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Pitching Biomechanics as a Pitcher Approaches Muscular Fatigue During a Simulated Baseball Game

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Background: The effects of approaching muscular fatigue on pitching biomechanics are currently unknown. As a pitcher fatigues, pitching mechanics may change, leading to a decrease in performance and an increased risk of injury.

Hypothesis: As a pitcher approaches muscular fatigue, select pitching biomechanical variables will be significantly different than they were before muscular fatigue.

Study Design: Controlled laboratory study.

Methods: Ten collegiate baseball pitchers threw 15 pitches per inning for 7 to 9 innings off an indoor throwing mound during a simulated baseball game. A pitching session ended when each pitcher felt he could no longer continue owing to a subjective perception of muscular fatigue. A 6-camera 3D automatic digitizing system collected 200-Hz video data. Twenty kinematic and 11 kinetic variables were calculated throughout 4 phases of the pitch. A repeated-measure analysis of variance ($P < .01$) was used to compare biomechanical variables between innings.

Results: Compared with the initial 2 innings, as a pitcher approached muscular fatigue during the final 2 innings he was able to pitch, there was a significant decrease in ball velocity, and the trunk was significantly closer to a vertical position. There were no other significant differences in kinematics or kinetics variables.

Conclusion: The relatively few differences observed imply that pitching biomechanics remained remarkably similar between collegiate starting pitchers who threw between 105 and 135 pitches for 7 to 9 innings and approached muscular fatigue.

Clinical Relevance: This study did not support the idea that there is an increase in shoulder and elbow forces and torques as muscular fatigue is approached. It is possible that if a pitcher remained in a fatigued state for a longer period of time, additional changes in pitching mechanics may occur and the risk of injury may increase.

Keywords: kinematics; kinetics; force; torque; injury; shoulder; elbow

Coaches, trainers, biomechanists, and sports medicine clinicians believe that many pitching injuries are attributed to overuse.[4,12] It is assumed that as the pitchers' muscles begin fatiguing, their pitching mechanics may be altered, and the stress or trauma on the body may be adversely affected. In an investigation of the role of fatigue in muscle strain injuries, it was concluded that as muscles fatigue, the ability to absorb energy decreases.[7] Therefore, there are greater stresses applied to articulations and inert structures. Muscular fatigue has also been shown to affect multijoint kinematics and postural stability during a repetitive endurance test.[11]

Thurston[12] attributed some of the factors related to injury in baseball pitching to common mechanical faults created by muscular fatigue. The effect of muscular fatigue on throwing mechanics is believed to cause altered arm and trunk positions during the arm cocking and arm acceleration phases of the baseball pitch.[12] It is reasonable to assume that if pitching kinematics are altered as muscular fatigue approaches,

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shoulder and elbow kinetics may also change. For example, muscular fatigue in a pitcher's trunk and legs may cause the pitcher to use shoulder and elbow musculature to a greater extent as a compensatory measure. It is possible that using the arm more and the trunk and legs less may increase shoulder and elbow forces and torques and increase injury risk.

The kinematics and kinetics of the pitching motion are well documented.[2-5] Baseball pitching studies in the literature primarily have focused on proper and improper mechanics and the relationship to common throwing injuries. However, there are no known baseball pitching studies that have investigated kinematic or kinetic changes that occur from pitchers' inability to continue pitching due to a subjective perception of muscular fatigue. Murray et al[10] conducted the only known study that quantified both kinematic and kinetic parameters during 5 to 6 innings of pitching. Compared with pitching in the first inning, pitching in the fifth or sixth innings produced significantly less ball velocity, peak shoulder external rotation, and peak shoulder and elbow forces and torques. Moreover, the lead knee flexed more at ball release. However, these authors did not report the number of pitches each pitcher actually threw or subjective ratings of muscular fatigue. Therefore, it is unknown from this study how tired pitchers were, how fatigued their muscles were, and if they were capable of pitching for a longer period of time.

Mullaney et al[9] investigated the effects of throwing a mean of 7 ± 2 innings (99 ± 29 pitches) on upper and lower extremity muscle strength and muscular fatigue. Compared with 14 upper and lower extremity strength measurements taken before pitching in a game, shoulder flexion and internal rotation strength were the only 2 parameters that were significantly less after pitching in a game. These authors concluded that only minimal fatigue occurred in shoulder, scapular, and lower extremity musculature after a pitching outing consisting of throwing approximately 100 pitches, with the exception of moderate fatigue found in the shoulder flexors and internal rotators. It can also be concluded from these data that not all muscles fatigue at the same rate during pitching. However, like Murray et al,[10] subjective ratings of muscular fatigue, how tired pitchers were, and if they could have continued pitching for a longer period of time were not reported.

One of the limitations in the few studies that have investigated pitching fatigue is that the number of innings pitched was limited to between approximately 5 and 7 innings, and the total number of pitches thrown during a game was limited to approximately 100 or fewer. It is possible that some of the pitchers examined in these studies were not very fatigued, whereas others may have been very fatigued, but no information was provided regarding each pitcher's perceived state of muscular fatigue. For some pitchers, it may require throwing more than 100 pitches before they approach a state of muscular fatigue in which they are unable to throw as hard and their pitching mechanics are altered. Other pitchers may fatigue throwing fewer than 100 pitches. Baseball coaches typically rely on both subjective and objective information in determining muscular fatigue in a pitcher. Subjective information is often a pitcher's perceived state of muscular fatigue. Objective information is often a decrease in ball velocity compared with previous innings. Because altered pitching mechanics due to muscular fatigue may be detrimental to a pitcher and increase injury risk, the purpose of this study was to quantify kinematic and kinetic changes that occur during pitching as a pitcher approaches muscular fatigue during a simulated baseball game. We hypothesized that as pitchers approached muscular fatigue in the final inning they are able to pitch, select pitching kinematic and kinetic variables (lead knee flexion, forward trunk tilt, ball velocity, and shoulder and elbow forces and torques) would be significantly different than they were during the initial 2 innings of pitching before muscular fatigue.

METHODS

Ten healthy collegiate Division I starting baseball pitchers served as subjects. All pitchers were not currently injured or recovering from an injury at the time of testing, had not ever undergone surgery, and felt they were able to pitch with the same 100% intensity as they would in a game environment. The subjects had a mean mass, height, and age of 82.9 ± 6.4 kg, 1.87 ± 0.45 m, and 20.0 ± 1.4 years, respectively.

