J Shoulder Elbow Surg (2019) 28, 357–364

ELSEVIER

Journal of Shoulder and Elbow Surgery

www.elsevier.com/locate/ymse

The relationship of elbow alignment and kinematics on shoulder torque during the softball pitch: a biomechanical analysis of female softball pitchers

Donna Moxley Scarborough, MS, PT, PhD*, Robert C. McCunney, BS, Eric M. Berkson, MD, Luke S. Oh, MD, MS

MGH Sports Medicine Service, Department of Orthopaedic Surgery, Massachusetts General Hospital, Boston, MA, USA

Background: Female softball pitchers commonly throw more pitches per game and season than their baseball counterparts. The greatest stress to the shoulder during a softball windmill pitch is at ball release (BR). This study investigated shoulder torques at BR among female softball pitchers and identified relationships to the kinematics of the elbow and forearm and alignment of the elbow (carrying angle and elbow extension).
Methods: High-speed 3-dimensional biomechanical analyses were performed in 33 pitchers (25 high school, 8 collegiate). Elbow and shoulder biomechanics at BR during fastball pitches and goniometric measures of carrying angle and elbow extension were collected and analyzed.
Results: Carrying angle correlated positively with shoulder extension torque at BR ($r_s = 0.371$, $P = .048$) and forearm pronation at BR ($r_s = 0.370$, $P = .048$). During the windmill pitch, the greater the elbow flexion, the greater shoulder adduction torque at BR ($r_s = -0.522$, $P = .007$). Multiple regression analysis revealed that the carrying angle, passive elbow extension, and elbow flexion/extension angle at BR predicted shoulder flexion/extension torque at BR ($F_{3,24} = 3.463$, $R^2 = .302$, $P = .032$.)
Conclusions: Our findings demonstrate that shoulder torques during the softball fastpitch are influenced by the carrying angle and the kinematic elbow flexion angle at BR. Sports medicine clinicians and coaches should consider the role that the elbow carrying angle plays in creating shoulder stress when treating and training fastpitch softball players.
Level of evidence: Basic Science Study; Kinesiology

Keywords: Windmill pitching; softball; fastpitch; shoulder; elbow; forearm; 3D motion analysis; biomechanics

The underhand windmill pitching motion in fastpitch softball contains a series of coordinated movements that transfer kinetic energy up from the legs through the trunk and into the shoulder, elbow, forearm, and wrist. This kinetic chain of events generates significant forces on the shoulder and elbow joints that could lead to acute or overuse injuries.

The Partners Human Research Committee approved this study (Protocol # 2015P000220/PHS).

*Reprint requests: Donna Moxley Scarborough, MS, PT, PhD, MGH Sports Medicine Service, Department of Orthopaedic Surgery, Massachusetts General Hospital, 175 Cambridge St, Flr 4, Boston, MA 02114, USA.

E-mail address: dscarborough@mgh.harvard.edu (D.M. Scarborough).

1058-2746/$ - see front matter © 2018 Journal of Shoulder and Elbow Surgery Board of Trustees. All rights reserved.
https://doi.org/10.1016/j.jse.2018.07.021

Biomechanical studies of baseball and softball pitchers report an association of shoulder and elbow injuries among players who generate high shoulder torques.[3,16,22] One suggested contribution to high shoulder torque values is the inefficient use of the lower body and trunk during the pitching sequence.[3,22] Little is known about the possible influence that the forearm and elbow position (kinematics) at the time of ball release (BR) has on shoulder torque generation during the windmill softball pitch. Furthermore, whether the individual softball pitcher's anatomic elbow alignment is related to shoulder torque production is not known.

Increasing attention has been given to shoulder biomechanics and injuries in baseball pitchers; however, studies on shoulder biomechanics in softball pitchers have been limited despite comparable prevalence of shoulder injuries.[7,9,13,17,21] An injury surveillance study monitoring 10 softball and 8 baseball high school teams revealed 50% of the softball pitchers and 46.4% of the baseball pitchers sustained injury during a single season.[17] This same study reported a similar but slightly greater shoulder injury rate among softball pitchers (38.1%) compared with baseball pitchers (32.1%). Results of biomechanics studies in baseball have led to pitch count regulations in an effort to reduce overuse injuries. In softball, however, there are no known pitch count restrictions for softball pitchers at any level, which may stem from the misconception that the underhand softball pitching motion is less mechanically stressful than the overhand baseball pitching motion.[6]

In an electromyography (EMG) study, Rojas et al[14] found that biceps muscle activity during the windmill softball pitch was higher than biceps activity in overhand baseball pitching, indicating high shoulder distraction forces generated during windmill softball pitches. These findings reveal that the underhand softball pitching motion is more stressful to the shoulder than previously thought. Another biomechanical baseball pitching study found forearm supination around the time of BR had significant relationships with several shoulder kinematic measures.[12] Remaley et al[13] reported that the greatest EMG muscle activity in forearm flexors occurred in the later phases of the softball motion near BR. These findings are likely enhanced by the extended elbow position performed throughout most of the pitch delivery, which biomechanically creates a long lever arm about the shoulder before and around BR.

