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Shooting motion in high school, collegiate, and professional men's lacrosse players

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Abstract

The purposes of this research were to quantify the kinematics of the lacrosse shot, based on arm dominance and player experience level. Male players (N = 39; 14–30 years; high school [n = 24], collegiate [n = 9], professional [n = 6]), performed overhead shots using dominant and non-dominant sides. Motion was captured using a high-speed, 12-camera optical system and high-speed filming. Body segment rotational velocities and joint angles were determined at key points in the shot cycle from foot contact (0% of shot) to ball release (100% of shot). All players shot with less anterior trunk lean, less transverse shoulder rotation, and slower trunk-shoulder rotational velocities with the non-dominant side than the dominant side (all $p < 0.05$). Professional players produced crosse angular velocities 21% faster than high school or collegiate players ($p < 0.05$). Transverse shoulder rotation range of motion on both dominant and non-dominant and trunk rotation sides was highest in the professional players ($p < 0.05$). These kinematic features enable professional players to produce faster ball speeds than younger players (138 ± 7 km/h vs. 112 ± 15 km/h, respectively; $p < 0.05$). Less anterior lean or suboptimal rotation sequence could increase proximal shoulder forces that could contribute to injury as in other throwing sports.

Keywords

Crosse; kinematics; velocity; throwing

Introduction

The National Collegiate Athletic Association 2011 reported that men's lacrosse experienced the greatest net gain in teams of 18% from 2010–2011 across all divisions compared with other sports (http://www.ncaa.com/news/ncaa/article/2011-11-02/ncaa-participation-rates-going-up). Despite the growing popularity, there are relatively few scientific studies of the key motions involved in lacrosse such as shooting. During play, there are several methods of

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shooting the ball (Millard & Mercer, 2014). Also, there are numerous game situations in which players must adjust their shot motion, such as dodging defencemen, shooting on the run (Millard & Mercer, 2014), and the position of the goalie in the goal. These factors have made the standardisation of measurements for lacrosse shots challenging. An understanding of the biomechanics of the basic overhead shot would be an important initial advancement in the identification of targets for performance enhancement, and of features that separate less experienced and professional players. In addition, analysis of the lacrosse shot may reveal potential kinematic characteristics that may be related to injury.

What is anecdotally known is that there are some common elements of throwing motion between men's lacrosse and other sports, such as baseball and football (Fleisig, Barrentine, Zheng, Escamilla, & Andrews, 1999; Meister, 2000). These elements include the lead foot plant, rotations of the pelvis, upper body and shoulders, release of the ball, and follow-through. However, there are several aspects to the lacrosse throw that are highly unique. First, lacrosse players throw the ball using a crosse. Second, the upper body is commonly positioned to conceal the crosse and ball before a shot to make it difficult for the goalie to predict the timing and placement of the shot. Third, players must develop shooting ability with both dominant and non-dominant arms to be as effective as possible during game play. As in other throwing sports, there may be kinematic differences that characterise the skill level of the player. For example, in baseball, less competitive pitchers demonstrate differences in foot placement, elbow angle, shoulder external rotation, and pelvis angular velocity compared to more competitive, skilled players (Fleisig, Chu, Weber, & Andrews, 2009). Also, professional pitchers demonstrate greater upper torso rotational velocities compared to high school pitchers (Fleisig et al., 1999). It is reasonable to surmise that there are differences in motion among lacrosse players of various skill levels, but this has yet to be quantified. Therefore, the purposes of this study were to: (1) Quantify the kinematics of the lacrosse shot in the dominant and non-dominant shooting arm; and (2) Compare key biomechanical parameters of the shot among players with varying experience. Identification of the motion and temporal patterns of the lacrosse shot is vital for the advancement of lacrosse sport performance protocols and for identification of areas in the kinematic chain that may be exposed to high mechanical stress. The hypotheses were that: (1) several kinematics differences would exist between the non-dominant arm and dominant arm (lower segmental angular rotation velocities, slower ball speed, and different trunk lean), and (2) professional players would demonstrate greater segmental angular velocities and different timing of maximal velocities during the shot compared to less experienced players.

