MUSCLE ACTIVATION PATTERNS OF THE UPPER AND LOWER EXTREMITY DURING THE WINDMILL SOFTBALL PITCH

GRETCHEN D. OLIVER, HILLARY A. PLUMMER, AND DAVID W. KEELEY

Department of Health, Kinesiology, Recreation, and Dance, University of Arkansas, Fayetteville, Arkansas

ABSTRACT

Oliver, GD, Plummer, HA, and Keeley, DW. Muscle activation patterns of the upper and lower extremity during the windmill softball pitch. *J Strength Cond Res* 25(6): 1653–1658, 2011—Fast-pitch softball has become an increasingly popular sport for female athletes. There has been little research examining the windmill softball pitch in the literature. The purpose of this study was to describe the muscle activation patterns of 3 upper extremity muscles (biceps, triceps, and rhomboids [scapular stabilizers]) and 2 lower extremity muscles (gluteus maximus and medius) during the 5 phases of the windmill softball pitch. Data describing muscle activation were collected on 7 postpubescent softball pitchers (age 17.7 ± 2.6 years; height 169 ± 5.4 cm; mass 69.1 ± 5.4 kg). Surface electromyographic data were collected using a Myopac Jr 10-channel amplifier (RUN Technologies Scientific Systems, Laguna Hills, CA, USA) synchronized with The MotionMonitor™ motion capture system (Innovative Sports Training Inc, Chicago IL, USA) and presented as a percent of maximum voluntary isometric contraction. Gluteus maximus activity reached (196.3% maximum voluntary isometric contraction [MVIC]), whereas gluteus medius activity was consistent during the single leg support of phase 3 (101.2% MVIC). Biceps brachii activity was greatest during phase 4 of the pitching motion. Triceps brachii activation was consistently >150% MVIC throughout the entire pitching motion, whereas the scapular stabilizers were most active during phase 2 (170.1% MVIC). The results of this study indicate the extent to which muscles are activated during the windmill softball pitch, and this knowledge can lead to the development of proper preventative and rehabilitative muscle strengthening programs. In addition, clinicians will be able to incorporate strengthening exercises that mimic the timing of maximal muscle activation most used during the windmill pitching phases.

KEY WORDS electromyography, fast pitch, muscle firing patterns

INTRODUCTION

Millions of girls participate in the sport of fast-pitch softball, and still there has been limited research conducted involving the sport. According to a report from all 5 governing bodies of fast-pitch softball, there were >2 million female adolescents between the ages of 12 and 18 competing in fast-pitch softball during 2003 (23). Softball has not only grown drastically over the years but it has also become a year-round sport for most serious participants. As with baseball, fast-pitch softball relies heavily on the ability of the pitcher to strategically control the game. It is not uncommon for a team to have a dominant pitcher that pitches most if not all of the games during a season. However, unlike baseball where the pitching mechanics has been intensively investigated, research concerning pitching mechanics for softball is scarce. It has been documented that the torques about the shoulder and elbow are similar in softball and in baseball, and therefore, with the risk of injuries in windmill softball pitching becomes as paramount as those in baseball. With the increased risk of injury, the mechanics of the windmill pitch are imperative to understand (2). To date, there are limited studies describing not only the mechanics of the windmill softball pitch but also descriptions of muscle activations throughout the phases of the pitch (2,13,23,24).

Biomechanically, the human body can be depicted as a kinetic link model based on the kinetic chain. The kinetic chain describes the body as interdependent segments; thus, contribution of the entire body during sport activities is essential (15). The proximal segments of the legs and trunk work sequentially in effort to accelerate the shoulder for optimal force production in upper extremity activities (18,19). Furthermore, the large muscles of the hips and trunk help position the thoracic spine to accommodate for effective movement of the scapula, which allows for functional shoulder motion (15). It is the efficiency of the

---

Address correspondence to Dr. Gretchen D. Oliver, goliver@uark.edu.

