Ladies' Javelin: Aerodynamics, Flight Simulation and Biomechanical Considerations

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INTRODUCTION

The javelin event, using both men's old and new rules javelins, has been reported in the literature from various aspects including biomechanical studies (e.g. 1, 2), aerodynamics (3), and computer modelling (4, 5, 6, 7, 8). However, consideration of the ladies' event, from the latter two aspects, has not previously been reported. If the flight of a javelin can be accurately simulated then it is possible to find, for any individual, an optimum set of release conditions which produce a maximum range. In previous papers, the authors have reported data for the aerodynamics (9) and computer simulation of javelin flight (10) for the men's new rules javelin. This paper presents the results of wind tunnel tests of the ladies' javelin, a consequent computer flight simulation of this implement and the implications for the biomechanics of the event.

TERMINOLOGY AND THEORY

Since javelin flight cannot be affected by an athlete once released the problem of flight simulation is defined mathematically as an initial condition problem and there are many release variables that influence range (11). However, some of these variables, such as long axis spin, yawing and javelin flutter (12), are of secondary importance in terms of range and grossly overcomplicate the problem (7, 10). Removing these secondary variables results in the release parameters described in figure 1. We can include do within the overall range (R) by defining javelin horizontal position (x) at release (xo) from the point of last contact on the javelin (i.e. xo = 0). Finally, we can neglect co as a variable in its own right allowing range to be expressed as R = R (vo, ao, bo, wo, zo, wd). There will be a particular optimal set of release parameters that maximises R for a given individual.

In flight, the javelin is subjected to aerodynamic forces that are a direct result of the javelin speed (v) and angle of attack (b) relative to the air flowing past it. By definition this includes the effects of the wind velocity (wd) as in figure 2, (11, 12). The aerodynamic pressure distributions acting on the javelin result in forces that can be summed as equivalent to a single force at a position known as the centre of pressure (CP). The CP position does not coincide with the javelin centre of gravity (CG), and thus the planar force system will produce a moment causing the javelin to rotate / pitch about its short, horizontal axis.

The above force system can be substituted by that described in figure 2 where the lift (L) and drag (D) forces, acting perpendicular and parallel respectively to the direction of the javelin velocity vector relative to the air, fully account for translational effects during flight, and where the pitching moment (M) fully accounts for the rotation of the javelin about its CG with a tranverse moment of inertia IG.

APPARATUS AND PROCEDURES

The aerodynamic forces and moments mentioned above were measured in the Environmental Wind Tunnel at the University of Salford aeronautical engineering laboratory. The 3 component manually operated mechanical balance system measured aerodynamic lift, drag and pitching moments at 5° angle of attack increments from 10° to 35° and 1 m/s air speed increments from 10 m/s to 30 m/s. The javelin used in this study, providing by courtesy of TI Apollo Limited, was a new 1986 top of the range ladies' aerodyne DR model. More detailed with tunnel procedures have been provided elsewhere (9). At b = 5° the forces were too small and errors (section 4) too large such that these results were discarded. At b = 40° boundary layer interference within the test section affected results, which were also discarded. Functional relationships

