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Muscle Firing Patterns of the Upper Body and Trunk during the Lacrosse Shot: An Electromyographic and Kinematic Analysis

Andrew Morris[1,2], Roger V. Ostrander[1,2], Adam W. Anz[1,2], James R. Andrews[1,2], Jessi Truett[1,2]* and Steve E. Jordan[1,2]

[1]Andrews Institute Center for Regenerative Medicine, Department of Research, Andrews Research & Education Foundation (AREF), USA

[2]ICMJE criteria for authorship:

1. Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work.

2. Drafting the work or revising it critically for important intellectual content.

3. Final approval of the version to be published.

4. Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

***Corresponding author:** Jessi Truett, Ed.D., BCBA, Andrews Research & Education Foundation (AREF), 1020 Gulf Breeze Parkway, Gulf Breeze, Florida, USA

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ABSTRACT

Purpose: This cross-sectional study's objective was to evaluate the primary muscles involved during each phase of a lacrosse shot. The data provided facilitates data-informed recommendations for muscle-targeted injury prevention and performance improvements. We hypothesized a specific subgroup of upper body muscles would be involved in each lacrosse shot phase, as shown by the primary effectiveness endpoint, electromyographic (EMG) muscle activity.

Scope: The ten participants were high school and collegiate lacrosse athletes with at least one year of experience and no current or history of upper or lower body injuries. Participants and lacrosse sticks were tracked using 13 motion capture cameras via 9mm retro-reflective markers. Sixteen muscles were analyzed during the lacrosse shot using EMG surface electrodes. Kinematic and EMG data were analyzed to determine which muscles or muscle groups were activating during each of the five phases of the lacrosse shot and duration of each shot phase.

Conclusion: This study demonstrated specific subgroups of upper body muscles are activated during each lacrosse shot phase. Conditioning and practice for the lacrosse shot should include awareness of the muscular contribution and phases of shot mechanics. Injury prevention activities should emphasize strengthening and engagement of the upper core musculature, both ipsilateral and contralateral.

Keywords: Lacrosse; Motion Analysis/Kinesiology; Biomechanics; Athletic Training; Electromyography

Introduction

Lacrosse was played in North America by native Americans prior to European contact. Historical evidence of the play exists, dating back to 1630 [1]. Until recently, interest in lacrosse was confined to local regions of the northeastern and mid-Atlantic states. The dramatic rise in popularity and participation in lacrosse over the last several years has led to an increased interest in biomechanical evaluation to improve performance and prevent injuries. The modern lacrosse shot has evolved into a complex coordinated movement sequence utilizing the entire body. Recent research has shed light on the biomechanics and sequence of phases of the lacrosse shot. At present, lacrosse performance and training primarily rely upon expert opinion, video analysis, three-dimensional and magnetic tracking, and EMG studies of the lower body. The original description of phases and events during a lacrosse shot was studied using video analysis by Mercer, et al. [2]. The authors described seven phases of the shot: 1-approach, 2-crank-back minor or 'drive step,' 3-crank-back major or 'wind-up,' 4-stick acceleration, 5-stick deceleration, 6-follow through, and 7-recovery [2]. Vincent et al. used motion analysis to derive kinematics for three experimentally reproducible phases: crank back combined (crank back minor and major were grouped for more straightforward analysis), acceleration, and follow-through [1].

They also compared the kinetic differences of throwing with the dominant versus non-dominant arm in high school, collegiate, and professional lacrosse players. It was determined that greater muscle mass, anterior trunk lean, transverse shoulder rotation, and trunk-shoulder rotational velocity contributed to faster ball and stick (crosse) velocity in a lacrosse shot. Plummer et al., using motion electromagnetic tracking analysis, studied the first six phases of the lacrosse shot, eliminating the recovery phase [3]. They pointed out that instead of continual trunk flexion during the acceleration phase, as seen in overhead throwing, during the lacrosse shot, the trunk changes from flexion to extension and rotation. It was also suggested that differences in lacrosse shot kinematics compared to other overhead throwing sports may have a protective effect against shoulder injury. For example, the lacrosse shot relies on the lever arm of the crosse instead of shoulder external rotation to create greater velocity [3]. Maximum shoulder external rotation is about 80 degrees during the lacrosse shot as compared to the 185 degrees of shoulder external rotation often seen in baseball pitchers [3,4].