Across all ages, and particularly in adolescents, females are known to have increased flexibility compared with their male counterparts and frequently exhibit hypermobility of the shoulder and elbow.[19] The cubitus valgum angle (elbow carrying angle) changes during development, stabilizing as the boney growth plates close. The average expected carrying angle is 18.47° ± 4.12° for women and 9.29° ± 2.98° among men.[1] A larger carrying angle may be advantageous for a softball pitcher because it could facilitate clearing the throwing arm around the hips before BR; however, a large carrying angle may result in higher torques at the shoulder joint. Gaining insight of the relationship of stresses incurred at the shoulder resulting from an individual's anatomy of elbow angle and the biomechanics of the forearm/elbow during pitching may help clinicians and coaches provide more targeted strength and conditioning training programs to softball pitchers vulnerable to injury.

To our knowledge, no studies have compared measured anatomic alignment of the elbow carrying angle or elbow extension angle to shoulder torques produced during the softball windmill pitch. Similarly, we are unaware of any studies that have systematically compared the 3-dimensional (3D) biomechanical elbow angle and forearm pronosupination position at the time of BR to shoulder torques during the softball pitch. This study investigated the relationships of the alignment of the elbow (carrying angle and elbow passive range of motion extension angle) and the pitching biomechanical kinematics of the elbow and forearm at BR to shoulder torque production among female softball pitchers. We hypothesized that (1) softball pitchers with large elbow carrying angles would encounter higher shoulder torques at BR than pitchers with smaller carrying angles and that (2) softball pitchers with a more pronated forearm at BR would incur greater shoulder rotation torque.

Materials and methods

Thirty-three female competitive fastpitch softball pitchers (25 high school, 8 collegiate) completed 3D biomechanical pitch analysis using 20 high-speed motion capture cameras (240 Hz). The inclusion criteria were females aged 14 years or older, playing in a competitive organized league at the time of enrollment, at least 3 months from report of any injury, free of pain during pitching, and in their normal training routine for the season in which they were tested. Participant demographics can be found in Table I.

This cross-sectional study design was performed at our sports biomechanics research laboratory. Before participation, all players and their parents or guardians were fully informed of the purpose, procedures, and risks of this study, and all enrolled participants provided written informed consent.

Data collection

Each pitcher completed upper extremity range of motion measurements before participating in the biomechanical pitch analysis study. All measurements followed a standardized protocol and were performed by a single senior physical therapist (D.M.S.) with more than 20 years of experience.

The throwing arm carrying angle was measured using a standardized plastic universal goniometer (Baseline 12" Plastic goniometer, 360° marked in 1° increments; Prestige Medical,

Table I Demographics of study participants

Level	No.	Age (yr)	Height (m)	Weight (kg)
High school	25	15.4 ± 1.4	1.7 ± 0.07	66.2 ± 14.43
College	8	20.00 ± 1.3	1.7 ± 0.07	74.5 ± 13.2
Total	33	16.5 ± 2.4	1.7 ± 0.07	68.2 ± 14.4

Data are presented as the average ± standard deviation.

Table II Definitions of 3-dimensional biomechanics of upper limb segments[23]

Joint center and arm segments	Marker location and joint center definition
Shoulder joint center	Estimated via linear regression based on markers placed on the dorsal portion of the acromioclavicular joint, the scapular spine, the inferior angle of the scapula, the acromial angle, and the coracoid process
Upper arm segment	Proximal end: dorsal acromioclavicular joint Distal end: medial and lateral epicondyles An additional tracking marker was placed laterally on the anterior deltoid and posteriorly on the midpoint of the triceps (right side only)
Elbow joint center	Midpoint between the medial and lateral epicondyles markers
Forearm segment	Proximal end: medial and lateral epicondyles Distal end: radial and ulnar styloid processes An additional tracking marker was placed on the middle of the dorsum of the forearm
Wrist joint center	Defined as the midpoint of the markers on the radial and ulnar styloid processes
Hand segment	Proximal end: radial and ulnar styloid processes Distal end: dorsum of the third metacarpal

