We hypothesised that increased pitch speed and increased joint loading would be associated with increased proximal-to-distal energy flow during the arm cocking and arm acceleration phases and increased distal-to-proximal energy flow during the arm deceleration phase.

Methods

Participants

Forty youth baseball pitchers were included in this study. Participants were retrospectively chosen from a database of local youth baseball pitchers. Inclusion criteria included no upper extremity injuries in the 6 months prior to data collection, no history of surgery to the upper extremity, and participation on a competitive, age-appropriate baseball team at the time of data collection. The mean age, height, and weight of participants was 15.7 ± 1.7 years, 1.78 ± 0.11 m, and 74.1 ± 14.2 kg. All testing protocols were approved by the University's Institutional Review Board and all players and parents provided written informed assent and consent prior to data collection.

Data collection

Participants reported to the laboratory prior to engaging in any throwing or vigorous physical activity on the day of testing. Following an overview of testing procedures, 14 electromagnetic sensors (Flock of Birds; Ascension Technologies Inc., Burlington, VT, USA) were affixed to the skin at the following locations: (1) posterior aspect of the thorax at the first thoracic vertebrae (T1) spinous process; (2) posterior aspect of the pelvis at the first sacral vertebrae (S1); (3–4) flat broad portion of the acromion on the bilateral scapula; (5–6) lateral aspect of the bilateral upper arm at the deltoid tuberosity; (7–8) posterior aspect of the distal bilateral forearm, approximately halfway between the radial and ulnar styloid processes; (9) dorsal aspect of the throwing-side hand, approximately halfway along the third metacarpal; (10–11) lateral aspect of the bilateral thigh, approximately halfway between the greater trochanter and lateral condyle of the knee; (12–13) lateral aspect of the bilateral shank, approximately halfway between the lateral condyle of the knee and lateral malleolus; (14) dorsal aspect of the non-throwing side foot, approximately halfway along the second metatarsal. Sensors were affixed to the skin using double-sided cohesive tape and then covered in a flexible adhesive stretch tape to ensure they remained secure throughout testing. A 15th sensor was affixed to a moveable plexiglass stylus for the digitisation of bony landmarks to develop a linked-segment model of the pitching arm and thorax consistent with International Society of Biomechanics recommendations (Wu et al., 2002, 2005).

After sensor attachment and segment digitisation, participants were offered an unlimited amount of time to warm up in preparation for full-effort pitching. Individual warm-up routines were allowed so that each participant could most closely mimic their in-game effort levels (Wasserberger et al., 2020). Once participants indicated they were ready, they pitched three, full-effort, fastball pitches from a pitching mound for strikes to a catcher at an age-appropriate regulation distance (between 14.0 and 18.4 m). Pitch speed was recorded to the nearest mile per hour using a calibrated radar gun (StalkerPro II; Stalker Radar; Plano, TX, USA). Sensor positions and orientations were collected at 238 Hz using an electromagnetic tracking device (trakSTAR™, Ascension Technologies

Inc.; Burlington, VT, USA) synchronised with The MotionMonitor software (Innovative Sports Training; Chicago, IL, USA).

Data processing

The fastest of the three pitches thrown by each participant was selected for analysis. Raw sensor position and orientation data were filtered using a fourth-order Butterworth low-pass filter with a cut-off frequency of 15.2 Hz (Yu et al., 1999). Since the focus of this study was on the shoulder and elbow joints, only the data for the thorax, pitching arm humerus, and pitching arm forearm were processed. The joint centres for the wrist and elbow were defined as the midpoint between the ulnar and radial styloids and the midpoint between the medial and lateral humeral epicondyles, respectively (Wu et al., 2005). The shoulder joint centre was estimated using the functional method (Biryukova et al., 2000; Meskers et al., 1999). Relevant kinematic and kinetic parameters were calculated using top-down equations provided in The MotionMonitor software (Winter, 1990; Zatsiorsky & Seluyanov, 1983) and then exported for further processing in MATLAB (described below) to calculate energy generation, absorption, and transfer across the shoulder and elbow joints (MATLAB version 2020a; MathWorks; Natick, MA, USA). Shoulder external rotation torque was defined as the torque applied by the humerus on the thorax about the positive longitudinal humeral axis (A. L. Aguinaldo et al., 2007). Elbow valgus torque was defined as the torque applied by the forearm on the humerus about the anterior forearm axis (Elliott et al., 2003). Upper extremity torques for right-handed pitchers were scaled by −1 to simplify the interpretation of correlation and regression analyses.