25(6)/1653–1658

Journal of Strength and Conditioning Research

proximal segments that initiate the movement of the more distal segments. Based on the kinetic chain, the core musculature is the key link in allowing seamless energy transfer from the lower extremity to the upper extremity. Therefore, it could be speculated that adequate firing of the gluteal muscle group would be vital in proximal to distal sequencing in dynamic movements, such as the windmill softball pitch (17), considering that the gluteal muscle group is a large contributor to core musculature. In an attempt to provide normal motor patterns of the upper extremity while performing the pitching motion, the lower extremity and trunk musculature must be activated before the arm motion occurs (1,7,19). Thus, adequate muscle activation of the gluteal muscle group as a part of the core musculature is vital in proximal to distal sequencing of upper extremity movements.

Previously, the research has focused solely on the upper extremity muscle function with the windmill softball pitch. Maffet et al. (13) have examined the activation patterns of 8 muscles of the upper extremity, and Rojas et al. (20) have examined the biceps during the 5 phases of the windmill pitch. However, there is no study to date that examines both the upper and lower extremity muscle activation patterns throughout the phases of the windmill softball pitch. In an attempt to understand the motion of the windmill softball pitch and the injury implications, it is imperative that we understand the muscle activations throughout the pitching motion. Therefore, the purpose of this study was to describe the muscle activation patterns of 3 upper extremity muscles (biceps, triceps, and rhomboids [scapular stabilizers]) and 2 lower extremity muscles (gluteus maximus and medius) during the 5 phases of the windmill softball pitch.

METHODS

Experimental Approach to the Problem

Surface electromyography (EMG) data were collected on the biceps, triceps, scapular stabilizers, gluteus maximus, and gluteus medius muscles throughout the 5 phases of the windmill softball pitching motion. The phases of this study were described according to Maffett and are listed in Table 1. In addition, data describing the kinematics of the motion were collected to allow for the identification of the instants the throwing arm was positioned at 6 o'clock, 3 o'clock, 12 o'clock, 9 o'clock, and ball release. The data in this study were collected in a manner such that participants threw a series of maximal effort fastballs to a catcher located at the regulation distance from the pitching mound. Only those data from the fastest pitch passing through the strike zone were analyzed (10,21). Descriptive statistics were used to quantify the muscle activations by examining normalized surface EMG (sEMG) data as the average percent of maximum voluntary isometric contractions throughout the different phases of the windmill softball pitch.

TABLE 1. Phases of the Windmill Softball Pitch

Phase	Description of motion
1.	From windup to 6 o'clock; first ball motion forward to 6 o'clock
2.	From 6 o'clock to 3 o'clock; body weight is on ipsilateral leg, trunk is squared toward the batter; arm is elevating to 90°
3.	From 3 o'clock to 12 o'clock; transfer of body weight forward; trunk open up to third base; arm reached 180° of elevation
4.	From 12 o'clock to 9 o'clock; trunk is open to third base; stride foot plant occurs
5.	From 9 o'clock to ball release; trunk closes to square with the batter; all weight transferred to stride leg

Subjects

Seven female postpubescent softball pitchers (age 17.7 ± 2.6 years; height 169 ± 5.4 cm; mass 69.1 ± 5.4 kg) regardless of throwing arm dominance volunteered to participate in this study. All participants had recently completed their competitive spring softball seasons and were thus deemed appropriately conditioned for competition. Additional criterion for participation included recommendation from their respective coaching staff, multiple years (up through the current season) of pitching experience, and freedom from injury throughout the current softball season.

Data collection sessions were conducted indoors at the University of Arkansas Health, Physical Education, and Recreation building and were designed to best simulate a competitive setting. All testing protocols used in this study were approved by the University of Arkansas Institutional Review Board and before participation the approved procedures, risks, and benefits were explained to all participants and their parents who then signed the appropriate paperwork to provide consent for testing.