Testing procedures were in accordance with previous work.[2,5] Reflective markers (3.81 cm diameter) were attached bilaterally at the lateral malleoli, lateral femoral epicondyles, greater femoral trochanters, lateral superior tip of the acromions, and lateral humeral epicondyles, and a reflective marker was positioned on the ulnar styloid process of the nonpitching wrist. A reflective band approximately 1 cm wide was placed around the wrist to track its motion. In each time frame, the location of wrist joint center was calculated as the center of the reflective band, and the locations of the shoulder and elbow joint centers of the throwing arm were translated from surface markers to estimated joint centers using a mathematical model previously described.[1,5] Once the markers were positioned on the body, the subject was given an unlimited amount of time for stretching, warm-up throwing, pitching off an indoor pitching mound (Athletic Training Equipment Company, Sparks, NV), and any other type of preparation he desired. Subjects were instructed to prepare just as if they were going to pitch in a game.

The data collection protocol consisted of a simulated baseball game conducted in an indoor throwing laboratory. Each subject pitched the simulated baseball game in place of one of his regularly scheduled pitching outings during his baseball preseason. Two pitchers were tested during each testing session with each pitcher alternating each half inning similar to a regulation game. Each pitcher threw with full effort to his team catcher, who was positioned behind home plate at a regulation distance of 18.4 m from the pitching rubber, with a team batter standing at the plate in the hitting position. The simulated game consisted of standardized innings consisting of 15 pitches per pitcher per inning (averaged over an entire game, 15 pitches per inning is a typical number of pitches thrown per inning); individualized rest periods between pitches, between batters, and between innings in accordance to rest periods each pitcher typically experienced during live competition (taking into consideration strikeouts, walks, base hits, groundouts, and fly outs while pitching, as well as time in the dugout resting while the other team bats); and a standardized number of pitches thrown for warm-up before each inning (in accordance with collegiate rules). Each pitcher's team catcher determined the type of pitch to be thrown based on the simulated game situation (eg, ball and strike count for each pitcher, base runners). The pitcher threw with a windup motion when there were no runners on base in the simulation and from the stretch position when there were runners on base.

Each pitch was thrown as in a game environment, and a pitching session ended when a pitcher felt he could not continue because of muscular fatigue. Each pitcher acknowledged that the muscular fatigue he experienced at the end of the pitching session was not isolated in any 1 area but rather involved varying amounts of muscular fatigue throughout the lower extremities, upper extremities, and trunk. Using a perceived muscular fatigue scale between 0 (no muscular fatigue perceived) and 10 (unable to continue pitching due to a strong perceived state of muscular fatigue), all subjects recorded between a 0 and 1 rating (very light to no muscular fatigue) during the initial 2 innings pitched and between a 7 and 9 rating (high to very high muscular fatigue) during the final inning they were able to pitch because of muscular fatigue. A decrease in ball velocity was used to help confirm that muscular fatigue was approaching. Each pitcher pitched between 7 and 9 innings (mean of 8.2 ± 0.9 innings), with 5 pitchers pitching the entire 9 innings, 2 pitchers pitching 8 innings, and 3 pitchers pitching 7 innings. Of the pitchers who pitched 9 innings, some of them expressed that they could have pitched additional innings, but their coaches did not want them pitching beyond the 9-inning simulated game for safety reasons. The mean number of pitches thrown during the simulated game was 123 ± 14 pitches.

For most starting collegiate pitchers, the fastball pitch is thrown more often than is any other pitch, typically by a 2:1 or 3:2 ratio of fastball to other pitches. For the pitchers used in the current study, the fastball to other pitch ratio was close to 3:2. Therefore, the fastball pitch was thrown during each inning for pitches 1 to 3, 7 to 9, and 13 to 15 (beginning, middle, and end of inning, respectively), with pitches 4 to 6 and 10 to 12 consisting of other pitches normally thrown in a game by that pitcher (eg, curveball, changeup, slider, etc). Kinematic data were collected during the simulated game only when the fastball pitch was thrown. Ball velocity was recorded from a Jugs Tribar Sport radar gun (Jugs Pitching Machine Company, Tualatin, Ore) as the ball left the pitcher's hand. The radar gun was calibrated before a testing session and was accurate within ±0.22 m/s.

A 3D automatic digitizing system (Motion Analysis Corp, Santa Rosa, Calif) was used to collect 200-Hz video data. Six electronically synchronized charged couple device cameras transmitted pixel images of the reflective markers directly into a video processor. The experimental setup is shown in Figure 1. Three-dimensional marker locations were calculated with Motion Analysis Expertvision 3D software using the direct linear transformation method.[13] Camera coefficients were calibrated by recording the position of markers attached to 4 vertically suspended wires, with 3 reflective markers spaced in 61-cm intervals attached to each wire.[2,5] The root mean square error in calculation of 3D marker location was found to be less than 1.0 cm. The position data were digitally filtered independently in the x, y, and z directions with a Butterworth second-order double-pass filter, with a cutoff frequency of 13.4 Hz.[2,5] This process has been demonstrated to be effective for rejecting noise while retaining position, velocity, and acceleration pitching data.[5]

As in previous work,[2,5] the pitching motion was divided into 6 phases (Figure 2): (1) windup, which was from the beginning motion until a balanced position; (2) stride, which was from a balanced position until lead foot contact; (3) arm cocking, which was from lead foot contact to maximum shoulder external rotation; (4) arm acceleration, which was from maximum shoulder external rotation to the instant of ball release; (5) arm deceleration, which was from the instant of ball release until maximum shoulder internal rotation; and (6) follow-through, which was from maximum shoulder internal rotation until the end of motion.

