Modeling the Lacrosse Stick as a Rigid Body Underestimates Shot Ball Speeds

Joseph J. Crisco, Michael J. Rainbow, and Eileen Wang
Brown University and Rhode Island Hospital

In the last decade, dramatic changes in lacrosse stick design are believed to be associated with changes in the play of the game; however, there is a limited understanding of how the lacrosse stick propels the ball. We predicted that the lacrosse stick would perform as a passive extension of the player’s hand and hypothesized that ball shot speed would be equal to the speed at the tip of the stick. Ball and shot kinematics of 16 male and 16 female lacrosse players using four various stick models were tracked at 250 Hz. The speed of the ball was compared with the speed at the tip of the stick, calculated by assuming the stick behaved as a rigid body. Ball shot speeds with men’s sticks were on average 3.5 m/s (7.8 mph) faster than the calculated speed at the stick tip, and ball shot speeds with women’s sticks were on average 0.7 m/s (1.5 mph) faster than stick tip speed. Some lacrosse stick models can shoot the ball significantly faster than predicted when considering the stick as a rigid, passive extension of the player’s hands.

Keywords: sports projectile mechanics

The objective of field lacrosse, the fastest growing sport in the U.S. today (Stenersen, 2008), is to shoot a rubber ball into the opposition’s 1.83m × 1.83 m (6 ft × 6 ft) goal using a stick. The stick consists of two sections: a straight shaft and a stick head with pocket. The stick can be used to pick the ball up from the ground to carry (or cradle), to catch, and to pass and shoot the ball (Figure 1). Until the mid-1950s, the stick used in lacrosse remained essentially similar to its wooden predecessor developed by the native Americans who engaged in lacrosse for play, warfare training, and even to settle disputes between tribes (Fisher, 2002; Vennum, 2007). In the late 1960s, plastic heads for lacrosse sticks quickly revolutionized the men’s game by eliminating the performance variability associated with hand-made wooden sticks, improving the playability, and—some believe—increasing the shot speeds. Plastic heads were not permitted in the women’s game until fairly recently.

In the past decade, the design of plastic heads has become even more creative and radical. These designs have raised some concerns because they are believed to allow greater ball retention, which requires more physical contact to dislodge the ball, and to increase shot speeds. Increased shot speed, especially in the women’s game where only protective goggles are worn, could potentially increase the risk of head and facial injury from ball impact. The sport’s governing bodies have therefore recently adopted stringent rules on acceptable designs and shapes of the lacrosse head in the women’s game (Dillon, 2006). These rules have been adopted in the hopes of maintaining the balance of offense and defense and to address concerns that the newer design may permit greater shot speeds.

In order for governing bodies to make informed decisions on limiting stick design, as well as to aid manufacturers in producing stick designs that encourage better play, a more thorough understanding of how a lacrosse stick propels the ball is required. However, little is currently understood about how the lacrosse stick actually propels the ball. In a previous study, Livingston examined the effects of stick design on the speed of the ball and on the release of the ball during passes in a two-dimensional (2D) video study of a single player and 24 different lacrosse stick models (Livingston, 2006). Livingston’s findings supported the general belief that stick design influences the game: shot speed was lowest for wooden sticks, increased for sticks with plastic heads, and increased even further with the more recent plastic head design. To date, there are no other known studies on the mechanics of the lacrosse stick.

In this study, we focused our attention on the mechanics of the release of the ball. We postulated that the lacrosse stick would perform as a simple, passive extension of the hands. This mechanism would be analogous to a pitched baseball. No matter who is...
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185 shots by each female were made with a modern-era women’s stick: Avanti (CF; Onyx Lacrosse, East Hanover NJ) and a women’s wooden lacrosse stick: P03 (DF; Patterson Lacrosse, St. Catharines, ON, Canada; Figure 2). Each player warmed up by making several passes. They were then instructed to shoot an overhead shot toward a standard lacrosse goal. The players took a running start into the shot. Shots were considered acceptable if they were within a few feet of the goal. All shots were performed in an indoor gymnasium (Olney-Margolies Athletic Center, Brown University). The ball was covered with retro-reflective tape, and the shaft was outfitted with six retro-reflective 9-mm markers (Figure 3). These were tracked at 250 Hz using a passive, four-camera Vicon MX-40 motion capture system (Vicon, Centennial, CO). The lacrosse stick was instrumented as follows. A five-marker cluster was affixed on the stick shaft a few centimeters from where it met the head. The cluster was made from nylon threading and carbon fiber tubing rigidly attached to the shaft. The tubing was used to create four-inch spokes fixed to the shaft and oriented in the direction of the shot. A sixth tracking marker was affixed at the base of the shaft. A calibration trial was taken with the ball in the pocket and a marker affixed at the tip of the head. This tip marker was removed during shooting trials, but it was tracked virtually using the rigid body kinematics generated from the

