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Energy Flow Analysis to Investigate Youth Pitching Velocity and Efficiency

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Abstract

Purpose

The purposes of this study were 1) to investigate the transfer of energy through the kinetic chain by youth baseball pitchers during the pitching motion and 2) to provide insight into how the total magnitude of energy flow and its linear and rotational components relate to both velocity and joint torque per unit increment of pitch velocity (joint load efficiency).

Methods

Twenty-four youth baseball pitchers participated in this study. Data collection occurred in an indoor research laboratory equipped with a 14-camera infrared motion capture system and an instrumented pitcher's mound with embedded force plates. Energy flow was calculated by integrating power transfer into and out of each segment. The magnitudes of key instances of energy flow were compared to pitch velocity and velocity-normalized joint torques using simple linear regressions.

Results

All of the energy flow variables calculated had a significant correlation to pitch velocity. Energy flow into the arm from the trunk had the strongest correlation to velocity of any variable investigated ($r = 0.900$, $P = 0.000$). The total magnitude of energy flow into the trunk had a significant correlation to increased horizontal shoulder adduction efficiency and shoulder internal rotation efficiency. The magnitude of energy flow into the trunk by only joint forces had a significant correlation to increased horizontal shoulder adduction efficiency, shoulder internal rotation efficiency, and elbow varus efficiency.

Conclusions

Energy flow analysis is an effective tool providing quantitative assessment of the kinetic chain to gain a deeper understanding of how energy moves through an athlete, and how specific pitching mechanics impact this movement. The results of this study support the importance of generating energy flow throughout the body to produce high velocities and energy flow through the trunk to increase pitch efficiency.

In baseball pitching, shoulder and elbow injuries are prevalent given the ballistic nature of the motion (1,2). Certain overuse injuries that were once predominantly seen in older pitchers, such as ulnar collateral ligament injury, have begun to permeate to younger athletes (1,3–7). Proposed explanations for the rise of injuries at the youth level have included a greater volume of pitches thrown, playing year-round baseball, playing for multiple teams, early specialization, and increased pressure to perform at a young age (1,3,4,8,9). Multiple studies have investigated youth pitching kinematics and joint kinetics; however, there is still no consensus on optimal pitching technique for youth pitchers, especially given the unique aspects of the developing musculoskeletal system (2,6,7,10–17). Because repetitive microtrauma may lead to acute injuries, understanding how youth pitchers can achieve high-performance levels with minimal joint loads could yield important information to help reduce the risk of injury in these athletes (2,10–12,18,19).

Baseball pitching is an application of an open kinetic chain. Pitchers begin by generating mechanical energy in the lower extremities and transfer it through the trunk and into their dominant arm, ultimately propelling the ball toward home plate (20,21,22). Optimal transfer of energy between segments is critically dependent on the correct muscle activation and timing of sequential steps during the pitching motion (10,19,20). It has also been proposed that less optimal management of the kinetic chain earlier in the delivery may subject the pitcher to larger upper-extremity joint torques (19,21,23,24). On the other hand, an optimal, or more efficient, pitching technique would be characterized by higher-energy generation and transfer coupled with relatively low shoulder and elbow joint torques (10,11,19).

Multiple studies have documented the importance of the kinetic chain and the timing of key events during the pitching motion (10,19,20,22,25). However, the tools used to evaluate the sequence and timing of movements of the body during the baseball pitching motion have been limited. These analyses have focused primarily on correlations between the magnitude of peak rotational velocities, timing of key kinematic events, and the duration of specific phases in relation to upper-extremity kinetics or ball velocity (10–12,18,19).

