INFLUENCE OF LANDING QUADRANT ON ELLIPTICAL ORBIT AND ITS RELATION TO RELEASE PARAMETERS OF THE HAMMER THROW

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Hammer throw official distance is determined by the velocity, angle, and height of the hammer at release, which is regulated by the acceleration arc of the hammer during the turns. This study aimed to examine the influence of position variables describing the elliptical orbit during each turn on the official distance and the release parameters. Competitive hammer throws from 35 athletes (17 men and 18 women) were digitized to obtain 3-D coordinates of the thrower and the hammer throughout the throw. Multiple regression models indicate that hammer positioning during turns 1 and 2 accounts for the greatest variance in the official distance. Male throwers use the acceleration arc to regulate the release angle throughout the throw, whereas female throwers use the acceleration arc to regulate both release velocity and release angle throughout the throw.

KEYWORDS: Acceleration, Angle, Arc, Distance, Position, Velocity

INTRODUCTION: Hammer throwing emerged as a sport centuries ago and has been an event at the modern Olympic Games since 1900 for men and since 2000 for women. The hammer's simple, basic design of a metal ball on a wire with a grip requires great strength to swing and throw far. Modern hammer throwing has developed into a complex set of explosive, rotational movements where the hammer and thrower form a co-orbiting system that progresses across the throwing circle from back to front in three or four turns (Brice, 2014; Judge, 2000; Brice, Ness, Rosemond, Lyons, & Davis, 2008). The thrower rotates the hammer in an elliptical acceleration orbit that is inclined so that the hammer has a low point approximately at the back of the circle and a high point at the front of the circle towards the throwing direction. The rotational elliptical orbit of the hammer is the most effective technique for optimizing velocity, angle, and height at the point of release of the hammer (Dapena, Gutierrez-Davila, Soto & Rojas, 2003; Jermy, Burgess, Feasey, Lensen, Willis, Tucker, & Syme, 2014; Liu, 2017). The winner of the event is determined by the distance the hammer is thrown, which depends on release parameters of velocity, angle, and height. The thrower needs to accelerate the hammer in the small amount of space allowed by the throwing circle to achieve optimal release parameters. The most effective throwers accelerate the hammer efficiently (Brice et al., 2008). The efficient acceleration of the hammer occurs when the thrower is in double support stance towards the back of the circle (Brice et al., 2008; Dapena, 1985; Judge, 2000). During the double support phase of the turn, the direction of the acceleration arc of the hammer is high-to-low, towards the ground, and the thrower has the benefit of gravity helping to supplement the acceleration generated by their strength and movements. When the thrower is in the single support phase at the front of the circle, the direction of the acceleration arc of the hammer is low-to-high, and the thrower is working against gravity. By working with gravity and not against it, the added acceleration of the double support phase can increase the release velocity (Brice et al., 2008; Liu, 2017). The ability to spend more time in the double support phase depends on the thrower, as they re-establish contact with the ground during their transition from single support stance (Brice et al., 2008; Judge 2000; Murofushi, Sakurai, Umegaki, & Takamatsu, 2007). When returning to double support during each turn, placement of the thrower’s foot in relation to the hammer ball determines the hammer's acceleration arc and ultimately the release height and angle (Brice et al., 2008). If the ball leads or lags behind the foot, the thrower must do more work to compensate for their inefficient positioning. If the ball is not in sync with the foot, then the optimal orbit could be compromised and will result in shorter throw distance. The purpose of this study was to investigate the relationship between hammer position variables that describe the hammer's acceleration arc and the official distances, and the constituent release parameters of competitive hammer throws.

METHODS: Subjects for this study were the top finishers in the Men's and Women's Hammer Throw at the 2016 USA Track and Field Olympic Team Trials in Eugene, Oregon (9 men and 9 women) and the top finishers in Men's and Women's Hammer Throw at the 2017 USA Track and Field National Championships in Sacramento, California (8 men and 9 women).

Two digital video cameras (Canon model ZR40, Canon, USA) were positioned on tripods facing the hammer throwing circle so that their optical axes were perpendicular. The cameras recorded video of every throw from the side and rear views at 59.95 frames/second. At the beginning and end of the competition, four survey poles of known heights were placed around the throwing circle. The distances between the poles were measured, and videos of the poles were recorded. The poles were used to establish a throwing-circle reference frame so that the throwing direction was positive X, upwards was positive Z, and to the left of the throwing direction was positive Y.