Prior to analysis, the pitching motion was divided into three phases consistent with previous research examining the baseball pitching motion (arm cocking phase, arm acceleration phase, and arm deceleration phase). The arm cocking phase was defined as the time between stride foot contact (SFC) and maximal external rotation of the throwing shoulder (MER) and the arm acceleration phase was defined as the time between MER and ball release (BR). The arm deceleration phase started at BR and ended 0.1 seconds after maximal internal rotation (MIR) of the throwing shoulder in order to examine the demands of controlling not only humeral rotation but also distraction and horizontal adduction during the pitcher's follow-through. Stride foot contact was identified using an in-ground, non-conductive force plate embedded into the pitching surface (Bertec 4060 NC sampled at 1200 Hz; Bertec Corp.; Columbus, OH, USA) and was defined as the first frame in which a non-zero ground reaction force was observed (Washington et al., 2018). Ball release was defined to be coincident with peak angular velocity of the hand segment in the global reference frame (Naito et al., 2019). Both MER and MIR were identified by the local minimum and maximum of humeral long-axis rotation between SFC and BR which was defined relative to the thorax using a Y-X'-Y" Euler rotation sequence (Wu et al., 2005).

Calculation of energy generation, absorption, and transfer

Patterns of energy generation, absorption, and transfer at the shoulder and elbow during the pitching motion were calculated using the segment power analysis methodology developed by Robertson and Winter (Robertson & Winter, 1980). Using this methodology, the rate at which energy enters or leaves a segment via the joint force and joint torque is estimated and then further partitioned into generation, absorption, and transfer at each measured frame depending on the relative sign and magnitude of energy entering or leaving neighbouring segments (Table 1).

The rate at which energy entered or left a segment via the joint force (joint force power; JFP) was defined as the scalar product of the joint force and joint linear velocity vectors (Equation (1)). Because adjacent segments share the same joint linear velocity vector but have opposite joint force vectors at their common joint, JFPs are equal in magnitude and opposite in sign across a joint. Therefore, JFPs represent only energy transfer between segments. Positive JFP values indicate energy entering (or work being done on) the segment via the joint force. Negative JFP values indicate energy leaving (or work being done by) the segment via the joint force. The rate at which energy enters or leaves a segment via the joint torque (segment torque power; STP) was defined as the scalar product of the joint torque and segment angular velocity vectors (Equation (2)). Unlike JFPs, STPs are not necessarily equal and opposite due to different angular velocities of adjacent segments. Therefore, STPs can indicate energy generation or absorption by the structures surrounding the joint in addition to energy transfer (Table 1).

$$JFP = \vec{F}_{ij} \cdot \vec{v}_j \tag{1}$$

where $\vec{F}_{ij}$ is the joint reaction force vector acting on segment i at joint j and $\vec{v}_j$ is the linear velocity vector of joint j in the global reference frame.

$$STP = \vec{\tau}_{ij} \cdot \vec{\omega}_i \tag{2}$$

where $\vec{\tau}_{ij}$is the joint torque vector acting on segment i at joint j and $\vec{\omega}_i$is the angular velocity (in radians per second) of segment i in the global reference frame.

To estimate the patterns of energy generation, absorption, and transfer across the shoulder and elbow joints, JFPs and STPs for the distal thorax (throwing-side shoulder endpoint), proximal and distal humerus, and proximal forearm were calculated. At each measured frame, the JFP of proximal humerus represented the rate of energy transfer across the shoulder by the shoulder joint force. Likewise, the JFP of the proximal forearm represented the rate of energy transfer across the elbow by elbow joint force. Depending on their signs and relative magnitudes, adjacent STPs represented some combination of generation, absorption, or transfer across the shoulder and elbow as described by Robertson and Winter (Table 1). Net energy transfer (hereafter referred to simply as *energy transfer*) across the shoulder and elbow was defined as the sum of the energy transfer by JFP and STP.

