

Hip Range of Motion and Strength and Energy Flow During Windmill Softball Pitching

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Context: Inadequate hip range of motion (ROM) and isometric strength (ISO) may interfere with energy flow through the kinetic chain and result in increased injury susceptibility.

Objective: To examine the relationship of hip ROM and ISO with energy flow through the trunk and pitching-arm segments during the windmill softball pitch in youth athletes. A subsequent purpose was to examine the relationship between energy flow and pitch speed.

Design: Descriptive laboratory study.

Setting: University research laboratory.

Patients or Other Participants: A sample of 29 youth softball pitchers (age = 11.2 ± 1.3 years, height = 155.0 ± 10.4 cm, mass = 53.2 ± 12.6 kg).

Main Outcome Measure(s): Bilateral hip internal-rotation and external-rotation (ER) ROM and ISO were measured. Net energy outflow and peak rates of energy outflow from the distal ends of the trunk, humerus, and forearm were calculated for the acceleration phase of the windmill softball pitch, and pitch speed was measured.

Results: Regression analysis revealed an effect of drive-hip ER ISO on the net energy flow out of the distal ends of the trunk ($P = .045$) and humerus ($P = .002$). Specifically, increased drive-hip ER ISO was associated with increased net energy outflow from the trunk to the humerus and from the humerus to the forearm. No significant effects of hip ROM or other hip ISO measures were observed. Additionally, pitchers who achieved higher peak rates of distal outflow tended to achieve higher pitch speeds.

Conclusions: An association was present between drive-hip ER ISO and the net energy flow out of the distal ends of the trunk and humerus during the acceleration phase of the windmill softball pitch, emphasizing the importance of hip and lower body strength in executing the whole-body windmill pitch. Overall, energy-flow analysis is an interesting new way to analyze pitching mechanics and will aid in furthering our understanding of performance and injury risk in windmill softball pitching.

Key Words: athlete assessment, clinical measures, energy transfer, injury susceptibility, kinetic chain, softball fast pitch

Key Points

- Drive-hip external-rotation range of motion and isometric strength were associated with net energy flow out of the distal ends of the trunk and humerus during the acceleration phase of the windmill pitching motion.
- Distal energy outflow at all segment ends was linked with pitch speed.
- Energy-flow analysis is a novel way to analyze pitching mechanics with the ultimate goal of reducing the injury risk in these pitchers.

The repetitive nature of windmill softball pitching requires an efficient proximal-to-distal flow of energy through the kinetic chain to reduce injury susceptibility. However, many factors can result in breaks in the kinetic chain that disrupt efficient energy flow, such as pain, insufficient muscular strength, or inadequate joint range of motion (ROM).^{1–4} Among these factors, muscular strength and joint ROM are of particular interest to sports medicine professionals because they can be easily measured in a clinical setting.

The windmill softball pitch requires the proximal aspect of the kinetic chain, specifically the lumbopelvic-hip complex, to exhibit adequate stability and mobility. To achieve maximal pitch speed, the large forces generated proximally need to be transferred distally through successive joints in an efficient manner. Adequate strength and mobility of the hip joint allow softball pitchers to achieve the most advantageous hip and pelvic position for postural

control at foot contact.^{4,5} Not only is this necessary for softball pitch execution and achieving high pitch speed, but researchers^{1,3} have also found that improper body positioning can increase injury susceptibility.

Investigators^{1–3,6} have linked decreases in passive hip ROM and strength with an increased risk of injury in softball pitchers. Although the specific mechanism responsible for this association with injury remains unclear, many have hypothesized that reduced hip ROM and strength may lead to suboptimal mechanics and disrupt energy flow through the kinetic chain.^{5,7,8} As a result, greater demand may be placed on the distal segments of the pitching arm to compensate for the reduced energy inflow from the proximal segments. This has been most notable in novice youth pitchers who struggle to efficiently use the full kinetic chain.^{9,10} Clinical measures of strength, ROM, and the kinetic chain have received significant attention in softball research, yet no authors have examined the

influence of hip ROM and strength on energy flow during the windmill softball pitch.