Energy flow (EF) analysis is a technique that offers certain advantages over the standard motion analysis techniques of previous research studies. Energy flow analysis is an extension upon a segment power analysis that quantifies how energy is both generated and transferred among body segments ([26,27]). Therefore, it allows researchers to determine how energy is generated and the direction, method, and efficiency by which it is transferred through the kinetic chain. Additionally, EF analysis can calculate the contribution of individual joint contact forces and joint torques to the transfer, generation, or absorption of energy across a joint. These components of the total EF allow for an additional depth of insight that could be particularly useful in baseball pitching because it involves both linear and rotational motion of a large number of body segments. Understanding the relative contributions of linear and rotational energy of individual body segments could lead to greater understanding into the interconnected aspects of pitching mechanics overall.

Energy flow analysis has been previously used to investigate the tennis serve ([26]), which is single-arm, open kinetic chain movement similar to pitching. The study found that athletes who transferred more energy from their trunk into their dominant arm not only had higher serve velocities but also were less likely to suffer overuse injuries. This finding provided some of the first empirical evidence that higher serve speeds are not necessarily related to greater loads on the arm or greater risks for injury.

Previous pitching research looking at youth athletes has largely focused on how upper-extremity and trunk kinematics relate to either shoulder and elbow joint loading or to ball velocity. These studies have found that larger athletes with higher pitch velocities are subjected to higher joint loads and increased risk for injury ([1,4,8,9,28,29]). Additionally, many of the kinematic parameters that relate to reduced joint loading are also related to a decrease in ball velocity ([6,19,30]). In short, previous studies have either identified nonmodifiable factors that relate to pitch velocity, or factors that improve pitch safety at the expense of pitch velocity. These findings are difficult for coaches and players to use, because they are forced to weigh the tradeoffs between performance and safety. Investigating joint loads with respect to pitch velocity, as the athlete's peak joint moment per mph of pitch velocity, for example, would provide an indicator of pitch efficiency and would allow coaches to evaluate the effects of pitch mechanics on both performance and indicators of injury risk ([11,18,19]).

The purposes of this study were ([1]) to investigate the transfer of energy through the kinetic chain by youth baseball pitchers during the pitching motion and ([2]) to provide insight into how the total magnitude of energy flow and its linear and rotational components relate to both pitching efficiency and velocity. The long-term goal of this project is to gain a better understanding of the underlying mechanics of energy transfer through the kinetic chain and to identify whether certain techniques can lead to improved velocity and decreased injury risk in youth pitchers.

Methods and Materials

Participants.

Twenty-four youth baseball pitchers, 19 right-handed and 5 left-handed, participated in this study. The subjects for this convenience sample were recruited by word of mouth through local youth baseball coaches. Athletes were asked to fill out an initial screening questionnaire regarding pitching injury history and their experience level. All pitchers were between the ages of 9 and 13 yr and had at least 1 yr of prior pitching experience. Exclusion criteria included any injury that affected their ability to pitch, or an unorthodox throwing motion as determined by the research team. No subjects were ultimately excluded based on the criteria. Upon arriving at the laboratory, the subjects and guardian were asked to sign an informed consent and assent documents before any testing occurred. The use of human subjects was approved by the institutional review board at Marquette University.

Instrumentation.

All testings occurred in an indoor research laboratory equipped with a 14-camera infrared motion capture system at 250 Hz (Vicon, Oxford, UK) and a custom pitcher's mound containing two embedded force plates

(Kistler, Winterthur, Switzerland); one under the pitching rubber and one under the landing area. The force plate under the landing area was mounted on an aluminum track that allowed the location of the plate to be adjusted based on the pitcher's natural stride length. Pitchers were asked to simulate their pitching motion on the mound, upon arriving at the laboratory, to determine their natural landing location. The force plate was then adjusted to the appropriate position, by a member of the research team, while the athlete warmed up.

Marker set.