Figure 1 — A schematic of a player shooting a ball with a lacrosse stick.

pitching the ball, or how fast the resulting pitch is, the speed of the ball is equal to the speed of the hand at the instant the ball is released. In our model of the passive lacrosse stick, we predict that the speed of the shot ball will be equal to the speed of the tip of the stick when the ball is released. We predict these speeds to be equal regardless of the motion of the stick or the length of the stick.

The purpose of this study was to measure ball speed and 3-D stick kinematics during lacrosse shots by various male and female players and to calculate the speed at the tip of the lacrosse stick, assuming the lacrosse stick behaves as a rigid body. We hypothesized that speed of the ball would be equal to the speed of the tip of the stick at the time of release. If this hypothesis proved to be true, the lacrosse stick could be considered to be a passive extension of the player’s hands.

Methods

Sixteen male and sixteen female lacrosse players (age 21 ± 4 years) at skill levels ranging from high school to college varsity were recruited to participate in this IRB approved study. Each male shot three times with two different men’s stick models: Assassin (AM) and Ripper (BM) (Onyx Lacrosse, East Hanover, NJ). The three shots by each female were made with a modern-era women’s stick: Avanti (CF; Onyx Lacrosse, East Hanover NJ) and a women’s wooden lacrosse stick: P03 (DF; Patterson Lacrosse, St. Catharines, ON, Canada; Figure 2). Each player warmed up by making several passes. They were then instructed to shoot an overhead shot toward a standard lacrosse goal. The players took a running start into the shot. Shots were considered acceptable if they were within a few feet of the goal. All shots were performed in an indoor gymnasium (Olney-Margolies Athletic Center, Brown University). The ball was covered with retro-reflective tape, and the shaft was outfitted with six retro-reflective 9-mm markers (Figure 3). These were tracked at 250 Hz using a passive, four-camera Vicon MX-40 motion capture system (Vicon, Centennial, CO). The lacrosse stick was instrumented as follows. A five-marker cluster was affixed on the stick shaft a few centimeters from where it met the head. The cluster was made from nylon threading and carbon fiber tubing rigidly attached to the shaft. The tubing was used to create four-inch spokes fixed to the shaft and oriented in the direction of the shot. A sixth tracking marker was affixed at the base of the shaft. A calibration trial was taken with the ball in the pocket and a marker affixed at the tip of the head. This tip marker was removed during shooting trials, but it was tracked virtually using the rigid body kinematics generated from the
The time of release was defined as the time when the distance between the ball and the stick tip was a minimum. Various kinematic variables were then analyzed at the time of release. Ball velocity (\( V_b \)) was assumed to be constant after release and was computed as the vector average of the ball’s position and time using finite differences. Linear ball speed was the magnitude of \( V_b \). The instantaneous center of rotation was defined as the point of intersection between the helical axis of motion and the plane best-fit to the stick’s motion just before and just after the release of the ball. Tip velocity (\( V_t \)) was calculated given the virtual location of the tip marker and the six degree-of-freedom kinematics of the stick. The linear speed at the tip of the stick was the magnitude of \( V_t \). The angle of the stick shaft with the horizon (\( \beta \)), the angle between the tip velocity and stick shaft (\( \phi \)), and the angle between the ball velocity and stick tip velocity (\( \alpha \)) were also calculated at release (Figure 4).

A paired Student t test was used to determine if the differences in linear speed between the ball and the stick tip were significantly different. The pairing was performed for each shot, and the significance of the difference between ball speed and stick tip speed were tested independently for each stick. The significance of the differences in the kinematic variables at the time of release was determined between the men’s stick (AM and BM) and between the women’s sticks (CF and DF) using a two-way repeated-measures ANOVA. The two factors in this analysis were the subjects and the three shots taken by each subject.

