Lower Extremity Muscle Activation During Baseball Pitching

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Abstract

Campbell, BM, Stodden, DF, and Nixon, MK. Lower extremity muscle activation during baseball pitching. *J Strength Cond Res* 24(4): 964–971, 2010—The purpose of this study was to investigate muscle activation levels of select lower extremity muscles during the pitching motion. Bilateral surface electromyography data on 5 lower extremity muscles (biceps femoris, rectus femoris, gluteus maximus, vastus medialis, and gastrocnemius) were collected on 11 highly skilled baseball pitchers and compared with individual maximal voluntary isometric contraction (MVIC) data. The pitching motion was divided into 4 distinct phases: phase 1, initiation of pitching motion to maximum stride leg knee height; phase 2, maximum stride leg knee height to stride foot contact (SFC); phase 3, SFC to ball release; and phase 4, ball release to 0.5 seconds after ball release (follow-through). Results indicated that trail leg musculature elicited moderate to high activity levels during phases 2 and 3 (38–172% of MVIC). Muscle activity levels of the stride leg were moderate to high during phases 2–4 (23–170% of MVIC). These data indicate a high demand for lower extremity strength and endurance. Specifically, coaches should incorporate unilateral and bilateral lower extremity exercises for strength improvement or maintenance and to facilitate dynamic stabilization of the lower extremities during the pitching motion.

Key Words EMG, stride leg, trail leg, throwing

Introduction

Baseball pitching involves optimally coordinating movements of the upper extremity, trunk, and lower extremity to produce maximum ball velocity. Kinematic, kinetic, and muscle activation patterns of the upper extremity for baseball pitching have been well documented (1–6,11,19,20). However, even though contributions from the lower extremities in pitching are suggested to be vital, research documenting the role of the lower extremities has been limited (8,9,22). The purpose of this study was to investigate the muscle activation levels of 5 lower extremity muscles during the pitching motion.

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Understanding lower extremity muscle activation patterns in baseball pitching is important not only to define the role of the lower extremities but also to assist in performance enhancement and to decrease injury potential. Knowledge of muscle activation levels will provide a greater understanding of how a pitcher uses the lower extremities to generate ball velocity and dynamically control the body in the different unilateral and bilateral loading progressions associated with different stages of the pitch. Only one study has attempted to address lower extremity muscle activity patterns (22). Yamanouchi (22) investigated several lower extremity muscles during the pitching motion, but only divided the pitch into 2 distinct phases. Bilateral electromyography (EMG) data on 6 lower extremity muscles (abductor, adductor, quadriceps, biceps femoris [BF], tibialis anterior, and gastrocnemius [GAST]) were analyzed for two 2-second intervals before stride foot contact (SFC) and after SFC. Thus, the entire pitching motion was divided into only 2 phases without a definitive understanding of when the pitching motion actually began or ended and without delineating important phases of the pitching motion. Yamanouchi (22) indicated that the first 2-second phase elicited moderate activity from the quadriceps (48 ± 14% maximal voluntary isometric contraction [MVIC]) and the adductor (84 ± 8% MVIC) of the stride leg. The second phase elicited moderate activity from the BF (60 ± 24% MVIC) of the trail leg and the adductor of both the trail leg (83 ± 12% MVIC) and the stride leg (84 ± 12% MVIC). Overall, the results of this study may have been more informative if the data collection intervals were based on the actual beginning and ending of the pitching motion and if the pitching motion had been divided into more than 2 phases. Analyzing lower extremity muscle activity in more than 2 phases of the pitch would seem to be a more appropriate method to address the differences in activation levels among phases.

The pitching motion is generally separated into 6 phases: windup, stride, arm cocking, arm acceleration, arm deceleration, and follow-through (4,9,14,15) (see Figure 1). The

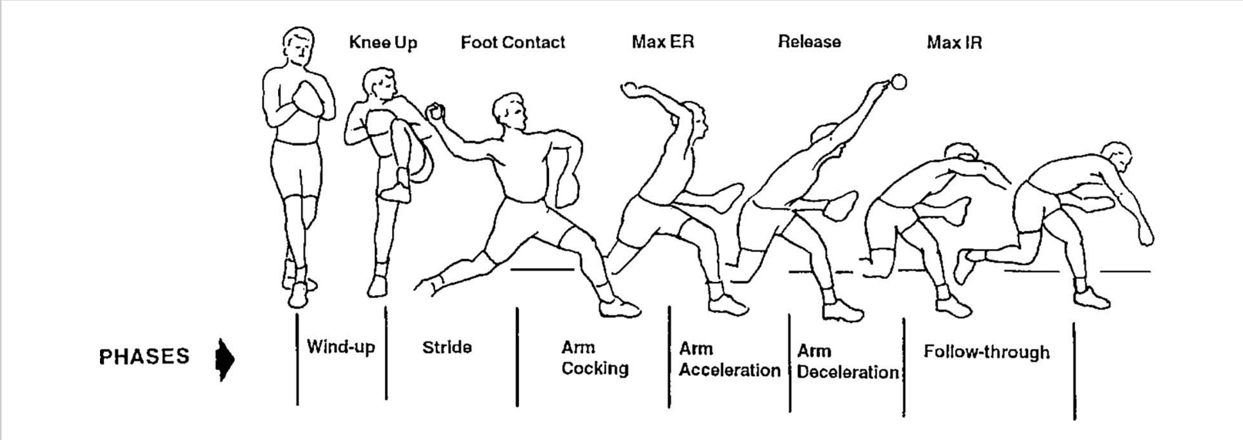

Figure 1. The 6 phases of pitching (Stodden et al. (15)).

