CRITIQUE OF THE LITERATURE ON THE
BIOMECHANICS OF JAVELIN THROWING

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Abstract

The purpose of this work is to present a critique of the literature concerning the biomechanics of javelin throwing.

The biomechanical analysis of any sporting activity may be used to assess the athlete's technique with a view to demonstrating those aspects of which modification may be desirable to improve performance. Owing to the complexity of the event itself, studies of javelin throwing have tended to concentrate on limited aspects such as the effect of the run-up on the distance travelled by the javelin and the aerodynamic characteristics of the javelin in flight. The few scientifically or mathematically-based studies carried out on the biomechanics of the thrower have employed two-dimensional cinematographic techniques.

This paper critically describes the scientific research on javelin throwing and draws attention to the limitations of examining the event form only one angle, which proved to be limited in producing accurate data. Hence, filming the event from three angles proved to be valuable. It concludes that further research on certain aspects of javelin throwing is necessary, particularly on the contribution of the thrower to the throw.

Introduction

The biomechanical analysis of any sporting activity may be used to assess the athlete's technique with a view to demonstrating those aspects of which modification may be desirable to improve performance. Owing to the complexity of the event itself, studies of javelin throwing have tended to concentrate on limited aspects such as the effect of the run-up on the distance travelled by the javelin and the aerodynamic characteristics of the javelin.
in flight. The few scientifically or mathematically-based studies carried out on the biomechanics of the thrower have employed two-dimensional cinematographic techniques.

The purpose of the present work is to survey the relevant literature and to indicate the limitations of attempting to analyse javelin throwing in two dimensions. For the purposes of this work, it is convenient to divide the literature into three loosely-defined areas, namely the run-up, the aerodynamic characteristics of the javelin and two-dimensional cinematographic analysis.

Glossary
The common terminology used to describe javelin throwing is defined as appropriate to the right-handed thrower.

Run-up: the distance over which the athlete runs before throwing the javelin.
Crossover: this occurs when the thrower's feet are in the air with the drive leg in front ready to land for the last stride.
Centre of pressure (P): This is the point on the javelin upon which the drag and lift forces act
Pitching moment: This is defined as the tendency of the javelin to rotate its point either down or up about its short axis.
Moment Intertia of the Javelin: This is a measure of the effectiveness of its mass in rotation about its short or long axis.
Body lean: the measurement of the angle of the body relative to the vertical axis at the moment the drive leg makes contact with the ground in preparation for the last stride.
Length of the last stride: the distance from the toe of the drive leg to the toe of the plant leg.
Throwing stage: the period between the drive leg hitting the ground at the start of the last stride and the release of the javelin.
Angle release (AR): the acute angle between the velocity vector of the center of gravity and the horizontal at the moment of release (Figure 1).
Angle of attitude (AA): the acute angle between the longitudinal axis of the javelin and the horizontal (Figure 1).
Angle of attack (AT): the acute angle of the difference between the angle of attitude and the angle of release (Figure 1).
Height at release (HT): the vertical distance between the ground and the centre of gravity of the javelin (Figure 1).
HT → Height at release.
L → Lift.
D → Drag.
CP → Centre of Pressure.
AR → Angle of release.
AA → Altitude angle.
At → Angle of Attack.
V → Speed at release (velocity)

Figure 1. Quantitative and Aerodynamic parameters of the javelin

Velocity at release (V): the magnitude of the resultant of three components of the velocity of the center of gravity of the javelin (Figure 1).

Angular velocity: "is the angular velocity of the javelin axis relative to an inertially fixed line in the plane" (Wade, 1967). i.e. rotational velocity about the longitudinal axis of the javelin.
**Drag force (D):** the horizontal force component caused by the passage of the javelin through the air (Figure 1).