Procedures

Participants reported for testing before engaging in resistance training or any vigorous activity that day. Location of the 3 upper extremity muscles (biceps, triceps, and rhomboids [scapular stabilizers]) and 2 lower extremity muscles (gluteus maximus and medius) were identified through palpation. Before testing, the identified locations for surface electrode placement were shaved, abraded and cleaned using standard medical alcohol swabs. Subsequent to surface preparation, adhesive 3M Red-Dot bipolar surface electrodes (3M, St. Paul, MN, USA) were attached over the muscle bellies and positioned parallel to muscle fibers using techniques described by Basmajian and Deluca (3). In this study, the selected interelectrode distance was 25 mm (9). Surface electrodes were chosen because they have been deemed to be a noninvasive technique that is able to reliably detect surface muscle activity (3,9,11).

To transmit sEMG data to The MotionMonitor^{TM} motion capture system (Innovative Sports Training Inc, Chicago, IL, USA), a Myopac Jr 10-channel amplifier (RUN Technologies Scientific Systems, Laguna Hills, CA, USA) with a common mode rejection ratio equal to 90 dB and set at a gain of 2,000 was employed. Throughout all testing, sEMG data were sampled at a rate equal to 1,000 Hz. Filtering of all sEMG data was completed using standard band-pass filtering techniques with band-pass filters set at cutoffs of 20 and 350 Hz, respectively. In addition, all sEMG data were notch filtered at frequencies of 59.5 and 60.5 Hz, respectively (5). All sEMG amplitudes were normalized to the MVIC obtained from manual muscle testing (MMT).

Once all electrodes had been secured, 3 MMTs were conducted for each muscle. The MMTs were conducted using techniques described by Kendall et al. (11). For example, the biceps muscle was tested with participants in a seated position, with their elbow slightly flexed at less than a right angle with forearm supinated. The investigators then placed 1 hand under the participant's elbow for support and applied pressure with their other hand against the participant's distal forearm just proximal to the wrist in the direction of extension. The participant was instructed to resist the extension pressure applied by the investigator. All MMTs consisted of a 5-second isometric contraction for each muscle, with the first and last seconds of each contraction removed so as to obtain steady-state results. Each MMT was conducted to establish baseline readings for the participant's maximum voluntary isometric contraction (MVIC). All sEMG data were presented as a percent of the participant's MVIC. Before performing the MMTs, the approved testing protocol was explained to all participants to ensure their full understanding.

In addition to sEMG data, kinematic data were also collected in an attempt to identify the different phases of the pitch. Kinematic data were collected using The MotionMonitor^{TM} motion capture system (Innovative Sports Training). Before completing test trials, participants had a series of 6-degrees-of-freedom electromagnetic sensors (Flock of Birds, Ascension Technologies Inc, Burlington, VT, USA) attached to their thorax, sacrum, distal throwing forearm, right and left mid-humerus, and right and left midshank. Sensors were affixed using double-sided tape and then wrapped using flexible hypoallergenic athletic tape. After the attachment of the electromagnetic sensors, a third sensor was attached to a stylus and used to digitize the palpated position of various bony landmarks (16). To accurately digitize the selected bony landmarks, participants stood in the neutral anatomical position while digitization was being completed. A segment link model was developed through digitization of joint centers of the ankle, knee, hip, shoulder, T12-L1, and C7-T1. The spinal column was defined as the digitized space between the associated spinous processes, whereas the ankle and knee were defined as the midpoints of the digitized medial and lateral malleoli, medial and lateral femoral condyle, respectively. The hip and shoulder joint centers were defined by virtue of the least-squares method (14).