Methods

Participants

This analysis was derived from a subset of players from a larger study of male and female lacrosse players. All males were used from this data-set. Players (aged 14–30 years) were recruited to participate in the study ($n = 24$ high school, $n = 9$ collegiate, and $n = 6$ professional) from the time frame of September 2013 to August 2014. Participants were recruited using study flyers and online postings and through word of mouth. This study was approved by the University of Florida Institutional Review Board, and all procedures on human subjects were conducted in accordance with the Helsinki Declaration of 1975, as revised in 1983. All participants provided written, informed consent.

Characteristics

Participant age, height, weight, and sex were collected using a medical grade scale. Participants self-reported the number of years of lacrosse play, seasonal participation, and participation in other sports. Position of play and weekly sessions were self-reported. Level of experience was determined based on the level of competition (enrolled in high school programme, enrolled in collegiate team, or on national level rosters including the Lacrosse World Games).

The group characteristics are expressed as means and standard deviations (*SD*) from the high school to the professional players. Among the three groups, significant differences existed for age (16.0 ± 1.3 years, 21.9 ± 1.4 years, and 24.8 ± 2.3 years; $p < 0.05$) and years of play (4.6 ± 1.7 years, 9.3 ± 2.5 years, and 20.2 ± 1.8 years, respectively; $p < 0.05$). Professional players were heavier than the high school and collegiate players (91.3 ± 10.3 kg versus 67.8 ± 11.5 and 74.4 ± 15.3 kg; $p < 0.05$), and both collegiate and professional players had a higher per cent of lean mass than high school players (85% and 84.3% versus 81.8%; $p < 0.05$). Professional players had the greatest number of current weekly training sessions (7.0 ± 0.0 versus 3.4 ± 1.7 and 3.3 ± 2.1, respectively, $p < 0.05$).

Body composition

Muscle mass may influence lacrosse motion measures. Body composition was determined using the air plethysmography technique (BOD POD; Chicago, IL, USA). This technique is reliable and is highly correlated to the gold standard of body composition assessment and underwater weighing. Lean mass and fat mass were determined.

Motion analysis of the lacrosse shot

Motion capture protocols that have been used and validated in similar upper body motions, such as baseball, were used as a reference (Fleisig et al., 1999). Motion was captured using a high-speed, 12-camera optical motion capture system (Motion Analysis Corp, Santa Rosa, CA, USA). Data were captured at 200 Hz. After piloting several marker sets in four players, a final set was chosen to calculate the variables of interest. Reflective markers were applied to the following anatomical landmarks: right scapula (offset), acromion processes, lateral epicondyles of the elbow, midway between the ulnar and radial styloid processes, third metacarpal, posterior superior iliac spines, anterior superior iliac spines, greater trochanters, lateral femoral epicondyles, lateral malleoli, heels, and great toes. Markers and reflective tape were also placed on the stick end of the crosse, the crosse shaft, and the right and left sides of the net. Only reflective tape was used on the ball. A standard lacrosse ball (National Operating Committee on Standards for Athletic Equipment approved; Brine, Milford, MA, USA) was used for the analysis.

Following a standard five-minute warm-up period of throwing, participants performed overhead shots with both the dominant and non-dominant arms within the camera capture volume area. Participants wore athletic, non-cleated practice shoes, and used their own crosses. The laboratory floor on which the participants were stationed was a rubberised, stiff surface. The order of testing was the same for all participants, with the dominant arm first and the non-dominant arm second. The dominant arm was defined as the arm with which the participant uses to write. The overhead shot was selected because it is easily replicated by players and has discrete events from which analysis can be developed. Each player was provided a set of standardised instructions to release the ball with as much speed and accuracy as possible, without compromising form for the sake of speed. Accuracy was defined as the ability of the ball to hit a marked area on a wall net that was the exact size of the goal. Film of the motion was captured using a high-speed camera (EXILIM; Casio America, USA) at 300 frames per second for later motion review with the participant and to verify that the shot landed within the goal target. If the ball did not land in the goal target, the trial was excluded from analysis. The data from three trials on the dominant and non-dominant sides were averaged to determine the performance of each side during a typical shot.