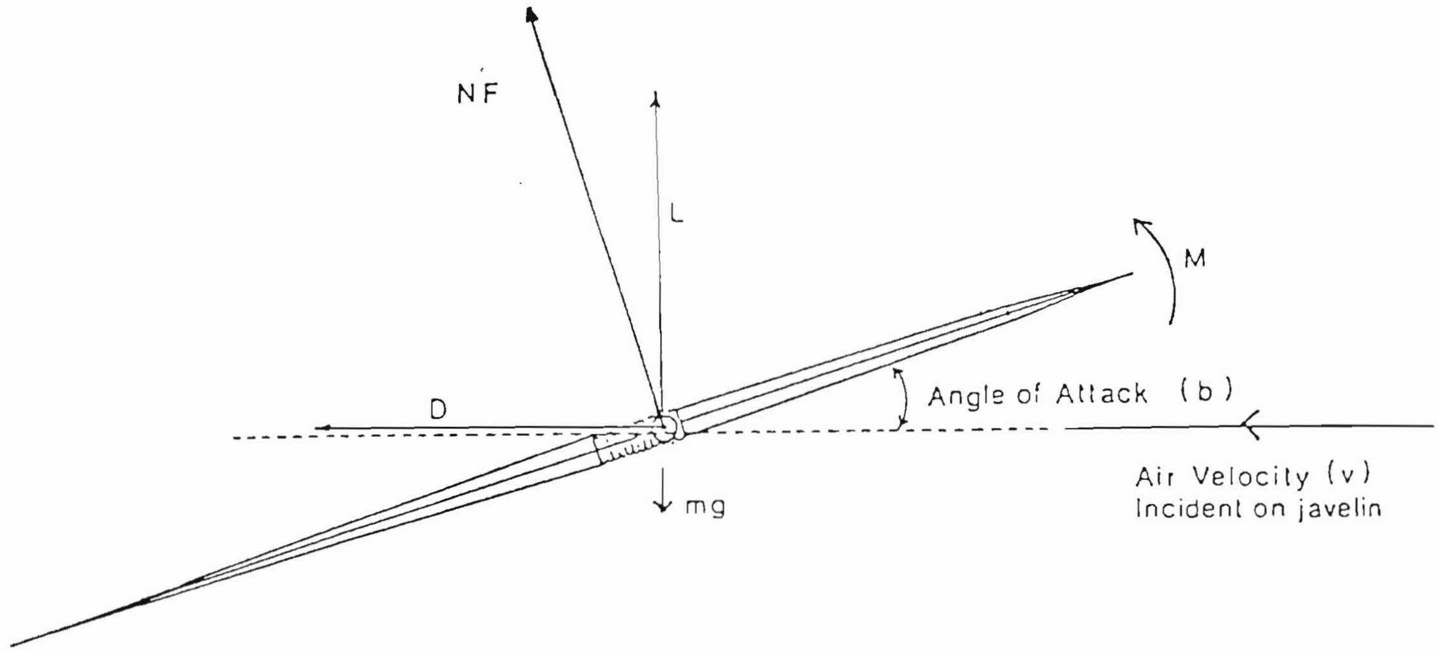

Fig. 1 Aerodynamic Force and Moment System in the Wind Tunnel.

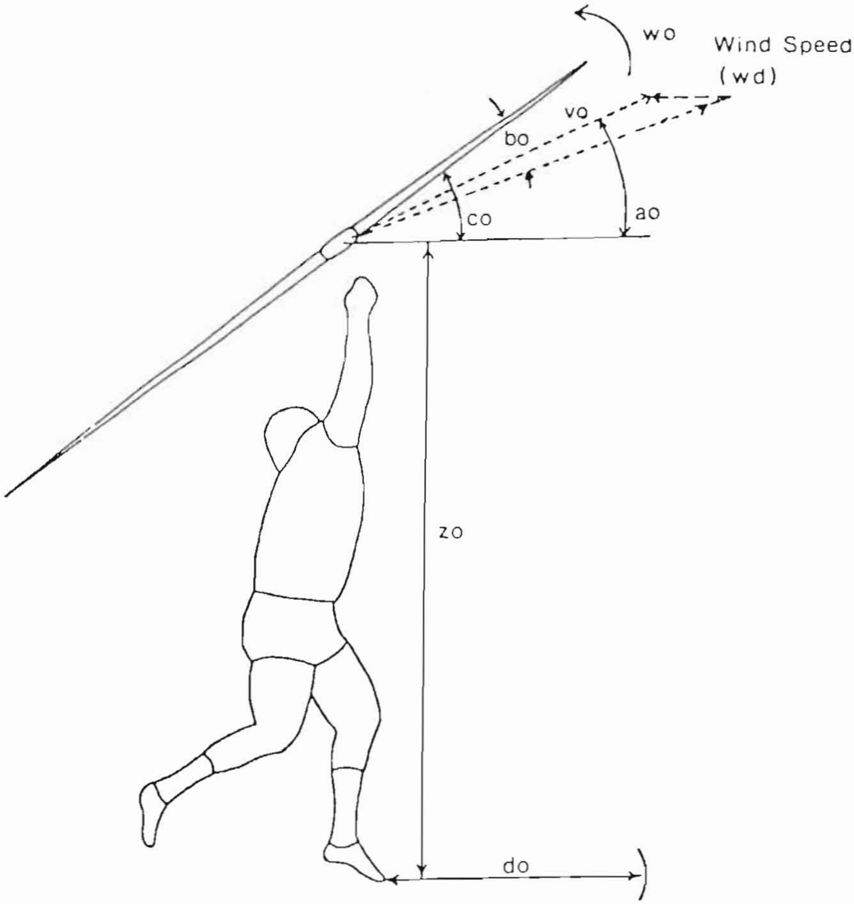

Fig. 2 Planar Javelin Release Variables.

between the aerodynamic coefficients and air speed were investigated using least squares curve fitting. Each relationship was then linearised and the Pearson product moment correlation coefficient (r) calculated. Finally each r value was tested for significance in the usual way.

