Association of Upper Extremity Pain With Softball Pitching Kinematics and Kinetics

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Background: There is a paucity of research regarding the relationship between fastpitch softball pitching mechanics and reported pain. Thus, understanding the pitching mechanics of athletes pitching with upper extremity pain and those pain free is paramount.

Purpose: To examine lower extremity pitching mechanics, upper extremity kinetics, and upper extremity pain in National Collegiate Athletic Association (NCAA) Division I female softball pitchers.

Study Design: Descriptive laboratory study.

Methods: A total of 37 NCAA Division I female softball pitchers (mean age, 19.84 ± 1.28 years; mean height, 173.67 ± 7.77 cm; mean weight, 78.98 ± 12.40 kg) from across the United States were recruited to participate. Participants were divided into 2 groups: upper extremity pain (n = 13; mean age, 19.69 ± 1.18 years; mean height, 172.60 ± 11.49 cm; mean weight, 86.75 ± 13.02 kg) and pain free (n = 24; mean age, 19.91 ± 1.35 years; mean height, 174.26 ± 4.96 cm; mean weight, 74.78 ± 9.97 kg). An electromagnetic tracking system was used to obtain kinematic and kinetic data during the riseball softball pitch.

Results: At foot contact ($F_{3,33} = 7.01$, $P = .001$), backward elimination regression revealed that stride length, trunk rotation, and center of mass (COM) significantly explained about 33% of variance with softball pitchers experiencing upper extremity pain (adjusted $R^2 = 0.33$).

Conclusion: At foot contact, the kinematic variables of increased trunk rotation toward the pitching arm side, increased stride length, and a posteriorly shifted COM were associated with upper extremity pain in collegiate softball pitchers. Variables early in the pitching motion that do not set a working and constructive proximal kinetic chain foundation for the rest of the pitch to follow could be associated with breakdowns more distal in the kinetic chain, possibly increasing the susceptibility to upper extremity pain.

Clinical Relevance: The identification of pitching mechanics associated with pain allows clinicians to develop exercises to avoid such mechanics. Avoiding mechanics associated with pain may help reduce the prevalence of pain in windmill softball pitchers as well as help coaches incorporate quantitative biomechanics into their instruction.

Keywords: injury; fastpitch softball; windmill softball pitch

As the popularity of fastpitch softball grows,[17] there has been a rise in the awareness of pain and injuries.[13,19,28,32,34-36] A common misconception about the windmill-style pitch utilized in fastpitch softball is that it is a natural motion and does not cause stress about the shoulder.[3] However, it is continually reported that the shoulder stress endured from the softball pitch is analogous to that of the baseball pitch.[4,30,39] Furthermore, shoulder injury rates and patterns are comparable with those reported in the sport of baseball,[13,26,28,29,33] and the most common mechanism of injury in softball is overuse.[13,28,31,32,34] With the increase in sport participation, the susceptibility to injuries is more widespread. Therefore, understanding the pitching mechanics related to pain and injury susceptibility is paramount.

Previous research highlighting softball pitching kinematics describes the windmill softball pitch as a dynamic motion, requiring the total body for ball control/accuracy and velocity.[18,19,23,38,39] This total-body dynamic ability is the result of an integrated, multisegmented system known as the kinetic chain. With proper utilization of the kinetic chain, maximum force and energy production can be developed from the lower extremity, then transferred distally through the upper extremity and into the ball. However, previous biomechanical investigations of the windmill softball pitch have focused primarily on the upper extremity,[4,18,19,23-25,30,38,39] with minimal examination of the entire system including the lower extremity and trunk.[10,22]

Although usually studied separately, it is known that habitual movement patterns of the upper extremity are dependent on lower extremity and trunk muscle activations.[15,43] More specifically, activation of the gluteal and lumbopelvic musculature assists in the initiation of both

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efficient energy transfer and proper upper extremity positioning during the windmill softball pitch.[10,22,38] Additionally, sufficient energy transfer from the lower extremity is crucial in decreasing the physical demands placed on the distal segments of the upper extremity, thereby minimizing the risk of injuries in throwing athletes.[27] With the known importance of utilizing the total body as an efficient kinetic chain,[10,18,22,38] and the increase in pain and injuries,[13,19,28,32,34-36] further investigations of the effects of kinematics as it relates to injuries and pain susceptibility during the windmill softball pitch are needed.