Key phases and events of the shot cycle

Mercer and Nielson provided a detailed description of multiple phases of a lacrosse throw (Mercer & Nielson, 2012). We describe here three key discrete phases related to the lacrosse shot that could be used reliably in motion analysis (Figure 1). The three phases include the crank back, acceleration, and follow-through. The crank back is the preparatory movement that represents the wind-up that precedes the acceleration of the crosse. Immediately after crank back, there is a drive forward with the lead foot. A key event of the lead foot plant initiates the acceleration phase. The acceleration phase involves increasing angular velocities of the body segments (pelvis, trunk, shoulders) and crosse to prepare for ball release. The ball release is the key event that terminates the acceleration phase. The final phase of the lacrosse shot is the follow-through. This phase involves the trunk-to-pelvis crossover motion and a deceleration of the body segment rotations. The maximal shoulder-to-pelvis crossover is the final event of the lacrosse shot. For the purpose of data analysis, we defined the starting point of the motion as the lead foot plant event (0%). The point of ball release was defined as the end of the shot (100%). Follow-through occurred after the ball release (>100% of the throw cycle) (Dick, 2013). Specific kinematic events were expressed as a per cent of the shot cycle.

Kinematics

Kinematics were derived from the marker data using standard rigid body mechanics equations implemented within commercially available software (MATLAB; R2011b, The Mathworks Inc., Natick, MA, USA). The following values were calculated from the software: (1) angular velocities of the pelvis, upper trunk, upper arm about the shoulder joint, and the crosse at key shot cycle events (2) orientation of the pelvis, upper trunk, and upper arm about the shoulder at key shot cycle events knee, elbow, upper arm about the shoulder, relative crossover of the shoulders to the pelvis was determined. Range of motion (ROM) values of knee flexion, shoulder rotation in the transverse plane, and pelvis orientation in the sagittal plane and rotation in the transverse plane were calculated. In the sagittal plane, the knee flexion angle was determined at ball release. The ROM of knee flexion during the shot cycle was determined from the difference in the maximum and minimum knee flexion angles of the lead leg. Anterior pelvis tilt at ball release and its maximum throughout the cycle was determined. In the transverse plane, the ROM of the pelvis rotation during the cycle was determined from the difference in the maximum and minimum angles. The maximum angular velocity and the time (expressed as per cent of the shot cycle) at which the maximum angular velocity occurred were identified. In the sagittal plane, trunk lean at ball release and trunk lean ROM throughout the cycle was determined. The ROM of the trunk during the shot cycle was determined from the difference in the maximum and minimum trunk lean angles. The maximum angular velocity and the time (expressed as per cent of the shot cycle) at which the maximum angular velocity occurred were identified. In the frontal plane, the maximum abduction angle of the arm about the shoulder at foot contact, ball release, and its maximum during the shot cycle were determined. To determine transverse ROM of the shoulders relative to the pelvis, two virtual lines were created in the data processing; the two anterior superior iliac spines created the ‘pelvis line’ and the acromion processes created the ‘shoulder line’. Shoulder-to-pelvis crossover was defined as the amount of line crossover that occurred from crank-back to follow-through. The total angular excursion from foot contact to maximal shoulder-to-pelvis crossover in the transverse plane was calculated as negative (shoulder line crossing back over pelvis line in crank back) or positive (shoulder line crossing forward over the pelvis during follow-through). The maximum angular velocity and the time (expressed as % of the shot cycle) at which the maximum angular velocity occurred were identified.

These phases and events of the shot cycle are shown in Figures 1a–c. In preparation for a shot, the throwing arm abducts, and the torso turns away from the target and is positioned for acceleration (crank-back phase, Figure 1a). This shoulder-to-pelvis crossover was defined as negative, as the rotation is away from the target on the net. As the crosse was brought forward for the shot during the acceleration phase (Figure 1b), the throwing arm moved anteriorly towards the target. After the ball-release event, the shoulder-to-pelvis crossover continued. This crossover was defined as positive, as the rotation occurred towards the target on the net (follow-through phase, Figure 1c). The ball speed was determined for each shot by 3D ball position at each frame and the change in distance of the ball divided by the reciprocal of the frame rate.

Statistics

Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS; v.22.0; IBM Corp., Chicago, IL, USA). Data were managed using REDCap (Research Electronic Data Capture) (Harris et al., 2009). Descriptive statistics and frequencies were obtained to characterise the study groups. One way analyses of variance (ANOVAs) were used to find differences in the characteristics of the three groups. Tukey’s *post hoc* tests were used to determine where differences occurred. Normality of the data was examined with Kolmogorov–Smirnov tests. Potential differences in main outcome variables were analysed using a mixed-model ANOVA. The dependent variables were kinematic outcomes. The independent variables were arm dominance (two levels: dominant, non-dominant arm) and player experience level (three levels: high school, collegiate, professional). Tukey’s *post hoc* tests were used to find where differences existed. A covariate was the lean body mass, a factor which could contribute to the kinematics and ball speed. Because of different sample sizes among the groups, the dominant and non-dominant arm data were also compared by player experience level using non-parametric Kruskal–Wallis tests to corroborate the ANOVA findings. Given that the findings were not different between statistical methods, the repeated measures ANOVA results are presented. All statistical tests were two-tailed. A priori alpha levels were established at $p < 0.05$ for all statistical tests.