Electromyographic (EMG) muscle activity analysis has been previously studied in athletes during sport-specific activities, including the seminal work on the baseball pitch by Dr. Frank Jobe et al. in the early 1980s [5]. Using indwelling fine needle EMG techniques in conjunction with high-speed video analysis, they mapped the activity of the biceps, triceps, pectoralis major, latissimus dorsi, serratus anterior, and the brachialis muscles during the pitching motion [6]. This work ushered in the modern use of biomechanical and EMG analysis to train athletes specifically for their sport and help prevent and recover from injuries. Millard et al. evaluated lower extremity muscle activity using surface electrode EMG during a women's lacrosse shot. In this study, the firing patterns of the biceps femoris (BF), rectus femoris (RF), medial gastrocnemius (GA), and tibialis anterior (TA) of the lead leg during a fast versus slow lacrosse shot were evaluated. They found that the BF, RF, and GA muscle activity increased with faster lacrosse shots and concluded that preparatory muscle activity was necessary to create a stable platform for shooting. To our knowledge, the sequencing of upper body and torso muscle activation during the lacrosse shot has not been investigated or published. Therefore, this paper aims to examine lacrosse shot upper body, torso, and arm EMG activity [7,8].

Methods

Participants

The institutional review board at Baptist Hospital in Pensacola, Florida, approved this study. The study was performed at the Andrews Institute in the Andrews Research & Education Foundation facility in Gulf Breeze, Florida. Informed consent was obtained from all participants before participation. Lacrosse athletes from local high schools and college-age men's leagues in the region with over a year of lacrosse experience were recruited to participate in the study. Potential subjects with current upper or lower body injuries or a history of upper body surgery within the past year were excluded. Ten male athletes with an average age of 19.2 years (sd=±4.8) were enrolled in this study. The height (180±4 cm) and weight (79.2±10 kg) of the participants are summarized in Table 1. Additionally, the participants' experience years were 9.1±5.7, and the average velocity was 70.0±7.6 mph. Three athletes (each 26 years of age) had college level lacrosse experience and remained active in competitive play. The remaining 7 athletes (ages 15-18) were active high school lacrosse team members at the time of testing. Two of the 7 high school players were Division 1 college prospects. The participants' lacrosse playing experience ranged from 4 to 21 years. One participant was left-hand dominant. Nine were right-hand dominant. For ex-college athletes, the years of club-level men's league playing after college were included in years of experience.

The Lacrosse Shot

Athletes had thirty-eight 9mm retro-reflective markers attached to bony landmarks for the motion analysis system. Reflective markers were attached to right and left back of the head, the right and left front of the head, the 7th cervical vertebra, the 10th thoracic vertebra, the manubrium of the sternum, xiphoid process, as well as bilaterally at the following locations: shoulders at the lateral edge of the acromion, laterally at mid-upper arm, lateral epicondyle of the humerus, dorsally on the mid-forearm, distal radial and ulnar styloid, 3rd metacarpal head, anterior superior iliac spine, posterior superior iliac spine, mid-lateral thigh, lateral knee at the joint line, mid-lateral leg, lateral malleolus, posterior calcaneus, and dorsum of the great toe. Also, four 9mm markers were attached to the left and right top corners of the crosse head, the crosse shaft near the head, and the crosse end or butt

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of the handle. These reflective markers were used to determine the kinematics of the motion using a 13-camera VICON Nexus version 1.4 (Oxford, UK) motion tracking system.