importance of lower extremities with regard to pitching performance is generally demonstrated within the first 4 phases. The windup begins when the pitcher initiates the first movement and ceases at maximal knee height of the stride leg. The length of time for this phase is variable dependent on both the individual pitcher and whether a pitcher is using the full windup or going from the "stretch" position. Concentric contraction of the hip flexors promotes hip flexion of the stride leg, whereas the hip extensors, knee extensors, and knee flexors dynamically stabilize the trail leg and hip musculature to promote a quasi-static balance point. Lower shank musculature involvement during this phase is generally thought to be low, although this has not been documented in the literature.

The stride phase begins as the stride leg begins its decent and ends with SFC. This phase generally lasts between 0.5 and 0.75 seconds (4). The stride functions to produce the initial linear momentum of the body and is the initial factor in the generation and transfer of momentum up through the kinetic chain (16). The role of lower extremity musculature during the stride phase has been debated yet remains unclear. Many coaches believe that a pitcher should "push off" the pitching rubber with the trail leg during the stride to increase initial forward momentum, whereas others suggest that pitchers should demonstrate a "controlled fall" toward home plate. Eccentric contractions of stride leg hip flexors control the lowering of stride leg during the initial aspects of the stride. If a pitcher would "push off" the rubber, the hip and knee musculature of the trail leg should forcefully contract to promote the "push off" or "drive" toward home plate (4). In contrast, a pitcher using the "controlled fall" method would presumably demonstrate less hip and knee muscular activity in the trail leg if there is no forceful push off the pitching rubber. Although Yamanouchi (22) indicated low to moderate activity of the trail leg quadriceps and GAST muscles up to SFC, this 2-second interval incorporated both the windup and stride phases of pitching motion. Thus, lower extremity activation levels during only the stride could not be delineated.

The arm-cocking phase begins at SFC and ends at maximal external rotation of the throwing shoulder. This phase generally only lasts between 0.10 and 0.15 seconds (4). During this phase, the stride knee either maintains its degree of flexion or begins to extend (9). Thus, the stride leg hip, knee, and ankle musculature generally begin to isometrically or concentrically contract during the arm-cocking phase, serving to stabilize the stride leg and promote the transfer of momentum through the trunk. Also, at this time, the trail leg foot begins to lose contact with the pitching rubber as the ankle plantar flexes, the hip continues into hyperextension, and the knee of the trail leg demonstrates approximately 50° of knee flexion (5).

The arm acceleration phase begins at maximal external rotation of the throwing shoulder and ends at ball release. Again, this phase lasts a very short time (0.03–0.04 seconds) with the lower extremity musculature of the stride leg continuing to dynamically stabilize the hip, knee, and ankle as the center of mass of the body begins to move forward over stride leg (4). At ball release, the trail leg is completely off the ground for most pitchers. Thus, the trail leg provides no functional importance at this point in the pitching motion. During arm deceleration and follow-through, the stride leg musculature is responsible for maintaining a dynamic single leg stance as the upper torso and upper extremities continue to rotate and linearly translate about the fixed-stride leg. Presumably, the hip extensors, knee extensors, knee flexors, and ankle plantarflexors would continue to be highly active during arm deceleration and the follow-through to dynamically control these joints. Yamanouchi (22) combined the arm cocking, acceleration, and follow-through into one 1-second interval, whereas we more appropriately delineated these into 2 phases (phases 3 and 4) as indicated by recent

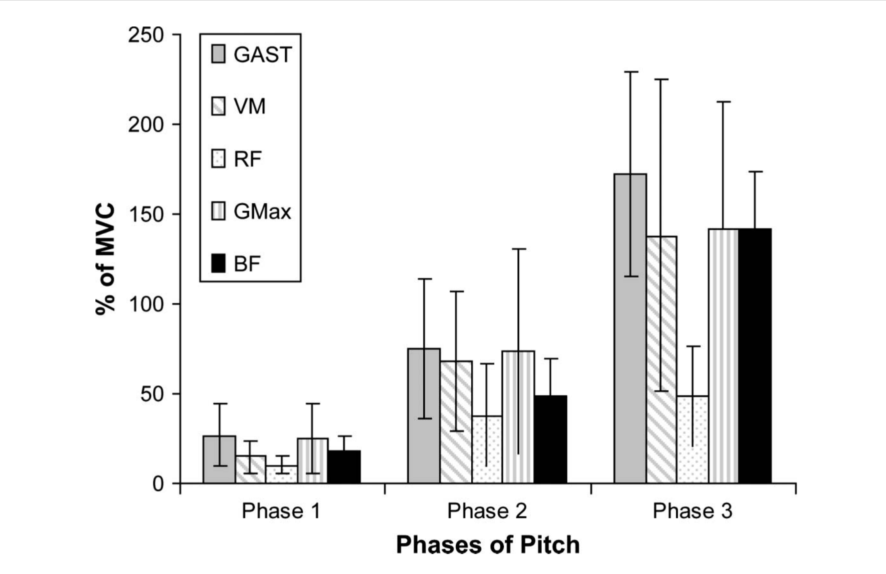

Figure 2. Percentages of MVIC mean electromyography (EMG) value (± *SD*) for the gastrocnemius (GAST), vastus medialis (VM), rectus femoris (RF), gluteus maximus (GM), and biceps femoris (BF) muscles of the trail leg during each of the phases of the pitch.