Throwing kinematics for right-handed participants were calculated using the standards and conventions for reporting joint motion recommended by the International Shoulder Group of the International Society of Biomechanics recommendations (25,26). Raw data describing sensor orientation and position were transformed to locally based coordinate systems for each of the respective body segments. Euler angle decomposition sequences were used to describe the position and orientation of both the pelvis and trunk relative to the global coordinate system (25,26). The use of these rotational sequences allowed the data to be described in a manner that most closely represented the clinical definitions for the movements reported (25). Throwing kinematics for left-handed participants were calculated using the same conventions; however, it was necessary to mirror the world z-axis so that all movements could be calculated, analyzed, and described from a right hand point of view (26). Before the conduction of test trials, the space in which the participants were to throw was calibrated using the following protocol: The origin of the world axis system was located on a wooden platform located 25.4 cm from the extended range transmitter used to generate the electromagnetic field. The orientation of the world axis system extended from the center of the pitching rubber toward the center of home plate; the world y-axis extended was orthogonal to the x-axis and extended vertically from the center of the pitching rubber (26). The world z-axis was orthogonal to both x and y axes, directed laterally to the right. To calibrate the space, a wooden stylus was attached to an electromagnetic sensor and placed at the world axis system origin, 15 cm from the origin along both the x and z axes, and at one random position above the origin per manufacturer recommendations. After the establishment and calibration of the world axes, the root mean square error in calculating the 3-dimensional location of markers within the calibrated space was determined to be <20 mm.

Once all initial setup and pretesting had been completed, participants were allotted an unlimited time to warm-up. Participants were allowed to perform their own specified precompetition warm-up routine and were asked to spend the latter portion of that warm-up time throwing from the indoor pitching surface to be used during the test trials. After completing their warm-up and gaining familiarity with the pitching surface, each participant threw a series of maximal effort fastballs for strikes using an official softball (12 in. circumference, 6 oz) to a catcher located the regulation distance from the pitching mound (12.2 m). A total of 5 trials were recorded after they were deemed a successful strike and between trials, pitchers were allowed a 40- to 60-second rest

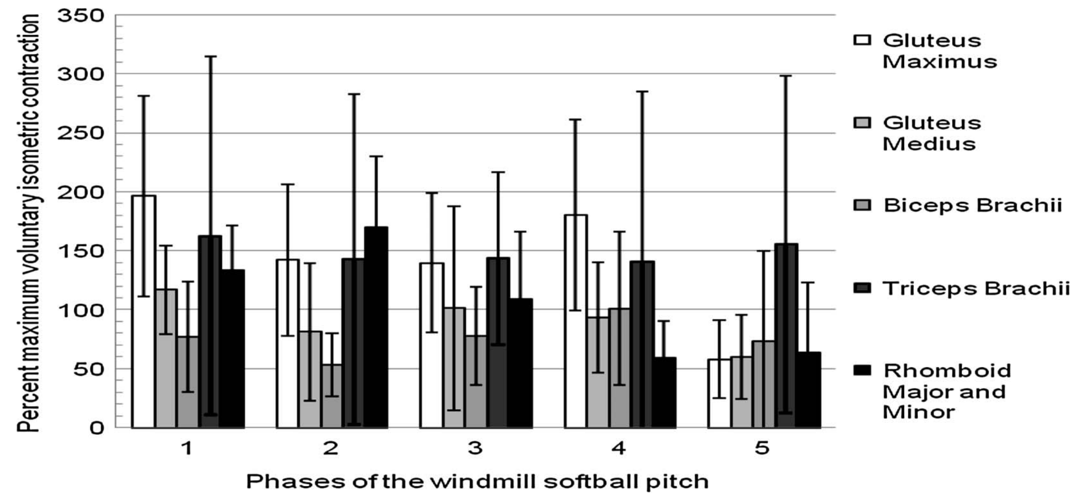

Figure 1. Mean and *SD*s (error bars) of muscle activation during the windmill softball pitch.

period to best simulate a game situation. For this study, those data from the fastest pitch passing through the strike zone were selected for detailed analysis (10,21).

Statistical Analyses

Statistical analyses were performed using SPSS 15.0 for Windows. Mean and *SD* of the normalized sEMG data were examined for each muscle's percent of their MVIC.

Results

Gluteus maximus activity was highest during phase 1 of the windup (196.3% MVIC) where there is stabilization of the pelvis in preparation for the striding of the contralateral leg with the second highest activity occurring at stride foot plant during phase 4 (180.1% MVIC). Gluteus medius activity was consistent during the single leg support phases 3 and 4 (101.2 and 93.2% MVIC, respectively). Biceps brachii activity was greatest during phase 4 with the second highest occurring at phase 5 (73.2% MVIC). Triceps brachii activities were consistently >150% MVIC throughout the entire pitching motion, whereas the scapular stabilizers were most active during phase 2 (170.1% MVIC). The results are graphically summarized in Figure 1.