Partitioning energy flow across the shoulder and elbow into generation, absorption, and transfer resulted in new time-series data which were then analysed during phases of interest throughout the pitching motion. The total amounts of energy transfer, generation, or absorption across the shoulder and elbow during the arm cocking, arm acceleration, and arm deceleration phases were estimated by isolating the positive and negative curve regions and integrating the appropriate power curves between the events that define the arm cocking (SFC to MER), arm acceleration (MER to BR), and

Table 1. Breakdown of energy generation, absorption, and transfer via joint moment depending on sign and relative magnitude as outlined by Robertson and Winter.[a,b]

Same Sign	Generation	Absorption	Transfer
Both positive	JMP_p TO proximal segment JMP_d TO distal segment	0	0
Both negative	0	JMP_p FROM proximal segment JMP_d FROM distal segment	0
Opposite Sign			
$\lvert JMP_p \rvert > \lvert JMP_d \rvert$			
JMP_p positive JMP_d negative	$JMP_p + JMP_d$ TO proximal segment	0	JMP_d TO proximal segment
JMP_p negative JMP_d positive	0	$JMP_p + JMP_d$ FROM proximal segment	JMP_d TO distal segment
$\lvert JMP_d \rvert > \lvert JMP_p \rvert$			
JMP_p positive JMP_d negative	0	$JMP_p + JMP_d$ FROM distal segment	JMP_p TO proximal segment
JMP_p negative JMP_d positive	$JMP_p + JMP_d$ TO distal segment	0	JMP_p TO distal segment

[a]JMP_d = distal joint moment power; JMP_p = proximal joint moment power.
[b]Robertson and Winter (1980): Mechanical Energy Generation, Absorption, and Transfer Amongst Segments During Walking. J. Biomechanics Vol. 13. pp. 845–854.

deceleration (BR to MIR) phases. For the energy transfer time series, positive values indicated distal energy transfer and negative values indicated proximal energy transfer (Figures 2 and 3, top). For the energy generation/abosorption time series, positive values indicated energy generation while negative values indicated energy absorption (Figures 2 and 3, bottom). The peak rate of energy transfer was estimated by identifying the local maximum of the shoulder and elbow energy transfer time series. The peak rates of energy generation and absorption were estimated by identifying the local maximum (generation) and minimum (absorption) of the shoulder and elbow generation time series. Energy calculations were performed such that positive power represented distal energy transfer (i.e., from the thorax across the shoulder to the humerus and from the humerus across the elbow to the forearm) and negative power values represented proximal energy transfer (i.e., from the humerus across the shoulder to the thorax and from the forearm across the elbow to the humerus).

Statistical analysis

Variables of interest included pitch speed, peak shoulder external rotation torque and peak elbow valgus torque as well as the total amounts and peak rates of energy transfer, generation, and absorption across the shoulder and elbow during the arm cocking, arm acceleration, and arm deceleration phases of the pitching motion. Bivariate associations between energy parameters and pitch speed were estimated using Pearson product-moment correlations. To determine which energy measures were most predictive of pitch speed and upper extremity torques, body mass, height, and energy parameters were entered into forward regressions models to determine the linear models that best predict 1) pitch speed, 2) peak shoulder external rotation torque, and 3) peak elbow valgus torque.

In each regression model, body height and weight were entered first into the model to estimate the proportion of variance accounted for by anthropometrics. The additional predictive value of energy flow parameters above and beyond the predictive effects of body mass and height were assessed using the change in variance accounted for by the model (Δr^2) and the proportional reduction in model error (η_p^2). Energy flow parameters, shoulder external rotation torque, and elbow valgus torque were not normalised to participant anthropometrics. We chose to not normalise given the potential issues of ratio measures in regression analyses (Allison et al., 1995; Curran-Everett, 2013), to better isolate the additional predictive value of energy flow measures beyond the predictive value of participant anthropometrics (Judd et al., 2009), and to ease interpretation of regression model coefficients. Model residuals were assessed for normality and multicollinearity between predictor terms was monitored using the variance inflation factor. To account for multiple regression analyses, a Bonferroni correction was applied *a priori* to the threshold for allowing energy parameters to enter the models ($\alpha = .016$). All statistical tests were performed in RStudio (R version 3.6.1).