literature. As just described, lower extremity movements during pitching are extremely dynamic providing both unilateral and/or bilateral support during specific phases. Thus, we believe it is important to delineate muscle activity patterns during specific phases of the pitching motion that would provide a more detailed and thorough examination of lower extremity muscle activity patterns. We believe that this information will also provide important information on how to more effectively train pitchers for the purpose of both performance enhancement and injury prevention.

Methods

Experimental Approach to the Problem

We used surface EMG to assess muscle activity of the vastus medialis (VM), BF, rectus femoris (RF), gluteus maximus (GM), and GAST during a series of maximal effort baseball pitches in highly skilled baseball pitchers. We chose these muscles because they represent critical lower extremity musculature associated with the pitching motion. We divided the pitching motion into 4 distinct phases, phase 1, initiation of pitch to maximum stride knee kick height; phase 2, maximum stride leg knee height to SFC; phase 3, SFC to ball release; and phase 4, ball release to 0.5 seconds after ball release (i.e., follow-through). We decided to combine the arm cocking and arm acceleration phases because both phases are both extremely short in duration, and there is no clear distinction in the roles of both lower extremities during these 2 phases. The same rationale was used for combining the arm deceleration and follow-through phases.

We compared mean EMG values during each pitching phase with the mean EMG value from the MVIC of each muscle. We used this method to determine at what percentage a specific muscle was active during any one of the four defined phases of the pitch.

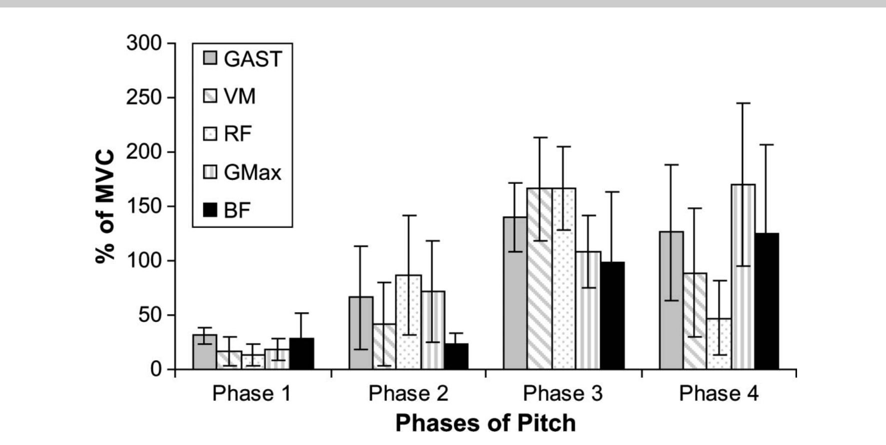

Figure 3. Percentages of MVIC mean electromyography (EMG) value (± *SD*) for the gastrocnemius (GAST), vastus medialis (VM), rectus femoris (RF), gluteus maximus (GM), and biceps femoris (BF) muscles of the stride leg during each of the phases of the pitch.

Subjects

Eleven highly skilled pitchers from a Midwestern University club baseball team (mean age = 22.5 years) participated in the study. Although we did not assess their current level of conditioning or their training history, the Club Baseball team was in season; therefore, the subjects were "competition" shape. Inclusion criteria required all pitchers to produce ball velocities greater than 31.3 $m \cdot s^{-1}$ (70 mph) and be healthy without any restrictions that would limit maximal effort pitching. Mean pitching velocity for this sample of pitchers was 35.1 $m \cdot s^{-1}$ (78.6 mph),