Northridge, CA, USA). One arm of the goniometer was centered along the midline of the humerus on the coronal plane with the axis of rotation placed at the center of the antecubital fossa. The second arm of the goniometer was oriented to the midpoint of the wrist between the ulnar styloid and the radial styloid process.[5] There are reports of high intra-rater reliability for this measurement with intraclass correlation coefficient (ICC) of 0.965 (95% confidence interval, 0.958-0.973).[5]

Elbow extension angle was measured with the stationary arm of the goniometer placed laterally along the midline of the humerus in line with the tip of the acromion, the axis at the lateral epicondyle and the mobile arm in line with the radial styloid. Measurement of elbow extension in this manner reports a high ICC of 0.96 for intra-rater reliability.[15]

Use of same evaluator and adherence to the test protocol has been reported to result in highest reliability for goniometric measurement suggesting measurements of ≤4° for intratester error.[2,4] The value at the end range of extension that reads as below the expected full extension of 0° represents hyperextension and is recorded as a positive value. An angle measure demonstrating lack of full elbow extension (inability to reach the expected full extension of 0°) is recorded as a negative value.[5]

The same trained evaluator followed our standardized marker placement protocol and adhered 62 spherical reflective markers (14-mm diameter) to each pitcher to create a 15-body segment 3D model. Table II provides information on the primary markers used to create the 3D upper extremity biomechanics model.

Each pitcher performed her typical stretching and warm up routine before pitching was recorded. After warm up, each pitcher was asked to throw 5 to 10 of each pitch type (fastball, curveball, changeup, etc) that she was comfortable throwing in her preferred order from the standardized pitching rubber placed at regulation distance of 13.11 m from home plate. An average of 56 pitches was thrown. The pitchers threw toward a standardized strike zone target positioned behind home plate. A Stalker ATS 5.0 radar gun (Stalker, Plano, TX, USA) recorded the speed of each pitch, and the tester recorded where each pitch ended relative to the strike zone target for determining pitch accuracy. The average fastball velocity was 23.53 ± 2.05 m/s.

3D motion capture of full-body kinematics during the softball pitches was collected at 240 Hz using 20 T-series cameras (Vicon MX 3D motion analysis system; Vicon Motion Systems Ltd., Oxford, United Kingdom).

Analysis

Data analysis was performed on 3 successful fastball pitch trials. Successful fastball trials were defined as pitches that accurately hit the designated strike zone target with the highest speed. All biomechanical variables were calculated in Visual3D v5 software (C-Motion, Inc., Germantown, MD, USA). The laboratory coordinate system consisted of an x-axis oriented between the pitching rubber and home plate, the vertical direction was identified as the z-axis, and the cross-product of the z- and x-axes resulted in the y-axis. A fourth-order zero-lag Butterworth low-pass filter with a cutoff frequency of 18 Hz processed all marker position data. In the 15 segment, 6 degree-of-freedom model, upper body segments were defined in accordance with International Society of Biomechanics definitions and outlined in Table II.[23]

BR is defined as the point during the softball pitch delivery when the ball is released from the hand and was identified using the synchronized video recording and created as an event for each pitch in Visual3D v5 software. Variables were computed and analyzed at that point in time as BR. The variables at BR were shoulder flexion/extension torque, shoulder adduction/abduction torque, shoulder external/internal rotation torque, elbow flexion, and forearm angle (supination/pronation; Fig. 1). The variables are defined in Table III.

Statistical analyses included nonparametric Spearman ρ correlations to assess relationships of elbow anatomic angles and kinematic variables with shoulder torques. Multiple regression analyses were performed to determine whether shoulder torques (including sagittal, frontal, and rotation plane torques) at BR can be predicted based on the variables of carrying angle, passive elbow extension, elbow flexion/extension at BR, and forearm pronosupination at BR. Statistical analyses were performed with a level of significance set at $P \leq .05$.

Results

The physical measurements of the elbow carrying angle and elbow extension angle of the pitching arm were analyzed to seek possible correlations to torques on the shoulder at the time of ball release during the windmill softball pitch. Table IV