A 24-point anatomical landmark model of the joints of the thrower and the hammer was developed to represent the hammer-thrower system. There is no name for the marker set because they are not markers, but instead digitized joint centers. The two videos of the throw with the longest official distance for each of the 35 hammer throwers were imported into the Vicon Motus system. The anatomical model was used in Vicon Motus to digitize every video to obtain digitized 2-D coordinates of the anatomical landmarks of the thrower and the hammer. Digitizing began when the thrower was centered on both feet at the beginning of the second wind and ended five frames after release. The videos of the survey poles were also digitized. Using the known locations and coordinates of the survey poles and critical time instants of foot takeoff and touchdown of each throw, the Direct Linear Transformation (DLT) procedure (Abdel-Aziz and Karara, 1971) was used to obtain 3-D coordinates of the anatomical landmarks and the hammer from the digitized 2-D coordinates. The 3-D coordinates were smoothed, and the location of the thrower and the hammer in the throwing-circle reference frame was calculated using MotionSoft software (MotionSoft LLC., Durham, NC, USA).

The throwing-circle reference frame was used to define polar coordinates in reference to the center of the throwing-circle rotating clockwise when viewed from above, such that 0° was towards the throwing direction and the front of the circle, 90° was towards the left of the circle, 180° was towards the back of the circle, and 270° was towards the right of the circle. This divides the throwing circle into four quadrants: Quadrant 1 = 0° to 90°, quadrant 2 = 90° to 180°, quadrant 3 = 180° to 270°, and quadrant 4 = 270° to 360°. The horizontal position of the hammer in this polar coordinate system was calculated at the high- and low-point of each of the four turns. This calculation produced eight variables that describe the acceleration arc of the hammer: the hammer's horizontal position at 1st low through the hammer's horizontal position at 4th high. Release parameters of release velocity, release angle, and release height were calculated in the throwing-circle reference frame from the position of the center of the hammer at the instant of release and the path of the center of the hammer from release to two frames after release. The official distances of each throw recorded by meet officials were obtained from the USA Track and Field website.

Eight stepwise linear regressions were conducted on SPSS 24 (IBM Corp., Armonk, NY) to determine the most parsimonious relationship between the horizontal hammer positions and official distance, release velocity, release angle, and release height for men and women throwers, respectively. Statistical significance was set at $p = 0.1$ for inclusion in the prediction model.

RESULTS: Men's official distance ($F_{1,15} = 10.63$, $p = 0.005$, $R^2 = 0.415$) was predicted by the hammer's horizontal position at 1st high ($t = 3.26$, $p = 0.005$). The mean hammer's horizontal position at 1st high was 145° and a more rotated horizontal position was related to a longer official distance.

Men's release velocity was not significantly related to any of the hammer's horizontal positions. The best predictor of men's release velocity was the hammer's horizontal position at 4th high ($t = 1.63$, $p = 0.124$).

Men's release angle ($F_{4,12} = 12.93$, $p < 0.001$, $R^2 = 0.812$) was predicted by a combination of the hammer's horizontal position at 2nd low ($t = 1.89$, $p = 0.083$), the hammer's horizontal position at 2nd high (t = -2.30, p = 0.040), the hammer's horizontal position at 3rd low (t = -3.75, p = 0.003), and the hammer's horizontal position at 4th high (t = 2.22, p = 0.047). The mean hammer's horizontal positions at 2nd low, 2nd high, 3rd low, and 4th high were 223°, 145°, 133°, and 58°, respectively. More rotated horizontal positions at 2nd low and 4th high were related to greater release angles. Less rotated horizontal positions at 2nd high and 3rd low were related to greater release angles.

Men's release height ($F_{1,15}$ = 3.27, p = 0.091, R^2 = 0.179) was predicted by the hammer's horizontal position at 3rd high (t = -1.81, p = 0.091). The mean hammer's horizontal position at 3rd high was 60° and a less rotated horizontal position was related to a greater release height.

Women's official distance ($F_{2,15}$ = 4.50, p = 0.030, R^2 = 0.504) was predicted by a combination of the hammer's horizontal position at 1st high (t = -2.93, p = 0.010) and the hammer's horizontal position at 2nd high (t = 2.80, p = 0.013). The mean hammer's horizontal position at 1st high was 162° and a less rotated horizontal position was related to a longer official distance. The mean hammer's horizontal position at 2nd high was 125° and a more rotated horizontal position was related to a longer official distance.