Once the aerodynamic forces and moments at all angles of attack and air speeds were measured, the flight of the javelin can be simulated and the range assessed for any parameter set vo, ao, bo, wo, zo, wd. The set of simultaneous differential equations of motion were solved numerically using a fourth order Runge - Kutta technique (e.g. 13). This method has been used previously by the authors for the men's javelins (10) and is similar to methods used in other simulations (7, 8). Figure 3 shows a flow diagram of the flight simulation program that predicts the flight of the javelin once the initial conditions vo, ao, bo, wo, zo, wd are set. An integration time of 0.05s was used and found to be accurate to a global truncation error of $<10^{-4}$ m. The set of initial conditions were varied until an optimal set were found which produce a maximum range. In addition, the relative effects of each individual condition on range was assessed.

ERROR ANALYSIS

The maximum absolute error values for any javelin plus tare measured aerodynamic data point are presented below and are the same as for men's javelins (9)

$$L = \pm\ 4.45 \times 10^{-2}\ \mathrm{N}\ (0.01\ \mathrm{lbf})$$

$$D = \pm\ 2.225 \times 10^{-2}\ \mathrm{N}\ (0.005\ \mathrm{lbf})$$

$$M = \pm\ 1.13 \times 10^{-2}\ \mathrm{N}\ (0.1\ \mathrm{lbf\ in})$$

These values are constant and consist of error owing to scale reading and to slight javelin instability in the test section. The error in tare only data was negligible in comparison with error in javelin plus tare results. Since the absolute errors are constant the relative error decreases with increasing b and v. All values with a relative error of greater than 18 per cent were not used in the results, thus, for example, at $b = 10°$, lift values corresponding to $v>23$ m/s only were within acceptable error limits. The forces and moments at $b = 5°$ were so small that the whole data set was discarded.

To calculate the error in d for each angle of attack, the errors in K_D, K_L and K_M were assessed. Once each r value has been calculated the percentage of variance unaccounted for in the linearised slope was taken as the relative error, i.e.