The full-body marker used in this study combined an upper-extremity marker set consistent with ISB recommendations (31) with a lower-extremity marker set used previously (25). The marker set consisted of 32 individual skin-mounted markers and seven marker clusters (Fig. 1). Individual tracking markers for the trunk were placed on the xiphoid process, sternal notch, spinous process of the seventh cervical vertebrae, spinous process of the eighth thoracic vertebrae, and the left and right acromion processes. Individual tracking markers for the pelvis were placed on the right and left iliac crests, right and left anterior superior iliac spines, and the right and left posterior superior iliac spines. Individual tracking markers for the foot were placed on the outside of the shoe at the 1st and 5th metatarsals and heel. Ten markers were used solely for calibration and were located bilaterally on the medial and lateral femoral condyles, and on the medial elbow, lateral elbow, medial wrist, lateral wrist, 2nd metacarpal, and 5th metacarpal of the dominant arm. Marker clusters to track the segments during pitching trials were attached bilaterally on the lateral aspects of the subjects' shanks and thighs, as well as on the upper arm, forearm, and hand of their throwing arm.

Calibration.

Two calibration trials were utilized to establish segment coordinate systems. For the first trial, the subjects stood motionless in anatomical position with both the tracking and calibration markers attached. The second calibration trial was used to calculate the location of the shoulder joint center using a dynamic joint calculation procedure in Visual3D (C-Motion, Germantown, MD) (32). The calibration trial was captured with the athlete standing in anatomical position while making small forward arm circles of approximately 15- for approximately 2 s.

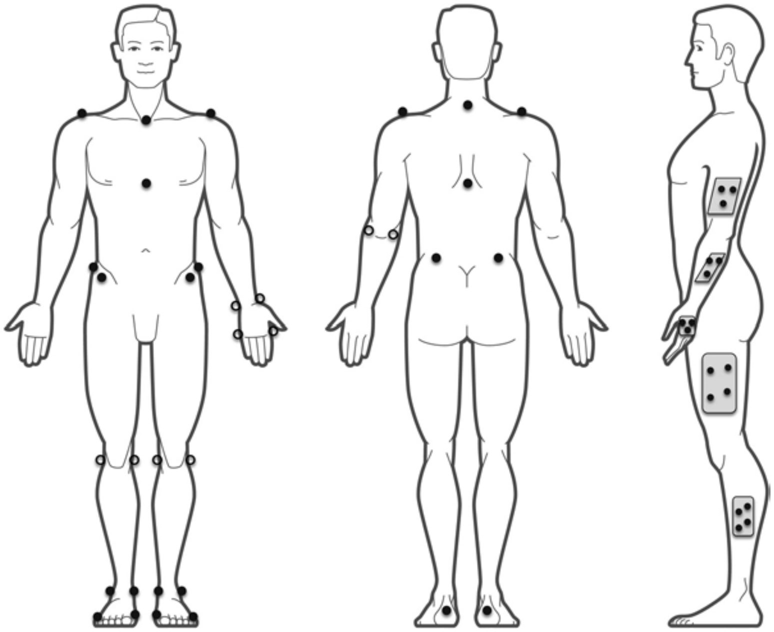

FIGURE 1 Marker placement. Open dots indicate calibration markers and filled dots indicate tracking markers.

Coordinate systems

The trunk and upper-extremity coordinate systems were established using ISB recommendations ([31]). The pelvis coordinate system was defined using the CODA pelvis (Charnwood Dynamics Ldt., UK) in Visual3D. During the pitching trials, rigid marker clusters on the dominant arm and lower extremities were used to track the segment orientations.

The standard forearm coordinate system used the elbow joint center and the midpoint between the medial and lateral wrist markers as the proximal and distal endpoints, respectively, to define the superior–inferior (S-I) axis. The anterior–posterior (A-P) axis was formed as the vector normal to the plane formed by the elbow joint center, the medial wrist marker, and the lateral wrist marker. The medial–lateral (M-L) axis was defined as the vector normal to the S-I and A-P axes. This coordinate system was used for elbow kinematics. However, because forearm pronation rotates the M-L and A-P axes of the forearm when using this coordinate system, a secondary forearm coordinate system was utilized for calculating the elbow varus moment. The varus moment is defined as the moment around the axis normal to long axis of the forearm and the flexion–extension axis of the elbow. Therefore, the secondary forearm coordinate system established one axis to always meet this definition by defining it normal to the plane formed by the wrist joint center, the medial elbow marker, and the lateral elbow marker. This coordinate system was only used to calculate the elbow varus moment.