Results

The mean pitch speed in our sample was 31.3 ± 3.9 m/s (70.1 ± 8.7 mph). The mean peak shoulder external rotation torque was 76.4 ± 24.6 Nm (5.8 ± 1.4% bodyweight•height) and the mean peak elbow valgus torque was 72.1 ± 28.2 Nm (5.6 ± 1.8% bodyweight•height). Descriptive statistics of energy generation, absorption, and transfer at the shoulder and elbow by pitching phase are presented in Figure 1 and ensemble average

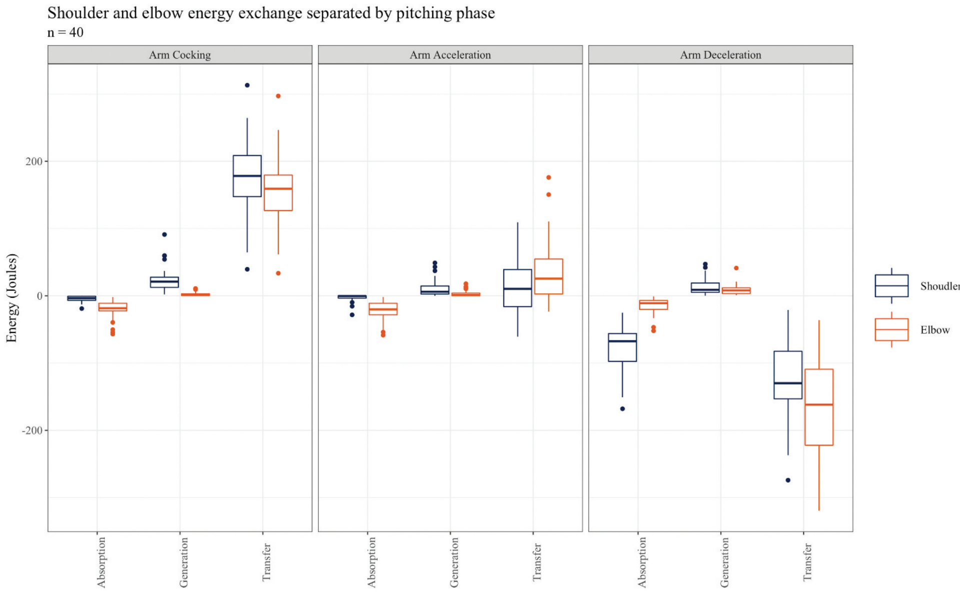

Figure 1. Descriptive boxplot of energy exchange at the shoulder and elbow separated by phase.