Results

Joint angles and ROM

Specific joint angles and ROM of specific body segments are presented in Table I for the three player experience levels. A significant arm dominance X player experience interaction existed for trunk lean angle at ball release (interaction $F = 4.349$; $p = 0.021$), with significant main effects of arm dominance and player experience level (both $p < 0.05$). No significant arm dominance X player experience levels interactions existed for knee flexion at ball release, knee flexion ROM during the shot, pelvic tilt at ball release, transverse plane ROM of pelvis, trunk lean ROM, maximum shoulder abduction, and shoulder motion ROM in the transverse plane. However, a main effect of arm dominance existed for anterior pelvic tilt ($F = 4.714$, $p = 0.037$) but not for player experience. There was a significant main effect of arm dominance on the transverse motion of the ROM of the pelvis in the transverse plane ($F = 14.241$; $p = 0.001$), but not for player experience. A significant main effect was found for arm dominance on shoulder ROM in the transverse plane ($F = 23.707$, $p < 0.0001$), and for player experience ($F = 3.757$, $p = 0.033$).

Relative shoulder to pelvis rotation and maximal segmental angular velocities

Table II provides the shoulder-to-pelvis-crossover values at crank-back and follow-through, and the maximal angular velocities of pelvis, trunk, upper arm about the shoulder, and the crosse. No significant arm dominance X player experience interactions existed for shoulder-to-pelvis crossover values, maximal angular velocities of the pelvis, trunk, shoulder, and crosse angular velocities or ball speed. However, a significant main effect of arm dominance was revealed for shoulder-to-pelvis crossover at crank-back ($F = 14.220$, $p = 0.001$). Also, a significant main effect of arm dominance was present for pelvis ($F = 7.629$, $p = 0.009$), trunk ($F = 18.377$, $p < 0.0001$), shoulder ($F = 12.116$, $p = 0.001$), and crosse maximal angular velocities ($F = 18.741$, $p < 0.0001$). A main effect of player experience existed for crosse maximal angular velocity ($F = 4.754$, $p = 0.025$) and ball speed ($F = 8.753$, $p = 0.001$).

Temporal patterns of maximal segmental angular velocities

The timing, or per cent of the shot cycle at which players achieved the maximal angular velocities of the pelvis, trunk, and arm about the shoulder, is shown in Table III. No significant arm dominance X player experience interactions existed for any of the timing of maximal angular velocities. However, a significant main effect of arm dominance existed for the timing of the maximal angular velocities for the pelvis ($F = 3.186$, $p = 0.008$), trunk ($F = 7.669$, $p = 0.009$), and the arm about the shoulder ($F = 9.223$, $p = 0.004$).

A summary of the timing of angular velocities is shown in Figure 2 for a typical high school player, collegiate player, and professional player. Each of these players had the highest ball speeds from their respective groups. Note the separation of the segmental angular velocities of the pelvis, trunk, and shoulders is greater with increasing levels of experience.

Discussion and implications

The purposes of this study were to quantify the kinematics of the lacrosse shot in the dominant and non-dominant arm, and to determine where kinematic differences existed among players of different experience levels. The key findings were that players of all experience levels shot the lacrosse ball with less anterior trunk lean, less transverse pelvis and shoulder rotation, and slower pelvis, trunk and shoulder rotational velocities with the non-dominant side compared to the dominant side. Shooting motion was, therefore, more constrained when shooting with the non-dominant arm. It was also found that professional players generated greater transverse shoulder rotation on dominant and non-dominant sides, and produced the highest crosse angular velocities and ball speeds. Our analysis revealed that muscle mass contributes to these higher speeds. These findings suggest that professional players are able to more effectively coordinate pelvis and upper body motions with more muscle mass to generate higher forces that enhance ball speed compared to less experienced players.