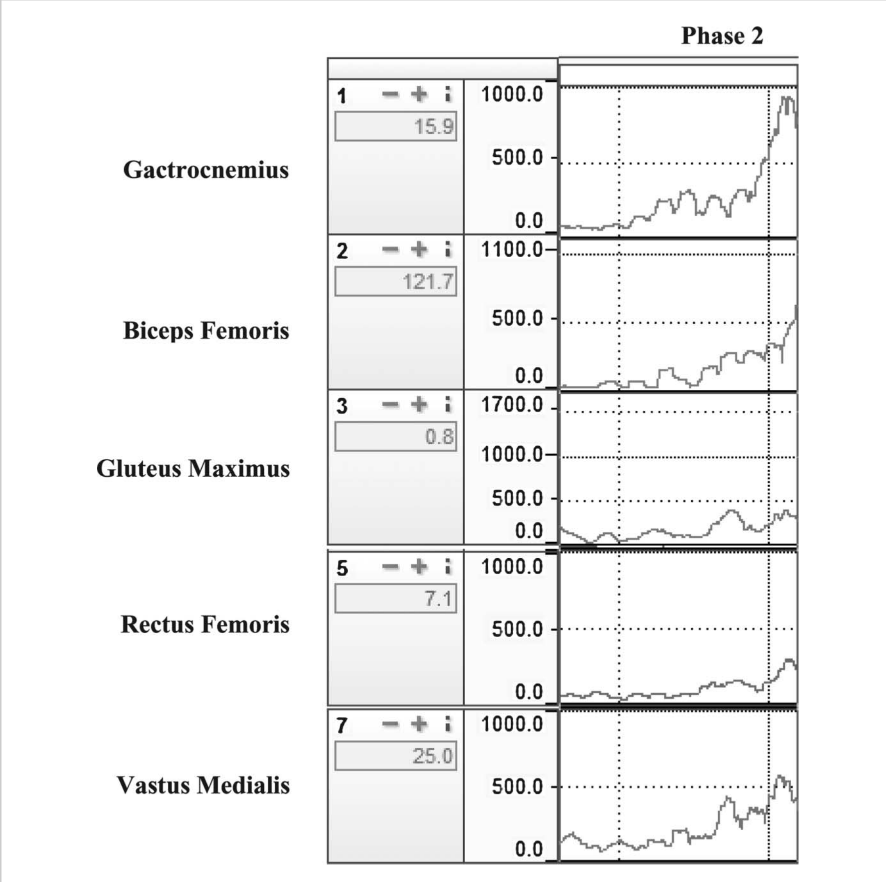

Figure 4. Graphic representation of phase 2 electromyography (EMG) data of the trail leg.

which was comparable to other baseball pitching studies using "highly skilled" collegiate and professional pitchers (9,14,15,22). The Universities' Human Subjects Review Board approved the current investigation, and each individual was informed of the experimental risks and provided written informed consent before testing.

Procedures

Each subject was allowed several minutes to warm-up and stretch to their satisfaction before the placement of surface electrodes over the prepared muscle bellies (12) of the 5 selected muscles on the stride and trail legs of each participant. After electrode placement, each subject participated in a 5-minute warm-up on a Monark cycle ergrometer. Submaximal voluntary contractions were performed before each MVIC to familiarize the subject with the testing protocol and to reduce the probability of muscular cramping. Two 5-second MVICs were collected bilaterally for each muscle using surface EMG. The MVICs were performed to serve as a normalization process, enabling comparisons of muscle activation levels among the 4 phases of the pitch and also among subjects. Manual muscle testing protocols were implemented according to Kendall et al. (7). Subjects were given a 30-second rest period between each MVIC trial and a 2-minute rest period between each muscle tested. After MVICs were collected, subjects were allowed additional time to complete warm-up throwing and warm-up pitches on an indoor practice mound in the biomechanics laboratory. When subjects felt sufficiently warmed up, 10 maximal effort fastball pitches were performed, whereas bilateral EMG data were being recorded. We instructed each pitcher to go through his/her complete windup before delivering each pitch.

Instrumentation and Equipment

We recorded muscle firing patterns using an 8-channel Noraxon Telemyo EMG system (Noraxon USA, Inc, Scottsdale, AZ, USA). Eleven 9-mm pregelled bipolar silver-silver chloride disposable electrodes (Danlee Medical Products, Inc, Syracuse, NY, USA), allowing 2 per muscle and 1 ground, were used for data collection. The EMG signal was telemetered to a Noraxon receiver/amplifier and then passed through an analog-to-digital converter interfaced with a Dell Latitude series (Dell, Inc, Round Rock, TX, USA) laptop computer. Noraxon MyoResearch XP (Noraxon USA, Inc) software was used for all data collection and reduction. Throws were performed off of an artificial regulation pitching mound toward a strike zone approximately 18.4 m (60 ft) away. We recorded ball velocities with a radar gun (Jugs Pitching Machine Company, Tualatin, OR, USA). We synced a Sony Digital 8 video camera (model DCR-TRV260, Sony Electronics Inc., San Diego, CA, USA) with the EMG software to appropriately identify the 4 phases of the pitching motion. After we collected data for each subject, we used the video data to identify markers defining each of the 4 phases. Phase 1 data began at the initiation of the pitching motion and ended when the stride knee was at peak vertical height. Phase 2 was defined from stride knee peak knee flexion until SFC. Stride foot contact was defined as the first frame of video data in which the foot contacted the ground. Phase 3 was defined from SFC to ball release. Ball release was determined as the first frame of video data after separation of the ball from the hand. Phase 4 was from ball release until 0.5 seconds after the ball was released.