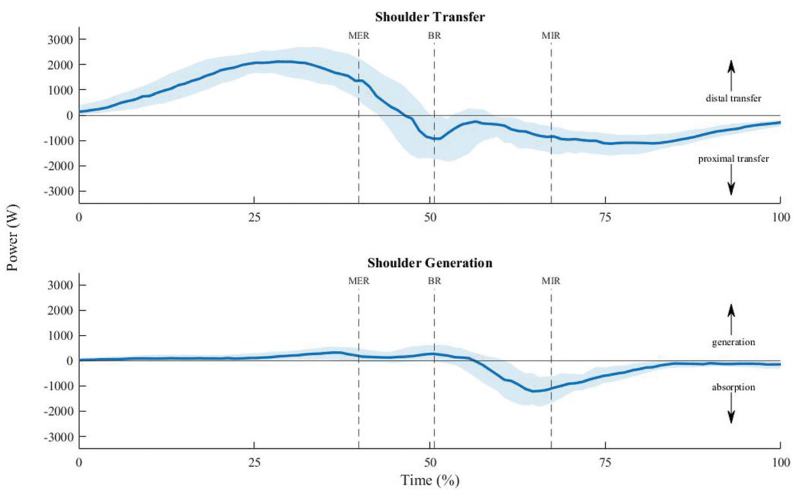

Figure 2. Energy transfer (top) and generation (bottom) across the shoulder joint vs. time (0% = stride foot contact; 100% = 0.1 seconds following MIR). Solid line represents the median value and the error cloud represents the inter-quartile range. Dashed lines represent the mean timing of pitching events. BR = ball release; MER = maximum humeral external rotation; MIR = maximum humeral internal rotation. John Onofrey (2020). Shaded Plots and Statistical Distribution Visualisations (https://www.mathworks.com/matlabcentral/fileexchange/69203-shaded-plots-and-statistical-distribution-visualisations), MATLAB Central File Exchange.

Table 2. Pearson product-moment correlations between energy parameters and pitch speed (n = 40).

Generation	*Arm Cocking*	Arm Acceleration	Arm Deceleration	Peak Rate
Shoulder	.324*	.032	.006	.281
Elbow	.144	−.053	.195	.162
Absorption				
Shoulder	.097	−.130	−.603***	−.461**
Elbow	−.500***	−.192	−.058	−.244
Transfer				
Shoulder	.717***	.172	−.553***	.577***
Elbow	.657***	.132	−.582***	.512***

*p < .05
**p < .01
***p < .001

Table 3. Pearson product-moment correlations between energy parameters and peak shoulder external rotation moment (n = 40).

Generation	*Arm Cocking*	Arm Acceleration	Arm Deceleration	Peak Rate
Shoulder	.066	.254	.139	.187
Elbow	−.043	−.071	.064	.122
Absorption				
Shoulder	−.132	.071	−.150	−.084
Elbow	−.341*	−.311*	−.174	−.317*
Transfer				
Shoulder	.550***	.322*	−.516***	.440**
Elbow	.416**	.486**	−.432**	.449**

*p < .05
**p < .01
***p < .001

Table 4. Pearson product-moment correlations between energy parameters and peak elbow valgus moment (n = 40).

Generation	*Arm Cocking*	Arm Acceleration	Arm Deceleration	Peak Rate
Shoulder	.089	.325*	.207	.244
Elbow	.026	.143	.047	.106
Absorption				
Shoulder	−.202	.084	−.181	−.186
Elbow	−.315*	−.281	−.317*	−.356*
Transfer				
Shoulder	.443**	.413**	−.456**	.444**
Elbow	.300	.590***	−.404**	.469**

*p < .05
**p < .01
***p < .001

time series for energy generation, absorption, and transfer are presented in Figures 2 and 3. Bivariate correlations between energy parameters, pitch speed, and upper extremity joint loads are presented in Tables 2–4.

Regression analyses showed that body mass and height predicted 38.1%, 36.5%, and 23.0% of the variance in pitch speed, shoulder external rotation torque, and elbow valgus torque, respectively. The predictive models for pitch speed and elbow valgus torque were improved by adding energy flow parameters. Pitch speed was best predicted by arm cocking phase shoulder transfer and peak elbow valgus was best predicted by arm acceleration-phase elbow transfer. No energy flow parameters improved the model for shoulder external rotation torque. The additional predictive value of significant energy flow parameters as well as relevant regression model statistics and effect sizes are presented in Table 5. On average, the pitch speed model predicted about a 1 mph increase in pitch speed for every 10 J increase in shoulder transfer during the arm cocking phase. Additionally, the pitch speed model predicted a 3.3 Nm increase in peak elbow valgus torque for every 10 J increase in energy transfer across the elbow during the arm acceleration phase. The root mean square errors of the pitch speed, peak shoulder external rotation torque and peak elbow valgus torque models were 5.5 mph, 20.1 Nm, and 21.5 Nm.