With respect to shooting performance based on arm dominance, our findings are similar to other throwing sports, such as baseball and cricket. In baseball, less experienced high school pitchers have lower pelvis angular velocities than experienced minor and major league pitchers (Fleisig et al., 1999, 2009). Few studies have compared the throwing/shooting performance of dominant and non-dominant arms. One study did compare the motor coordination patterns of baseball throwing using the dominant (‘skilled’) and non-dominant arms (‘unskilled’), and found that the dominant arm generated faster wrist velocities before ball release than the non-dominant arm (Gray, Watts, Debicki, & Hore, 2006). Similarly, in cricket players, the throwing motion of the dominant side was associated with more coordination, and a separation of the initiation of motion in the pelvis and torso compared to the non-dominant side (Chaudhari, Hearn, & Andriacchi, 2005). Improving the performance and ball shot speed on the non-dominant side can be improved with training. The ability to shoot and throw equally well with both sides is a desirable trait for lacrosse players at any level. Kinematic analysis of the shot using both the dominant and non-dominant shooting arms is directly translatable to skill development for players and coaches. This initial analysis can be used as a starting point to develop normative data on shooting motion at different age levels, skill levels and position types.

Implications

Key differences in shooting kinematics were identified based on experience level. Compared to less experienced players, the professional players achieved greater shoulder ROM in the transverse plane, and closer joint ROM values and segment angular velocities while shooting with non-dominant and dominant arms. The end result is faster crosse angular velocities and ball velocities. The main differences in the motion and the speed of motion among the three groups of players may be in part due to different patterns of muscle activation and coordination of movement. Several studies have demonstrated the importance of gluteal muscle activation on pelvis and trunk position and rotation in other throwing sports, such as softball (Oliver, 2014) and baseball (Plummer & Oliver, 2014). Gluteal activation stabilises the pelvis (Plummer & Oliver, 2014) to permit energy transfer to the torso, shoulder, and arm during a throw. It is possible that the more experienced lacrosse players had improved activation magnitude or timing to permit rapid acceleration of the body segments during a shot. As athletes improve skill, agonist, and antagonist muscle activation magnitude and timing change to permit improvements in throwing speed (Aggelousis et al., 2001). It would be important to determine whether the same experience pattern occurs in female players, and if the patterns are similar in all player positions including goalie. This additional information can be used to develop sport performance strategies and skill drills for different player positions.

These findings suggest potential areas that could contribute to injury. In baseball, maximal angular velocity of the pelvis that occurs later in the shot cycle (57.8% of shot cycle) is associated with higher shoulder proximal force than earlier maximal pelvic velocity (34.5% of the shot cycle) (Lincoln et al., 2013). Here, in our young lacrosse players, the pelvic and torso maximal angular velocities occurred later in the throw cycle compared to more experienced players. It is possible that younger players could develop relatively high shoulder forces and subsequent injury compared to collegiate and professional players. It has been shown that improper rotation sequencing of the trunk by high school pitchers can increase the maximal shoulder external rotation angle, and subsequently the shoulder joint force (Oyama et al., 2014). Also, a more upright trunk observed in the throws with the non-dominant arm for the high school and professional players, there is the potential for the mechanical forces to injure the superior labrum of the shoulder. Superior labrum anterior-posterior tears can occur in baseball pitchers who throw a ball with inadequate anterior trunk lean (Laughlin et al., 2014).

Limitations and future directions

This study has some limitations that deserve comment. We acknowledge that throwing a lacrosse ball indoors is not identical to shooting outdoors. The study of the shot motion is challenging because the player can shoot in a variety of ways (Millard & Mercer, 2014), and players typically must shoot with defensive coverage. The players may be unable to use the full potential of trunk-to-pelvis crossover while on the field. Fortunately, our laboratory configuration is large enough for running and shooting sport measurement. Standardised instruction and acclimatisation to the testing may have helped to minimise error. This study had a relatively low number of professional players and collegiate players. Larger cohorts are necessary to improve statistical power and reveal other kinematic characteristics of interest to players, coaches, and scientists. Our findings of optimal shooting conditions of the overhead shot in laboratory controlled conditions can be extrapolated to help players develop the shooting skill on the field. Additional study of the muscle activation patterns and interaction torques of the body segments would provide insight on the different shooting performance and injury patterns between less experienced and professional players.