Women's release velocity ($F_{4,13}$ = 24.54, p < 0.001, R^2 = 0.883) was predicted by a combination of the hammer's horizontal position at 2nd high (t = 7.48, p < 0.001), the hammer's horizontal position at 3rd low (t = 5.12, p < 0.001), the hammer's horizontal position at 3rd high (t = -4.80, p < 0.001), and the hammer's horizontal position at 4th high (t = 3.86, p = 0.002). The mean hammer's horizontal positions at 2nd high, 3rd low, 3rd high, and 4th high were 125°, 137°, 56°, and 55°, respectively. More rotated horizontal positions at 2nd high, 3rd low, and 4th high were related to greater release velocities. A less rotated horizontal position at 3rd high was related to a greater release velocity.

Women's release angle ($F_{2,15}$ = 10.99, p = 0.001, R^2 = 0.595) was predicted by a combination of the hammer's horizontal position at 2nd high (t = -2.16, p = 0.047) and the hammer's horizontal position at 4th low (t = -4.57, p < 0.001). The mean hammer's horizontal position at 2nd high was 125° and the mean hammer's horizontal position at 4th low was 136°. Less rotated horizontal positions at 2nd high and 4th low were related to a greater release angle.

Women's release height was not significantly related to any of the hammer's horizontal positions. The best predictor of women's release height was the hammer's horizontal position at 4th high (t = -1.70, p = 0.108).

DISCUSSION: In hammer throwing, the official distance is primarily determined by the release parameters of release velocity, release angle, and release height, per the range equation (Dapena et al., 2003; Liu, 2017; Murofushi et al., 2007). Our results show that hammer throwers can control the elliptical orbit and regulate the release parameters to maximize official distance. Our results indicate that the hammer's horizontal position at 1st high point is of great importance for male and female throwers. The 1st high point position predicted over 40% of the variance in the official distance for all throwers. This result suggests that it is vital for hammer throwers to achieve the proper positioning and path of the hammer from the very start of the throw. The 2nd high point predicts official distance for women, but not men, which may mean the start of the throw is more important for men than women. Our results indicate that male throwers use the acceleration arc to regulate the release angle in subsequent turns. Our results also demonstrate that female throwers use the acceleration arc to regulate release velocity and release angle in the subsequent turns. The later turns seem to be used to control the acceleration arc set up in the first turn of the throw.

Release velocity is the principal determinant of throwing longer distances (Brice et al., 2008; Murofushi et al., 2007). Our results indicate that the acceleration arc is not related to variation in release velocity for male hammer throwers. The lack of a relationship between hammer horizontal position and release velocity for male throwers probably reflects their reliance on greater muscular strength to develop release speed. Our results show that acceleration arc is strongly related to release velocity for female throwers. More rotated positions in the second, third, and fourth turns predicted greater release velocities. The relationship between a larger rotation and greater release velocity indicates female throwers used more effective technique during the double support to allow gravity to supplement the acceleration the athletes generate through their muscular strength (Brice et al., 2008; Rojas-Ruiz & Gutierrez-Davila, 2009).

The release angle is the inclination of the path of the hammer immediately after release. The path of the hammer after release is a continuation of the path of the hammer before release, so variations in the acceleration arc during the turns will cause variations in the release angle. The temporal effects of the acceleration arc can be seen in our results, particularly for the male throwers, where appropriate horizontal positioning of the hammer in turns 2, 3, and 4 was necessary to increase the release angle (Judge, 2000; Liu, 2017). Approximately 60% of the variance in release angle for female hammer throwers was predicted by the acceleration arc, whereas about 80% release angle variance was predicted for male throwers. This lower percentage for female throwers could be explained by the use of the acceleration arc to regulate both release velocity and release angle, whereas male throwers only regulate release angle.

Release height was not predicted by acceleration arc for female throwers and weakly predicted by acceleration arc for male throwers. The acceleration arc describes both the orbit and the precise 3-D point of release of a hammer throw, which is a combination of release height and release angle. The weak relationship between acceleration arc and release height alone, therefore, may be because release angle is the better descriptor of the release point along the acceleration arc (Liu, 2017).

CONCLUSION: The position of the hammer at the 1st high point is critical for longer official distances. There may be an optimal 1st high point position between 145° and 162°, towards the middle of the second quadrant. Male throwers rely on strength to generate release velocity and regulate release angle with the acceleration arc throughout turns 2, 3, and 4. Female throwers regulate release velocity and release angle together throughout turns 2, 3, and 4, and may be more adept at using the acceleration arc to optimize the release.

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