The skin of the participants was cleansed with alcohol, and hair was shaved to prepare the area for adhesive foam to secure the electrodes. Sixteen pairs of surface electrodes (ag/AgCL) were placed 2 cm apart over muscles of interest longitudinally over the center of the muscle belly. Since only sixteen pairs of 8mm disc electrodes were available, only specific muscles of interest were tested. Electrodes on the participant's dominant arm are termed ipsilateral, and the electrodes on the participant's non-dominant arm are termed contralateral. Surface electrodes were placed over the following muscle groups: ipsilateral pectoralis major, ipsilateral flexor carpi ulnaris, ipsilateral erector spinae, ipsilateral serratus anterior over the 6th rib, contra-lateral upper rectus abdominis, contra-lateral middle trapezius, bilateral biceps, bilateral triceps, bilateral posterior deltoid, bilateral latissimus dorsi, and bilateral abdominal oblique. The signals from these wireless electrodes were collected with a Noraxon DTS (Scottsdale, AZ) EMG system integrated into the Vicon system to maintain synchronization of the EMG and motion analysis data. Maximal voluntary isometric contraction testing was performed for each muscle to confirm bipolar electrode placement and standardize the EMG data across subjects. This testing involved the subject being asked to isometrically maximally contract each of the muscle groups against a stationary object three times for 3-5 seconds, and the highest EMG value for each muscle group was recorded as maximal. After the equipment was attached to the athletes, they were allowed 10-20 minutes for a self-selected warm-up and practice shots.

Shot Sequence Parameters

The athletes were instructed to throw a lacrosse ball overhand with maximum velocity into the target during testing. Each subject performed shots with their dominant arm until 5 shots hit the target. The target was 1.5 by 1.5 feet (0.4572 by 0.4572 meters), with the shot taken 5 meters away from the target. The bottom of the target was 4.5 feet (1.3716 meters) high off the ground. The target distance was limited by lab space. A standard lacrosse goal size is six by six feet. The size and height of the target were chosen in a way that simulates the shooting mechanics used to make an upper corner shot on goal. When taking a shot, athletes were instructed to plant the lead foot on a Bertec (Columbus, OH) force plate (0.4m x 0.8m) mounted in the floor. This helped ensure shots were taken from the same distance and angle to the target. The approach started one meter from the force plate with both feet perpendicular to the direction of the target. The participant tossed the lacrosse ball in the air to himself, and upon catching the ball, the approach was started. Each athlete employed their preferred approach style: crow hop, phenom hop, or sidestep.

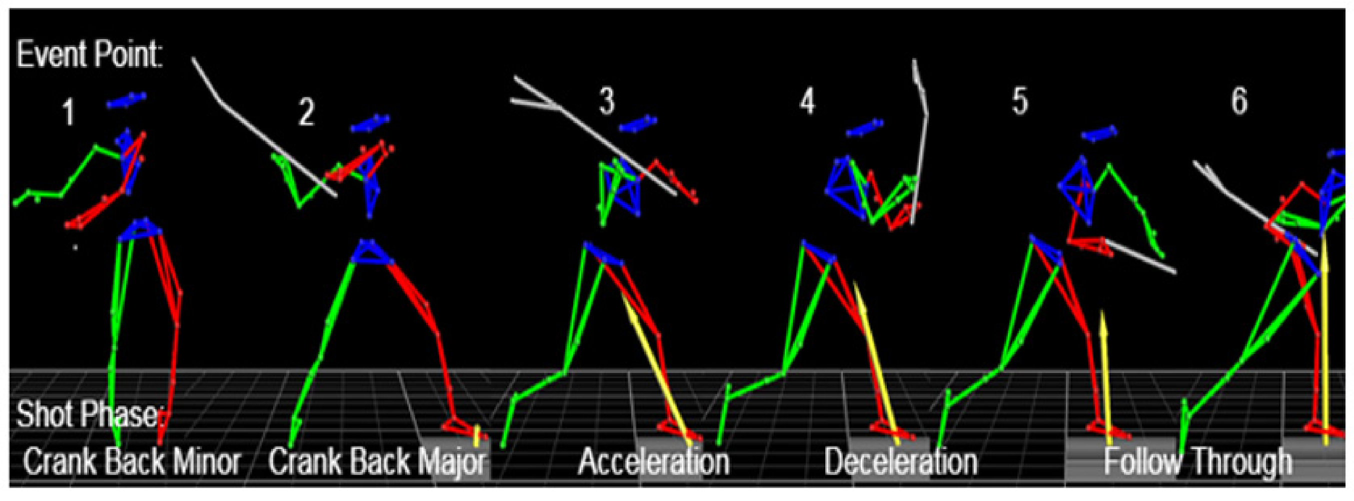
The seven lacrosse shot phases were defined as follows: the approach phase