A recent examination of pain and pitching mechanics in collegiate softball pitchers revealed that those pitching with upper extremity pain have different kinematics than those pitching without pain.[19] Specifically, those pitching with upper extremity pain showed greater shoulder horizontal abduction at foot contact, less trunk lateral flexion toward the throwing side, and greater shoulder distraction forces at ball release.[19] Although these results are an insight into pitching mechanics and upper extremity pain, it has yet to be determined how the kinematics of the more proximal kinetic chain relate to upper extremity pain: specifically, kinematics of the stride, trunk, and center of mass (COM) at foot contact during the windmill softball pitch.

The purpose of this study was to examine lower extremity and trunk pitching mechanics, upper extremity kinetics, and upper extremity pain in National Collegiate Athletic Association (NCAA) Division I softball pitchers. Specifically, we examined the association of stride knee flexion, trunk flexion, trunk rotation, trunk lateral flexion, body COM in relation to the base of support, stride length (height normalized), and shoulder kinetics (shoulder flexion/extension torque, shoulder abduction/adduction torque, shoulder internal/external rotation torque, and shoulder compression/distraction force, all normalized to body weight) with softball pitchers experiencing upper extremity pain while throwing a riseball. We hypothesized that inefficient lower extremity and trunk pitching mechanics at foot contact would be associated with softball pitchers experiencing upper extremity pain.

METHODS

A total of 37 NCAA Division I female softball pitchers (mean age, 19.84 ± 1.28 years; mean height, 173.67 ± 7.77 cm; mean weight, 78.98 ± 12.40 kg) from across the United States were recruited to participate. The inclusion criteria required the participants to be actively competing on the team roster as a pitcher; additionally, they had to be surgery free for the past 6 months. The university's institutional review board approved all testing protocols, and informed written consent was obtained from each pitcher before participation.

Participants were asked the following: "Do you currently experience any pain/discomfort in your upper extremity, specifically your throwing side?" Based on the yes/no response, participants were grouped into 2 groups: those who were currently experiencing upper extremity pain (ie, experiencing pain before, during, and/or after pitching) and those who were not. Those who answered "no" were deemed pain free (n = 24; mean age, 19.91 ± 1.35 years; mean height, 174.26 ± 4.96 cm; mean weight, 74.78 ± 9.97 kg). Those who answered "yes" were then required to select the area of the body where they were experiencing pain, and all participants who selected anything in the area of the shoulder and elbow were assigned to the pain group (n = 13; mean age, 19.69 ± 1.18 years; mean height, 172.60 ± 11.49 cm; mean weight, 86.75 ± 13.02 kg).

Testing was conducted in an indoor biomechanics laboratory. Kinematic data were collected at 100 Hz using an electromagnetic tracking system (trakSTAR; Ascension Technology) synchronized with biomechanics analysis software (The MotionMonitor; Innovative Sports Training). Intraclass correlation coefficients (ICCs) greater than 0.96 for axial humeral rotation in both loaded and unloaded conditions have been reported for the electromagnetic tracking system.[14] The current system was calibrated using previously established protocols before data collection.[8,19,21] After calibration, the error in position and orientation of the electromagnetic sensors was less than 1 mm and 3°, respectively. Additionally, intrarater reliability on a pilot sample of 9 collegiate softball athletes was ICC(3,*k*) of 0.75 to 0.93 for all measurements.