**Lift force (L):** the vertical force component caused by the passage of the javelin through the air (Figure 1).

**The effect of the run-up on the distance travelled by the javelin**

It could be considered that the thrower builds up kinetic energy in the body during the run-up and that some of it would be transferred to the javelin in the throwing stage. It might be expected, therefore, that the thrower with the highest run-up velocity would have the potential to transfer the greatest kinetic energy to the javelin and thus achieve the longest throw, other factors being equal. The run-up for coaching purpose is broken down into the following parts:-

a) **Run and transition:** There is no biomechanical evidence that the run should be any longer than eight steps. During the first three steps the transition of the javelin is brought back to a throwing position.

b) **Cross-over transition:** one of the primary aims of this transition is to get the body lean so that the more powerful muscles of the trunk can be used in the throw; this would increase the distance over which the force acts on the javelin. The first two steps of the cross over are identical to the run and the difference starts with step three where the drive leg lands. Once the plant leg is landed, the linear momentum is transferred to angular momentum and the angular momentum is passed up the link system of the body.

C) **Throwing phase:** once the plant leg is landed the throwing arm strike takes place. The body forces acting at throwing are the external force (it is force which is generated during the run-up) and the internal force is the muscular effort which begins with the large muscles of the legs and trunk and culminates in the delivery of the javelin.

Many researchers have stressed the importance of the run-up notably wade, (1979) Flatter (1980) Atting (1981) Mazzalitis (1968) and Whithread (1982) and have implied a direct relationship between the velocity of the run-up and the length of the throw. They stated, however, that velocity must be controlled so as to enable the athlete to remain balanced in the throwing stage. Regrettably, these studies did not give quantitative
measurements to support their conclusions, which appear to be based on the authors' experience and observations of outstanding performers.

Maximov (1979) stressed that the run-up should be fast. He reported that Lusis (World record holder in 1968 and 1972) threw the javelin with and without a run-up, resulting in throws of 93.8 m and 64 m respectively. Although this demonstrated a large difference in the distances thrown and suggested that the run-up makes an important contribution to the distance thrown, no quantitative data on the speed of the run-up was reported and no attempt made to compare different throws using different run-up velocities.

Kunz and Kaufmann (1980, 1983) found, by using statistical correlation methods on the data obtained from high speed cine film at a speed of 102 fps, that the run-up was an important factor in achieving the maximum velocity at release. Again no quantitative data on the run-up velocity was reported, nor detailed interpretation of the result attempted.

Bartlett (1983) carried out a study on the run-up of an international javelin thrower. The athlete was filmed at a speed of 200 fps and a digitizing rate of 50 fps selected. He reported that the velocity did not exceed 5.5 ms⁻¹ compared with a value of 6.75 ms⁻¹ for an Olympic thrower.

Al-Kurdi (1987, 1988) examined the effect of the velocity of the run-up on the distance thrown by a group of five athletes, both male and female, of different ages and technical accomplishment. He demonstrated that the velocity of the run-up was not in itself the most important factor in achieving a long throw and concluded that the most significant contribution of the run-up was in providing a stable base from which to release the javelin. The thrower with the highest run-up speed would have the potential to transfer greatest energy to the javelin (other things being equal).

The literature on the run-up indicates the need for detailed quantitative investigation into its effect on the length of the throw.

**The aerodynamic characteristics of the javelin**

The distance travelled by a projectile depends on its velocity, angle and height at release and upon such factors as gravitational and aerodynamic forces. The theoretical optimum angle of release for a projectile is 45 deg when the point of release and landing are at the same height and aerodynamic forces are ignored. A javelin, however, does not behave in the same way as a projectile *in vacuo* because of the fact that it is released from a point above the ground and because of the aerodynamic forces affecting its flight. Several researchers
have focussed their studies on the aerodynamic characteristics of the javelin in flight in an attempt to understand how these affect the trajectory and optimal release conditions.