Energy-flow analysis has recently gained popularity for enabling sports medicine professionals to characterize the flow of mechanical energy during open kinetic chain sport movements such as the baseball pitch and tennis serve.^{11,12} Specifically, *energy flow* is defined as the movement of mechanical energy through the human body, including energy generation and absorption by muscles at joints and energy transfer between segments.¹² Energy flow between segments has emerged as one of the most critical concepts related to injury susceptibility^{13–15} because inefficient proximal-to-distal energy transfer can result in distal extremity compensation to maintain performance.¹² Therefore, describing the patterns of energy flow between segments during the windmill softball pitch would be interesting for sports medicine personnel from the training, rehabilitative, and injury-prevention perspectives.¹⁶ Furthermore, bridging the gap between clinical measures such as joint ROM and muscular strength with laboratory measurements such as energy flow through the kinetic chain could prove beneficial in providing a knowledge base for the development of injury-prevention protocols. Similarly, understanding the relationship between energy flow and pitch speed is especially valuable for athletes and coaches as they continue to improve player-development strategies. Identifying relationships among functional measures, energy flow, and pitch speed can assist in the development of practices that both decrease injury susceptibility and improve performance.

The associations between hip ROM and strength and trunk and upper extremity energy flow are currently unclear. Therefore, the primary aims of our study were to explore the associations (1) between measures of hip ROM and strength and energy flow through the trunk and pitching-arm segments, and (2) between energy flow through the trunk and pitching-arm segments and pitch speed during the windmill softball pitch in a sample of youth softball athletes. We hypothesized that greater hip ROM and strength would allow pitchers to achieve greater energy flow out of the trunk and pitching-arm segments. Additionally, we proposed that increased pitch speed would be correlated with greater energy outflow out of the trunk and pitching-arm segments. Understanding patterns of energy flow in conjunction with clinical measures and pitch speed is warranted for developing rehabilitative and conditioning programs to assist pitchers in achieving adequate hip strength and ROM, which could result in decreased injury susceptibility and improved performance.

METHODS

Participants

A convenience sample of 29 right-handed youth softball pitchers (age = 11.2 ± 1.3 years, height = 155.0 ± 10.4 cm, mass = 53.2 ± 12.6 kg) participated. Given the scarce literature containing information about the differences in energy flow in various age groups or at various maturation levels, we purposefully selected a small age range. The inclusion criteria required pitchers to be actively competing as pitchers on a team roster and being surgery and injury free for the past 6 months. *Injury* was defined as being diagnosed by a physician or athletic trainer and resulting in

time loss from practice or competition. The recruits completed a health history form before the study began. The Institutional Review Board of Auburn University approved all testing protocols. Informed written consent was obtained from each participant and a parent before testing.

Procedures

Hip ROM and isometric strength (ISO) data were collected based on procedures outlined in previous articles.^{2,5,6,17–19} No warmup or stretching was performed before the ROM and ISO measurements were taken. These measurements were collected before the kinematic data were obtained. Hip internal-rotation (IR) and external-rotation (ER) ROM and ISO were performed with the participant seated with knees flexed to 90° and a rolled towel placed under the distal femur. For the ROM measures, the investigator placed the inclinometer on the shaft of the fibula just proximal to the lateral malleolus for IR and on the shaft of the tibia just proximal to the medial malleolus for ER. The investigator passively rotated the hip in both IR and ER until a firm capsular end-feel was perceived. In the same seated position, hip IR and ER ISO data were examined. For the ISO measures, the dynamometer was positioned proximal to the lateral malleolus for IR and proximal to the medial malleolus for ER. Participants were instructed to push for 3 seconds with maximal effort against the investigator in both IR and ER. To establish the reliability of the ROM and ISO measures, we performed a pilot study of 8 participants (2 measures on 2 consecutive days). Using the techniques described, the investigator reported a high intrarater reliability with an intraclass correlation coefficient (2,k) of 0.92 to 0.99. The standard error of measurement (SEM) was calculated for each ROM (SEM = 0.12° – 0.42°) and ISO (SEM = 0.08–0.33 N) measure. The hip on the nonpitching-arm side was defined as the *stride hip*, and the hip on the pitching-arm side was defined as the *drive hip*. Pitch speed was measured via a calibrated radar gun (model Pro II; Stalker Radar, Plano, TX) and recorded to the nearest mile per hour.