Discussion

The windup or phase 1 displayed greater muscle activity in the gluteus maximus than any of the upper extremity muscles. During the windup, there is a weight shift; thus, activation of the gluteals is required. During the stride motion of Phase 2, the gluteus medius acted to stabilize and generate torque of the pelvis. In addition during forward arm flexion to 90, the rhomboids had increased their firing in attempt to stabilize the scapula throughout arm elevation in the scapular plane. The gluteal muscles provide pelvic stabilization when on the single leg support. Pelvic stabilization during phase 2 is important in an attempt to efficiently transfer energy up the kinetic chain from the hips to the pelvis to the scapula to the shoulder, elbow and on to the wrist and hand. This premise follows the notion of the legs and trunk providing 51–55% of the total kinetic energy in upper extremity activities (12).

In addition, when referring to the increased muscle activation of the scapular stabilizers during phase 2, previous investigations have noted, that before fatigue, overhead throwers have increased upward rotation of the scapula compared to nonoverhead throwers, indicating altered movement of the scapula (16). However, in a separate investigation, after pitching a simulated game, the scapula exhibited decreased upward rotation and external rotation (4); after a swimming event, investigators noted similar findings in altered scapular motion (22). An unstable scapula or inefficient movement of the scapula during such a dynamic movement would predispose the glenohumeral joint to migrate superiorly, which is associated with impingement syndrome (6). Scapular movement during the pitching motion allows for elevation of the acromion; thus, the scapular stabilizers must efficiently fire in an attempt to rotate the scapula so that it can clear the acromion for the function of the rotator cuff musculature.

During phase 3, the activity of the gluteus medius increased, and where the humerus was not only being elevated but also externally rotated, the triceps brachii activity remained consistent. Phase 4 displayed a continuation of the triceps brachii activity and decreased activation of the scapular stabilizers. Contrary to baseball mechanics, the biceps brachii is most active during the acceleration phase during the windmill softball pitch as compared to the deceleration phase

(8) during the baseball pitch. In phase 4, when the pitcher is attempting to "post" for ball delivery on the stride leg during stride foot plant, the dominant gluteus medius must hold the dominant hip upright, while the pitcher is balanced on the stride leg (opposite leg).This stabilization is evident by the reported gluteus medius activity (Figure 1). During phase 5, the triceps brachii experienced high activation, whereas the core musculature of the gluteus maximus and medius decreased in activation. Throughout phases 1–3, the rhomboids stayed consistent to stabilize the scapulae, as the arm was dropping below 90° of elevation. During the motion of the humerus dropping below 90°, the humerus was also internally rotating and the rhomboids were exhibiting a decrease in activity. Future investigations with a larger sample size may look into the differences and relationships between experience level and muscular activation throughout the phases.

When discussing pitching, 2 major differences between baseball and softball are apparent. The main differences are (1) how the pitchers are managed and (2) the pitching surface from which the pitchers throw (24). In baseball, the pitchers throw from a mound that allows gravity to assist with the movement, whereas in softball, pitchers throw from a level surface without the assistance of gravity. It has been reported that peak ground reaction forces in windmill pitchers are similar to those of baseball pitchers with some instances of windmill pitchers reporting higher ground reaction forces (23). We can speculate that the greater ground reaction forces reported in windmill pitchers are because of the posting of the plant leg during phase 4 of the pitching cycle and throughout ball release. Although posting occurs throughout the final phases of the pitching cycle, the element of balance is required. The dominant gluteus medius displays great activity during this time, as does the gluteus maximus. Gluteal muscle activity on the dominant side represents an attempt to stabilize the pelvis while on single leg support. This notion of pelvic stabilization while on single leg support is essentially the Trendelenburg effect representing the action of the gluteus medius (11).