**Results**

Ball shot speeds by the males using the men’s sticks AM and BM ranged from 25 m/s (55 mph) to 40 m/s (85 mph) and were notably and significantly (\( p < .01 \)) faster than the computed stick tip speed at the time of release (Table 1; Figure 5. Note that the dashed line in Figure 5 is the predicted ball shot speed). On average, the ball shot speeds were approximately 3.1 m/s (7.0 mph) and 3.9 m/s (8.7 mph) faster than the speed of the tip of the AM and BM sticks, respectively. The ball shot speeds by the females with the women’s sticks CF and DF were also significantly faster than the stick tip speed (\( p < .01 \),
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but only by a mean difference of 0.9 m/s (2.1 mph) and 0.4 m/s (0.9 mph), respectively.

Although it was not the specific goal of this study, we were able to detect statistically significant differences between the two men’s sticks and the two women’s sticks. After accounting for subject and for trial in a two-way repeated ANOVA, we found that stick model BM shot the ball on average 1.03 m/s (2.3 mph) faster than stick AM. The plastic women’s stick head (CF) did shoot the ball significantly faster than the wooden model (DF), but the difference, given the comparison is between plastic and wood heads, was less than might be expected (0.94 m/s [2.1 mph]).

The instantaneous center of rotation (ICR) at the time of release was found to be located near the knob of the stick and slightly behind the shaft (Table 2; Figure 6). The ICR for the men’s stick tended to be located closer to the knob than the ICR of the women’s stick and also tended to be further behind the shaft of the stick. These locations can be generally described as being located near the wrist and forearm of the bottom hand of the player.

Interestingly, the direction of the tip velocity vector ($\phi$) at the time of the ball release was acute to the long axis of the shaft for all shots, and typically slightly less than 80° degrees (Table 3; Figure 7). In contrast, the direction of the ball velocity relative to the shaft ($\phi + \alpha$) was typically about 95° from the long axis of the shaft. In most shots, the stick was nearly vertical at the time of release, but tended to be past vertical (less than 90°).
Table 1  Ball Shot Speeds (Mean ± 1 SD) Were Significantly Faster Than Stick Tip Speed (Mean ± 1 SD) for All Sticks, and Dramatically More So With the Men’s Sticks (AM and BM) Than With the Women’s Sticks (CF and DF)

| Stick | Shots | Ball Shot Speed (|\mathbf{V}_b|), (m/s (mph)) | Stick Tip Speed (|\mathbf{V}_t|), (m/s (mph)) | P    |
|-------|-------|--------------------------------|--------------------------------|------|
| AM    | 44    | 31.7 ± 2.4 (70.9 ± 5.4)       | 28.6 ± 2.96 (63.9 ± 6.5)      | < 0.01 |
| BM    | 41    | 32.7 ± 2.1 (73.2 ± 4.6)       | 28.8 ± 2.5 (64.5 ± 5.7)       | < 0.01 |
| CF    | 51    | 19.7 ± 2.8 (44.1 ± 6.2)       | 18.8 ± 3.0 (42.0 ± 6.6)       | < 0.01 |
| DF    | 50    | 18.8 ± 2.1 (42.1 ± 4.8)       | 18.5 ± 2.1 (41.3 ± 4.6)       | < 0.01 |

Figure 5 — The dashed line on this graph is the predicted ball shot speed when the lacrosse stick is modeled as a rigid body and a passive extension of the player’s hands. Stick models AM and BM shot the ball about 4.5 m/s (10 mph) faster than predicted. The same phenomenon, but to a much smaller extent (approximately 0.7 m/s [1.5 mph]), was observed with stick models CF and DF.
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during the shot, and similar to a golf club shaft, the stored bending energy is released at the appropriate time, increasing the speed of the head of the stick. We believe that this is not likely since lacrosse shafts are quite stiff. Another possibility is that the plastic head of the stick is acting in this fashion, since it is certainly capable of bending and returning to its initial shape. However, the plastic head of the men’s and women’s sticks are reasonably similar in design. One might surmise that the increase in ball speed is dependent upon the speed of the stick; that is, the increased ball speed only occurs at the higher stick speeds. This hypothesis is consistent with the observation that shots by the females were substantially slower than those by the men. Our data cannot refute this rigorously, although it is interesting to note that one male author shot with both men’s and women’s sticks. These shots with the women’s stick were faster than any of the women’s