Data collection

Pitchers were allowed unlimited time to warm-up as they would for a normal game. After the warm-up, the marker set was attached to the subjects. The pitchers were then instructed to throw as many practice pitches from the mound in the laboratory as they wanted until they were comfortable with the markers and mound. Once ready, each pitcher threw 15 maximal effort fastballs toward a hanging strike zone 46 ft from the pitching rubber. The fastest three strikes thrown for each pitcher were chosen for analysis.

Data analysis

Marker coordinate data were filtered using a fourth-order, 14 Hz, zero-lag, low-pass Butterworth filter and the force plate data were filtered with a fourth order, 300 Hz, zero-lag, low-pass Butterworth filter. Joint forces and torques were calculated using standard inverse dynamics equations using Visual3D software. Energy flow was quantified using a segment power analysis for the drive leg, pelvis, trunk, and throwing arm ([27]). The rate of work done on each segment by the joint forces (JFP; equation 1) and joint torques (STP; equation 2) were calculated at the proximal and distal ends of each segment. These powers can be summed to calculate the total segment power (SP; equation 3), or they could be utilized individually ([26,27]).

$$\mathrm{JFP} = (\text{joint reaction force}) \times (\text{linear joint velocity}) \qquad [1]$$

$$\mathrm{STP} = (\text{joint moment}) \times (\text{segment angular velocity}) \qquad [2]$$

$$\mathrm{SP} = \mathrm{JFP}_{\mathrm{prox}} + \mathrm{STP}_{\mathrm{prox}} + \mathrm{JFP}_{\mathrm{dist}} + \mathrm{STP}_{\mathrm{dist}} \qquad [3]$$

$$\mathrm{SP}_{\mathrm{prox}} = \mathrm{JFP}_{\mathrm{prox}} + \mathrm{STP}_{\mathrm{prox}} \qquad [4]$$

When the total SP is integrated over a specified interval of time, the result is net energy transfer into or out of the segment. In addition, the JFP or STP at the proximal or distal end of a segment can be integrated to find the energy transfer at the specific joint attributed to joint forces or muscular contributions, respectively. The power variables for each segment were integrated over the period that they were positive to calculate the energy the segment gained, and integrated over the period that they were negative to calculate the energy transferred out of the segment. The time interval of integration for each segment varied due to the sequential activation through the kinetic chain. Therefore, the specific intervals of energy generation and energy transfer occurred earlier for proximal segments and later for more distal segments. Energy flow during the pitch was analyzed starting when pitcher's stride leg reaches its maximum height at the beginning of the motion and ending when the ball is released.

The primary EF variables calculated included EF into the pelvis through the drive hip, EF into the trunk, EF into the arm from the trunk, EF into the upper arm, EF into the forearm, and EF into the hand. Energy flow into the pelvis was calculated during the interval from maximum stride knee height to stride foot contact. Energy flow into the trunk, upper arm, forearm and hand were calculated during the period from stride foot contact to ball release. In addition, the magnitudes of the components of the total EF produced by joint forces or joint torques were calculated for the pelvis, trunk, and arm.

Because the pelvis and trunk energy transfer exhibits distinct periods of linear and rotational motion during the pitching motion, energy transfer by JFP and STP occurred over a different time interval. The components of power transfer for these two segments were integrated separately and then summed together to calculate total energy flow through the segment (Fig. 2). Other segments did not exhibit this separation between rotational and linear motion, and thus, the energy transfer was calculated based on total segment power. As shown in the figure, the positive power transfer from the pelvis to trunk by joint forces was calculated as the shaded positive area under the "Pelvis to Trunk JFP" curve. The energy into the trunk by joint torques was calculated as the positive area under the "Trunk STP" curve. The two results were then summed to calculate the total EF into the trunk. In the case of JFP at the drive hip and JFP between the pelvis and trunk, these variables were calculated only in the direction of the pitch to remove influences in the calculations from extraneous lateral motion and energy the segment loses from decreases in gravitational potential energy.