A total of 11 electromagnetic sensors were attached to the participants using previously established methodologies.[19,23] A linked-segment model was developed using the digitized joint centers for the ankle, knee, hip, shoulder, T12-L1, and C7-T1 by the digitized medial and lateral aspects of each joint and then calculating the midpoint between those 2 points.[20,21,41,42] The ankle and knee joints were calculated as the midpoint between the digitized medial and lateral malleoli and medial and lateral femoral condyles, respectively. The spinal column was defined as the digitized space between C7-T1 and T12-L1. Additionally, a rotation method was utilized to estimate the joint centers of the shoulders and hips.[11,37] The rotation of the

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Ethical approval for this study was obtained from the Auburn University Institutional Review Board (protocol No. 15-474 EP 1512).

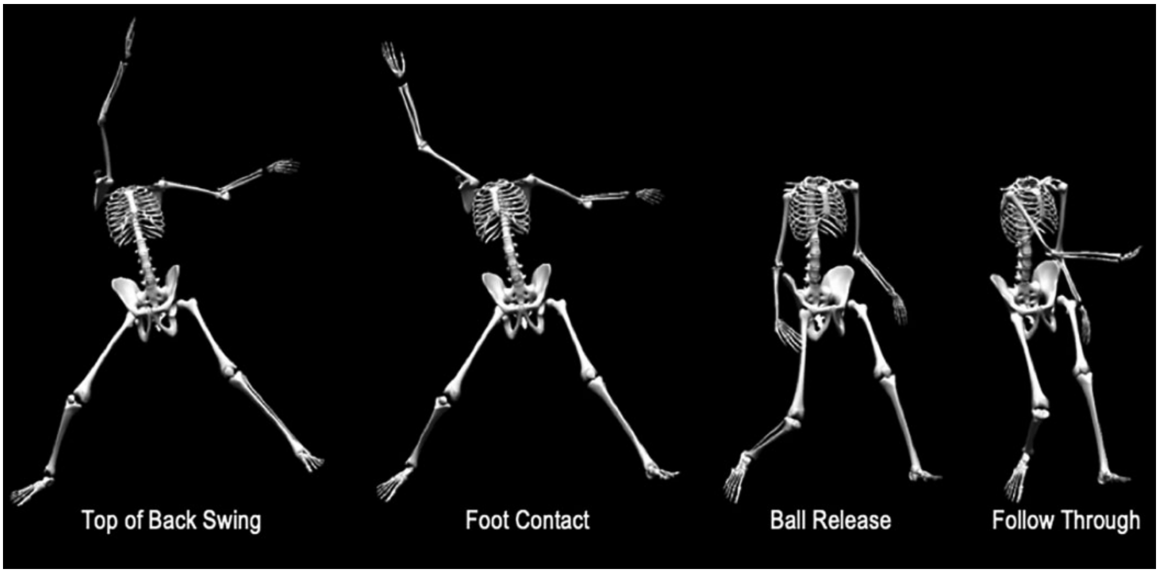

Figure 1. Pitching events.

humerus relative to the scapula was used to determine the shoulder joint center, while the rotation of the femur relative to the pelvis was used to determine the hip joint center.[11,37] The world axis was represented with a positive y-axis in the vertical direction; anterior to the y-axis and in the direction of movement was the positive x-axis, and orthogonal and to the right of the x- and y-axes was the positive z-axis. Raw data regarding sensor positioning and orientation were transferred to a locally based coordinate system. Euler angle sequences consistent with the International Society of Biomechanics standards and joint conventions were used to define the position and orientation of the body segments.[41,42] For trunk motion relative to the world axis, the Euler sequence of $ZX'Y''$ was used, while the sequence of $YX'Y''$ was used for shoulder motion relative to the trunk. All raw data were independently filtered along each global axis using a fourth-order Butterworth filter with a cutoff frequency of 13.4 Hz.[20,21,40]