1. Ends, and the crank back minor phase
2. Begins when the drive leg (right leg of a right-hand dominant thrower) contacts the floor before the lead leg landing on the force plate. The crank back minor phase ends when the lead leg contacts the force plate on the ground. The very brief and dynamic crank back major phase
3. Starts with contact of the lead leg on the ground. It ends when the motion-tracking markers on the wrist and elbow begin traveling toward the target, which marks the beginning of the acceleration phase
4. The acceleration phase ends, and the deceleration phase
5. Begins at ball release. Deceleration ends, and the follow-through phase
6. Begins when the top arm reaches maximum extension. Follow-through ends, and the recovery phase
7. Begins when trunk rotation stops. Lacrosse shots were repeated and recorded until at least three shots hit the target with the dominant arm and at least two shots hit the target with the non-dominant arm.

Statistical Analysis

Kinematic variables from the motion analysis and data from the force plate were used to determine the initiation and conclusion of each phase during the lacrosse shot, which was synced with the EMG data collection to allow determination of the muscle activity during each phase of the lacrosse shot. Motion analysis data was processed and smoothed using the Nexus software and combined with force plate data processed within the Bertec software to calculate ball velocity and lacrosse shot phase temporal measures throughout the duration of the shot. EMG data was exported and processed in Noraxon MyoResearch-XP version 1.08 software. The data was rectified and smoothed with a Root Mean Square (RMS) algorithm within the Noraxon software. This data was then standardized across subjects by calculating a percentage of maximum voluntary isometric contraction (MVIC) to allow for appropriate comparison between subjects.

MVIC is calculated by dividing muscle activity during the lacrosse shot by the maximum muscle activity achieved during isometric baseline testing. It should be noted that during baseline testing, all contractions are isometric, while muscle activity during the lacrosse shot is dynamic and may switch between concentric and eccentric. The sample size was chosen based on similar descriptive studies in the exercise literature and the expected sample of convenience available. EMG data was transferred into an Excel spreadsheet to calculate the percentage of MVIC, and sections of the shot were divided into phases to calculate average muscle activity during each phase. Figure 1 depicts how the participants appeared on Nexus software, and each figure represents the six events that define the beginning and end of each lacrosse shot phase.



Note:

- Event point 1: When the drive leg contacts the ground,
- Event point 2: When the Lead leg contacts the ground,
- Event point 3: Elbow of the top hand reaches maximum flexion, arm starts to extend, and the epicondyles start moving anterior in the x-direction,
- Event Point 4: Ball release,
- Event Point 5: Top arm reaches maximum extension,
- Event Point 6: Termination of trunk rotation.

Figure 1: Nexus software representation of participants across the six events of the lacrosse shot and the shot phases.

Results

Body mass and experience level were directly proportional to the average shot velocity the player achieved (Table 1). There was statistical significance found between mass (p=.008) and experience (p=.001) on the average velocity for the participants. Using motion analysis combined with force plate data, we accurately recorded the shot phase temporal measurements. The average total time required to complete all 5 phases of the lacrosse was 0.74 seconds (max 0.89, min 0.525, SD=0.136). Average times for each phase were as follows: crank back minor 0.331sec+/- 0.032(SD), crank back major 0.114sec+\-0.017(SD), acceleration 0.068sec+\-0.006(SD), deceleration 0.067 sec +\- 0.011 (SD), follow through 0.163 sec +\- 0.055(SD). Therefore, as total shot time decreased, the shot velocity did not increase. The phase times of all participants versus the three players who had the highest velocity versus the three players who had the slowest velocity are presented in Figure 2 to graphicly represent this relationship.