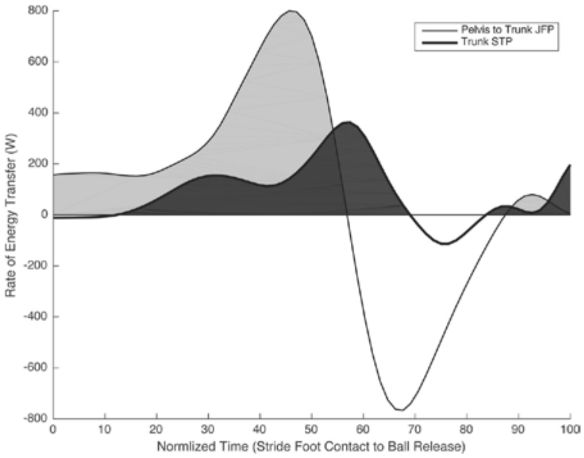

FIGURE 2 Power transfer through the pelvis and trunk.

In this study, the term "joint load efficiency" is used to describe key joint torques at the shoulder and elbow that have been normalized to body mass, height, and pitch velocity, such that they represent joint load per increment of velocity (i.e., elbow varus torque per miles per hour) as proposed in previous research ([11,18,19]). The three upper-extremity joint torques investigated in this study were horizontal shoulder adduction, shoulder internal rotation, and elbow varus torque. Energy flow variables were compared with pitch velocity and the joint load efficiencies with simple linear regressions using the SPSS statistical software package (Armonk, NY).

RESULTS

The mean age for subjects is this study was 11.1 ± 1.3 yr with a range of 9 to 13 yr. The mean subject mass was 45.5 ± 11.9 kg and the mean subject height was 1.549 ± 0.116 m. The mean velocity of the three fastest pitches from each subject was 23.5 ± 3.3 $m \cdot s^{-1}$ (52.6 ± 7.3 mph). The kinematic and kinetic variables from this study were comparable to values reported in previous research ([2,10,12]). The average values across the subject population for elbow varus moment are shown below with error bars equal to the standard deviation of the data at each point normalized in time from stride foot contact to ball release (Fig. 3). The mean peak varus moment for the subject population was 29.7 ± 13.1 N·m and the mean peak shoulder internal rotation was 31.8 ± 13.8 N·m.

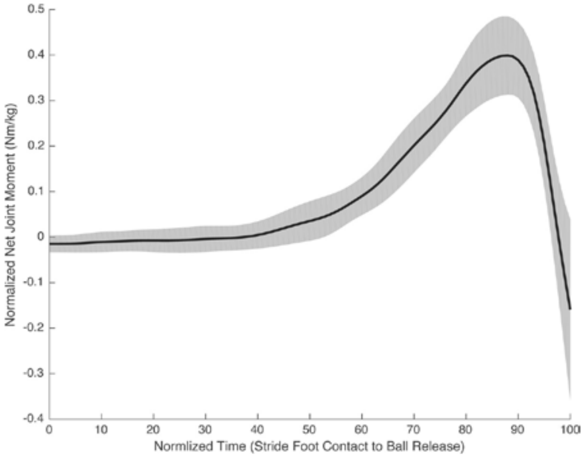

FIGURE 3 Mean (±SD) normalized elbow varus moment as a function of time normalized from stride foot contact to ball release.

The average magnitudes of EF into the pelvis, trunk, total arm, upper arm, forearm, and hand are shown below (Fig. 4). As evident by the large error bars, there was significant variation between subjects based on size and skill level.