Kinematic data were collected at 100 Hz using an electromagnetic tracking system (trakSTAR Ascension Technologies, Inc, Burlington, VT) synchronized with The MotionMonitor system (Innovative Sports Training, Chicago, IL). Nine electromagnetic sensors were attached at the following locations: (1) posterior aspect of the trunk at the first thoracic vertebra (T1) spinous process; (2) posterior aspect of the pelvis at the first sacral vertebrae (S1); (3–4) flat, broad portion of the acromion on both scapulae; (5–6) lateral aspect of the bilateral humerus at the deltoid tuberosity; (7–8) posterior aspect of the bilateral distal forearm, centered between the radial and ulnar styloid processes, and (9) dorsal aspect of the third metacarpal of the dominant hand. A tenth moveable sensor was attached to a plastic stylus for the digitization of bony landmarks.

Raw data regarding sensor orientation and position were filtered using a fourth-order, Butterworth low-pass filter with a cutoff frequency of 6.0 Hz, consistent with previous research²⁰ examining the throwing motion. The global reference frame identified the Y axis as in the vertical direction. The positive X axis was anteroposterior, with the positive X axis pointing toward home plate in the direction

Table 1. Hip Range of Motion and Isometric Strength Descriptive Measures^a

Variable	Motion	Range of Motion, °	95% CI	Isometric Strength, N/kg	95% CI
Stride hip	Internal rotation	40.4 ± 6.9	37.8, 43.0	2.07 ± 0.61	1.84, 2.30
	External rotation	47.3 ± 8.6	44.0, 50.6	1.84 ± 0.58	1.62, 2.06
Drive hip	Internal rotation	41.7 ± 8.9	38.4, 45.1	1.91 ± 0.58	1.69, 2.13
	External rotation	46.4 ± 8.3	43.2, 49.5	1.83 ± 0.54	1.62, 2.03

^a Data are presented as mean ± SD.

of the pitch. The positive Z axis was orthogonal to X and Y and to the right (mediolateral and parallel with the pitching rubber). Euler angles of rotation were used to quantify relative motion between segments for identifying key events during the pitching motion. Specifically, humeral motion was defined relative to the trunk reference frame using a Y-X'-Y'' decomposition sequence.²¹ Trunk, forearm, and hand motion were defined relative to the proximal segment (the trunk was defined relative to the global reference frame) using a Z-X'-Y'' decomposition sequence.²¹ After the sensors were attached and digitization completed, participants performed their preferred warmup routine to prepare for full-effort pitching (average time = 7 minutes). Individual warmup routines ensured that each person could most closely replicate in-game performance.^{1-3,9,22,23} Once the participant indicated readiness, she was instructed to pitch game-effort fastballs to a catcher at regulation distance (43 ft [13.1 m]).