Ganslen (1967) was the first to report javelin aerodynamic forces measured in a wind tunnel. Because of the limited size of the tunnel and the pressure of turbulent air flows near its walls, he was not able to locate the centre of pressure when the angle of attack was greater than 30 deg. To overcome this problem, Terauds (1972) carried out a large-scale experimental study on the aerodynamics of the javelin and the quantitative parameters at release using a large wind tunnel. He studied the physical parameters of 14 different javelins, providing the first extensive experimental data on the flight of the javelin. He concluded that the most important variable for maximum gains in flight is the pitching moment. In addition, there was no significant relationship between the javelin's optimum lift-drag ratio and its performance.

Soong (1975) carried out the first theoretical computer simulation of the aerodynamics of the javelin in flight in which five non-linear differential equations were used to describe the javelin. He assumed a constant velocity for all angles of release. However, it is unlikely that a thrower could produce constant initial velocity for all angles at release. He concluded that by modifying the javelin by reducing the distance between the centre of pressure and the centre of gravity, longer distances could be thrown. Shortly after the Olympics of 1984, the International Amateur Athletics Federation (IAAF) proposed a major modification in the structure of the men's javelin which would move the centre of gravity of the javelin forward by 40 mm. The IAAF believed that this would reduce the distances thrown which it considered necessary for the safety of spectators. The use of the new javelin became compulsory in men's competitions in April 1986.

Red and Zogaib (1977) carried out a study using equations similar to those derived by Soong. They questioned his assumption of a constant velocity for all angles at release and showed that the velocity and angle of release are inversely related; similar results had been obtained by Terauds in his 1972 study.

Hubbard and Rust (1984a) used both equations similar to those derived by Soong and the experimental data published by Terauds (1972) in their computer simulation. In a subsequent study (1984b) they used a similar computer simulation technique and reported that the optimum release conditions for a given javelin depended on its particular aerodynamic characteristics. Hubbard (1984) stated that the distance travelled by the javelin was a unique function of factors at release, namely, velocity, height, angle at release, angle
of attack and angular velocity of the javelin, and concluded that the velocity and height at release should be as great as possible.

The work of Hubbard and Rust presents a more realistic assessment of the aerodynamic characteristics of the javelin by the application of experimental data to a theoretical model similar to that developed by Soong and avoids his unrealistic assumption that velocity is constant for all angles at release. In addition, their work is the first to show the effect of the angular velocity on the distance thrown.

Bartlett and Best (1988) studied the design characteristics of the new javelin and reported that a forward-location by 1 cm of the position of the centre of pressure would increase the distance travelled by the javelin by 10 cm. They also recommended that manufacturers should alter the specification of the new javelin to improve performance.

**Release and Launch Phase**

Several researchers have applied two-dimensional analysis to the study of the quantitative parameters at release. Ikekami et al. (1979) reported that the velocity at release was the most important factor for maximising the distance travelled by the javelin. Although such a result is consistent with basic mechanical principles, the authors do not describe the experimental set-up or explain how the velocity data was derived. However, similar conclusions were reached by Kunz and Kaufmann (1980) using statistical correlation methods on biomechanical data. Bartlett (1982) found that specialist javelin throwers released the javelin with greater velocity than decathletes, but again, no description of the experimental layout is provided nor details of the camera speed given.

Terauds (1978) showed a direct relationship between the distance the javelin travels and the velocity at release using the correlation co-efficient method and reported similar results in a further study in 1984. He claimed a high degree of accuracy in both camera set-up and in obtaining the cinematographic data. The fact that he used a camera speed of only 50 fps suggests difficulty in identifying exactly when the javelin leaves the hand of the thrower, thus tending to magnify any margin of error in his calculations.

Miller and Munro (1983) reached the similar conclusion that there is a direct relationship between the velocity and the distance travelled by the javelin. However, they concluded that a camera speed of at least 200 fps should be used in studying the javelin throw. They also stated that "a detailed study of javelin throwing would require two or more phase-locked
cameras and a reasonably large reference frame to calibrate the space occupied during this period of performance.

Rich et al. (1985) found that the angle of release, attack and attitude were similar in both men and women, but that the velocity and height at release achieved by women were significantly lower than those of men. The similarity in the results of men and women was perhaps coincidental, although it is unlikely that a number of throwers would produce similar angles of release or attack.