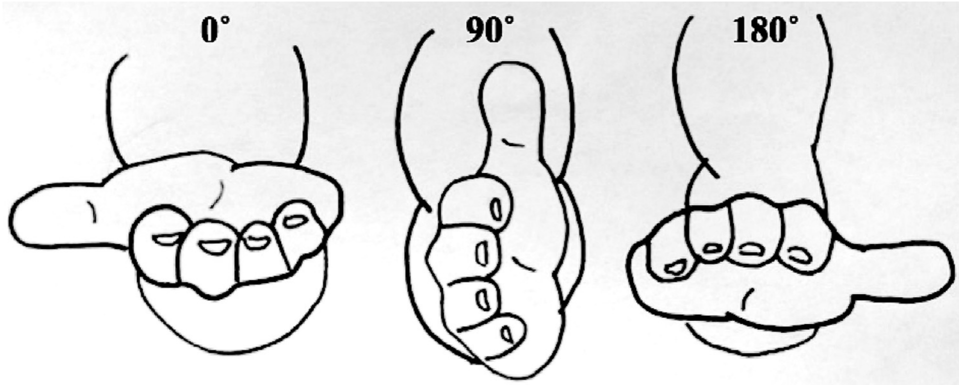

Figure 1 Illustration of how the 3-dimensional kinematic forearm angle at ball release is defined: supination (0°-90°) and pronation (91°-180°).

Table III Definition of primary 3-dimensional biomechanical variables calculated at time of ball release

Variable	Definition
Shoulder flexion/ extension torque	The required force to rotate the humerus about the frontal axis into extension (negative value) or flexion (positive value): sagittal (*x*) plane in N-m.
Shoulder adduction/ abduction torque	The required force to rotate the upper arm about the sagittal axis into adduction (negative value) or abduction (positive value): frontal (*y*) plane in N-m
Shoulder internal/external rotation torque	The required force to rotate the humerus about the transverse axis internally (negative value) or externally (positive value): transverse (z) plane in N-m
Elbow flexion	The angle formed between the humerus and forearm: sagittal (*x*) plane in degrees
Forearm angle (Fig. 2)	The rotational angle of the forearm (supination = 0°-89°, neutral = 90°, pronation = 91°-180°): transverse (*z*) plane in degrees

Table IV Descriptive and numerical results for variables measured

Variable	Mean ± SD	Clinical plane
Average carrying angle, °	11 ± 3.7	Cubitus valgus
Average elbow extension angle, °	4 ± 2.9	Extension angle
Average values at ball release		
Shoulder flexion/extension torque, N-m	−13.2 ± 28.2	Extension torque
Shoulder adduction/abduction torque, N-m	−31.4 ± 44.4	Adduction torque
Shoulder internal/external rotational torque, N-m	−9.6 ± 14.2	Internal rotation torque
Average forearm angle, °	43 ± 20.1	Supination angle
Average elbow flexion°	35 ± 9.6	Elbow flexion

SD, standard deviation.

includes the descriptive and numeric results for the key variables.

Relationship of forearm and elbow alignment to shoulder torques at BR

Carrying angle correlated negatively with shoulder flexion/extension torque at BR ($P = .003$; Fig. 2, Table V). In other words, a larger carrying angle is related to increased extension torque at BR. Shoulder flexion/extension torques were graphed throughout the windup for 1 pitcher, represented by the modified pitch phase originally described by Maffat et al,[11] and outlined in Fig. 3.

A multiple regression was run to predict shoulder flexion/extension torque at BR from 3 variables: carrying angle, passive elbow extension, and elbow flexion/extension angle at BR. These variables statistically significantly predicted shoulder flexion/extension torque at BR ($F_{3,24} = 3.463$, $R^2 = .302$, $P = .032$). The carrying angle contribution to the prediction model was statistically significant ($P = .011$). Therefore, when controlling for passive elbow extension and elbow flexion/extension at BR, for every 1° increase in carrying angle, there is a decrease in the flexion/extension torque plane (meaning, directionally there is an increase in shoulder extension torque) of 4.03 N-m. Passive elbow extension and the elbow flexion/extension angle at BR did not statistically

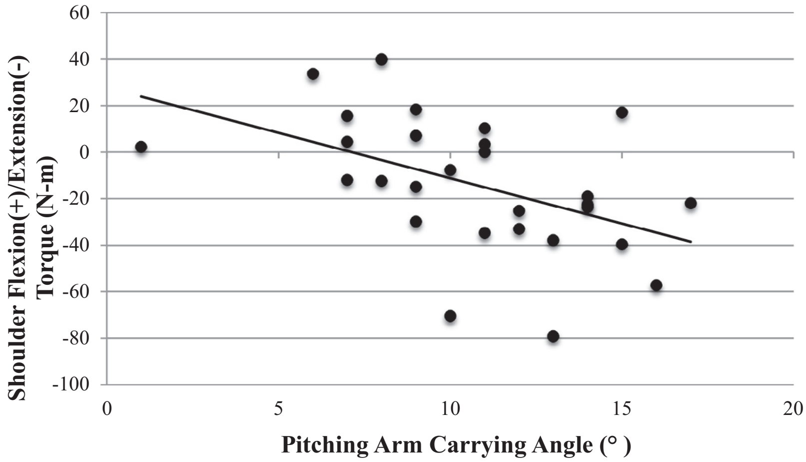

Figure 2 Correlation of carrying angle and shoulder flexion (+)/extension (–) torques at ball release of average fastball, windmill softball pitch ($r_s = -0.545$, $P = .003$; n = 28).