Table 2  The Instantaneous Center Of Rotation (ICR) in the Plane of the Shot Motion Was Located Behind the Shaft and Between the Knob and Head of the Stick. ICR Location Along the Shaft Is the Distance From the Knob of the Stick. ICR Location From the Shaft Is the Perpendicular Distance from the Axis of the Stick Shaft (See Also Figure 6)

<table>
<thead>
<tr>
<th>Stick</th>
<th>ICR Along the Shaft (mm)</th>
<th>ICR From the Shaft (mm)</th>
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<tbody>
<tr>
<td>AM</td>
<td>58 ± 59</td>
<td>168 ± 52</td>
</tr>
<tr>
<td>BM</td>
<td>51 ± 42</td>
<td>154 ± 52</td>
</tr>
<tr>
<td>CF</td>
<td>118 ± 74</td>
<td>147 ± 101</td>
</tr>
<tr>
<td>DF</td>
<td>85 ± 60</td>
<td>134 ± 83</td>
</tr>
</tbody>
</table>

more often with the men’s stick than with the women’s sticks (β in Table 3). None of these kinematic variables were found to correlate with ball shot speed (Figure 7).

Discussion

This study was undertaken to determine whether the lacrosse stick performs as a passive extension of the player’s hands during the shot, or whether the stick contributes a “whipping action” that further increases the ball shot speed. We found that the linear speed of the ball was significantly faster than the linear speed at the tip of the stick at release, suggesting that the lacrosse stick shoots the ball faster than if the stick performed only as a passive extension of the player’s hands. While this increase in speed was significant for both men’s and women’s sticks, the increase in ball speed with the men’s stick was dramatically greater than the increase in ball speed with the women’s stick. Our study design and analysis allows us to conclude that certain lacrosse sticks are capable of shooting a ball faster than the speed predicted by a rigid body model of the stick. However, there are important limitations of this study that need to be considered before one attempts to extrapolate these findings to all lacrosse sticks.

Only four specific stick models were used in this study and therefore these results may not pertain to other stick models. We chose to use these four specific sticks because we needed to drill holes into the shaft to mount the marker frames and that precluded us from using the players’ own sticks. If the players had used their own sticks we would have anticipated higher shot speeds on average.

What caused the increase in ball shot speed, and specifically what caused the dramatic increase in ball shot speed with the men’s stick, is not known at this time. The shafts of the sticks of this study, other than the wood stick, are modern metal shafts whose exact composition is unknown but are primarily aluminum and titanium. It is possible that these shafts are bending during the shot, and similar to a golf club shaft, the stored bending energy is released at the appropriate time, increasing the speed of the head of the stick. We believe that this is not likely since lacrosse shafts are quite stiff. Another possibility is that the plastic head of the stick is acting in this fashion, since it is certainly capable of bending and returning to its initial shape. However, the plastic head of the men’s and women’s sticks are reasonably similar in design. One might surmise that the increase in ball shot speed is dependent upon the speed of the stick; that is, the increased ball speed only occurs at the higher stick speeds. This hypothesis is consistent with the observation that shots by the females were substantially slower than those by the men. Our data cannot refute this rigorously, although it is interesting to note that one male author shot with both men’s and women’s sticks. These shots with the women’s stick were faster than any of the women’s.
Table 3  Mean (± 1 SD) Angular Speed of the Shaft, the Angle of the Shaft (β), the Angle Between the Stick Tip Velocity (Vt) and the Shaft, and the Angle Between Ball Velocity (Vb) and Stick Tip Velocity at the Time of Release. Statistical Differences Between Variables Were Determined Only Within the Men’s Sticks (AM vs. BM; *P* < 0.05) and Within the Women’s Sticks (CF vs DF; †P < 0.05)