Hubbard and Alaways (1987) examined the optimum release conditions for the new javelin and concluded that they differed from those of the old, resulting in a reduction at 10% in the distance travelled by the javelin.

The angles of release, attack and attitude reported by other researchers are shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td><strong>Comparison of Angles of Release, Attack and Attitude Reported (1968-1987)</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Year</th>
<th>Angle at release (deg)</th>
<th>Angle of attack (deg)</th>
<th>Angle of attitude (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wade</td>
<td>1968</td>
<td>35.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Royal</td>
<td>1968</td>
<td>35.0-40.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aircraft Est.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paich</td>
<td>1972</td>
<td>30.0-40.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Terauds</td>
<td>1972</td>
<td>27.0-30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Soong</td>
<td>1975</td>
<td>42.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dyson</td>
<td>1977</td>
<td>35.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Red &amp; Zogaib</td>
<td>1977</td>
<td>35.0-38.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ikengami et al.</td>
<td>1979</td>
<td>29.0-34.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Kunz &amp; Kaufmann</td>
<td>1980</td>
<td>37.5</td>
<td>1.0</td>
<td>38.5</td>
</tr>
<tr>
<td>Bartlett</td>
<td>1982</td>
<td>15.7</td>
<td>26.9</td>
<td>42.5</td>
</tr>
<tr>
<td>Whitbread</td>
<td>1982</td>
<td>25.0-30.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hubbard</td>
<td>1984</td>
<td>17.0</td>
<td>-15</td>
<td>32.0</td>
</tr>
<tr>
<td>Komi &amp; Mero</td>
<td>1985</td>
<td>33.0-47.0</td>
<td>2+/12</td>
<td>29.0-51.0</td>
</tr>
<tr>
<td>Hubbard</td>
<td>1987*</td>
<td>30.0</td>
<td>changes with speed 20-35 m/s</td>
<td>changes with speed 20-35 m/s</td>
</tr>
</tbody>
</table>

* new javelin

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Gregor and Pink (1985) examined the quantitative parameters at release of Petranoff (World record holder 1983), using a camera speed of 200 fps. A release velocity of 32.3 ms\(^{-1}\) was reported, the highest value reported in the literature. A high degree of accuracy in obtaining the cinematographic data was claimed, although the fact that no markers were placed on the joints would inevitably reduce the accuracy of the digitizing. They stated that javelin throwing is a three-dimensional event that requires two cameras for its successful study, they also stated that “while we were fortunate to obtain quantitative information on this World record performance, the limitations of a planar analysis were recognised.”

Komi and Mero (1985) studied the quantitative parameters at release of five men and six women javelin finalists in the Los Angeles Olympic Games (1984) using a single camera. They found that both the release and attitude angles showed considerable individual variation. Study of the elbow angle position and velocities during the throwing stage indicated that “Movement around the elbow joint in Javelin throwing is expected to be very three-dimensional, and therefore considerable errors could be made when the interpretation is limited to the results from the two-dimensional analysis.”

Although a number of researchers have referred to the fact that javelin throwing is a three-dimensional event and that a single camera fails to describe the event precisely, none of them has studied the event in three dimensions. However, in order to obtain high quality data, the experimental procedure must be carefully carried out and requires a number of people to prepare the site and operate the equipment. Obtaining coordinates from the film is thus complex and time-consuming. Al-Kurdi (1987) examined the quantitative parameters at release using three high speed cine cameras and showed that any angle of release within the range 34.5-41.4 deg is equally effective.

The literature relating to the biomechanics of the thrower is limited. Fitzsimmons (1968) reported that the body angle lean should be approximately 30 deg from the vertical as measured from vertical to horizontal. He based his contention on his experience and observation of outstanding performers. Given, however, that javelin is a high-speed event particularly from body lean to release, it is hard to observe the body lean accurately in the absence of any recording device.