We were able to quantify and describe muscle activation for the upper and lower extremities during the windmill softball pitch in postpubescent girls. It should be noted that our sample size was small; however, the protocol performed has been previously validated (11,20) and the investigator, a certified athletic trainer, was sufficiently trained in sEMG data collection. Further investigations need to not only address a different population group, such as prepubescent or professional, but also examine the activation of the scapular stabilizers. The data in this study revealed that the scapular stabilizers were most active during phases 1–3 of the pitching motion. It is the scapular stabilizers that allow for efficient movement of the scapula. During the pitching motion, from the start of the pitch to the arm reaching the 12 o'clock position, the muscles surrounding the scapula allow for elevation of the acromion in an attempt to allow the humerus to reach full range of motion. Because this is the only investigation of our knowledge looking at the rhomboids or scapular stabilizers throughout the windmill softball pitch, we are not able to specifically define the functionality throughout the windmill pitch. However, based on our participants, we were able to generalize the muscle activation pattern of the scapular stabilizers.

In addition, further investigations are needed on the implications of the lower extremity and the pitching motion. An investigation of both dominant and nondominant lower extremity and core musculature would provide an insight into the dynamic balance required to perform the windmill softball pitch.

Practical Applications

Softball pitchers throw thousands of pitches throughout their career, and this increases their risk of sustaining an overuse injury in both the upper and lower extremities. The knowledge of muscle activations during the windmill pitching motion provides a premise for prevention and rehabilitative programs for those clinicians working with windmill softball pitchers. Athletic trainers, physical therapists, and coaches now have a qualitative description of the muscle activation patterns required to pitch. In addition, clinicians should incorporate strengthening exercises that mimic the timing of maximal muscle activation most used during the pitching phase. Example, if the scapular stabilizers are most activated from the 6 o'clock to 3 o'clock phase then rehabilitations exercises should be performed in those phase positions. Or if one was trying to rehabilitate a windmill softball pitcher with biceps tendonitis, focus should be on conditioning from just before 9 o'clock and throughout the follow through. In addition, there is a need for core strengthening to help properly transfer energy to decrease the stress placed on the shoulder when performing a successful pitch. Core strengthening should focus on gluteal activations and on trunk rotational activities.

References

1. Aguinaldo, AL, Buttermore, J, and Chambers, H. Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various levels. *J Appl Biomech* 23: 42–51, 2007.
2. Barrentine, S, Fleisig, G, Whiteside, J, Escamilla, RF, and Andrews, JR. Biomechanics of windmill softball pitching with implications about injury mechanisms at the shoulder and elbow. *J Ortho Sports Phys Ther* 28, 405–415, 1998.
3. Basmajian, JV and Deluca, CJ. Apparatus, detection, and recording techniques. In: *Muscles Alive, Their Functions Revealed by Electromyography* (5th ed.). Butler, JP, ed. Baltimore, MD: Lippincott Williams and Wilkins, 1985. pp. 19–64.
4. Birkelo, JR, Padua, DA, Guskiewicz, KM, and Karas, SG. Prolonged overhead throwing alters scapular kinematics and scapular muscle strength. *J Athl Train* 38: S10–S11, 2003.
5. Blackburn, JT and Pauda, DA. Sagittal-plane trunk position, landing forces, and quadriceps electromyographic activity. *J Athl Train* 44: 174–179, 2009.
6. Deutsch, A, Altchek, DW, Schwartz, E, Otis, JC, and Warren, RF. Radiologic measurement of superior displacement of the humeral

head in the impingement syndrome. *J Shoulder Elbow Surg* 5: 186–193, 1996.