Conclusions

Differences exist in kinematics of the lacrosse shot based on dominance of the arm used and by experience level. Higher muscle mass, execution of the shot with more rotation of the shoulders relative to the pelvis, higher crosse angular velocities, and separation of segmental peak angular velocities were all associated with higher ball speed. Professional players can more effectively coordinate pelvis and torso motions to produce high ball speed compared to less experienced players. Potential injury concerns may be for the shoulder of the non-dominant arm and for the dominant throwing shoulder of youth players.

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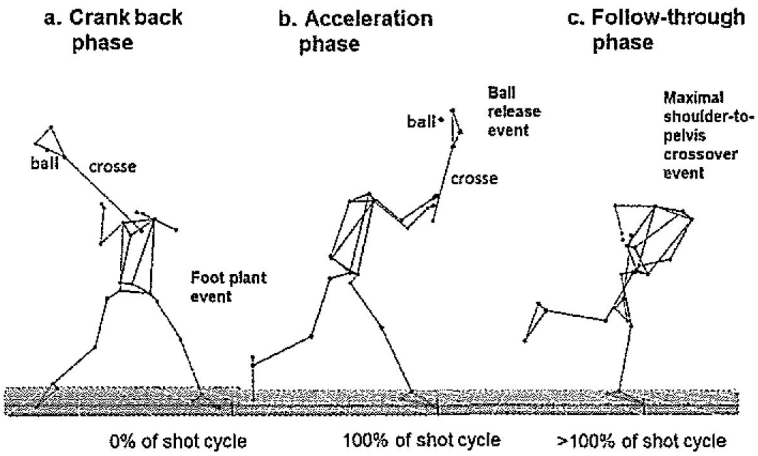

Figure 1.

Key phases of the lacrosse shot used for this analysis. The stick figure represents the computer model position during these phases, 1a) Crank-back: the wind-up phase in which the shooting shoulder abducts and the trunk turns away from the target as the lead foot makes contact with the ground; 1b) Acceleration: the phase in which angular velocities of the body segments (pelvis, trunk, upper arm about the shoulder) and crosse are increased to prepare for ball release; and 1c) Follow-through; this phase represents the time at which the shooting shoulder crosses over the pelvis and body segment deceleration occurs.

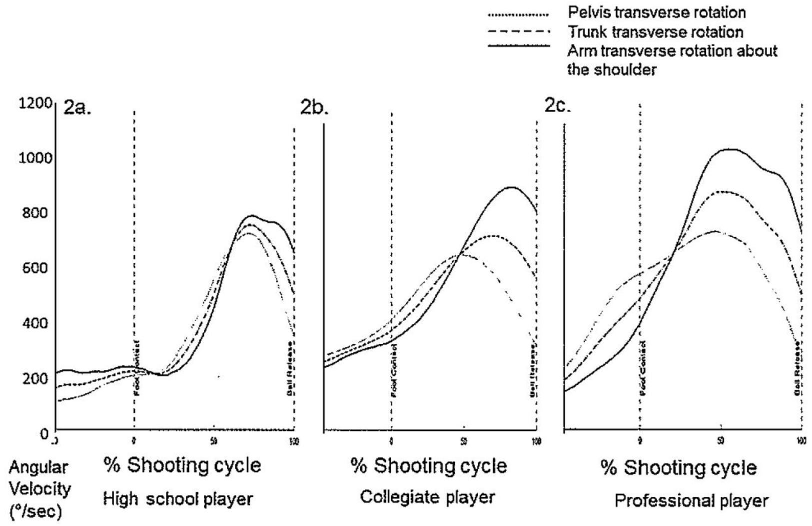

Figure 2.

Pelvis, trunk and, shoulder angular velocities of a high school (2a), collegiate (2b) and professional lacrosse player (2c) during a lacrosse shot. All three sample players were attack, and each generated the highest ball speeds among the players from their respective groups.

Table I

Joint angles and range of motion generated during lacrosse shooting motion from the dominant and non-dominant arms. Values are means ± *SD*.