Table V The relationship of the physical characteristics of the elbow (carrying angle and elbow extension) on shoulder torques at ball release across all pitchers

Variable	Spearman correlation	*P* value
Correlation with carrying angle		
Shoulder flexion/extension torque at BR	–0.545	.003*
Shoulder abduction/adduction torque at BR	–0.149	.450
Shoulder rotational torque at BR	0.040	.838
Correlation with elbow extension angle		
Shoulder flexion/extension torque at BR	0.051	.777
Shoulder abduction/adduction torque at BR	0.190	.290
Shoulder rotational torque at BR	0.242	.183

BR, ball release.
* Statistically significant ($P < .05$).

significantly add to the prediction ($P = .131$ and $P = .962$, respectively).

Forearm and elbow kinematics relationship during the windmill pitch at BR to shoulder torque

The first step of the analyses included assessing the relationship of carrying angle to windmill pitch kinematics of the forearm and elbow at the time of BR. During the fastball windmill pitch, the forearm angle at BR correlated positively with the carrying angle ($r_s = 0.370$, $P = .048$), revealing that the larger the carrying angle, the greater the forearm pronation at BR. However, forearm angle at BR not reach the established level of significance when correlated with shoulder rotation torque, shoulder adduction torque, shoulder extension torque, or elbow flexion angle at BR.

The influences of forearm and elbow kinematics during the windmill pitch at the time of BR on shoulder torques during the fastball pitch were analyzed. Elbow flexion at BR correlated negatively with shoulder adduction/abduction torque at BR ($r_s = -0.522$, $P = .007$), demonstrating that the greater the elbow flexion at BR, the greater shoulder adduction torque at BR (Fig. 4). However, the elbow flexion at BR did not correlate with shoulder rotation torque at BR.

Discussion

Fastpitch softball is one of the fastest growing sports. One of the USA's largest fast pitch softball organizations, USA Softball, registers more than 2.4 million players, of which there are more than 80,000 adolescent girls' softball teams.[20] The popularity of the sport has resulted in an increased recognition of softball-related injuries. Of injuries sustained among high school softball players (collected by athletic trainers from 74 schools during 2005-2008), 35% included shoulder muscle strain and incomplete tears.[10] In an adolescent player-reported single season injury surveillance study by Smith et al,[18] 48 softball pitchers reported 18 injuries, and 61% involved the shoulder. There is a gradual rise in epidemiology studies tracking injuries among softball players. However, there is a paucity in research relating injury risk to physical make-up of the athlete, such as elbow joint anatomy, and pitch biomechanics.

Biomechanical studies on softball pitching primarily describe pitch mechanics or report the differences in kinematic and kinetic variables across level of play.[3,22] Our study offers insight into the relationship of anatomic characteristics of the elbow (elbow carrying angle and maximum elbow extension) and the shoulder torques at BR during the fastball pitch among female softball pitchers. Similarly, our study reports the influence of elbow and forearm kinematics at BR to shoulder torques at time of BR.

The biomechanical relationship of carrying angle and shoulder torques during windmill pitching may provide clinicians