Kinematic parameters were measured using methods previously described.[2,5] Angle conventions for kinematic parameters are shown in Figure 3. At instant of lead foot contact, 6 kinematic parameters were measured on the pitching arm and lead leg: (1) stride length (measured from pitching rubber to lead ankle); (2) elbow flexion (Figure 3A); (3) shoulder external rotation (Figure 3B); (4) shoulder abduction (Figure 3C); (5) shoulder horizontal abduction (Figure 3D); and (6) knee flexion (Figure 3E). Five kinematic parameters were measured during the arm cocking phase: (1) maximum pelvis angular velocity (Figure 3H); (2) maximum upper torso angular velocity (Figure 3H); (3) maximum elbow flexion; (4) maximum shoulder external rotation; and (5) maximum shoulder horizontal adduction. Three kinematic parameters were measured during the arm acceleration phase: (1) maximum elbow extension angular velocity; (2) maximum shoulder internal rotation angular velocity; and (3) mean shoulder abduction. Six kinematic parameters were measured at the instant of ball release: (1) knee flexion; (2) forward trunk tilt (Figure 3F); (3) lateral trunk tilt (Figure 3G); (4) shoulder horizontal adduction; (5) elbow flexion; and (6) ball velocity.

Resultant joint forces and torques were calculated with inverse dynamics in the inertial global reference frame and then separated into orthogonal components in local shoulder and elbow reference frames.[4,5] Using inverse dynamic equations, calculated shoulder forces and torques were applied by the trunk to the upper arm while calculated elbow forces and torques were applied by the upper arm to the forearm.[4,5] Force and torque conventions for kinetic parameters are shown in Figure 4. Eleven kinetic parameters were quantified during the pitch as they reached their maximum values: (1) shoulder anterior force (force that resists posterior shoulder translation); (2) shoulder horizontal adduction torque (torque that resists shoulder horizontal abduction); (3) shoulder internal rotation torque (torque that resists shoulder external rotation); (4) elbow medial force (force that resists lateral elbow translation); (5) elbow varus torque (torque that resists elbow valgus); (6) elbow flexion

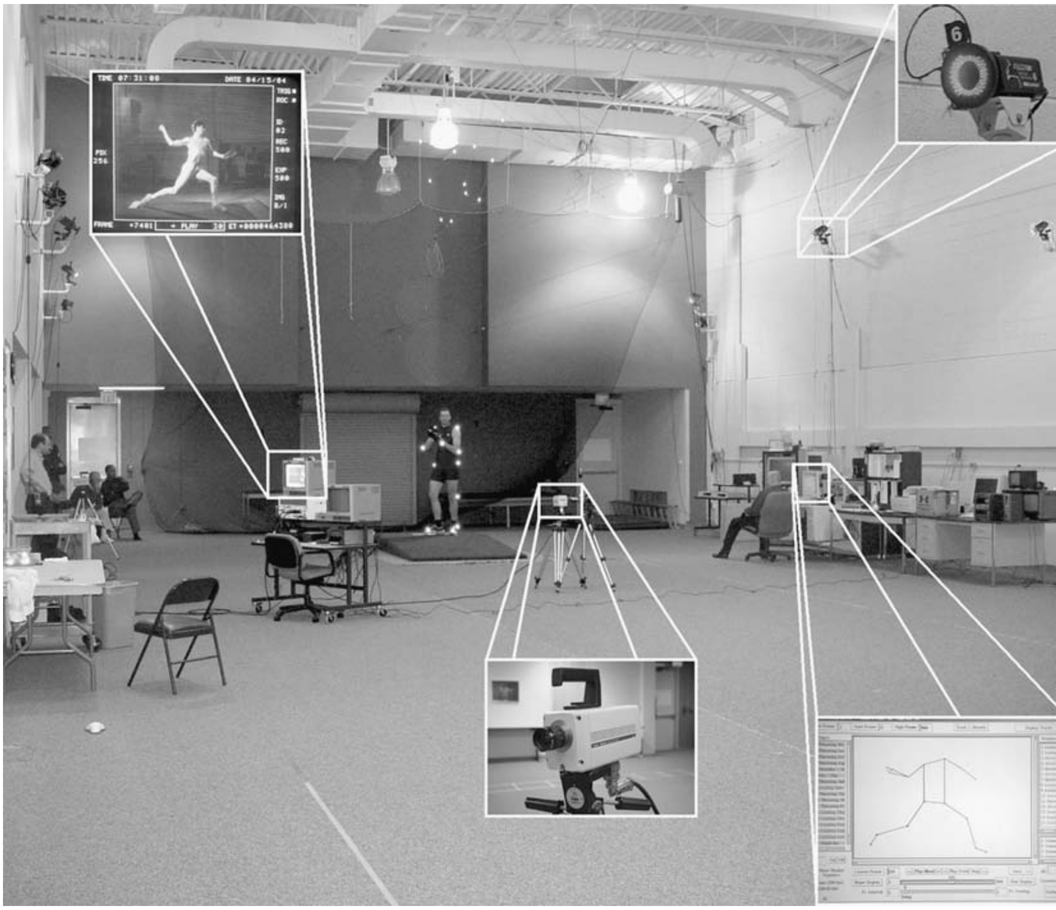

Figure 1. Experimental setup.

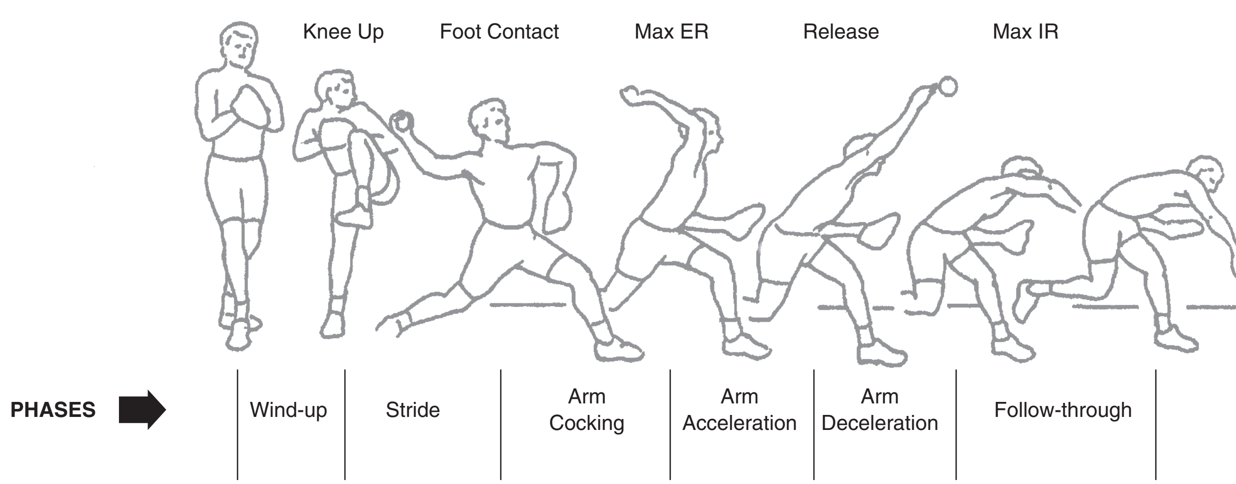

Figure 2. Pitching phases and key events. ER, external rotation; IR, internal rotation. Modified from Fleisig et al[5] (with permission).