		High School	Collegiate	Professional
Knee flexion(°)	Dominant	24.6 ± 6.4	22.4 ± 6.5	20.9 ± 3.7
ROM	Non-dominant	22.3 ± 7.6	25.8 ± 6.6	21.8 ± 4.0
Knee flexion angle (°)	Dominant	154 ± 9	154 ± 10	154 ± 6
at ball release	Non-dominant	151 ± 9	153 ± 11	156 ± 14
Pelvic tilt (°)	Dominant	27.2 ± 8.6	28.2 ± 8.5	28.3 ± 4.4
at ball release (anterior)	Non-dominant	23.6 ± 8.4	26.5 ± 11.0	22.3 ± 8.1[*]
Transverse pelvis (°)	Dominant	76.1 ± 15.9	68.9 ± 15.1	82.1 ± 10.4
ROM	Non-dominant	60.1 ± 24.5	57.0 ± 23.6	71.1 ± 19.4[*]
Trunk lean (°)	Dominant	39.8 ± 11.9	38.3 ± 12.4	42.5 ± 4.5
ROM	Non-dominant	32.7 ± 10.7	40.6 ± 10.1	42.4 ± 9.4
Trunk lean (°)	Dominant	20.1 ± 10.5	8.3 ± 20.1	22.7 ± 3.2[**]
at ball release (anterior)	Non-dominant	14.8 ± 11.3	11.3 ± 18.0	12.5 ± 9.1[*,***]
Maximal shoulder (°)	Dominant	61.5 ± 25.5	57.4 ± 15.1	67.3 ± 16.2
abduction	Non-dominant	52.6 ± 24.1	64.7 ± 29.3	56.3 ± 25.9
Transverse shoulder	Dominant	103.9 ± 27.5	97.6 ± 9.7	128.1 ± 10.6
ROM (°)	Non-dominant	84.2 ± 26.5	86.6 ± 15.4	115.5 ± 15.5V[*,**]

[*] Significant main effect of arm dominance at $p < 0.05$.

[**] Significant main effect of player experience at $p < 0.05$.

[***] Significant interaction of arm dominance by player experience level at $p < 0.05$.

Table II

Relative shoulder and pelvis rotation and maximal angular velocities of lacrosse shooting motion from the dominant and non-dominant arms. Values are means ± *SD.*

		High School	**Collegiate**	**Professional**
	Shoulder-to-pelvis-crossover			
Crank-back (°)	Dominant	−30.6 ± 9.7	−32.6 ± 5.6	−39.2 ± 8.2
	Non-dominant	−21.2 ± 10.1	−27.3 ± 12.8	−24.9 ± 11.7[*]
Follow-through (°)	Dominant	57.3 ± 15.7	66.6 ± 26.0	49.8 ± 13.6
	Non-dominant	53.6 ± 18.9	51.2 ± 15.4	57.2 ± 15.5
	Maximal angular velocity			
Pelvis (°/s)	Dominant	582 ± 110	594 ± 158	562 ± 101
	Non-dominant	483 ± 157	492 ± 225	561 ± 115[*]
Trunk (°/s)	Dominant	698 ± 152	700 ± 139	727 ± 107
	Non-dominant	578 ± 179	563 ± 202	681 ± 99[*]
Upper arm About the Shoulder (°/s)	Dominant	923 ± 197	909 ± 163	995 ± 118
	Non-dominant	796 ± 191	759 ± 211	951 ± 79[*]
Crosse (°/s)	Dominant	1540 ± 365	1677 ± 360	2046 ± 244
	Non-dominant	1347 ± 334	1410 ± 457	1789 ± 274[**]
Ball speed (km/hr)	Dominant	112 ± 16	112 ± 15	138 ± 7
	Non-dominant	95 ± 16	100 ± 16	127 ± 18[*,**]

[*] Significant main effect of arm dominance at $p < 0.05$.

[**] Significant main effect of player experience at $p < 0.05$.

Table III

Temporal patterns of maximal angular velocities in high school, collegiate, and professional players during a shot with the dominant and non-dominant arms. Values are expressed as a per cent of the shot cycle. Values are means ± *SD*.

		High School	**Collegiate**	**Professional**
Pelvis (%)	Dominant	62 ± 11	45 ± 15	43 ± 17
	Non-dominant	67 ± 27	58 ± 18	46 ± 12 [*]
Trunk (%)	Dominant	74 ± 11	63 ± 7	58 ± 17
	Non-dominant	79 ± 18	75 ± 14	70 ± 11 [*]
Upper arm about the shoulder (%)	Dominant	83 ± 9	70 ± 10	79 ± 12
	Non-dominant	87 ± 19	85 ± 9	94 ± 13 [*]

[*] Significant main effect of arm dominance at $p < 0.05$.