Table 1. Mean EMG percentage values of MVIC for the stride leg and trail leg during each pitching phase.*

	Phase 1	Phase 2	Phase 3	Phase 4
Stride leg				
GAST	31 ± 8	66 ± 47	140 ± 31	126 ± 63
VM	17 ± 13	42 ± 38	166 ± 47	89 ± 59
RF	14 ± 10	86 ± 55	167 ± 38	47 ± 34
GM	19 ± 10	72 ± 47	108 ± 33	170 ± 75
BF	29 ± 22	23 ± 10	99 ± 64	125 ± 81
Trail leg				
GAST	27 ± 17	75 ± 39	172 ± 57	–
VM	15 ± 9	68 ± 39	138 ± 87	–
RF	10 ± 5	38 ± 28	49 ± 28	–
GM	25 ± 19	73 ± 57	141 ± 71	–
BF	18 ± 8	48 ± 21	142 ± 31	–

*BF = biceps femoris; EMG = electromyography; GAST = gastrocnemius; GM = gluteus maximus; RF = rectus femoris; VM = vastus medialis.

Data Reduction

We rectified and smoothed all EMG data using a 50-millisecond root mean square method. We selected the middle 3 seconds of the 5-second MVIC from each of the MVIC trials for analysis. This method allowed 1 second for the participant to reach MVIC and also avoided possible fatigue at the end of the MVIC. We then averaged the mean EMG values (mV) for all trials to give one mean EMG value per muscle for each subject.

We compared the mean EMG values from each of the 4 phases with the mean EMG values from the MVIC trials. In each phase, muscle activity was expressed as a percentage of each subject's MVIC values.

Muscle Activation Criterion

Currently, there is a debate as to what level of muscle activation is "significant" because it is a subjective process. Townsend et al. (17) examined glenohumeral muscles during a baseball rehabilitation program and determined that any EMG reading >50% of the maximum manual muscle strength testing (MMT) was a significant challenge to the individual. Moseley et al. (10) investigated scapular muscle activity during a shoulder rehabilitation program and used a criterion where mean EMG activity between 40 and 50% of MMT was optimal for rehabilitation purposes.

For the purpose of this investigation, we adopted criteria based on a recent article by Tucker et al. (18). They operationally defined mean EMG activity of 0–20% of the MVIC as minimal activity, 20–35% as moderate activity, 35–50% as moderately strong activity, and >50% of the MVIC as significantly high muscle activity.

Statistical Analyses

Data were presented as percentages of MVIC. We divided the mean EMG value from each muscle during each of the 4 phases of the pitch by each of the corresponding muscle mean EMG value sampled from the MVICs. No statistical analyses were run on these data as the purpose of the study was to provide descriptive data on muscle activation levels of selected lower extremity muscles at each phase of the pitch based on the MVIC value from each of the muscles tested.

Intraclass correlation coefficients for the mean EMG values for the BF, GAST, GM, RF, and VM during throwing and MVIC data were 0.96, 0.94, 0.93, 93, 0.91, and 0.98, respectively.

Results

The Table illustrates the mean EMG percentage values for the stride leg and trail leg during each of the 4 phases of the pitch.

Trail Leg Electromyography

Figure 2 illustrates the mean muscle activity elicited from the trail leg during first 3 defined phases of the pitch. Electromyography data for the trail leg was only reported for the first 3 phases of the pitch through ball release. After ball release, the trail leg was not in contact with the ground; therefore, EMG data would not have any substantial value to the pitching motion. The trail leg elicited minimal to moderate amounts of muscle activity from all 5 of the muscles tested based on the standardized isometric contractions during phase 1. In phase 2, trail leg musculature elicited significantly greater muscle activity compared with phase 1. In phase 3, the trail leg musculature generally elicited the highest muscle activity for all 5 muscles tested during the first 3 defined phases of the pitch.

Stride Leg Electromyography

Figure 3 illustrates the mean muscle activity elicited from the stride leg musculature during all 4 of the defined phases of the pitch. The stride leg elicited minimal to moderate amounts of muscle activity from all 5 muscles tested based on the standardized isometric contractions during phase 1. In phase 2, stride leg musculature elicited moderate to significantly high amounts of muscle activity from all 5 muscles tested. In phases 3 and 4, stride leg musculature generally elicited significantly high amounts of muscle activity from 4 of the 5 muscles tested. The RF (47%) was the only muscle that did not show a high amount of muscle activity during phase 4 of the pitch.

Discussion

The purpose of this study was to investigate the muscle activation levels of select lower extremity muscles during

4 phases of a pitching motion. Overall, data from this investigation elicited much higher EMG values compared with data from the only other previous study on lower extremity EMG levels in pitching for 2 reasons (22). First, as documented by Yamanouchi (22), the 2-second collection period after SFC included muscle activity data well after the pitch had been completed. Muscle activity of the trail leg would, most likely, significantly decrease during this time because it is no longer bearing weight and the thrust of the pitch has been completed. Therefore, including muscle activity from this portion of the pitch could have significantly decreased the average muscle activity reported. Second, the 2-second period before SFC included EMG activity levels of the stride leg from the initiation of the pitch to SFC. Stride leg muscle activity during the initiation of the pitch (windup) would most likely be low until just before SFC where we may see evidence of a "ramping" effect. This would significantly decrease overall EMG levels during Phase One of the Yamanouchi (22) study. In this study, the pitch was divided into 4 phases instead of 2. Dividing the pitch into 4 phases more appropriately delineated important phases of the pitch as defined by recent literature (4,9,14,15). Thus, the EMG activity levels during these 4 phases allow for a more appropriately defined examination of lower extremity muscle activity levels during baseball pitching.