Table 1: Participant demographic data summary and the relationship to the average velocity of the lacrosse shot.

Participant #	1	2	3	4	5	6	7	8	9	10	Avg	SD	Max	Min	*p*
Age (y)	15.0	16.0	16.0	18.0	18.0	26.0	26.0	16.0	26.0	15.0	19.2	4.8	26.0	15.0	
Mass (kg)	61.7	73.5	88.5	65.8	88.5	91.2	83.0	80.3	84.8	74.4	79.2	10.0	91.2	61.7	.008
Height (m)	1.83	1.78	1.86	1.78	1.83	1.84	1.78	1.80	1.73	1.75	1.80	0.04	1.86	1.73	
Experience(y)	4.0	6.0	12.0	3.0	6.0	21.0	15.0	6.0	6.0	12.0	9.1	5.7	21.0	3.0	.001
Avg Velocity (mph)	62.1	68.8	79.4	59.7	65.4	83.2	75.0	65.3	73.2	67.8	70.0	7.6	83.2	59.7	

Note: y, years; kg, kilograms; m, meters; mph, miles per hour

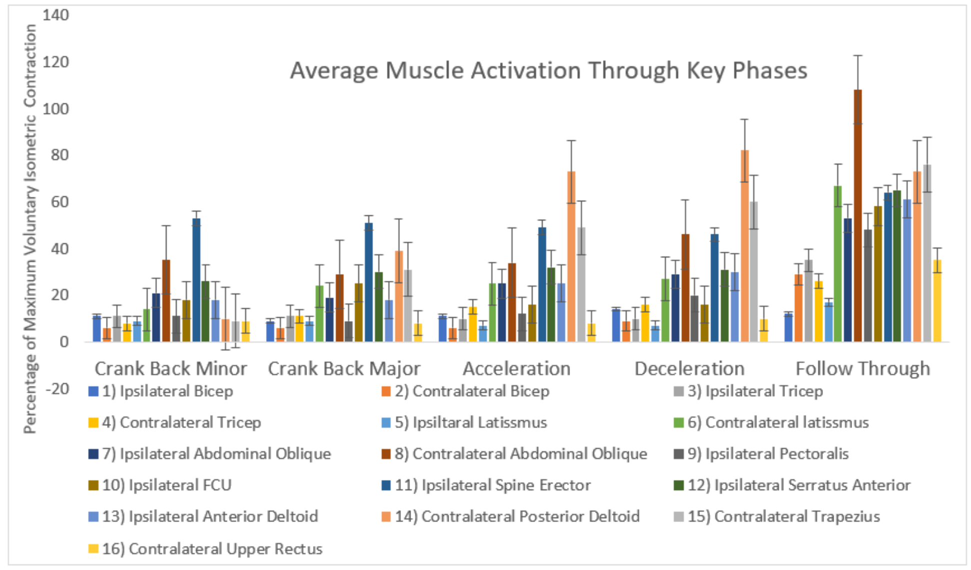


Figure 2: Average muscle activation through key phases of lacrosse shot: crank back minor, crank back major, acceleration, deceleration, follow through.

Muscle Activity with Phases

The overall muscle activity is represented in the percentage of maximum voluntary isometric contraction (MVIC) and is summarized in Table 2. We presented the average muscle activity of only the top five of the ten highest velocity participants to best represent what an above-average lacrosse athlete should strive to reproduce. Figure 3 presents the percentages in bar graph form. The number below the bar graph refers to the electrode number and correlates with each bar from left to right on the graph. Figure 4 shows the muscle activity in the waveform, and each number correlates with the electrode number of the mentioned muscles (Table 3).

Table 2: Average activation (%MVIC) across five participants' time based on shot velocity.