Discussion and implications

This study is the first to examine patterns of energy generation, absorption, and transfer across the shoulder and elbow in a sample of youth baseball pitchers and model the associations between energy flow measures, pitch speed, and traditional measures of shoulder and elbow joint loading. Our findings indicate that energy transfer was the predominant method of energy flow across the shoulder and elbow before and following BR. This is in agreement with previous research suggesting that the majority of energy generation occurs in the proximal kinetic chain rather than in the pitching arm (A. L. Aguinaldo & Escamilla, 2020; Chu et al., 2016; Naito et al., 2017). Additionally, the amount and peak rate of energy transfer across the shoulder and elbow generally exhibited the strongest correlations to pitch speed, peak shoulder external rotation torque, and peak elbow valgus torque, which is in support of our original hypothesis (Tables 2–4). These data provide a descriptive reference regarding the amounts and peak rates of energy transfer, generation, and absorption not previously found in the literature and reinforce the importance of energy transfer through the kinetic chain for producing maximal pitch speeds.

Patterns of energy flow at the shoulder and elbow

Arm cocking was characterised by large amounts of energy transfer distally through the shoulder and elbow as the thorax rotated towards home plate following SFC (Figures 2 and 3). During this phase, pitchers transferred 177 ± 54 J of energy across the shoulder to the humerus and 155 ± 49 J of energy across the elbow to the forearm. The prominence of energy transfer opposed to generation or absorption is consistent with Kimura et al., who demonstrated energy transfer from the torsional torques across the lumbosacral and thoracolumbar joints was responsible for the majority of energy flow from the pelvis to the upper thorax (Kimura et al., 2020). In the present study, maximum rates of distal energy transfer were also highest during arm cocking, reaching 2,952 ± 1,381 and 3,516 ± 1,637 W (39.3 and 46.6 W/kg) at the shoulder and elbow, respectively. These values are considerably higher than those reported by Aguinaldo and Escamilla, who reported normalised peak upper arm and forearm powers for high school pitchers of 14 and 17 W/kg, and Naito et al. who reported peak upper arm and forearm powers of approximately 1,500 and 2,000 W (A. Aguinaldo & Escamilla, 2019; Naito et al., 2011). One potential reason for the observed difference between whole and proximal

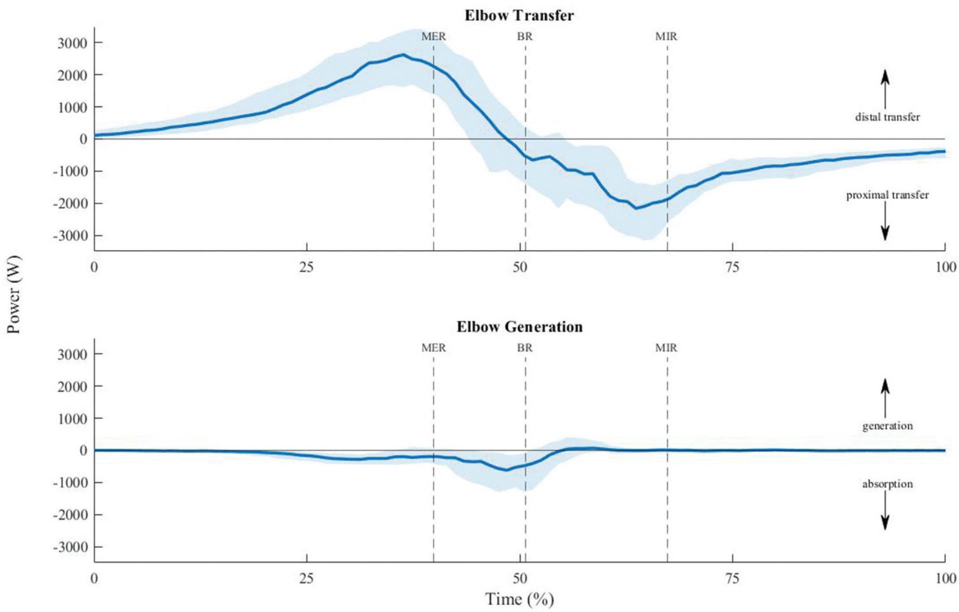

Figure 3. Energy transfer (top) and generation (bottom) across the elbow joint vs. time (0% = stride foot contact; 100% = 0.1 seconds following MIR). Solid line represents the median value and the error cloud represents the inter-quartile range. Dashed lines represent the mean timing of pitching events. BR = ball release; MER = maximum humeral external rotation; MIR = maximum humeral internal rotation. Plot produced using John Onofrey (2020). Shaded Plots and Statistical Distribution Visualisations (https://www.mathworks.com/matlabcentral/fileexchange/69203-shaded-plots-and-statistical-distribution-visualisations), MATLAB Central File Exchange.