We estimated energy flow between the trunk and pitching arm during the acceleration phase of the pitch using a segment power analysis similar to that of Howenstein et al.¹¹ We chose to analyze the *acceleration phase* (ie, the time between foot contact and ball release) because that is the most dynamic aspect of the windmill softball pitch. Further, it is during the acceleration phase that the pitching arm experiences the largest stress and peak angular velocities.^{1,2,6,24,25}

The rate of energy flow from the joint forces was calculated as the scalar product of the resultant joint force and joint center linear velocity vectors (JFP; Equation 1). The rate of energy flow from the joint torques was calculated as the scalar product of the net joint torque and segment angular velocity vectors (STP; Equation 2). The JFP and STP at each end of each segment were then summed to calculate the segment power (SP) at each end. A positive SP indicates an inflow of energy into the segment at that joint. A negative SP indicates an outflow of energy from the segment at that joint. For this study, we focused on the SPs at the distal ends (Equation 3). The distal SPs were then integrated between stride-foot contact and ball release to estimate the net amount of energy flow into or out of the distal ends of the trunk and pitching-arm segments during the acceleration phase of the pitching motion. The *peak rate of outflow* from the distal ends of the segments was defined

as the local minimum of the distal SP curve between stride foot contact and ball release.

$$\text{Joint Force Power (JFP)} = \vec{F}_r \cdot \vec{V}_{jc} \quad (1)$$

$$\text{Segment Torque Power (STP)} = \vec{T}_j \cdot \vec{\theta} \quad (2)$$

$$\text{Distal Segment Power (SP}_{\text{dist}}) = \text{JFP}_{\text{dist}} + \text{STP}_{\text{dist}} \quad (3)$$

Statistical Analysis

We calculated multivariate general linear models to explore the association between measures of hip ROM and ISO and distal energy outflow during the windmill softball pitch. Four exploratory models were developed with clinical measures as predictors and energy-outflow measures as responses. In the first model, passive bilateral hip IR and ER ROM measures were used to predict net energy flow out of the distal ends of the trunk, humerus, and forearm during the acceleration phase. In the second model, passive bilateral hip IR and ER ROM measures were used to predict the peak rates of energy outflow from the distal ends of the trunk, upper arm humerus, and forearm over the same period. The third and fourth models were identical to the first 2 but with hip IR and ER ISO as predictors in place of hip ROM. Follow-up univariate regressions were conducted for the models in which significant multivariate effects were observed ($P < .05$) to determine the direction of the association between predictors and responses. Associations between energy outflow and pitch speed were explored using Spearman rank order correlations.

RESULTS

Descriptive data for ROM and ISO and energy flow are presented in Tables 1 and 2, respectively. A multivariate effect of drive-hip ER ISO on the net distal energy outflow was evident ($F_{3,22} = 5.532$, $P = .006$, $\eta^2_p = 0.430$), as was a multivariate effect of drive-hip ER ROM on the peak rate of distal energy outflow ($F_{3,22} = 4.087$, $P = .019$, $\eta^2_p = 0.265$). Post hoc univariate regression revealed an ability of drive-hip ER ISO to predict the net energy flow out of the distal ends of the trunk and humerus (trunk: $F_{1,27} = 4.403$, $P = .045$, $\Delta r^2 =$

Table 2. Energy Transfer Descriptive Measures^a

Location	Net Distal Energy Transfer, J/kg	95% CI	Peak Rate of Energy Transfer, W/kg	95% CI
Trunk to humerus	-0.60 ± 0.30	-0.71, -0.48	-9.60 ± 3.49	-10.92, -8.27
Humerus to forearm	-0.10 ± 0.27	-0.20, 0.01	-8.36 ± 2.56	-9.34, -7.38
Forearm to hand	-0.10 ± 0.17	-0.17, -0.03	-4.65 ± 2.20	-5.48, -3.81

^a Data are presented as mean ± SD.