Average Activation (%MVIC) of time five performers based on Velocity					
Targeted Muscle	**Crank Back Minor**	**Crank Back Major**	**Acceleration**	**Deceleration**	**Follow Through**
1) Ipsilateral Bicep	11	9	11	14	12
2) Contralateral Bicep	6	6	6	9	29
3) Ipsilateral Tricep	11	11	10	10	35
4) Contralateral Tricep	8	11	15	16	26
5) Ipsilateral Latissimus	9	9	7	7	17
6) Contralateral latissimus	14	24	25	27	67
7) Ipsilateral Abdominal Oblique	21	19	25	29	53
8) Contralateral Abdominal Oblique	35	29	34	46	108
9) Ipsilateral Pectoralis	11	9	12	20	48
10) Ipsilateral FCU	18	25	16	16	58
11) Ipsilateral Spine Erector	53	51	49	46	64
12) Ipsilateral Serratus Anterior	26	30	32	31	65
13) Ipsilateral Anterior Deltoid	18	18	25	30	61
14) Contralateral Posterior Deltoid	10	39	73	82	73
15) Contralateral Trapezius	9	31	49	60	76
16) Contralateral Upper Rectus	9	8	8	10	35

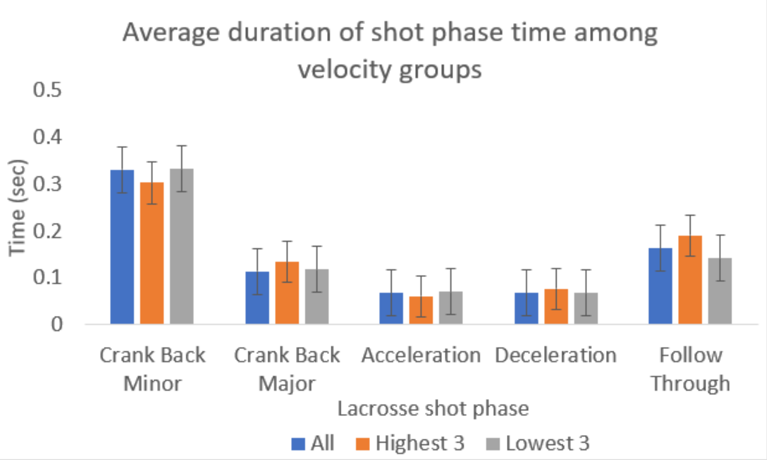


Figure 3: Presenting the average duration of each lacrosse shot phase for shot velocity groups for all shot velocities, the three participants with the highest shot velocities, and the three participants with the lowest shot velocities.

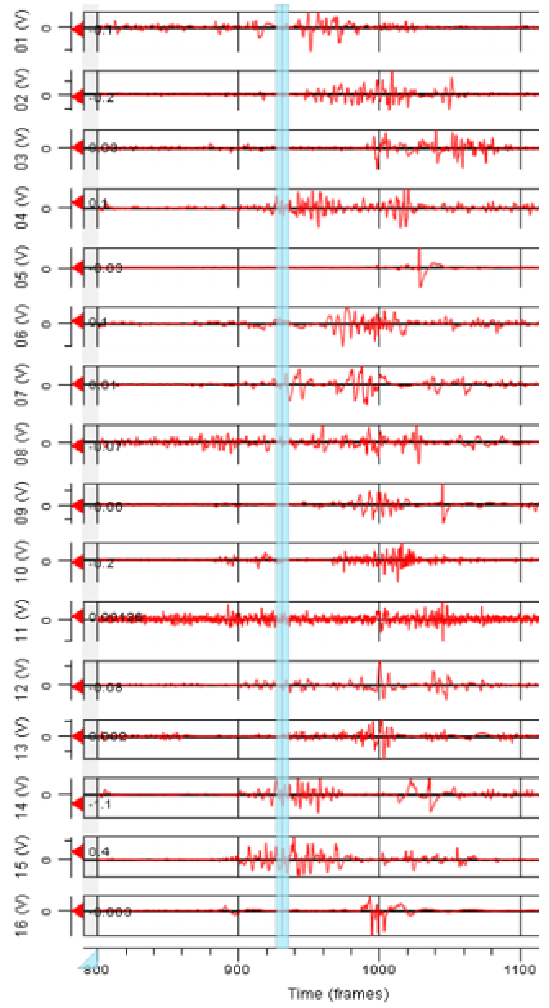


Figure 4: Muscle activity in the waveform number correlates with the electrode number of the targeted muscles.