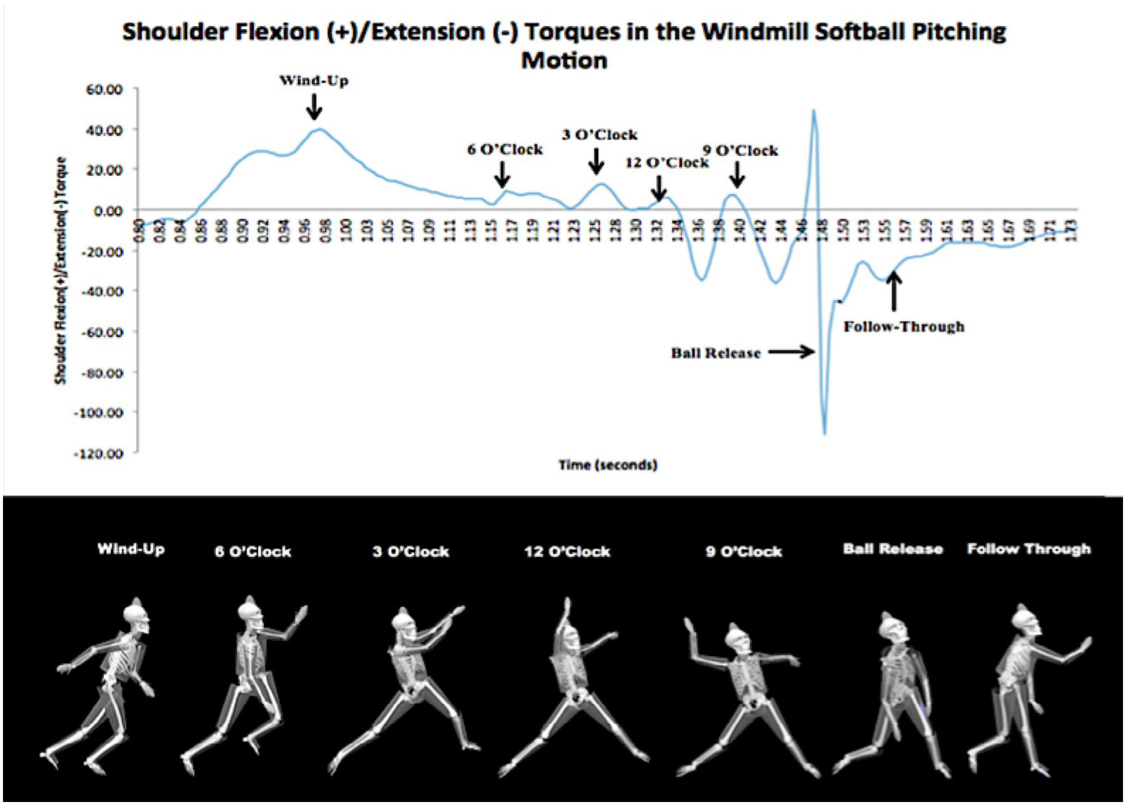

Figure 3 Illustrates the relationship of elbow flexion and shoulder adduction/abduction torque at ball release during the fastball pitch. Key events of the pitching motion are illustrated in the graph and represent a modified pitch phase originally described by Maffat et al.[11]

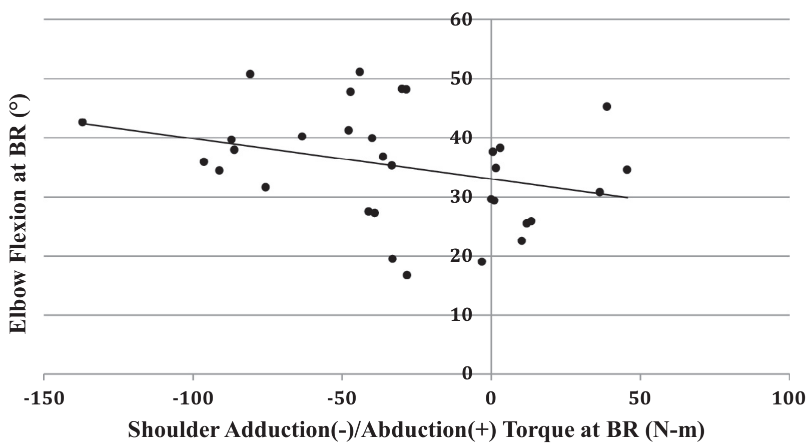

Figure 4 Correlation of elbow flexion at ball release (*BR*) and shoulder abduction (+)/adduction (–) torque at ball release of average fastball, windmill softball pitch ($r_s = -0.386$, $P = .029$; n = 32).

with a possible screening tool for injury prevention. Early identification of possible anatomic risk of injury could direct strength training specific to areas vulnerable to injury. Similarly, identification of elbow position during pitch delivery and anatomic vulnerability associated with possible risk of injury could direct coaches to prioritize pitch technique training.

Our first hypothesis was supported, because increased carrying angle correlated positively with increased shoulder extension torque among all female athletes investigated. During the fastball pitch, the throwing limb abruptly decelerates just before BR. During the final approach to BR, the elbow is primarily extended, followed by immediate elbow flexion after BR (Fig. 3). Pitchers with an increased carrying angle create a mechanically different lever arm than those with a smaller angle at the time of ball BR. Our findings suggest that stresses placed on the shoulder extensor muscles will be greater among pitchers with a larger carrying angle because the shoulder incurs greater extension torque than those pitchers with smaller carrying angles when the musculature creates the abrupt breaking motion for ball release. The carrying angle measurement may be a screening tool for clinicians to identify female pitchers who will demonstrate greater shoulder extension torques and stress on the shoulder during the fastpitch windmill pitch. Future studies gathering carrying angle measurements among female players with and without shoulder injury are warranted to determine whether this provides reliable risk information.