After sensor attachment and participant digitization, each participant was given unlimited time to perform her individual prethrowing warm-up (average warm-up time was 10 minutes) and become familiar with the testing procedures. We chose not to standardize the warm-up in an attempt to better simulate each participant's individual prethrowing game preparation. Testing required the participants to throw 3 riseball pitches, for strikes, to a catcher located at 13.11 m (43 ft). Pitch trials were saved if the ball was in the strike zone. Foot contact was determined as the point in time at which the foot contralateral to the pitching arm contacted the ground.[19,23,38,39]

Data from the fastest riseball were included for analysis,[1,16] as Fleisig and colleagues[9] noted that there is minimal variability among pitches within elite populations. All data were processed using customized MATLAB script (R2010a; MathWorks). Statistical analyses were performed using SPSS Statistics 24 software (IBM). Normality of the data was tested with the Shapiro-Wilk test. Once data were determined to be normal, a logistic backward elimination regression analysis excluding variables with a greater than 10% probability of an association by chance alone ($P > .10$) was performed at the pitching event of foot contact (Figure 1). The dependent variable was upper extremity pain and the independent variables consisted of stride knee flexion, trunk flexion, trunk rotation, trunk lateral flexion, body COM over the base of support, stride length (normalized to height), shoulder flexion/extension torque, shoulder abduction/adduction torque, shoulder internal/external rotation torque, and shoulder compressive/distraction force, with all kinetics being normalized to body weight. COM was expressed as a percentage indicating where the COM sits over the athlete's base of support. With only right-handed pitchers included, 0% indicates that the COM is located entirely over the stance (right) leg, while 100% indicates that the COM is located entirely over the stride (left) leg. Significance was set a priori at $P < .05$ to limit type I errors. Effect size and adjusted R^2 were calculated to determine the fit of the backward elimination regression model by indicating the variance of upper extremity pain explained by the significant independent variables.

RESULTS

Descriptive statistics for demographic variables are presented in Table 1, and descriptive statistics for kinematic and kinetic variables can be found in Table 2. For the event of foot contact ($F_{3,33} = 7.01$, $P = .001$), backward elimination regression revealed that the model including stride length, trunk rotation, and COM was significantly associated with upper extremity pain. Stride length, trunk rotation, and COM contributed to about 33% of variance with softball pitchers experiencing upper extremity pain (adjusted $R^2 = 0.33$). Stride length ($t = 3.09$, $P = .004$), trunk rotation ($t = 3.54$, $P = .001$), and COM ($t = –2.52$,

TABLE 1
Demographic Variables[a]

Variable	Without Pain (n = 24)	Upper Extremity Pain (n = 13)	Total (N = 37)	P
Height, cm	174.26 ± 4.96	172.60 ± 11.49	173.67 ± 7.77	.543
Weight, kg	74.78 ± 9.97	86.75 ± 13.02	78.98 ± 12.40	<.004[b]
Age, y	19.91 ± 1.35	19.69 ± 1.18	19.84 ± 1.28	.681

[a]Data are reported as mean ± SD.
[b]Significant difference between study groups at $P < .05$.

TABLE 2
Kinematics and Kinetics at Foot Contact During Windmill Softball Pitching[a]

Variable	Mean ± SD
Left knee flexion	19.18 ± 10.02
Normalized stride length	0.50 ± 0.10
Trunk flexion	13.28 ± 14.19
Trunk rotation	81.37 ± 14.89
Trunk lateral flexion	8.30 ± 10.20
Normalized shoulder flexion/extension	–0.21 ± 1.20
Normalized shoulder abduction/adduction	0.84 ± 0.95
Normalized shoulder rotation	0.02 ± 0.88
Center of mass (%), right to left	44.59 ± 6.16
Shoulder distraction/compression force	–4.67 ± 2.97
Upper extremity pain	0.34 ± 0.48

[a]Knee flexion: (+) flexion, (–) extension; normalized stride length: % of body height; trunk flexion: (+) flexion, (–) extension; trunk rotation: 0° = facing forward to the catcher, 90° = rotated toward the pitching arm side; trunk lateral flexion: (+) toward pitching arm side, (–) toward glove arm side; normalized shoulder flexion/extension: (+) flexion, (–) extension; normalized shoulder abduction/adduction: (+) adduction, (–) abduction; normalized shoulder rotation: (+) internal rotation, (–) external rotation; center of mass (%), right to left: (>50%) left side, (<50%) right side; shoulder distraction/compression force: (+) compression, (–) distraction.