Table 3: Shot phase starting and Ending event alignment.

Phase	Starts	Ends
Crank Back Minor	Event 1	Event 2
Crank Back Major	Event 2	Event 3
Acceleration	Event 3	Event 4
Deceleration	Event 4	Event 5
Follow Through	Event 5	Event 6

Discussion

Lacrosse shot velocity increased in direct relationship to the mass and experience of the participants. These results align with the common assumption that experience leads to better technique. The results of this prospective study show that better mechanical technique aids progression through the phases in a more efficient fluid manner while allowing athletes to recruit more muscle activity to contribute to shot velocity.

Notable Observations by Phase

The trunk muscles were more active than the extremities in all phases. The electrodes placed in line with the ipsilateral spine erector muscles at the level of the rhomboids experienced the greatest average muscle activity through all phases. These electrodes may have experienced cross-talk with the rhomboids since they are surface electrodes and the spine muscles are deeper. The authors propose that additional testing is required to eliminate this concern.

Approach Phase

The approach style of the participants used to travel the one meter from the starting line to planting their lead leg on the force plate varied and was not analyzed. The effects of the variation of this phase require future investigation as well.

Crank Back Minor Phase

The crank back minor phase was the longest phase by duration (0.33 seconds +/- 0.03(SD)). The fastest players who completed this phase also had higher shot velocities (p=0.002). This would be intuitive since this phase involves both winding back the lacrosse stick while traveling toward the target and those who travel toward the target the fastest, which would theoretically transfer more momentum to their shot. Figure 5 presents the relationship between each participant's mass, experience, and average velocity. The ipsilateral serratus anterior (26%MVIC), contralateral abdominal oblique (35%MVIC), and ipsilateral spine erector muscles (53%MVIC) had the highest activity in this phase. This is evidence that the torso musculature is engaged and significant from the beginning of the shot sequence.