Ariel (1976) conducted a two-dimensional cinematographic analysis on seven throwers who took part in the 1975 Olympic Javelin training camp. Two throws from a series by each athlete were selected for analysis. He reported that cinematographic data showed that throwers who achieved throws exceeding 91.44 m had a body lean angle of approximately
30-40 deg from the vertical. Regrettably no description of the experimental layout or camera speed was given. In addition, since body lean occurs in more than one plane it cannot be measured satisfactorily in only two dimensions. Al-Kurdy (1987) found that the body lean when the left foot hits the ground to be of greater significance in aligning the force with the javelin and hence in maximising the length of the throw than at the moment the right foot hits the ground.

The last stride provides the base of the throw and varies from athlete to athlete. Paish (1967), in an analysis of 12 European javelin throwers, found that the length of the last stride varied from 1.22 m to 1.83m, whilst Bartlett (1983) reported a last stride of over 1.6 m for specialist throwers. It should be noted, perhaps, that the length of the last stride must, to some extent, be dependent upon the athlete’s leg length as well as his style. Using a statistical correlation method with two-dimensional cinematographic data, Witchey (1972) found that good throwers had greater right ilioc crest velocity than poor throwers during the last stride.

Ariel (1973) studied the relationship between the maximum angular velocities and accelerations of seven segments. Two dimensional cinematographic data was obtained at a speed of 64 fps of which lusis (as of which Lusis (a former World record holder) was the subject. he concluded that the shank, thigh and trunk do not develop high angular velocities and acceleration relative to the shoulder, forearm and hand, and that the timing and sequence of velocity, acceleration and deceleration of successive body parts produce biomechanical advantages in the javelin throw.

The use of a single camera, as employed by Ariel, is insufficient to provide a complete quantitative analysis of either the angular velocities or the accelerations of the segments. One should also question the accuracy of some of the resultant data, and note that the greatest angular velocity recorded is that of the shoulder. Although Ariel’s work represents the first major quantitative study of the thrower relating to angular data, no quantitative measurements of either the linear velocity or acceleration of the segments were reported and the fact that the camera speed was only 64 fps makes it difficult to calculate the above parameters accurately.

Terauds, at the 1976 Montreal Olympics, recorded most of the qualifying and final rounds of the javelin competition using a camera operated at 50 and 100 fps. His computer analysis showed that the deceleration and acceleration of body segments were accomplished remarkably well by Nemeth in both throws (Nemeth was World record holder at the time of
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the Montreal Olympics). Although the timing of maximum velocity of the segments with respect to the release was reported, no values for velocities and acceleration patterns were provided.

Ariel and Terauds (1980) carried out a study on the throwing stage of some of the top American javelin throwers and compared them with the Montreal Olympic finalists. A high speed camera at an angle of 90 deg to the sagittal plane was used to film the athletes. The American throwers were filmed at 200 fps and the Olympic finalists at either 50 or 100 fps. It was claimed that computer analysis showed that the peak values of the upper arm velocities for the American throwers were considerably higher, is some instances twice those produced by the Olympic finalists, and that the peak upper arm angular velocities of the Olympic finalists closely coincided with the release of the javelin. However, the American throwers did not release the javelin until the upper arm velocity had decreased to near zero. Finally, it was reported that the velocity of the javelin for the Olympic finalists was greater than that of the Americans and that the American throwers achieved constant velocity from the time they initiated the throw until the release, i.e. there was no acceleration.

It should be noted that the results reported in their study are at great variance with those found by Ariel in his (1973) study of the angular velocities of the selected body segments. Al-Kurdi (1973) considered the angular velocities of the arm segments but was unable to define the relationship between the angular velocity of either the upper or the lower arm and the distance thrown. As these are believed to be the only studies to quantify the angular velocities of the body segments of the various segments.

Koltai (1978) identified a number of factors which he considered important in achieving a greater distance in javelin throwing. He stated the importance of applying the force to the javelin along its longitudinal axis. However, no quantitative measurements were reported of the magnitude or direction of the force. In studies using the old (1987) and new (in press) javelins Al-Kurdi considered the importance of the alignment of the force with the javelin and concluded that the force must be aligned as closely as possible with its longitudinal axis in order to achieve a Long throw.