Our second hypothesis was not supported, because no relationship was found between the pitching kinematics of the forearm angle and shoulder torques at BR. Although the carrying angle correlated positively with forearm angle at BR, the relationship of forearm angle at BR did not reach statistical significance with any of the shoulder torques. However, this study only performed analyses on the fastball pitch delivery, and other delivery types rely on varying degree of forearm position. This investigation led to findings of interesting correlations of kinematics at the time of BR and shoulder torques and velocities associated with shoulder injury that have not previously been reported.

Elbow flexion at BR correlated positively with the greater adduction torque at BR across pitchers. Within the final moments leading to and through BR, the humerus internally rotates and adducts across the body. Having increased elbow flexion at this time mechanically requires greater shoulder adduction torque, as our data show. Mechanically, an arm with greater elbow flexion will require increased shoulder internal velocity and torque to bring the arm into position quickly for ball release compared with an arm with in a straighter position. High internal rotation torques have been associated with shoulder injuries among baseball pitchers[3] and may likely contribute to such injury susceptibility in the female softball pitchers as well. This finding supports pitching coaches to correct elbow position during the pre-BR phase to reduce the additional required shoulder adductor torque generation.

Additional limitations to discuss include constrictions due to technology for data capture of high-speed activity, such as pitching, and the ability to extrapolate beyond the study design. A careful standardized procedure, common to current practice of 3D motion analysis capture, was followed using synchronized video to manually obtain BR time. The motion of the windmill pitch is extremely fast, and it is possible that the sampling rate is not high enough to capture the instance of BR at the exact moment. Our capture system's sample rate was set higher than that reported in most previous publications, and we implemented a systematic approach of identifying BR across 2 trained personnel to improve the methodology. As technology improves, the ability to have a higher sample rate will improve this identification of BR release time and data capture.

Our study design looked at only one type of softball pitch. A recent review performed by Grantham et al[8] consistently found differences in forearm supination between fastballs and curveballs in baseball pitchers and found implications on shoulder forces. Our study only examined fastballs; therefore, additional research is needed in assessing the effects of different pitch types, such as curveballs, on forearm angles and subsequently on shoulder torques in softball pitchers.

The results of our study provide clinicians, athletic trainers, and softball coaches with insight to the interconnectedness between elbow and shoulder biomechanics. Softball pitchers who present with increased carrying angle on their throwing side should be mindful of their shoulder health. Strength and conditioning programs for softball pitchers should include elbow flexors, elbow extensors, and shoulder extensor, abductor, and rotator musculature. Increasing strength in the flexors and extensors of the elbow may also help control the amount of pronation and elbow extension during softball BR and decrease the stresses on the shoulder. Additional research is needed to understand what role strength and conditioning of the elbow and forearm plays in reducing adverse shoulder stress without decreasing performance. Softball coaches and strength coaches must be cognizant of unique physical characteristics of each player, such as elbow carrying angle, because player-specific mechanical adjustments may be necessary. Additional understanding can allow coaches to protect arm health through pitching mechanics while improving performance.

Conclusion

This study suggests that among female fastpitch softball pitchers, shoulder torques at BR correlate with the elbow carrying angle in addition to elbow flexion kinematics at BR. Future studies are warranted to study softball pitchers who present with an increased elbow carrying angle to determine whether they are more susceptible to shoulder injury than those with smaller elbow carrying angles. These factors may be important in clinical and biomechanical understanding of injury risk and preventive training program design among female fastpitch softball pitchers.

Acknowledgments

The authors recognize Shannon Linderman, MA, MS, for support during data collection, and Denise Davis, BS, MBA (founder and owner of Planet Fastpitch, LLC), for recruitment support and inspiration to study female softball pitchers.

Disclaimer

The authors, their immediate families, and any research foundation with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