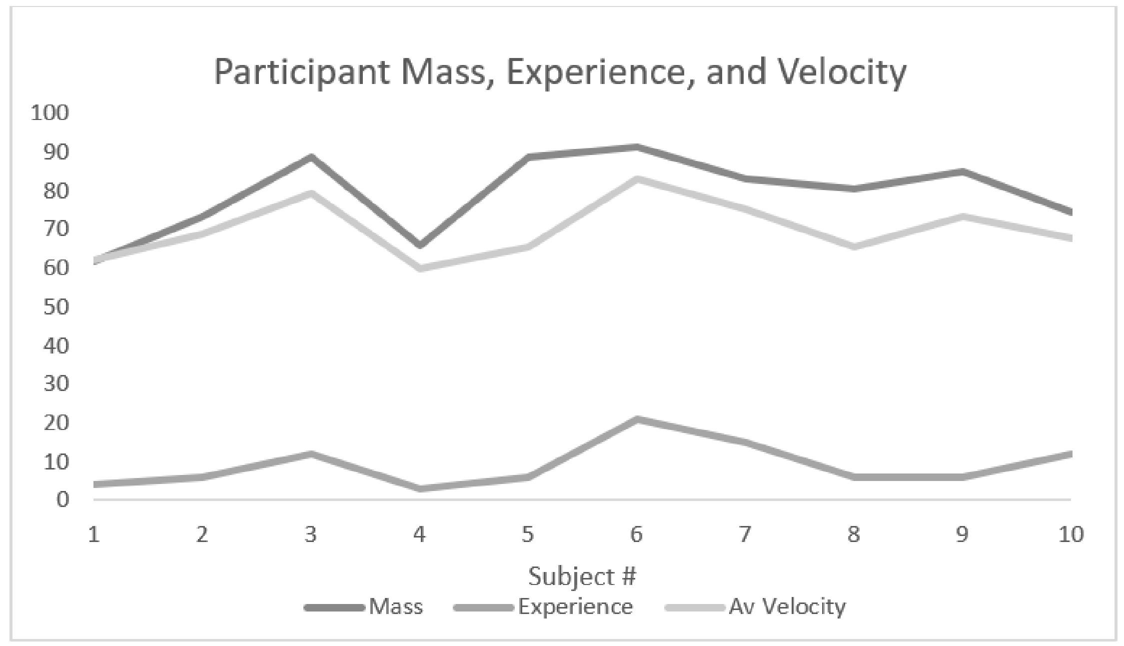


Figure 5: Presents each participant's mass, experience, and average velocity.

Crank Back Minor Phase

This dynamic phase involves a brief crank back or windup of the crosse after the lead leg contacts the ground prior to forward acceleration toward the target. The phase lasted 0.114sec+\-0.017(SD) on average, and it was observed that the higher velocity players had a longer average crank back major phase time (avg. 0.133sec) compared to the three lowest velocity participants (avg.0.118sec). This difference was minor, but it implies that it is essential to crank back further and lengthen the muscles after the lead leg touches the ground before acceleration. The three muscles that highlight this phase and increased the most from crank back minor were the contralateral latissimus, contralateral posterior deltoid, and contralateral trapezius, which increased in average muscle activity by10%, 19%, and 22%, respectively. The contralateral musculature is essential as it eccentrically contracts before acceleration.

Acceleration

The muscles that generated the most power in this phase appear to be the contralateral posterior deltoid and the contralateral trapezius, which increased muscle activity from 39% to 73% and 31% and 49%, respectively.

Deceleration

The deceleration phase begins after the ball has been released. Most significant in this phase is the activity of the contralateral abdominal oblique muscles, the contralateral posterior deltoid, and the contralateral trapezius, which increased to 46%, 82%, and 60%, respectively; the average maximum activity of the remaining 13 muscles averaged 28% activation.

Follow Through

The players with the three highest velocities had longer follow-through durations than the three slowest velocity participants, 0.19sec versus 0.14sec. This aligns with the expectation of the need to accommodate the greater rotational forces generated by the torso and posterior musculature during crank back and acceleration. All muscles significantly increased average muscle activity in this phase except for the ipsilateral bicep. The increased muscle activity in this phase may make this the most likely phase for injury. Validation of this would require further research. Two technique factors related to greater shot velocity are a shorter crank back minor phase and a longer crank back major (late wind up) phase. This involves speed toward the target and increased time to generate rotational trunk force. This increased trunk force and velocity toward the target results in longer follow-through times. The highest muscle activities overall are seen in the follow-through phase. The data collected in this study on the activation of upper body and trunk muscle groups in the lacrosse shot revealed that the contribution of the trunk musculature was greater than that of the upper extremity musculature. This conclusion was evidenced by the levels of activation of the specific muscle groups during each shot phase. Sports-specific training for the lacrosse shot should include awareness of the muscular contributions and biomechanical phases of the shot. Lacrosse training and conditioning programs should continue to emphasize core muscle strengthening exercises while focusing on the contralateral posterior muscle groups to increase torsional force and shot velocity.

Conclusion

The contribution of trunk musculature is greater than that of the upper extremity with respect to lacrosse shot velocity. Conditioning and practice for the lacrosse shot should include awareness of the muscular contribution and phases of shot mechanics. Injury prevention activities should emphasize strengthening and engagement of the upper core musculature, both ipsilateral and contralateral.

Author Contributions

Andrew Morris, Roger V. Ostrander III, Adam W. Anz, James R. Andrews, Jessi Truett are the co-investigators & are responsible for all ICMJE criteria for authorship (1-4). Specifically played a large role in concept design of work, patient recruitment, data interpretation, manuscript drafting, manuscript approval and revision questions. Steve E. Jordan is the primary investigator and is responsible for all ICMJE criteria for authorship (1-4).

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Jessi Truett. Biomed J Sci & Tech Res