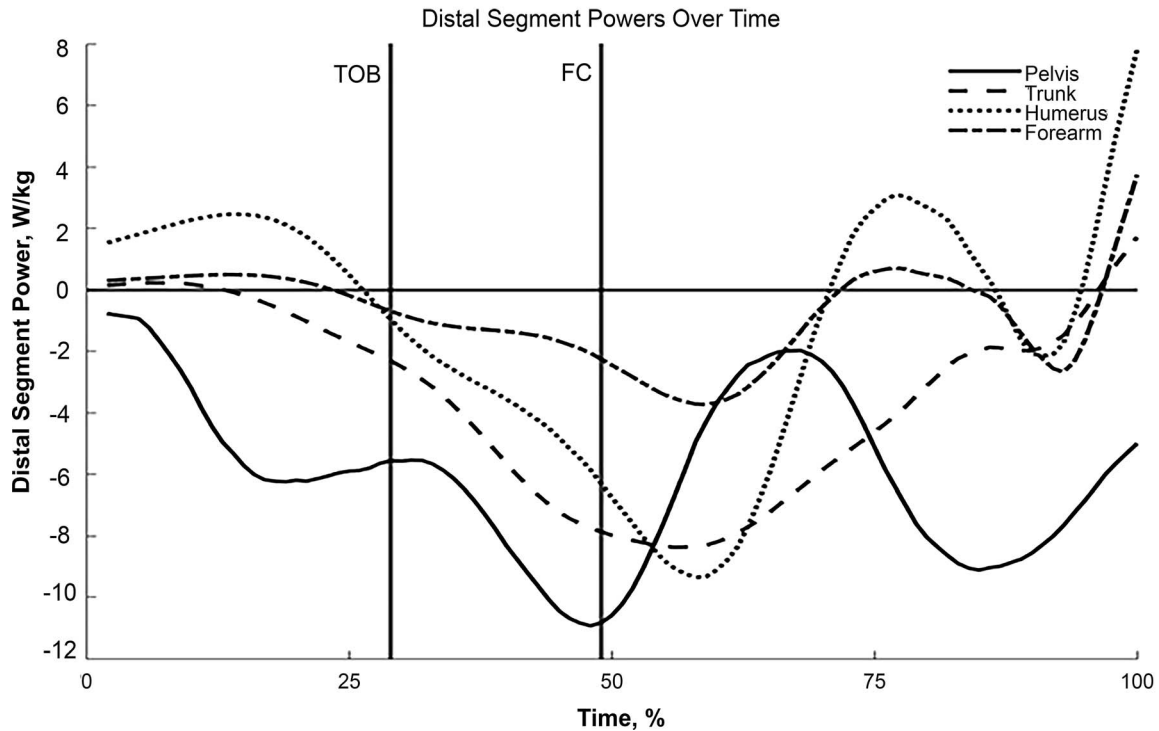


Figure. Distal energy flow throughout the softball pitch. Negative values indicate energy leaving the segment at its distal joint (energy outflow), while positive values indicate energy entering the segment at its distal joint (energy inflow). After foot contact (FC), peak rates of distal energy outflow occur approximately in a proximal-to-distal manner starting with the pelvis and ending with the forearm. Abbreviation: TOB = top of backswing.

0.140, $\beta = .374$, achieved power = 0.68; humerus: $F_{1,27} = 12.107$, $P = .002$, $\Delta r^2 = 0.310$, $\beta = .556$, achieved power = 0.97). No post hoc tests reached a priori significance for drive-hip ER ROM (trunk: $P = .716$; humerus: $P = .243$; forearm: $P = .955$). No multivariate effects of other hip ROM or ISO measures were observed for net distal energy outflow (drive-hip IR ROM: $P = .497$; drive-hip ER ROM: $P = .288$; stride-hip IR ROM: $P = .666$; stride-hip ER ROM: $P = .425$; drive-hip IR ISO: $P = .120$; stride-hip IR ISO: $P = .061$; stride-hip ER ISO: $P = .690$) or peak rate of distal energy outflow (drive-hip IR ROM: $P = .075$; stride-hip IR ROM: $P = .238$; stride-hip ER ROM: $P = .073$; drive-hip IR ISO: $P = .392$; drive-hip ER ISO: $P = .074$; stride-hip IR ISO: $P = .157$; stride-hip ER ISO: $P = .857$).