Second, the 2-second collection periods for the MVICs employed by Yamanouchi (22) did not allow for the ramping effects typically seen when asking an individual to maximally contract a muscle. Thus, the MVIC values most likely included the "ramping up" and "ramping down" of muscles attempting to achieve maximal force and could have significantly impacted average EMG data. In the current investigation, a 5-second MVIC was used and only the middle 3 seconds of EMG data was used for data comparisons.

During phase 1 (initiation of the pitching movement to peak stride knee height), minimal to moderate activity (10–31% of MVIC) was seen in the stride leg and the trail leg from all 5 muscles tested. This is not a surprising finding as this phase is defined as the initiation of the pitch to peak stride leg knee height. In general, limited effort is demanded during this phase of the pitching motion, whether it is from the stretch or from the windup. Phase 2 demonstrated a marked increase in muscle activity in both the stride leg and trail leg.

Phase 2 (maximum stride knee height to SFC) demonstrated a significant increase in muscle activity in both the trail leg and stride leg. Electromyography levels approximately tripled in most muscles of both extremities. During phase 2, all muscles were bilaterally eliciting moderately active to highly active contractions with the exception of the BF on the stride leg. During phase 2 of the pitch, the GAST, VM, RF, and GM of the stride leg elicited muscle activity levels of 66, 42, 86, and 72% of their MVIC, respectively, likely promoting plantarflexion, knee extension, and hip extension in preparation for SFC. The BF only elicited activation levels of 23% of MVIC. Being that the BF is a hip extensor and a knee flexor, it is quite possible that it was not being more highly recruited due to the passive lengthening at the knee (knee extension) and active shortening at the hip (hip extension) it was experiencing during this phase. The GAST, VM, GM, and BF of the trail leg elicited average muscle activity levels of 75, 68, 73, and 48% of their respective MVICs during phase 2 of the pitch, which promoted concentric plantarflexion, knee extension, and hip extension, respectively. The RF only elicited an activation level of 38% of its MVIC due to the limited amount of knee and active hip extension during this phase of the pitch.

It is important to note that Figure 4 illustrates a representative "ramping" effect of the EMG activity of the trail leg during phase 2 of the pitch. The progressive increase in EMG levels for the trail leg in phase 2 suggests that pitchers do not explosively "push" off the mound during the stride. Rather, pitchers may be controlling their rate of force production up to SFC. Stride foot contact through release (phase 3) actually demonstrates much higher EMG levels (approximately 2 to 3 times higher) compared with phase 2, in 4 of 5 trail leg muscles. The only exception being the rectus femoris, which increased a minimal amount from phases 2 to 3 (38–49% MVIC). The progressive increase in trail leg EMG levels through the end of phase 2 and the very high levels in phase 3 suggest that pitchers may, indeed, be demonstrating a controlled "fall" in the first part of the stride phase. The term "fall" here is used to describe a pitcher who begins the initial forward movement toward home plate with limited lower extremity force being used to generate this forward movement. Thus, pitchers in this study did not explosively propel the body forward using the trail leg knee and hip extensors, as would be the case with pitchers who would be described as "pushers." These data and the representative EMG progression in Figure 4 suggest that the lower extremity muscles in the trail leg were not being significantly called upon for most of phase 2 compared with phase 3. These data seem to contradict a long-standing tradition disseminated by many pitching coaches who suggest that the initial phase of the windup, up to SFC, is an important phase where pitchers forcefully "push off" the pitching rubber.

However, we do believe that muscle activity elicited by the BF and GM of the trail leg during the later aspects of phase 2 does play a vital role promoting pelvis rotation from a more side-facing orientation to a more forward-facing orientation, relative to the target. During the end of phase 2, the pelvis begins to open toward the target demonstrating angular velocities of $400–600° \cdot s^{-1}$ (15,21). Interestingly, during phase 2, the GAST, RF, and the GM of the stride leg are producing significantly high amounts of muscle activity, even though the stride foot has not yet touched the ground. During phase 2, the hip and knee are actively extending and the ankle generally is plantarflexing, thus promoting significant activation of the GM, RF, and GAST.

Phase 3, which is defined from SFC to ball release, generates the highest EMG activity in musculature from both lower extremities. The GAST, VM, GM, and BF of the trail leg and the GAST, VM, RF, and GM of the stride leg all exceeded the mean 100% MVIC EMG levels, whereas the BF of the stride leg achieved approximately 100% of the mean MVIC EMG level. While achieving mean EMG activities greater than 100% of MVIC may seem extreme is not uncommon (13). The maximal MVIC that has been routinely employed to serve as a basis of comparison is a static contraction (18). When an individual is asked to maximally contract a specific muscle against manual resistance, it is possible that it is not a true maximum contraction. Thus, exceeding the 100% MVIC may simply be a marker for demonstrating where the lower extremity musculature is most active.