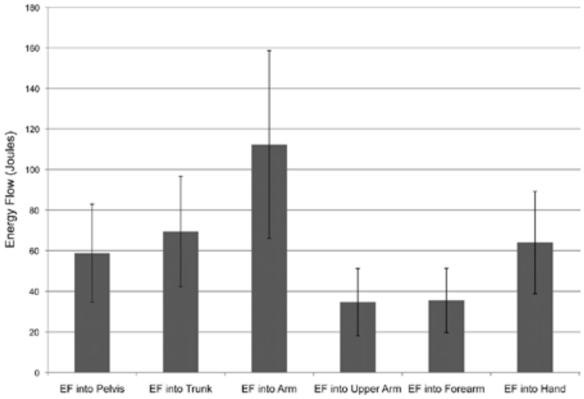

FIGURE 4 Mean magnitude of EF at key points in the kinetic chain for the subject population. Error bars indicate the standard deviation for each instance of EF.

All of the EF variables were positively correlated to pitch velocity, and all the correlations were statistically significant at alpha = 0.05 (Table 1). Energy flow into the arm from the trunk had the strongest correlation to ball velocity (r = 0.900, P = 0.000).

TABLE 1 Pearson correlation coefficients quantifying the relationships between primary energy flow values and pitch velocity and joint load efficiency.

	Velocity	Shoulder Horizontal Adduction Efficiency	Shoulder Internal Rotation Efficiency	Elbow Varus Efficiency
EF into pelvis	**0.769 (0.000)**	**-0.434 (0.034)**	-0.277 (0.190)	-0.283 (0.180)
EF into trunk	**0.828 (0.000)**	**-0.497 (0.013)**	**-0.417 (0.043)**	-0.365 (0.080)
EF into arm (shoulder)	**0.900 (0.000)**	-0.268 (0.205)	-0.160 (0.456)	-0.122 (0.570)
EF into upper arm	**0.839 (0.000)**	-0.373 (0.073)	-0.266 (0.209)	-0.190 (0.373)
EF into forearm	**0.843 (0.000)**	-0.314 (0.135)	-0.297 (0.159)	-0.273 (0.197)

EF into hand	**0.845 (0.000)**	-0.295 (0.162)	-0.193 (0.365)	-0.146 (0.496)

P values are displayed in parenthesis. Significant P values ($P < 0.05$) are highlighted in bold font.

Energy flow into the pelvis, trunk and arm was broken into its subcomponents produced by joint force power (the joint contact forces) and segment torque power (the joint torques). The correlations between velocity and the magnitude of EF from each of these components of segment power were also statistically significant (Table 2). This included EF into the pelvis from JFP, EF into the pelvis from STP, EF from the pelvis to trunk by JFP, EF into the trunk by STP, EF into the arm from the trunk by JFP, and energy into the arm from the trunk by STP.

TABLE 2 Pearson correlation coefficients quantifying the relationships between component energy flow values and pitch velocity and joint load efficiency.

	Velocity	Shoulder Horizontal Adduction Efficiency	Shoulder Internal Rotation Efficiency	Elbow Varus Efficiency
EF into pelvis by JFP	**0.752 (0.000)**	**-0.411 (0.031)**	-0.309 (0.142)	-0.308 (0.143)
EF into pelvis by STP	**0.470 (0.020)**	-0.171 (0.424)	-0.043 (0.842)	-0.002 (0.992)
EF pelvis to trunk by JFP	**0.814 (0.000)**	**-0.555 (0.005)**	**-0.490 (0.015)**	**-0.440 (0.032)**
EF into trunk by STP	**0.670 (0.000)**	-0.252 (0.224)	-0.157 (0.464)	-0.112 (0.602)
EF out of shoulder by JFP	**0.874 (0.000)**	-0.398 (0.054)	-0.204 (0.338)	-0.157 (0.464)
EF out of shoulder by STP	**0.872 (0.000)**	-0.105 (0.626)	-0.099 (0.645)	-0.075 (0.729)

P values are displayed in parenthesis. Significant P values ($P < 0.05$) are highlighted in bold font.