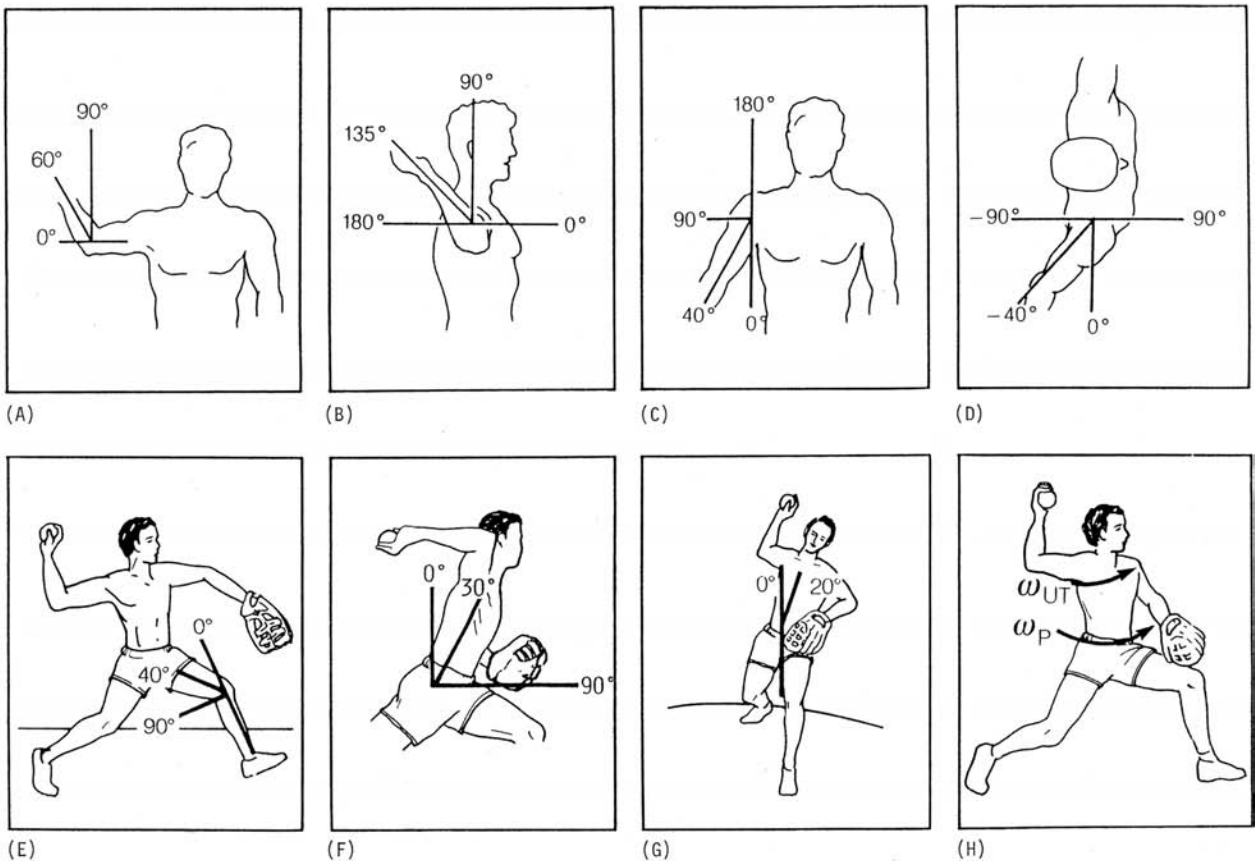

Figure 3. Definition of kinematic parameters. A, elbow flexion; B, shoulder external/internal rotation; C, shoulder abduction; D, shoulder horizontal adduction (positive values) and horizontal abduction (negative values); E, lead knee flexion; F, forward trunk tilt; G, lateral trunk tilt; H, pelvis angular velocity (ω_P) and upper torso angular velocity (ω_{UT}). Modified from Escamilla et al[2] (with permission).

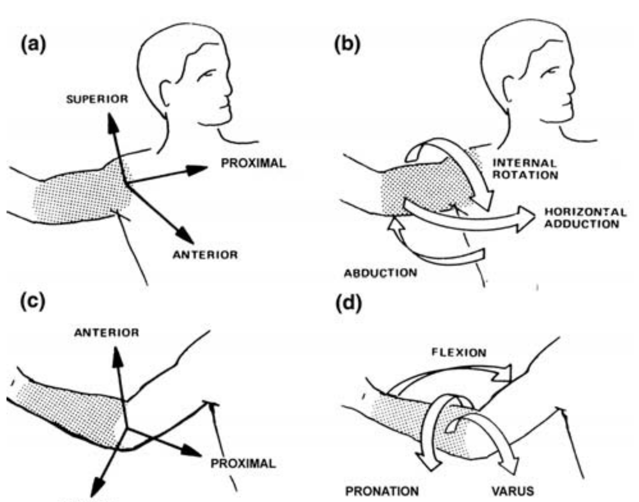

Figure 4. Definition of kinetic parameters. A, forces applied by the trunk to the upper arm at the shoulder; B, torques applied by the trunk to the upper arm about the shoulder; C, forces applied by the upper arm to the forearm at the elbow; D, torques applied by the upper arm to the forearm about the elbow. Modified from Fleisig et al[5] (with permission).

torque (torque that resists elbow extension); (7) shoulder proximal force (force that resists shoulder distraction); (8) elbow proximal force (force that resists elbow distraction); (9) shoulder adduction torque (torque that resists shoulder abduction); (10) shoulder posterior force (force that resists shoulder anterior translation); and (11) shoulder horizontal abduction torque (torque that resists shoulder horizontal adduction).