References

1. Alsubael MO, Hegazy AA. Radiographic evaluation of the normal elbow carrying angle in adults. J Med Sci Alert 2010;10:40-4. http://dx.doi.org/10.1016/j.jse.2011.10.026
2. Armstrong AD, MacDermid JC, Chinchalkar S, Stevens RS, King GJ. Reliability of range-of-motion measurement in the elbow and forearm. J Shoulder Elbow Surg 1998;7:573-80.
3. Barrentine SW, Fleisig GS, Whiteside JA, Escamilla RF, Andrews JR. Biomechanics of windmill softball pitching with implications about injury mechanisms at the shoulder and elbow. J Orthop Sports Phys Ther 1998;6:405-14.
4. Boone DC, Azen SP, Lin CM, Spence C, Baron C, Lee L. Reliability of goniometric measurements. Phys Ther 1978;11:1355-60.
5. Chapleau J, Canet F, Petit Y, Laflamme GY, Rouleau DM. Validity of goniometric elbow measurements: comparative study with a radiographic method. Clin Orthop Relat Res 2011;11:3134-40. http://dx.doi.org/10.1007/s11999-011-1986-8
6. Corben JS, Cerrone SA, Soviero JE, Kwiecien SY, Nicholas SJ, McHugh MP. Performance demands in softball pitching: a comprehensive muscle fatigue study. Am J Sports Med 2015;8:2035-41. http://dx.doi.org/10.1177/0363546515588179
7. Flyger N, Button C, Rishiraj N. The science of softball: implications for performance and injury prevention. Sports Med 2006;9:797-816.
8. Grantham WJ, Iyengar JJ, Byram IR, Ahmad CS. The curveball as a risk factor for injury a systematic review. Sports Health 2015;7:19-26. http://dx.doi.org/10.1177/1941738113501984
9. Holtz KA, O'Connor RJ. Upper extremity functional status of female youth softball pitchers using the Kerlan-Jobe Orthopaedic Clinic questionnaire. Orthop J Sports Med 2018;6:2325967117748599. http://dx.doi.org/10.1177/2325967117748599
10. Krajnik S, Fogarty KJ, Yard EE, Comstock RD. Shoulder injuries in US high school baseball and softball athletes, 2005-2008. Pediatrics 2010;125:497-501. http://dx.doi.org/10.1542/peds.2009-0961
11. Maffet MW, Jobe FW, Pink MM, Brault J, Mathiyakom W. Shoulder muscle firing patterns during the windmill softball pitch. Am J Sports Med 1997;25:369-74.
12. Matsuo T, Jinji T, Hirayama D, Nasu D, Ozaki H. Radio-ulnar joint supinates around ball release during baseball fastball pitching. Sports Biomech 2016;2:220-33. http://dx.doi.org/10.1080/14763141.2016.1159725
13. Remaley DT, Fincham B, McCullough B, Davis K, Stausmire JM. Surface electromyography of the forearm musculature during the windmill softball pitch. Orthop J Sports Med 2015;3:1-8. http://dx.doi.org/10.1177/2325967114566796
14. Rojas IL, Provencher MT, Bhatia S, Foucher KC, Bach BR, Romeo AA, et al. Biceps activity during wind-mill softball pitching: injury implications and comparison with over-hand throwing. Am J Sports Med 2009;37:558-65. http://dx.doi.org/10.1177/0363546508328105
15. Rothstein JM, Miller PJ, Roettger RF. Goniometric reliability in a clinical setting. Elbow and knee measurements. Phys Ther 1983;10:1611-5.
16. Sabick MB, Torry MR, Kim YK, Hawkins RJ. Humeral torque in professional baseball pitchers. Am J Sports Med 2004;32:892-8. http://dx.doi.org/10.1177/0363546503259354
17. Shanley E, Raugh MJ, Michener LA, Ellenbecker TS. Incidence of injuries in high school softball and baseball players. J Athl Train 2011;46:648-54. http://dx.doi.org/10.1177/0363546511408876
18. Smith MV, Davis R, Brophy RH, Prather H, Garbutt J, Wright RW. Prospective player-reported injuries in female youth fast-pitch softball players. Sports Health. 2015;6:497-503. http://dx.doi.org/10.1177/1941738115606058
19. Soucie JM, Wang C, Forsyth A, Funk S, Denny M, Roach KE, et al.; Hemophilia Treatment Center Network. Range of motion measurements: reference values and a database for comparison studies. Haemophilia 2011;17:500-7. http://dx.doi.org/10.1111/j.1365-2516.2010.02399.x
20. USA Softball. US Olympic Committee <http://www.teamusa.org/usa-softball/about/about-us>; 2016, accessed October 9, 2016.
21. Wang Q. Baseball and softball injuries. Curr Sports Med Rep 2006;3:115-9.
22. Werner SL, Guido JA, McNeice RP, Richardson JL, Delude NA, Stewart GW. Biomechanics of youth windmill softball pitching. Am J Sports Med 2005;4:552-60. http://dx.doi.org/10.1177/0363546504269253
23. Wu G, van der Helm FC, Veeger HE, Makhsous M, Van Roy P, Anglin C, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—part II: shoulder, elbow, wrist and hand. J Biomech 2005;5:981-92.