The very high activation levels of the VM in the stride and trail legs during phase 3 explain their important roles to control/stabilize knee joint positions, whereas the upper extremity and torso forcefully rotate about the stride hip. In fact, many high-level pitchers actually demonstrate stride knee extension during arm cocking and acceleration (9), which is occurring during phase 3 of the pitch. Additionally, the very high EMG levels elicited from the BF and GM of the stride and trail legs have similar roles in their function of dynamically controlling/stabilizing the lower extremities during phase 3, which encompasses the 2 most explosive phases of the pitching motion from an upper extremity standpoint (arm cocking and arm acceleration) (4). During the end of phase 2 and phase 3, the upper extremity and torso forcefully rotate about a base of support, which includes both the trail and stride legs. These results support the basic tenet of Newton's Third Law of Motion, for every action there is an equal and opposite reaction. Rotating the trunk and upper extremity requires a stable base of support upon which to rotate and, thus, simultaneous and substantial muscle activity from the stride leg and trial leg. This brief bilateral base of support serves to promote the optimal transfer of momentum generated from the initial phases of the pitch. Furthermore, during the later part of phase 3 and throughout phase 4, the stride leg musculature must eccentrically and dynamically control the ankle, knee, and hip joints as the trunk and upper extremities are decelerating.

Data from phase 4 (ball release to 0.5 seconds after ball release) is presented for the stride leg only. During this phase, the trial leg is non–weight bearing and provides no benefit to pitching performance. However, we feel that the EMG data from the stride leg during phase 4 are very important from a stabilization and strength point of view. In general, this phase required a very high amount of muscle activity with the GAST, GM, and BF eliciting mean EMG values of greater than 100% of their MVIC, whereas the mean EMG value for the VM and RF was approximately 89 and 47% of the MVIC, respectively.

In general, the muscle activity elicited from the stride leg musculature during phase 4 functions to dynamically stabilize the hip and knee joints to maintain standing posture and promote a controlled follow-through. During phase 4, the stride leg is the only leg in contact with the ground and, therefore, is responsible for maintaining a single-leg stance while rotation of the torso and upper extremities continue. The significant amount of muscle activity elicited by the BF (125%) and GM (170%) eccentrically controls hip flexion deceleration and deceleration of the throwing arm that accompanies the follow-through portion of the pitch. The moderately strong activity from the RF (47%) and the significant amount of activity from the VM (89%) and GAST (126%) serve to dynamically stabilize stride knee and ankle joint positions, whereas the trunk and upper extremity pivot about the stride leg during follow-through.

In conclusion, SFC to ball release was the most demanding phase of the pitching motion with very high bilateral muscular activation. Muscle activation of the trail leg significantly increases in the latter part of phase 2, leading up to SFC, and facilitates the generation of linear momentum that can be transferred to the trunk and upper extremities during the proceeding phases of the pitch. Muscle activation levels in the stride leg continue to be very high after ball release, with this musculature being critically important to help decelerate the trunk and upper extremities and maintain dynamic balance after ball release.

Practical Applications

Data from this study indicate that muscle activity in both the stride leg and trail leg reaches very high levels during the pitch. Although high levels of lower extremity strength are not necessarily demanded in pitching, the fact that all pitchers demonstrated high levels of muscle activity within various phases of the pitch indicates that improvements in dynamic muscular strength/power and high levels of muscular endurance are warranted as a pitcher may throw up to 30 pitches per inning and over 100 pitches per game (for starting pitchers). It has been suggested that improvements in lower extremity muscular strength levels may lead to improvements in pitching velocity (9). Within individual pitchers, Stodden et al. (14,15) demonstrated that variations in pitching velocity within pitchers (between 6–10 pitches) were primarily attributed to variations in lower extremity and trunk kinematics (stride knee extension angle, hip angular velocity, and upper torso angular velocity), which are indisputably linked to momentum generated by lower extremity musculature during the initial phases of the pitch. In addition, Matsuo et al. (9) indicated that certain lower extremity kinematics were important in distinguishing between high- and low-velocity pitching groups. In effect, momentum generated from lower extremity musculature is a critical contributor to pitching velocity. Furthermore, although high levels of lower extremity muscle activity are generated in a brief time ($\leq$1 second), the potential for short-term (within an inning) and long-term (between 9 innings) lower extremity fatigue is highly probable. Thus, promoting increases in lower extremity muscular endurance is warranted. When discussing the importance of these data from an injury perspective, the high muscle activity levels (both unilaterally and bilaterally), in conjunction with the high unilateral loading joint loading and extreme ranges of motion in the lower extremities, indicate that pitchers need to have sufficient levels of lower extremity strength and endurance to limit muscle strains and repetitive joint injuries. In addition, lower extremity fatigue decreases the initial generation and transfer of momentum attributed to the lower extremities. This loss of initial momentum that normally would be transferred to the upper extremity places a greater demand on the upper extremity for producing ball velocity and thus may increase injury probability for the upper extremities.