For each pitcher, kinematic and kinetic parameters were calculated from the 9 fastball pitches thrown each half inning in which data were collected, and these data were subsequently averaged. Because the number of innings pitched varied between subjects depending on subjective perceptions of muscular fatigue, the innings were normalized according to the number of innings each pitcher completed. Seven innings were normalized using the mean of the kinematic and kinetic data from the first 2 innings (F2) and the mean kinematic and kinetic data from the last 5 innings pitched (L4, L3, L2, L1, and L, respectively). Differences between these normalized innings were analyzed using a 1-way repeated-measures analysis of variance, and Tukey post hoc pairwise comparisons were conducted to isolate differences between the normalized innings. The significance level was set at $P < .01$.

TABLE 1
Kinematic Measurements Between Innings Pitched[a]

Measurement	Inning					
	F2	L4	L3	L2	L1	L
Instant of lead foot contact						
Stride length, percentage height	76 ± 5	78 ± 5	77 ± 6	77 ± 5	77 ± 5	76 ± 6
Shoulder abduction, deg	93 ± 10	96 ± 11	94 ± 11	96 ± 11	95 ± 12	96 ± 15
Shoulder external rotation, deg	51 ± 26	54 ± 28	58 ± 27	59 ± 27	56 ± 29	62 ± 26
Shoulder horizontal adduction, deg	–20 ± 12	–19 ± 12	–18 ± 12	–19 ± 13	–17 ± 12	–19 ± 13
Knee flexion, deg	47 ± 11	46 ± 11	47 ± 11	46 ± 13	46 ± 13	47 ± 12
Elbow flexion, deg	96 ± 20	99 ± 20	99 ± 20	99 ± 18	98 ± 19	99 ± 22
Arm cocking phase						
Maximum shoulder external rotation, deg	175 ± 10	174 ± 12	175 ± 9	173 ± 12	173 ± 10	173 ± 10
Maximum shoulder horizontal adduction, deg	19 ± 8	17 ± 8	20 ± 9	17 ± 9	20 ± 10	18 ± 9
Maximum elbow flexion, deg	110 ± 14	108 ± 15	110 ± 12	111 ± 11	111 ± 11	112 ± 12
Maximum pelvis angular velocity, deg/s	622 ± 70	629 ± 69	624 ± 64	626 ± 63	614 ± 87	640 ± 74
Maximum upper torso angular velocity, deg/s	1205 ± 135	1190 ± 105	1183 ± 109	1212 ± 133	1162 ± 59	1191 ± 74
Arm acceleration phase						
Mean shoulder abduction, deg	95 ± 10	95 ± 10	94 ± 9	94 ± 10	94 ± 12	93 ± 9
Maximum elbow extension angular velocity, deg/s	2205 ± 392	2245 ± 462	2315 ± 389	2249 ± 257	2230 ± 347	2272 ± 336
Maximum shoulder internal rotation angular velocity, deg/s	6382 ± 895	6772 ± 630	6344 ± 562	6527 ± 793	6144 ± 814	6494 ± 622
Instant of ball release						
Knee flexion, deg	41 ± 13	42 ± 15	41 ± 15	40 ± 16	39 ± 16	39 ± 16
Forward trunk tilt, deg	34 ± 12	33 ± 11	32 ± 11	31 ± 11	31 ± 11	29 ± 11[b]
Lateral trunk tilt, deg	29 ± 11	29 ± 11	28 ± 12	28 ± 13	28 ± 14	27 ± 13
Elbow flexion, deg	31 ± 9	29 ± 9	30 ± 7	30 ± 9	31 ± 8	30 ± 8
Shoulder horizontal adduction, deg	10 ± 10	9 ± 10	10 ± 10	10 ± 10	11 ± 11	10 ± 10
Ball velocity, m/s	34.7 ± 1.8	34.4 ± 1.7	34.3 ± 1.6	34.3 ± 1.4	33.8 ± 1.1[b]	33.7 ± 1.5[b]

[a]Data are means ± SD. F2 is the mean kinematic data during the first 2 innings pitched; L4 is the mean kinematic data 4 innings before the last inning pitched; L3 is the mean kinematic data 3 innings before the last inning pitched; L2 is the mean kinematic data 2 innings before the last inning pitched; L1 is the mean kinematic data 1 inning before the last inning pitched; and L is the mean kinematic data during the last inning pitched.
[b]Significantly different from F2.

RESULTS

Kinematic measurements between normalized innings are shown in Table 1. Two kinematic variables demonstrated significant differences as fatigue was approached. Compared with the mean of initial 2 innings pitched, ball velocity was significantly less during the last 2 innings pitched (from 34.7 ± 1.8 m/s to 33.7 ± 1.5 m/s), and the trunk was significantly closer to a vertical position during the last inning pitched (from 34° ± 12° to 29° ± 11°). There were no significant differences in kinetics observed between innings (Table 2). Intersubject and intrasubject variability for both kinematic and kinetic variables during the entire simulated game is shown in Tables 3 and 4. These tables illustrate that throughout the simulated game, intersubject kinematic variability and kinetic variability were relatively high, whereas intrasubject kinematic variability and kinetic variability were relatively low.

DISCUSSION

One of the most important findings in the current study is that pitching mechanics remained remarkably consistent within our pool of collegiate pitchers who threw between 105 and 135 pitches during a simulated baseball game. Because muscular fatigue is believed to influence pitching mechanics, the fact that pitching mechanics were similar throughout the simulated game implies that muscular fatigue may occur later in these and other starting pitchers who commonly throw in excess of 100 pitches in a game. This hypothesis is supported by data reported from Mullaney et al,[9] who investigated the effects of starting collegiate pitchers' throwing a mean of approximately 100 pitches on upper and lower extremity muscle strength and fatigue. Only 2 of 14 upper and lower extremity strength measurements were significantly different between pregame and postgame measurements. These authors concluded that only minimal fatigue occurred in shoulder, scapular, and lower extremity musculature (with the exception of moderate fatigue in the shoulder flexors and internal rotators) due to throwing approximately 100 pitches in a game environment.