Distal outflow from the thorax was significantly associated with pitch speed ($r = -0.670$, $r^2 = 0.448$, $P < .001$). Pitchers who exhibited higher magnitudes of outflow also achieved faster pitch speeds (pitch speed range = 31–52 mph [49–84 kph]). Additionally, pitch speed was significantly associated with the peak rates of distal outflow from the thorax ($r = -0.741$, $r^2 = 0.549$, $P < .001$), humerus ($r = -0.724$, $r^2 = 0.524$, $P < .001$), and forearm ($r = -0.558$, $r^2 = 0.311$, $P = .002$). Pitchers who achieved higher peak rates of distal outflow tended to also achieve higher pitch speeds.

Visual representation of the distal segment energy flow time series appears in the Figure.

DISCUSSION

The windmill softball pitch is a strenuous task that requires efficient proximal-to-distal sequencing to reduce the risk of upper extremity injury.²⁶ Inadequate hip ROM and strength may interfere with energy flow through the kinetic chain and result in an increased injury risk. However, the association of hip ROM and strength measures with energy flow during the windmill softball pitch has yet to be examined. Therefore, one purpose of our study was to evaluate the multiple associations of hip ROM and strength with energy flow through the trunk and pitching-arm segments during the windmill softball pitch. Our hypothesis that greater hip ROM and strength would allow pitchers to achieve greater energy flow through the trunk and pitching-arm segments was partially supported. Specifically, increased drive-hip ER ISO was associated with increased net energy flow out of the distal ends of the trunk and humerus. However, no associations were found between hip ROM or other ISO measures and energy flow.

The association between drive-hip ER ISO and energy flow is not surprising. The drive leg is essential in generating force

and pushing the body forward and off the mound toward home plate. More specifically, while the body is accelerating toward the target, the trunk begins to rotate toward the pitching-arm side. The drive-leg hip not only needs to have adequate ER ROM but also adequate ER strength to enable the trunk to rotate and open toward third base (for a right-handed pitcher), allowing the pitching arm to clear the hip. Researchers¹ have reported that a posteriorly shifted center of mass (COM) was associated with increased upper extremity pain. Increased drive-leg strength may help propel the body into a balanced position, preventing a posterior shift of the COM and thereby lessening the degree of upper extremity injury susceptibility. Thus, the ER strength of the drive hip is an important factor in dictating the pitcher's ability to drive the COM forward and properly position the body for the rest of the pitch.^{2,17,18} Conversely, drive-hip ER weakness may lead to a less dynamic push-off from the mound and result in decreased energy flow through the kinetic chain, thereby increasing the demands on more distal aspects of the kinetic chain.^{5,17,18} In addition, previous authors² who examined hip ER strength in collegiate softball pitchers observed that pitchers with pain had less drive-hip ER strength than pitchers without pain. Together, these results highlight the importance of developing ER strength of the drive hip, as it leads to increased net energy flow out of the distal ends of the trunk and humerus. Although we did not see a significant association between ER strength of the drive hip and energy flow out of the forearm, that may, in part, have been due to the limited joint angular velocity seen at the wrist during the acceleration phase of the windmill pitching motion. If relative angular velocity does not differ between the forearm and hand segments (ie, they act more as 1 rigid body), then only the joint force can transfer energy. This may suggest that the STP component of SP energy flow (Equation 3) plays a critical role in energy flow out of the trunk and humerus as opposed to the forearm.

The lack of a significant association between hip ROM and energy flow was not expected. This result may have in part reflected the youth population we studied. Previous researchers^{5,6,27} showed that youth throwing athletes tended to have greater hip ROM and less bilateral asymmetry than older populations due to increased joint laxity and a lower total volume of career pitches. Therefore, our youth participants may have not yet fully developed the hip musculoskeletal asymmetries typically observed in older populations that have been associated with suboptimal mechanics and an increased risk of injury. Irrespective of competitive season, increased ROM asymmetries present in older populations may have a greater effect on energy flow. Additionally, we measured hip ROM at different timepoints during the pitchers' training. This is a limitation, as hip ROM adaptations tend to occur over the course of a competitive season and are associated with workload.²⁸ We can therefore hypothesize that the association between hip ROM and energy flow may vary with the change in hip ROM during a competitive season, which could have influenced the current results.