Terauds (1984) conducted a two-dimensional cinematographic analysis in which Petrovoff (World record holder in 1983) was a subject. He examined the run-up and the throwing stages of his performance. He used a camera with an electronic timer at 200 fps to film the athlete during a competition between the USA and the GDR and concluded that
there was no significant difference in the run-up, claiming that the last part of the throw, or the release, seemed to determine the outcome.

However, Miller and Munro (1983) reported that the final 50% of the javelin release velocity was built up within 0.04-0.05 sec prior to the beginning of the javelin’s flight (before the release). They used camera speeds of 100, 150 and 200 fps to study the position and velocity of the javelin during the plant leg preceding the release. They stated that “because of the three dimensional nature of the throwing motion, only limited research-based information is available on body segment contributions to the magnitude and direction of the javelin’s velocity at release”. Komi and Mero (1985) reported conclusions similar to those of Miller and Munro, namely that the javelin velocity increased by a similar amount during the final 0.05 s before the release. This implies that the throwing stage (from drive leg to the point of release) contributes most to the throw.

Paish (1972) stated that the velocity at which the arm “strikes” the javelin is responsible for a very large proportion of the throw but unfortunately gave no quantitative measurements in support of his statement. The absence of quantitative measurements was referred to by Gregor and Pink (1985), who suggested the importance of an investigation of such quantitative parameters as release velocity, angle of release, linear and angular acceleration, mechanical energy transfer and net moments of force about a joint.

Al-Kurdi (1987) examined the energy patterns of the arm segments and the javelin of five throwers and concluded that a higher percentage of kinetic energy was transferred from the body to the javelin by the experienced throwers.

Bartlett and Best (1988) reviewed the scientific literature relevant to javelin throwing but failed to show the consequences of examining the event in two dimensions. However, this may be due principally to the scarcity of scientifically-based analyses of the event in three dimensions.

**Other factors**
A number of researchers and coaches have stated that for a thrower to achieve a long throw, the throwing arm should be fully extended backwards in the throwing stage as this would increase the distance over which force is exerted by the athlete. Schmolinsky (1978) stated that “the arm and the javelin have not changed position during the impulse stride and the throwing stage as this would increase the distance over which force is exerted by the athlete. Schmolinsky (1978) stated that “the arm and the javelin have not changed position during
the impulse stride and the throwing position. In this phase the full extension of the forearm by the hand is important; under no circumstances must the arm be flexed. Fitzsimmons (1968) also referred to the importance of the extension of the arm. Attig (1981) stated that throwing with an extended arm "provides a large distance over which to apply force to the javelin during the throw...Whenever the athlete, prior to throwing allows his elbow to flex, he decreases the distance of the application of the force."

Al-Kurdi (1987) in examining 21 throws by five throwers, however, reported that bending the throwing arm slightly at the beginning of the throwing stage did not appear to reduce the length of the throw. Similarly Housden (1969) pointed out that throwers do bend their elbows slightly as the drive leg makes contact with the ground.

Al-Kurdi (in press) described his development of a new method for measuring directly the acceleration applied along the longitudinal axis of the new specification javelin, using a light-weight, wireless, telemeterized accelerometry system. The output signal from the accelerometry system is transferred directly to the computer via an analogue digital converter. This reduces the potential for error inherent in the method of obtaining data from cine film, which involves manual digitizing; any human error introduced during the digitizing process may be compounded in the differentiation of the displacement data.

Conclusion
On the basis of this critique, the researcher recommends that more work be done on the biomechanics of the event, especially on quantifying the total forces at throwing and transformation of the angular momentum involved in the throwing. The performance of javelin throwers might be improved if researchers in the field of biomechanics were able to develop an effective mathematical model of the thrower holding the javelin so that the output of performance could be predicted and compared with experimental data obtained during the performance.
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