It is difficult to determine how many pitches a pitcher can throw before muscular fatigue sets in and injury risk increases. Some starting pitchers may not start to fatigue until they throw more than 100 pitches, whereas many

TABLE 2
Maximum Forces (N) and Torques (N·m) Between Innings Pitched[a]

	Inning					
Measurement	F2	L4	L3	L2	L1	L
Arm cocking phase						
Shoulder anterior force	444 ± 80	447 ± 76	481 ± 89	438 ± 97	456 ± 127	452 ± 73
Shoulder horizontal adduction torque	113 ± 18	128 ± 39	113 ± 19	113 ± 30	110 ± 25	113 ± 23
Shoulder internal rotation torque	65 ± 8	68 ± 11	70 ± 9	66 ± 13	67 ± 12	67 ± 11
Elbow medial force	322 ± 59	338 ± 49	332 ± 65	307 ± 56	322 ± 74	315 ± 44
Elbow varus torque	66 ± 8	68 ± 11	69 ± 9	68 ± 12	67 ± 12	66 ± 11
Arm acceleration phase						
Elbow flexion torque	56 ± 10	55 ± 12	60 ± 12	58 ± 14	54 ± 11	57 ± 11
Arm deceleration phase						
Shoulder proximal force	884 ± 134	889 ± 127	841 ± 104	844 ± 110	832 ± 109	850 ± 112
Elbow proximal force	768 ± 114	786 ± 105	758 ± 107	751 ± 105	725 ± 118	747 ± 104
Shoulder adduction torque	87 ± 19	81 ± 20	84 ± 19	79 ± 18	85 ± 21	89 ± 13
Shoulder posterior force	328 ± 103	369 ± 103	397 ± 140	352 ± 124	368 ± 66	380 ± 126
Shoulder horizontal abduction torque	87 ± 19	80 ± 22	84 ± 19	78 ± 18	85 ± 22	89 ± 13

[a]Data are means ± SD. F2 is the mean kinematic data during the first 2 innings pitched; L4 is the mean kinematic data 4 innings before the last inning pitched; L3 is the mean kinematic data 3 innings before the last inning pitched; L2 is the mean kinematic data 2 innings before the last inning pitched; L1 is the mean kinematic data 1 inning before the last inning pitched; and L is the mean kinematic data during the last inning pitched.
[b]No significant differences ($P < .01$) were found between kinetic variables.

"relief" pitchers fatigue throwing fewer than 50 pitches. Muscular fatigue is very individualized, both subjective and objective, and depends on many factors, such as genetic disposition, overall conditioning and specificity of training, rest duration between pitching outings, cumulative stress to the musculoskeletal system throughout the course of a baseball season, and the number and type of pitches thrown.[6] In Little League pitchers, a direct relationship has been shown between the number of pitches thrown in a game and the rate of elbow and shoulder pain.[6] In adult pitchers, this same relationship may exist, which is why both collegiate and professional baseball teams monitor and limit the number of pitches thrown by an individual pitcher during a game. However, during live competition, a pitcher may not want to come out of a game and may continue pitching even though fatigued, which can increase injury risk. During the simulated game in the current study, it is unlikely that the pitchers entered the same level of muscular fatigue that they enter during a live baseball game. This is in part because in live competition, a pitcher typically throws a different number of pitches every inning and has different rest durations between innings. For example, during live competition, a pitcher may throw 10 to 15 pitches in 1 inning and more than 30 pitches the following inning. As the innings progress, it is these high-pitch count innings that are more likely to cause muscular fatigue and increase injury risk. In addition, with increased levels of excitement and motivation during live competition, a pitcher may throw with supramaximal effort relative to throwing in a simulated game environment. In contrast, in a simulated game, a pitcher may not be motivated to throw as hard or throw as many pitches compared with live competition. However, one of the advantages of measuring kinematic and kinetic variables in a laboratory setting rather than a competition setting is that joint centers and body landmarks can more easily and accurately be determined in a laboratory environment because reflective markers can be positioned in specific and exact locations on the body, whereas in live competition these same joint centers and body landmarks must be estimated through clothing, which may affect the accuracy of subsequent kinematic and kinetic measurements. However, the advantage of analyzing biomechanical variables during live competition is it is more indicative of what happens during a real-game situation.

Our initial hypothesis that significant kinematic and kinetic differences would be observed was partially correct in that kinematic differences were found, but kinetic differences were not found. The decrease in ball velocity and forward trunk tilt observed during the last 1 to 2 innings pitched, along with the subjects' perceived muscular fatigue, implies that the subjects approached a certain level of muscular fatigue. A decrease in forward trunk tilt may influence the ability to generate optimal ball velocity. Matsuo et al[8] found that as forward trunk tilt increased, ball velocity increased, and as forward trunk tilt decreased and became more vertical, ball velocity decreased. These findings support the findings in the current study, which also demonstrated that as forward trunk tilt decreased, ball velocity also decreased. Matsuo et al also suggested that fatigue in the knee extensors may inhibit forward trunk tilt, causing a pitcher to throw with a more upright trunk. The gradual decrease in forward trunk tilt observed during the simulated game may decrease the transfer of momentum from the trunk segment to upper arm, diminishing the forward acceleration of the arm and resulting in a lower ball velocity.

A greater forward trunk tilt not only helps transfer energy to the arm and enhances ball velocity, it may also help dissipate forces during the arm deceleration phase.