Table 5. Forward regression analysis results[a]

Pitch Speed	B	Δr^2	η_p^2
Cocking Phase Shoulder Transfer	.104 (.061; .147)	.246	.397
Peak External Rotation Moment			
	No significant predictors		
Peak Valgus Moment			
Acceleration Phase Elbow Transfer	.330 (.161; .499)	.234	.304

[a]B = unstandardised regression coefficient [estimate (95% CI)]; Δr^2 = change in model r^2 above body mass and height; η_p^2 = proportional reduction in model error

segment powers is opposing energy flow at a segment's opposite ends. If occurring simultaneously, proximal inflow and distal outflow (or proximal outflow and distal inflow) will undergo wave interference, cancelling each other out and resulting in lower observed power when measured at the whole-segment level.

To test this hypothesis, we performed a post-hoc analysis of our participants' peak humerus and forearm segment power inflows and outflows. The average peak humerus and forearm segment power inflows for pitchers in the present study were 1,076 W (14.4 W/kg) and 1,693 W (22.1 W/kg) and the average peak humerus and forearm segment power outflows were −1,365 W (−18.4 W/kg) and −2,256 W (−30.1 W/kg). These values are consistent with those reported by Aguinaldo and Escamilla (A. Aguinaldo & Escamilla,

2019) as well as Naito et al. (2011), indicating that the energetic profiles of the pitchers in the present study were similar to those from previous studies. Consequently, when measured at the whole-segment level, it appears that energy inflow and outflow underestimate the demands placed on the tissues surrounding the shoulder and elbow joints.

During arm acceleration, rates of distal energy transfer at the shoulder and elbow decreased, and the rate of energy absorption at the elbow increased, reaching a peak of −1,398 ± 746 W prior to BR. Increased energy absorption at the elbow was likely facilitated by passive restraints surrounding the elbow joint and eccentric activity of the elbow flexors as they controlled elbow extension (Buffi et al., 2015; Digiovine et al., 1992). Arm deceleration was characterised by energy dissipation as large amounts of energy were transferred proximately out of the pitching arm through the elbow (168 ± 72 J) and shoulder (129 ± 61 J). Also observed was a large amount of energy absorption at the shoulder (79 ± 36 J), likely from the posterior shoulder girdle musculature eccentrically controlling throwing arm distraction, internal rotation and horizontal adduction after BR. Interestingly, a considerable portion of the shoulder absorption occurred during later portions of the deceleration phase, following MIR. Although initial studies examined shoulder mechanics through the entirety of the pitcher's follow through (Fleisig et al., 1995), more recent studies have quantified the demands of arm deceleration by analysing shoulder kinetics between BR and MIR (Escamilla et al., 2017; Fleisig et al., 2011). By stopping their analyses at MIR, these studies may have missed stresses placed on the posterior shoulder not related to humeral rotation, but that still play a role in the health of the deceleration musculature and connective tissue. Indeed, repeated energy absorption at the shoulder following MIR may help explain the posterioinferior capsular hypertrophy commonly seen in pathologic overhead throwing alterations like glenohumeral internal rotation deficit (Bakshi & Freehill, 2018; Kay et al., 2018).

Associations between energy flow, pitch speed, and upper extremity joint loads

Energy transfer across the shoulder during the arm cocking phase accounted for almost twice the variance in pitch speed compared to peak shoulder external rotation torque (51% vs. 30%) suggesting increased energy transfer at the shoulder was more closely associated with improved pitching performance than increased shoulder joint loading in our sample. Although body mass and height accounted for 38.1% of variance in pitch speed and 36.5% of shoulder external rotation torque, cocking phase shoulder energy transfer improved the model for pitch speed by approximately 40% but did not improve the model for shoulder external rotation torque. These results suggest that, while pitch speed and shoulder external rotation torque were similarly influenced by anthropometrics in our sample, pitch speed was more influenced by energy transfer across the shoulder. One potential explanation is that the more skilled pitchers in our sample employed different mechanical strategies to more effectively transfer energy across the shoulder to produce higher pitch speeds while minimising concurrent increases in shoulder external rotation torque.