DISCUSSION

Baseball pitching is an open kinetic chain motion, beginning with the initialization of forward momentum by the back leg, and terminating with the release of the ball toward home plate. The correct timing and contribution of events in the kinetic chain has been suggested to be critical both for producing high ball velocity as well as for limiting the joint load on the pitcher ([12,19,20]). Although the importance of the kinetic chain is often referenced in regard to baseball pitching ([19,20,22]), energy generation and transfer during the movement have not been reported. In addition, many baseball biomechanics studies have focused solely on the upper trunk and throwing arm. Although these studies have provided significant insight into proper throwing mechanics, there remains a gap in the understanding of how power generation in the lower extremities, trunk, and arm relate to the upper-extremity kinetics and ball velocity.

The calculated upper-extremity joint moments for this study were very similar to those reported for this age group in previous research. Fleisig et al. ([12]) reported a mean peak varus moment of 28 ± 7 N·m and a mean peak shoulder internal rotation moment of 30 ± 7 N·m for a population of 10- to 15-yr-old athletes. In addition, Aguinaldo et al. ([10]) reported a mean peak shoulder internal rotational moment of 33 ± 3 N·m in a subject population with a mean age of 12 yr. The mean elbow varus moment found for this study was 29.7 ± 13.1 N·m and the mean shoulder internal rotation moment was 31.8 ± 13.8 N·m. The kinematic data were also consistent with previously reported data. The patterns of mean shoulder external rotation angle and mean elbow flexion angle from stride contact to ball release for this population are in agreement with those reported for this age group by Sabick et al. ([2]).

The results of this study give strong evidence regarding the importance of EF in regard to producing high pitch velocities as every energy flow variable quantified in this study was significantly correlated with velocity. This finding is logical because the velocity of the ball is closely related to its kinetic energy at release. Therefore, if the pitcher is able to transfer more energy into the ball, the ball will have a greater kinetic energy and subsequent ball velocity.

Total EF into the throwing arm from the trunk had the strongest correlation to ball velocity ($r = 0.900$, $P = 0.000$) of all energy components quantified. This EF value was also the largest energy value of any instance calculated, emphasizing the importance of the lower extremities and trunk in producing the energy to move the ball at high velocities. However, EF into the upper arm, EF into the forearm, and EF into the hand all also had strong relationships to velocity, indicating that effective energy flow through the arm is critical in delivering the energy from the trunk to the ball.

Pitch efficiency was characterized by three key upper-extremity joint moments: horizontal shoulder adduction moment, shoulder internal rotation moment, and elbow varus moment each normalized by subject height, mass, and velocity. The effective units of these metrics became “joint load per miles per hour.” The goal of investigating upper-extremity loading from this perspective was to identify movement patterns that minimized joint loads without necessarily compromising pitch velocity.

Given that the magnitude of EF was shown to be strongly related to pitch velocity, it was hypothesized that certain methods or patterns of energy generation and transfer may be more effective in producing the overall EF required for high pitch velocity, while placing less load on the upper-extremity joints. The results from this study reinforce this hypothesis that specific instances of EF were related to increased pitch efficiency. Energy flow through the trunk appeared to be particularly important for improved efficiency of the pitch. The total EF into the trunk and the EF into the trunk by JFP both had significant relationships to horizontal shoulder adduction efficiency and shoulder internal rotation efficiency, whereas the EF from JFP also had a significant relationship to elbow varus efficiency. These results reinforce the findings in previous literature on the importance of pelvic and trunk timing, kinematics, and control in regard to upper-extremity kinematics, upper-extremity kinetics, and pitch velocity ([19,23,24,33–36]). Oyama previously found that pitchers with improper pelvis and trunk sequencing had a greater magnitude of proximal force acting on the shoulder. Oyama and Urbin both stressed the importance of proximal to distal sequencing of segment rotation in regard to ball velocity and minimizing joint kinetics ([19,24]). Urbin proposed that incorrect timing might cause disruptions in the energy generated and transferred to the upper extremity. This disconnect in the energy transfer was theorized to either adversely affect ball velocity or require additional loading of the upper extremity to compensate for the lost energy ([19]). Energy flow analysis is an excellent tool to investigate this assertion because it can quantitatively identify disconnects in energy transfer and investigate their impact on pitch velocity and upper-extremity joint loading. It should be noted that improved efficiency does not necessarily imply a decrease in the magnitude of upper-extremity joint torques. Instead, increased pitch efficiency could also be the result of increasing ball velocity without increasing joint moments.