TABLE 3
Intersubject and Intrasubject Variability for Kinematic Variables During the Entire Simulated Game[a]

Variable	Subject Number 1	2	3	4	5	6	7	8	9	10
Instant of lead foot contact										
Stride length, percentage height	74 ± 3	79 ± 2	75 ± 6	80 ± 3	79 ± 1	77 ± 2	77 ± 1	73 ± 1	66 ± 2	85 ± 2
Shoulder abduction, deg	91 ± 4	84 ± 3	99 ± 8	80 ± 4	114 ± 3	90 ± 3	88 ± 3	113 ± 6	96 ± 5	94 ± 6
Shoulder external rotation, deg	39 ± 10	27 ± 14	31 ± 8	67 ± 8	36 ± 13	75 ± 8	99 ± 5	52 ± 10	35 ± 15	91 ± 13
Shoulder horizontal adduction, deg	–16 ± 4	–29 ± 6	–31 ± 7	–21 ± 7	–20 ± 4	–2 ± 5	–1 ± 3	–24 ± 7	–39 ± 3	–14 ± 5
Knee flexion, deg	59 ± 8	46 ± 6	39 ± 9	55 ± 2	61 ± 2	44 ± 5	57 ± 3	31 ± 2	30 ± 2	48 ± 5
Elbow flexion, deg	75 ± 5	123 ± 5	78 ± 10	125 ± 5	85 ± 3	115 ± 3	110 ± 6	103 ± 6	87 ± 9	82 ± 8
Arm cocking phase										
Maximum shoulder external rotation, deg	160 ± 6	181 ± 3	187 ± 2	179 ± 3	175 ± 3	162 ± 2	168 ± 2	165 ± 2	175 ± 3	189 ± 3
Maximum shoulder horizontal adduction, deg	29 ± 8	17 ± 8	6 ± 3	21 ± 4	18 ± 4	26 ± 2	19 ± 5	11 ± 3	9 ± 3	23 ± 4
Maximum elbow flexion, deg	91 ± 8	121 ± 5	95 ± 8	124 ± 8	108 ± 9	121 ± 3	119 ± 2	122 ± 4	105 ± 3	103 ± 8
Maximum pelvis angular velocity, deg/s	501 ± 69	623 ± 53	564 ± 22	683 ± 26	652 ± 41	676 ± 23	637 ± 87	720 ± 76	633 ± 69	580 ± 92
Maximum upper torso angular velocity, deg/s	1083 ± 53	1102 ± 68	1134 ± 44	1441 ± 107	1273 ± 44	1235 ± 83	1239 ± 57	1159 ± 49	1192 ± 51	1114 ± 46
Arm acceleration phase										
Mean shoulder abduction, deg	93 ± 5	113 ± 4	109 ± 1	93 ± 4	82 ± 2	90 ± 2	101 ± 2	86 ± 1	87 ± 4	91 ± 3
Maximum elbow extension angular velocity, deg/s	1454 ± 238	2224 ± 246	2253 ± 237	2446 ± 181	2433 ± 231	2333 ± 215	2135 ± 309	2601 ± 151	2202 ± 224	2490 ± 228
Maximum shoulder internal rotation angular velocity, deg/s	4557 ± 876	6155 ± 504	6707 ± 574	6755 ± 639	6557 ± 419	6494 ± 761	6930 ± 685	6923 ± 537	7050 ± 627	6440 ± 405
Instant of ball release										
Knee flexion, deg	67 ± 5	42 ± 6	32 ± 5	40 ± 5	61 ± 4	29 ± 5	37 ± 4	37 ± 3	17 ± 4	47 ± 5
Forward trunk tilt, deg	34 ± 4	48 ± 2	33 ± 7	35 ± 3	29 ± 2	24 ± 3	28 ± 3	15 ± 1	24 ± 3	53 ± 3
Lateral trunk tilt, deg	40 ± 4	25 ± 2	14 ± 3	34 ± 2	32 ± 2	16 ± 4	30 ± 3	8 ± 3	17 ± 3	49 ± 2
Elbow flexion, deg	39 ± 4	34 ± 6	25 ± 3	23 ± 3	32 ± 3	32 ± 3	19 ± 3	31 ± 3	24 ± 4	30 ± 3
Shoulder horizontal adduction, deg	25 ± 3	24 ± 2	1 ± 3	16 ± 2	4 ± 2	15 ± 2	11 ± 2	2 ± 2	1 ± 2	11 ± 3
Ball velocity, m/s	31.3 ± 0.8	32.3 ± 0.7	34.5 ± 0.7	34.0 ± 0.6	35.2 ± 0.9	35.8 ± 0.9	35.4 ± 0.5	33.9 ± 0.9	36.3 ± 1.0	35.4 ± 0.5

[a]Data are means ± SD.

TABLE 4
Intersubject and Intrasubject Variability for Kinetic Variables During the Entire Simulated Game[a]

Variable	Subject Number									
	1	2	3	4	5	6	7	8	9	10
Arm cocking phase										
Shoulder anterior force, N	401 ± 83	417 ± 120	468 ± 75	468 ± 113	367 ± 75	452 ± 108	451 ± 58	507 ± 119	556 ± 120	393 ± 119
Shoulder horizontal adduction torque, N·m	110 ± 69	110 ± 26	128 ± 19	101 ± 23	93 ± 19	95 ± 17	134 ± 15	117 ± 19	134 ± 16	120 ± 37
Shoulder internal rotation torque, N·m	54 ± 5	74 ± 5	75 ± 14	61 ± 12	58 ± 10	66 ± 7	74 ± 6	61 ± 10	76 ± 8	72 ± 12
Elbow medial force, N	243 ± 22	313 ± 35	337 ± 74	350 ± 89	255 ± 44	314 ± 39	368 ± 33	335 ± 55	387 ± 55	311 ± 43
Elbow varus torque, N·m	52 ± 4	73 ± 6	72 ± 11	68 ± 8	57 ± 10	65 ± 6	74 ± 5	64 ± 12	76 ± 9	72 ± 11
Arm acceleration phase										
Elbow flexor torque, N·m	50 ± 8	54 ± 10	58 ± 7	45 ± 8	65 ± 7	56 ± 6	40 ± 9	64 ± 9	64 ± 11	74 ± 11
Arm deceleration phase										
Shoulder proximal force, N	696 ± 59	966 ± 65	974 ± 59	683 ± 55	891 ± 74	815 ± 74	961 ± 109	830 ± 49	932 ± 75	871 ± 117
Elbow proximal force, N	506 ± 72	870 ± 39	826 ± 57	667 ± 70	760 ± 47	733 ± 56	790 ± 38	751 ± 45	852 ± 57	848 ± 70
Shoulder adduction torque, N·m	73 ± 18	58 ± 17	92 ± 17	70 ± 13	92 ± 11	103 ± 13	103 ± 12	73 ± 16	90 ± 16	89 ± 19
Shoulder posterior force, N	266 ± 89	430 ± 163	539 ± 131	303 ± 78	371 ± 88	303 ± 56	244 ± 48	344 ± 95	379 ± 70	410 ± 128
Shoulder horizontal abduction torque, N·m	74 ± 13	79 ± 12	86 ± 10	81 ± 12	88 ± 14	80 ± 12	88 ± 15	79 ± 12	86 ± 14	85 ± 10

[a]Data are means ± SD.