A subsequent purpose of our investigation was to examine the relationship of energy flow out of the trunk and pitching-arm segments with pitch speed. Pitchers who achieved higher peak rates of distal energy outflow threw at higher pitch speeds, consistent with our hypothesis. Therefore, we suggest that functional measures leading to higher energy outflow, such as increased hip ISO, may also affect pitch speed. This

highlights the effect of functional measures, not only on potential injury mechanisms but also on performance outcomes. Earlier authors who examined other sports related energy flow to performance and pain. Greater energy flow from the trunk into the dominant arm during the tennis serve led to higher serve velocities and a lower risk of overuse injury.¹² These results affirm our findings, which indicated a potential relationship between energy flow and both injury and performance in softball pitchers. Future researchers should continue exploring these associations and include crucial pitching-arm kinetics, such as shoulder distraction force. Understanding energy flow in conjunction with kinetics may provide further insight into injury susceptibility and pitching performance outcomes.³

We found that hip strength played a role in energy flow throughout the windmill softball pitch and may have a subsequent effect on pitch performance. Thus, combining our results with previous results that demonstrated the importance of hip ROM indicated that clinicians should measure both hip ISO and ROM in youth softball pitchers throughout the competitive season. Even if baseline testing was conducted, the large number of games might lead to alterations in these values. Consequently, energy flow may be altered throughout the kinetic chain. Understanding energy flow and its association with performance and injury predictors may better assist clinicians, athletes, and coaches in developing optimal and safe throwing practices.

LIMITATIONS AND FUTURE RESEARCH

As mentioned earlier, testing a youth population is a limitation of our study because hip ROM symmetry may decrease in older populations due to the increased number of career pitches thrown. In addition, although understanding the association of clinical measures such as hip ROM and strength with energy flow is valuable, understanding the association between dynamic hip ROM during the windmill pitching motion and energy flow is also warranted. However, the passive measurements of hip ROM simplify the application of our findings for those without access to expensive equipment and resources. Given the regular assessments that occur in both baseball and softball athletes,^{2,5,6,17-19} we selected the functional hip testing position to permit better comparisons across studies. Another limitation is that only clinical hip measures were included. The relationship between clinical shoulder measures and energy flow would provide additional beneficial insight because decreased shoulder ISO strength has also been associated with an increased risk of upper extremity injury in windmill softball pitchers.² The inclusion of only the trunk and pitching arm is another limitation. We chose to focus on segments distal to the hip, yet examination of lower extremity energy flow would afford further insight into how youth softball pitchers interact with the ground and use their lower extremities to produce and transfer energy up into the kinetic chain. Moreover, the laboratory nature of this study did not fully replicate a competitive game atmosphere, which could have limited the intensity of the pitches thrown and, therefore, the magnitude of energy flow through the kinetic chain. Finally, we measured only net and peak rates of energy flow out of the distal segment ends. Including proximal SPs or characterizing the individual components of the SPs (JFP

and STP) throughout the acceleration phase of the windmill softball pitch would provide a more in-depth analysis of the association between clinical hip measures and energy flow.

CONCLUSIONS

Our study revealed an association between drive-hip ER ISO and net energy flow out of the distal ends of the trunk and humerus during the acceleration phase of the windmill softball pitching motion. Additionally, distal energy outflow at all segment ends was associated with pitch speed. Further investigation is needed to relate these findings to both injury predictors and performance in order to provide guidance for clinical practice and training. Overall, energy-flow analysis is an interesting way to analyze pitching mechanics and will aid in further understanding injury risk in windmill softball pitchers.

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