<table>
<thead>
<tr>
<th>Stick</th>
<th>Players</th>
<th>Shots</th>
<th>Stick Shaft Angular Speed (dβ/dt), (rad./s (deg./s))</th>
<th>Stick Shaft Angle (β), (rad. (deg.))</th>
<th>Stick Tip Vel.–Shaft Angle (φ), (rad. (deg.))</th>
<th>Ball Vel.–Stick Tip Vel. Angle (α), (rad. (deg.))</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM</td>
<td>16</td>
<td>44</td>
<td>29.1 ± 4.5 (1667 ± 256)</td>
<td>1.56 ± 0.13† (89.5 ± 7.7)</td>
<td>1.35 ± 0.05 (77.4 ± 2.9)</td>
<td>0.24 ± 0.07† (13.9 ± 4.2)</td>
</tr>
<tr>
<td>BM</td>
<td>16</td>
<td>41</td>
<td>29.9 ± 3.3 (1715 ± 187)</td>
<td>1.42 ± 0.16† (81.2 ± 9.1)</td>
<td>1.36 ± 0.05 (77.9 ± 3.1)</td>
<td>0.31 ± 0.11† (17.8 ± 6.5)</td>
</tr>
<tr>
<td>CF</td>
<td>16</td>
<td>51</td>
<td>19.5 ± 4.3§ (1120 ± 248)</td>
<td>1.64 ± 0.20§ (94.1 ± 11.7)</td>
<td>1.39 ± 0.08§ (79.7 ± 4.5)</td>
<td>0.23 ± 0.1 (13.0 ± 6.0)</td>
</tr>
<tr>
<td>DF</td>
<td>16</td>
<td>50</td>
<td>18.5 ± 2.6§ (1060 ± 148)</td>
<td>1.53 ± 0.24§ (87.7 ± 14.0)</td>
<td>1.40 ± 0.08§ (80.4 ± 4.4)</td>
<td>0.28 ± 0.17 (16.1 ± 8.7)</td>
</tr>
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Figure 7 — The angle between stick tip velocity vector and stick shaft was less than 90 degrees in all shots. This was expected because the ICR was located behind the stick shaft at the time of release (Figure 6). The angle between the ball velocity vector and stick shaft was on average greater than 90 degrees. Neither variable was found to correlate with ball shot speed.

shots, but were still located close to the line of predicted ball speeds (Figure 5), supporting the hypothesis that the increase in ball speed is due to the difference between men’s and women’s sticks rather than the gender of the player. There may also be a range of speeds within which the observed effect is maximized. The difference between predicted and actual ball speed began to decrease at the highest ball speeds, suggesting that the release of elastic energy may be inappropriately timed at the higher shot speeds. Another explanation for this decrease could simply be the challenge associated with maintaining good stick technique during higher stick speeds.

While there may be several explanations for the dramatic increase in speed found with the men’s stick, we believe that the greater depth of the men’s pocket, in contrast to the women’s pocket, could be a substantial factor. The rules that establish the maximum depth of the pocket differ between men’s and women’s games, such that the depth of the men’s pocket is typically greater by at least one diameter of a ball. We believe that the increased depth of the pocket, perhaps in conjunction with the shooting strings, permits the player to generate greater stick speeds before release. We could not, however, find any differences in the angle of the shaft, or in the direction of the ball and tip velocity vectors. Thus, while the deeper pocket may explain why the ball speeds on average were greater with the men’s sticks than with the women’s sticks, the deeper pocket does not necessarily explain why the men’s ball speeds were
so much faster than predicted. The lack of a complete understanding of the release mechanism in the stick head and pocket more than likely contributes to our failure to explain the increased ball speeds.

In examining Figure 5, we postulate that at any given stick speed there is a maximum ball speed, which is stick specific and independent of the player. This postulate arises from the observation that there is a non-normal distribution of ball speeds at each stick speed: data are dense near this optimal ball speed, with a distribution of ball speeds below this value. These lower ball speeds are considered to be shots with sufficient stick speed but with less than optimal technique. This lack of optimal technique is especially evident at the higher stick speeds.

To our knowledge, there is only one other study that examines lacrosse shot speed using different types of lacrosse sticks. While our study addresses a different question, our results are in general agreement with Livingston (Livingston, 2006). Both studies show that peak stick angular velocities are greater for synthetic sticks than for wooden sticks. Livingston (2006) also demonstrated increased ball speeds with the more contemporary sticks, but direct comparison of absolute ball speeds is not possible as Livingston (2006) examined passes and we examined shots. Interestingly, Livingston (2006) found a tendency for balls to be released sooner with the wooden stick than with the plastic sticks, and sooner among conventional plastic designs than with more modern designs. We were unable to demonstrate this tendency in our study, perhaps because of our lower statistical power, in contrast to Livingston’s (2006) study in which one player passed with all sticks.

This study concludes that some lacrosse stick models are capable of shooting the ball faster than predicted when the stick is considered to be a passive extension of the player’s hands. The stick mechanism associated with these increased speeds remains to be determined.

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References