Data from this study provide strength and conditioning professionals more definitive evidence for the importance of lower extremity muscular strength and endurance training for pitchers. Specifically, training regimens promoting both bilateral and unilateral lower extremity muscular strength and endurance in multiple planes (similar to the movements in pitching) are critical to address the specific demands of the pitching motion. Examples of sport-specific exercises for pitchers include multidirectional lunges, single-leg squats, squats, and step-ups. In addition, coaches may integrate dynamic unilateral balance exercises emphasizing control of the trunk and upper extremities while simulating the follow-through phase of the pitching motion. These exercises should progress by adding resistance (e.g., dumbbells, resistance bands, bodyblades) after the initial exercise has been mastered. These types of exercises should focus on improving both muscular strength and muscular endurance.

References

1. Escamilla, RF, Barrentine, SW, Fleisig, GS, Zheng, N, Takada, Y, Kingsley, D, and Andrews, JR. Pitching biomechanics as a pitcher approaches muscular fatigue during a simulated baseball game. *Am J Sports Med* 35: 23–33, 2007.
2. 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.
3. Fleisig, GS, Andrews, JR, Dillman, CJ, and Escamilla, RF. Kinetics of baseball pitching with implications about injury mechanics. *Am J Sports Med* 23: 233–239, 1995.
4. Fleisig, GS, Escamilla, RF, and Andrews, JR. Biomechanics of throwing. In: *Athletic Injuries and Rehabilitation.* Zachazewski, JE, Magee, DJ, and Quillen, WS, eds. Philadelphia, PA: W.B. Saunders Company, 1996. pp. 332–353.
5. Fleisig, GS, Escamilla, RF, Andrews, JR, Matsuo, T, Satterwhite, Y, and Barrentine, SW. Kinematic and kinetic comparison between baseball pitching and football passing. *J Appl Biomech* 12: 207–224, 1996.
6. Jobe, FW, Moynes, DR, Tibone, JE, and Perry, J. An EMG analysis of the shoulder in pitching: A second report. *Am J Sports Med* 12: 218–220, 1984.
7. Kendall, FP, McCreary, EK, Provance, PG, Rodgers, MM, and Romani, WA. *Muscles: Testing and Function With Posture and Pain* (5th ed.). Baltimore, MD: Williams & Wilkins, 2005.
8. Macwilliams, BA, Choi, T, Perezous, MK, Chao, EYS, and McFlarland, EG. Characteristic ground-reaction forces in baseball pitching. *Am J Sports Med* 26: 66–71, 1998.
9. Matsuo, T, Escamilla, RF, Fleisig, GS, Barrentine, SW, and Andrews, JR. Comparison of kinematics and temporal parameters between different pitch velocity groups. *J Appl Biomech* 17: 1–13, 2001.
10. Moseley, JB, Jobe, FW, Pink, M, Perry, J, and Tibone, J. EMG analysis of the scapular muscles during a shoulder rehabilitation program. *Am J Sports Med* 20: 128–134, 1992.
11. Pappas, AM, Zawacki, RM, and Sullivan, TJ. Biomechanics of baseball pitching: A primary report. *Am J Sports Med* 13: 216–222, 1987.
12. Perotto, AO. *Anatomical Guide for the Electromyographer* (4th ed.). Springfield, IL: Charles C. Thomas, 2005.
13. Shaffer, MD, Jobe, FW, Pink, M, and Perry, J. Baseball batting: An electromyographic study. *Clin Orthop Relat Res* 292: 285–293, 1993.
14. Stodden, DF, Fleisig, GS, McLean, SP, and Andrews, JR. Relationship of biomechanical factors to baseball pitching velocity: Within pitcher variation. *J Appl Biomech* 21: 44–56, 2005.
15. Stodden, DF, Fleisig, GS, McLean, SP, Lyman, SL, and Andrews, JR. Relationship of pelvis and upper torso kinematics to pitched baseball velocity. *J Appl Biomech* 17: 164–172, 2001.
16. Stodden, DF, Langendorfer, SJ, Fleisig, GS, and Andrews, JR. Kinematic constraints associated with the acquisition of overarm throwing part I: Step and trunk actions. *Res Q Exerc Sport* 77: 4 417–427, 2006.
17. Townsend, H, Jobe, FW, Pink, M, and Perry, J. Electromyographic analysis of the glenohumeral muscles during a baseball rehabilitation program. *Am J Sports Med* 19: 264–275, 1991.
18. Tucker, WS, Armstrong, CW, Swartz, EE, Campbell, BM, and Rankin, JM. An electromyographical analysis of the cuff link rehabilitation device. *J Sport Rehabil* 14: 124–136, 2005.
19. Tullos, HS and King, JW. Throwing mechanisms in sports. *Orthop Clin North Am* 4: 709–720, 1973.
20. Werner, SL, Fleisig, GS, Dillman, CH, and Andrews, JR. Biomechanics of the elbow during baseball pitching. *J Orthop Sports Phys Ther* 17: 274–278, 1993.
21. Wight, J, Richards, J, and Hall, S. Influence of pelvis rotation styles on baseball pitching mechanics. *Sports Biomech* 3: 67–84, 2004.
22. Yamanouchi, T. EMG analysis of the lower extremities during pitching in high school\baseball. *Kurume Med J* 45: 21–25, 1998.