7. Escamilla, RF, Fleisig, GS, Barrentine, SW, Zheng, N, and Andrews, JR. Kinematic comparisons of throwing different types of baseball pitches. *J Appl Biomech* 14: 1–23, 1998.
8. Fleisig, GS, Barrentine, SW, Zheng, N, Escamilla, RF, and Andrews, JR. Kinematic and kinetic comparison of baseball pitching among various levels of development. *J Biomech* 32: 1371–1375, 1999.
9. Hintermeister, RA, Lange, GA, Schultheis, JM, Bey, MJ, and Hawkins, RJ. Electromyographic activity and applied load during shoulder rehabilitation exercises using elastic resistance. *Am J Sports Med* 26: 210–220, 1998.
10. Keeley, DW, Hackett, T, Keirns, M, Sabick, MB, and Torry, MR. A biomechanical analysis of youth pitching mechanics. *J Pediatr Orthoped* 28: 452–459, 2008.
11. Kendall, FP, McCreary, EK, Provance, PG, Rodgers, MM, and Romani, WA. *Muscles: Testing and Function* (4th ed.). Baltimore, MD: Lippincott Williams and Wilkins, 1993.
12. Kibler, WB. Biomechanical analysis of the shoulder during tennis activities. *Clin Sports Med* 14: 79–85, 1995.
13. Maffet, MW, Jobe, FW, Pink, MM, Brault, H, and Mathiyakom, W. Shoulder muscle firing patterns during the windmill softball pitch. *Am J Sports Med* 25: 369–374, 1997.
14. McGregor, AH, Zeenat, SP, and Bull, AMJ. Longitudinal changes in the spinal kinematics of oarswomen during step testing. *J Sport Sci Med* 6: 29–37, 2007.
15. McMullen, J and Uhl, TL. A kinetic chain approach for shoulder rehabilitation. *J Athl Train* 35: 329–337, 2000.
16. Myers, JB, Laudner, KG, Pasquale, MR, Bradley, JP, and Lephart, SM. Scapular position and orientation in throwing athletes. *Am J Sports Med* 33: 263–271, 2005.
17. Oliver, GD and Keeley, DW. Gluteal muscle group activation and its relationship with pelvic and torso kinematics in high school baseball pitchers. *J Strength Cond Res.* 24: 3015–3022, 2010.
18. Putnam, CA. A segment interaction analysis of proximal-to-distal sequential segment motion patterns. *Med Sci Sports Exerc* 23: 130–144, 1991.
19. Putnam, CA. Sequential motions of body segments in striking and throwing skills: Descriptions and explanations. *J Biomech* 26(Suppl. 1): S125–S135, 1993.
20. Rojas, IL, Provencher, MT, Bhatia, S, Foucher, KC, Bach, BR, Romeo, AA, Wimmer, MA, and Verma, NN. Biceps activity during windmill softball pitching. *Am J Sports Med* 37: 558–565, 2009.
21. Sabick, MB, Torry, MR, Young-Kyu, K, and Hawkins, RJ. Humeral torque in professional baseball pitchers. *Am J Sports Med* 32: 892–898, 2004.
22. Scibek, JS and Borsa, PA. Swimming practice significantly reduces scapular upward rotation. *J Athl Train* 28: S11, 2003.
23. Werner, SL, Guido, JA, McNeice, RP, Richardson, JL, Delude, NA, and Stewart, GW. Biomechanics of youth windmill softball pitching. *Am J Sports Med* 33: 552–560, 2005.
24. Werner, SL, Jones, DG, Guido, JA, and Brunet, ME. Kinematics and kinetics of elite windmill softball pitching. *Am J Sport Med* 34: 597–603, 2006.
25. Wu, G, Siegler, S, Allard, P, Kirtley, C, Leardini, A, Rosenbaum, D, Whittle, M, D'Lima, DD, Cristofolini, L,Witte, H, Schmid, O, and Stokes, I. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human motion–part I: Ankle, hip, and spine. *J Biomech* 35: 543–548, 2002.
26. Wu, G, van der Helm, FCT, Veeger, HEJ, Makhsous, M, Van Roy, P, Anglin, C, Nagels, J, Karduna, AR, McQuade, K, Wang, X, Werner, FW, and Buchholz, B. ISB recommendation on definitions of joint coordinate systems of various joint for the reporting of human joint motion–part II: Shoulder, elbow, wrist, and hand. *J Biomech* 38: 981–992, 2005.