$P = .017$) all significantly correlated with upper extremity pain. These results indicate that greater stride length, trunk rotation to the pitching arm side, and a COM shifted toward the stance foot could be factors that help understand upper extremity pain within softball pitchers. Table 3 displays the unstandardized regression coefficient (B), standardized regression coefficient (β), t values, and P values for the backward elimination regression model used.

DISCUSSION

Previous work evaluating softball pitching mechanics and upper extremity pain found differences in upper extremity kinematics and kinetics between those pitching with pain and those pitching pain free.[19] With the known mechanical implications of pain during the windmill softball pitch, the present study aimed to examine the association of lower extremity and trunk kinematics and shoulder kinetics with pain in collegiate softball pitchers. Our hypothesis, that inefficient lower extremity and trunk mechanics during the softball pitching motion would be associated with upper extremity pain, was supported. Increased trunk rotation to the pitching arm side, COM position, and stride length were significantly associated with upper extremity pain at foot contact. This study adds to the growing body of knowledge that relates pitching biomechanics with pain and injury susceptibility.

TABLE 3
Coefficients in Backward Elimination Regression Model

Variable	B	β	t	P
Normalized stride length	2.600	0.513	3.092	.004[a]
Trunk rotation	0.017	0.516	3.537	.001[a]
Center of mass (%), right to left	–0.032	–0.403	–2.520	.017[a]

[a]Significant at $P < .05$.

Although the present study did not find shoulder kinetics to be associated with upper extremity pain, it has previously been reported that those pitching with upper extremity pain demonstrate greater shoulder distraction forces at ball release.[19] Additionally, it has been hypothesized that anterior shoulder pain in windmill softball pitchers is caused by increased shoulder kinetics occurring during the acceleration phase of the pitch.[4,5,38,39] Thus, further investigations into upper extremity pain and shoulder kinetics are warranted.

The finding of increased trunk rotation to the pitching side being associated with pain at foot contact could indicate an issue in the timing of segmental sequencing throughout the windmill softball pitch. If the trunk is not positioned to allow for a straight and smooth throwing arm circle, the upper extremity may need to compensate for the inefficient transfer of energy through the kinetic chain because of early trunk rotation. Coaches relying on qualitative pitching analysis often instruct pitchers to push out and off the mound before initiating trunk rotation. Previously, it has been reported that novice (less skilled) pitchers do not efficiently use their trunk in a proximal-to-distal sequencing manner and thus are unable to generate optimal ball speeds.[18] Concordantly, efficient utilization of the kinetic chain allows for maximum force and energy production that can be developed from the lower extremity, transferred distally through the trunk to the upper extremity and into the ball.[6,7,12] Thus, the present study's finding of trunk rotation being significantly associated with upper extremity pain is not surprising.

In addition to trunk rotation toward the pitching arm side, the position of COM and stride length at foot contact were also found to be associated with upper extremity pain. Specifically, COM of the pitcher toward the back push-off leg was related to upper extremity pain, as was increased stride length. These findings possibly indicate that as the pitchers increase stride length, there is a struggle to maintain proper balance. This lack of balance results in the COM being shifted toward the push leg instead of the stride leg as the pitch progresses into foot contact. In softball, this is commonly known as "anchoring" when the back foot prevents the body from exploding forward through the pitch and results in a backward-shifted COM. Although previous studies have indicated that longer stride lengths result in greater ball velocity,[38,39] it has also been noted that there is a stride length of diminishing returns, as the body must be in an optimal position to create resistance in which the body can rotate through to ball release.[10] A stride that is too long will cause the pitcher's COM to be located closer to the back push-off leg rather than centered within the base of support.[23]