Peak elbow valgus torque was most closely associated with energy transfer across the elbow during the arm acceleration phase. After accounting for body mass and height, arm acceleration phase energy transfer across the elbow accounted for an additional 23.4% of the variance in peak elbow valgus torque and reduced model error by 30.4%. Interestingly, elbow energy transfer during arm acceleration was not associated with pitch speed, potentially indicating a mechanical pattern that increases elbow joint loading without necessarily increasing pitch speed.

That body anthropometrics accounted for a significant proportion of variance in pitch speed, shoulder external rotation torque, and elbow valgus torque is not suprising. Particularly in youth, where body weight and height are more varied than in older and more skilled populations, bigger and taller pitchers tend to throw with higher pitch speed and experience larger shoulder and elbow joint loads (Fleisig et al., 1999, 2018). Therefore, separation of the predictive effect of participant anthropometrics from the predictive effects of our measures of interest (i.e., energy flow parameters) was an important step in isolating the value of energy flow analyses for performance and injury risk evaluations.

Limitations and future directions

While our study provides novel insight regarding the modes of energy flow across the shoulder and elbow in a diverse sample of youth baseball pitchers, it is not without limitations. The mean pitch speed of our sample was 31.3 m/s (70.1 mph). Although this speed is comparable to other studies on pitchers of similar ages (Fleisig et al., 2018), it is considerably lower than those previously reported by collegiate and professional pitchers (Bushnell et al., 2010; Fleisig et al., 2006). Research has shown differences in the timing and magnitude of kinematic (A. L. Aguinaldo et al., 2007) and kinetic (A. Aguinaldo & Escamilla, 2019) parameters between levels of play, and energy flow is likely no exception. Caution is therefore encouraged when attempting to apply our findings to more skilled pitchers. Furthermore, while the large age range (11–18 years old) in our sample allows generalisability of our findings to a broader range of youth pitchers, it resulted in considerable variability in energy measures, particularly when not normalising for anthropometrics. Additionally, while we did use conventional anthropometic norms for kinetic calculations, future studies using individually derived segment mass and inertia parameters may provide improved results as recently reported DXA-driven analyses suggest that joint kinetics are sensitive to pitcher-specific segmental properties (Sterner et al., 2020).

We attempted to minimise the effect of a controlled laboratory setting by allowing self-selected warm-up protocols. Nevertheless, the non-game environment, along with unfamiliarity with laboratory equipment, likely resulted in lower pitch speeds compared to what pitchers would normally achieve in game settings which could, in turn, affect calculated energy flow. Lastly, while our study provides a detailed analysis of the two most commonly injured joints in youth pitchers, we felt that examination of the entire kinetic chain was outside our current scope. Future research should examine the influence of the pelvis and lower extremities on upper extremity energy flow as well as the kinematic strategies that influence shoulder and elbow energy transfer and their effects on pitch speed and upper extremity joint loading to develop possible technique interventions in youth pitchers.

Conclusions

This study separated the flow of mechanical energy across the shoulder and elbow during the baseball pitch into energy generation, absorption, and transfer. In doing so, we hoped to provide additional insight into the stresses experienced by two commonly injured joints in youth baseball pitchers. We hypothesised that increased proximal-to-distal energy flow prior to ball release and increased distal-to-proximal energy flow following ball release would be associated with increased pitch speeds and increased upper extremity joint loading. Our results supported our hypothesis in that several measures of energy transfer were correlated with pitch speed, shoulder external rotation torque, and elbow valgus torque. Therefore, this study supported previous work that found energy transfer was the predominant method of energy flow through the pelvis and trunk (Kimura et al., 2020). This study also provided the first descriptive data regarding magnitudes and rates of energy generation, absorption, and transfer during the baseball pitch.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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