The results of this study are also consistent with the findings of a similar study investigating energy flow during the tennis serve ([26]). That study found that tennis players who transferred more energy from the shoulder into the serving arm had higher serve speeds and fewer overuse injuries. The importance of the energy transfer from the trunk to the dominant arm in generating ball velocity was supported by our data. The fact that multiple instances of energy flow were significantly related to several different efficiency metrics providing evidence that certain energy transfer patterns may also positively impact joint loading in pitching.

The magnitude of EF from the pelvis to trunk by JFP had a significant correlation to all three efficiency metrics. This component of energy flow is calculated as the integral of the positive joint force power transfer at the pelvis/trunk joint after stride foot contact. Therefore, it represents the energy transfer that drives the trunk, over the stride leg, toward home plate. This same energy component also comprises a large portion of the total

EF out the pelvis and total EF into the trunk. Therefore, energy flow from the pelvis to trunk by JFP is likely a major reason that EF into the trunk also had significant correlations to horizontal shoulder adduction efficiency and shoulder internal rotation efficiency. These results give evidence that EF through the trunk by JFP may be particularly important to producing a high velocity and efficient pitch. Because the joint forces driving the trunk forward occur above the blocking front hip, a moment arm is created, and these forces would also contribute to the forward flexion of the trunk. Stodden reported that increased forward flexion of the trunk was related to increased pitch velocity ([37]). It was, additionally, found by Laughlin that pitchers with a history of shoulder injuries had decreased forward trunk flexion at release compared to healthy subjects ([38]). Together these findings support the idea that appropriate trunk EF is improved for improved pitch efficiency.

The age range of 9 to 13 yr encompassed athletes who participated at youth levels but who varied greatly in size, skill, and pitching experience. The impact of collecting data in a laboratory and using a constructed pitching mound on the results is unknown, although the subjects were able to throw their regulation distance to the strike zone. Additionally, the data collection occurred in the fall, after the subjects' baseball season ended, or in the spring, before the season began. There is a potential that the subjects were not at the peak performance level achieved during the season. However, the mean pitching velocity of this population at 23.5 $m \cdot s^{-1}$ was consistent with other studies on the same age group, indicating a reasonable level of proficiency and conditioning. There is no previous research on energy flow in baseball to compare the values calculated for the youth subjects so it is difficult to determine how their energy flow data varies from adults. It is also unclear what normal EF values are for a well-developed pitcher.

Future research should apply energy flow analysis to additional subject populations to better characterize how pitchers at different levels generate and transfer energy. Additionally EF analysis should be utilized in conjunction with a kinematic analysis to understand how specific movement patterns and timing relate to EF through the kinetic chain.

CONCLUSIONS

Energy flow analysis is an effective tool that can be utilized as a quantitative assessment of the kinetic chain to gain a deeper understanding of how energy is transferred among body segments, and how specific pitching mechanics impact this movement. The results of this study support the importance of generating energy flow throughout the body to produce high velocities and greater magnitudes of energy flow through the trunk to improve pitch efficiency. Given the increased pressure on youth athletes perform at a high level and participate in a greater volume of games, understanding how these athletes can maintain this performance while minimizing the load on their elbow and shoulder is critical to curbing the increase in major arm injuries that have become more prevalent in youth pitchers.

There were no external funding sources or conflicts of interest relating to this study. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of this study do not constitute endorsement by the American College of Sports Medicine.

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Keywords:

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