The dynamic movement of the windmill softball pitch requires adequate energy transfer from the lower extremity in an attempt to decrease the physical demands placed on the distal segments of the upper extremity.[27] The finding of increased stride length and a posterior shift in the COM over the base of support could ultimately decrease the ability to not only generate but also transfer energy up the kinetic chain for optimal ball velocity.[10,23] Because the lower and upper extremities are integrated within the kinetic chain, a premature lower-half drive before the delivery phase of the pitch may result in a faulty kinetic chain link and increased susceptibility to injuries. Coaches and clinicians should take this information and develop programs that promote athletes' ability to balance their COM over their base of support, even through the dynamic pitching motion.

Discovering the indicators of current upper extremity pain may provide valuable information for coaches, clinicians, and sports medicine personnel. Understanding the factors related to pain within windmill softball pitchers before a pain-induced time-loss injury may postpone or even prevent such injuries. Through research such as this, sports medicine professionals can use this information to clinically assess for pain-predicative pathomechanics and counter any deficiencies through interventions, such as core strengthening for lagging trunk rotation, proprioceptive training for COM, and stride leg positioning. The increase in participation in competitive softball[17] necessitates a call for the dedication of more sports medicine professionals to be trained in the recognition and prophylactic treatment of injuries through corrective exercises of pitching pathomechanics.

While certain pathomechanics may cause pain, the possibility of pain affecting pitching mechanics also exists. In a previous study,[19] we reported that NCAA Division I pitchers pitching with pain experienced greater shoulder kinetics during the pitch. It is unknown whether the kinematic variables associated with pain discussed in this study are also associated with upper extremity kinetics. However, a logical conclusion is that in the presence of pain, an athlete may be inclined to compensate mechanically to reduce the amount of stress placed on the painful structure. Further studies are needed to determine which of these, pain or pathomechanics, affects the other.

When examining the study groups, a difference in weight was observed between the pain and pain-free groups (Table 1) that was not included in the analysis. Body fat measurements were not taken to determine differences in lean mass versus fat mass, so kinetic measurements being normalized to weight may not be quite as meaningful in that greater lean body mass could indicate a better ability to respond to stress compared with greater mass. Differences in weight have not been observed in the previous softball pitching literature examining pain and pain-free groups; thus, further research is warranted to determine the consistency of this result and its potential impact on kinematic and kinetic factors associated with pain.

Other limitations to this research include the sample size and the variables included in the statistical analysis. Using G*Power 3.1.9.2 for postcollection sample size analysis, 28 participants were needed for a power of 0.80. Therefore, it was concluded that an ample sample size was collected for this study. As far as the number of variables first used in the backward elimination regression, Austin and Steverberg[2] have suggested that 2 participants per variable is adequate for regression analysis. This analysis used 3.7 participants per variable. Other limitations include the laboratory setting, which may hinder the athlete's level of effort as well as typical fatigue responses under normal in-game, competitive circumstances. As well, only the riseball was used for analysis, which is not fully transferable to in-game exposures. Future research should look at kinematic and kinetic differences between the types of pitches to determine if similarities exist.

Self-reported pain as a binary measurement is also a study limitation. However, utilizing the pain measure in this fashion opens the door for future research to expand. Ideally, future research should examine the pitcher's mechanics over time to prospectively track changes in kinematics and kinetics as well as the incidence and degree of pain in specific anatomic locations. The current study sought to answer the relationship between mechanics and pain, while future research is needed to determine if a causal relationship exists.

CONCLUSION

The kinematic variables of increased trunk rotation toward the pitching arm side, increased stride length, and a posteriorly shifted COM were associated with upper extremity pain in collegiate softball pitchers. Variables early in the pitching motion that do not set a working and constructive foundation for the rest of the pitch to follow could be associated with breakdowns later in the kinetic chain, potentially increasing pain susceptibility in the upper extremity. Observation of kinematic variables through simple motion capture can help coaches and athletes identify those variables associated with pain.

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