Insufficient forward trunk tilt may cause a pitcher to throw too much with the arm and not enough with the body, which may increase arm stress and injury risk. A forward tilting trunk can help the arm slow down gradually. Consequently, we hypothesized that throwing with a more upright trunk would result in higher shoulder or elbow forces and torques. However, the fact that forces and torques were not significantly greater as pitchers approached muscular fatigue may be because the pitchers in the current study did not achieve a high enough state of muscular fatigue, did not stay in a fatigued state long enough, or perhaps matched their pitching mechanics to their decrease in ball velocity to minimize stress on the body and optimize performance.

The only other known study that has quantified biomechanical variables during multiple innings was conducted by Murray et al,[10] who examined the effects of pitching 5 to 6 innings on kinematic and kinetic variables in professional baseball pitchers. These authors reported several significant differences in select variables in the last inning pitched compared with the first inning pitched, including decreases in maximum shoulder external rotation, lead knee flexion at the instant of ball release, ball velocity, shoulder and elbow proximal forces, and shoulder horizontal adduction torque at the instant of ball release. Unfortunately, these authors did not report how many pitches were thrown by each pitcher and each pitcher's subjective level of muscular fatigue, so it is difficult to know how fatigued each pitcher was during the last inning pitched. For example, 1 pitcher who throws for 6 innings may throw a mean of 20 pitches per inning for a total 120 pitches, whereas another pitcher who throws for 6 innings may throw a mean of 15 pitches per inning for a total of 90 pitches. Therefore, it is more helpful to know how many pitches were thrown rather than how many innings were pitched because the number of pitches thrown will have a greater effect on muscular fatigue than will the number of innings pitched. Another limitation to the study conducted by Murray et al is that the authors only compared a single pitch thrown in the first inning and a single pitch thrown in the last inning, and these 2 pitches may not be representative of early- and late-inning kinematics and kinetics. In addition, joint centers were determined from manual digitizing through a pitcher's clothing, which may have affected the accuracy in calculating joint forces, torques, and angles.

A pitcher's perception of muscular fatigue is not constant throughout the year. For example, a pitcher may fatigue earlier in the preseason when his body is not fully conditioned to throwing a high number of pitches, compared with in-season pitching when the body is better conditioned for longer pitching outings. In addition, excessive pitching over the course of a season may gradually cause the body to break down physically and fatigue prematurely. Nevertheless, it was not possible to perform a simulated baseball game in a laboratory setting during the in-season because each pitcher's in-season pitching outings are against live competition.

The lack of kinematic and kinetic differences found in the current study may partially be attributed to limitations due to pitching in a simulated game and a noncompetitive environment. This is partially because a simulated game cannot completely replicate the conditions experienced during a competitive game. First, because of injury considerations, a coach will not want a pitcher to throw until his muscles are so fatigued he literally cannot continue throwing. Therefore, in the current study, the pitchers only approached a state of complete muscular fatigue. Second, in a laboratory setting, there is little incentive to pitch as hard as occurs in live competition, which involves facing a batter, competing against another team, and playing in front of a live crowd. In addition, in a controlled laboratory environment, a perceived state of muscular fatigue and a fear of injury probably prevent a pitcher from reaching an extreme level of muscular fatigue. In contrast, during live competition, a pitcher may be willing to remain in a fatigued state for a longer period of time and reach a more extreme state, especially in important games in which the game is "on the line." Therefore, the subjects in the current study probably did not reach an extreme state of muscular fatigue, but as indicated by their 7 to 9 rating on a perceived muscular fatigue scale, they did achieve a high to very high perception of muscular fatigue, as was evident by the significant decrease in ball velocity during the last 2 innings pitched compared with the initial 2 innings pitched.

Although kinematic and kinetic measurements had relatively high variability between the 10 pitchers, each pitcher's kinematic variability and kinetic variability were relatively low throughout the course of the simulated game. For example, the angular displacement measurements shown in Table 3 typically only varied a few degrees between the initial innings pitched and the final innings pitched, which demonstrates that each pitcher's kinematics were very similar throughout the simulated game. It can be concluded from these data that a pitcher's throwing mechanics remain remarkably similar even after throwing more than 100 pitches and approaching muscular fatigue.

The results of the current study have implications for the clinician, biomechanist, trainer, and coach. Understanding what kinematic and kinetic changes occur during prolonged activity provides information regarding how long pitchers can pitch before their pitching mechanics begin to break down, which can affect performance as well as increase injury risk. This information may also be insightful for the treatment and rehabilitation of a pitcher after a throwing-related injury. Furthermore, the changes observed from the current study may be observed qualitatively by a coach, biomechanist, clinician, or trainer. With a focus on specific pitching mechanics, a trained professional may be able to identify the onset of changes and determine potentially injurious conditions before an acute injury occurs.

CONCLUSION

The primary finding from the current study was that pitching mechanics in collegiate starting pitchers were remarkably consistent throughout a simulated baseball game involving each pitcher throwing between 105 and 135 pitches. A more vertical trunk position and a decrease in ball velocity in the last inning pitched compared with the first inning pitched, as well as subjective perceptions of muscular fatigue and a desire to stop pitching, imply that each pitcher did approach a state of muscular fatigue. Data from the current study imply that approaching muscular fatigue during baseball pitching in a simulated game results in few changes in overall pitching mechanics. The similarity in joint forces and torques throughout the simulated game implies that injury risk may not increase as a greater number of pitches are thrown. However, there are many other variables to consider when determining injury risk that could not be controlled for in the current study, such as a subject's pitching mechanics, the total number and type of pitches thrown during a game and during a season, rest and recovery between pitching outings, muscular strength and conditioning level, muscular fatigue, and age. Further biomechanical and fatigue studies are needed during live competition to determine how pitching kinematics and kinetics are affected when a pitcher remains in a fatigued state for a longer period of time and how these findings may affect injury risk.

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