$$\text{percentage error} = (1 - r^2) \times 100$$

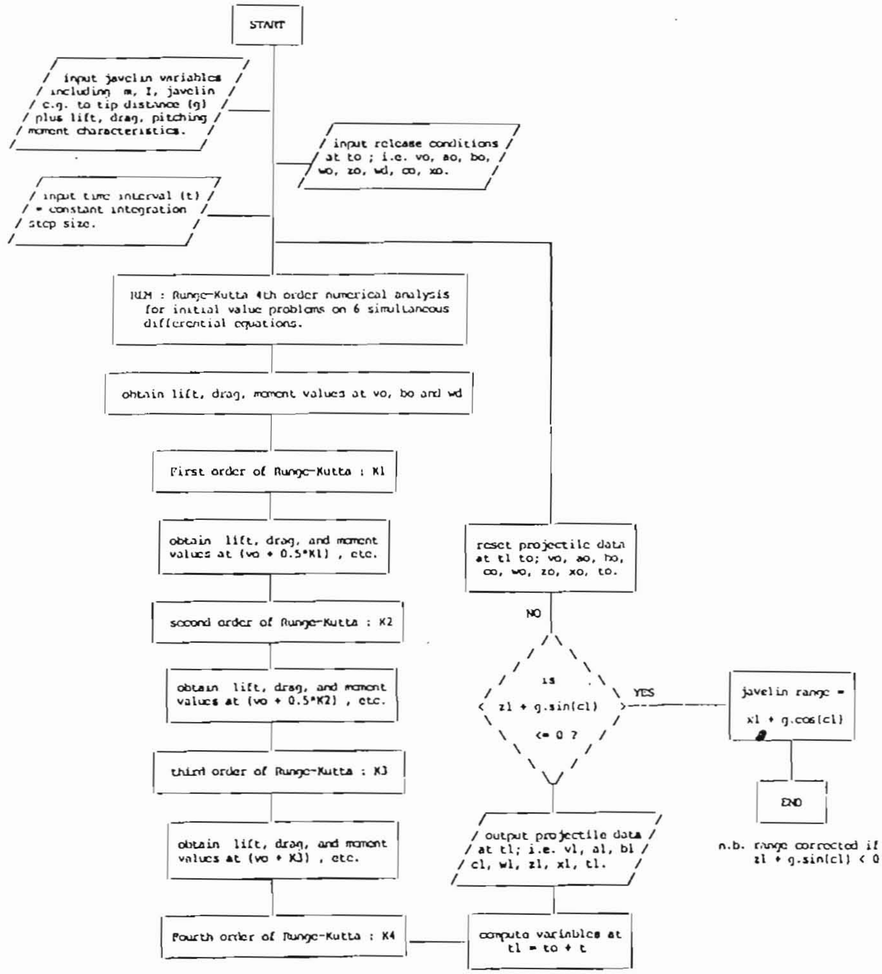

Fig. 3 Flowchart of Flight Simulation Program.

This assumes that all of the variance of the slope is error and not an unconsidered variable. The greatest error, as expected, occurs at $b = 10°$ with approximately 6% error in each K value. The error then decreases for each K value as b increases, until at $b = 35°$ the error in each K value is as small as 0.8%. Eventually, the error in d can be calculated, data for which is presented in Table 1.

TABLE 1

Error in CP data

Angle of attack/degrees	error in d/%
35	0.8
30	1.2
25	1.8
20	2.8
15	4.6
10	10.0

RESULTS AND DISCUSSION

Overview

For a given angle of attack, L, D and M were all found to vary as a function of the square of v ($p<0.01$) using least squares curve fitting. This coincides with well established laws of aerodynamics (e.g. 14) and data presented previously on javelins (9). The functional relationships below therefore apply:

$$L = K_L V^2$$

$$D = K_D V^2$$

$$M = K_M V^2$$

where K_M, K_L and K_D are constants for a given angle of attack (9). Since the lift and drag forces act at the CP, a distance d from the javelin's CG, then:

$$d = \frac{K_M}{K_L\,(\cos b) + K_D\,(\sin b)}$$

TABLE 2
Summary of aerodynamic results

b/degrees	$K_D/Nm^{-2}s^2$	$K_L/nm^{-2}s^2$	$K_M/Nm^{-1}s^2$	L/D ratio	d/cm
35	4.71×10^{-3}	5.51×10^{-3}	1.15×10^{-3}	1.17	0.15
30	2.92×10^{-3}	4.11×10^{-3}	8.90×10^{-4}	1.41	0.17
25	1.97×10^{-3}	2.69×10^{-3}	6.30×10^{-4}	1.37	0.19
20	1.28×10^{-3}	1.66×10^{-3}	4.40×10^{-4}	1.27	0.22
15	8.00×10^{-4}	9.60×10^{-4}	3.00×10^{-4}	1.20	0.26
10	5.40×10^{-4}	5.00×10^{-4}	1.80×10^{-4}	0.93	0.30

Table 2 gives a summary of K values, L/D ratios and the CP position (d) as a function of b. The results are presented graphically in figures 5 (K_D), 6 (K_L), 7 (K_M), 8 (L/D ratio) and 4, (CP position, d) along with comparable data from men's new rules javelins where appropriate.

Figures 8 and 4 afford an interesting comparison between men's and ladies' javelins showing the two implements to differ substantially. Table 3 shows significant relationships between K_D, K_L, K_M and d as functions of angle of attack (b). Unfortunately, since no other data has been found for ladies' javelins it is difficult to relate these results to previous literature. Although the relationships in table 3 are unusual, such functions facilitate the simulation of the javelin's flight. As with new rules men's javelins (9) the centre of pressure on ladies' javelins is always behind the CG (relative to the tip). However, the constant d = 25.5 cm found for men's javelins (9) is not seen here.

TABLE 3
Functional relationships K_D, K_L, K_M and d (b); 10<b<30 degrees

Variable (x)	x as function of b	r
K_D	$2.44\times10^{-4}\exp(0.833b)$	0.997
K_L	$b/(32200-994b)$*	0.995
K_M	$b/(68000+1140b)$	0.0098
d	$1/(2.04+0.123b)$	0.998

* Doesn't include b = 35° because stalling has begun at this value.
Results quoted to 3 significant figures.

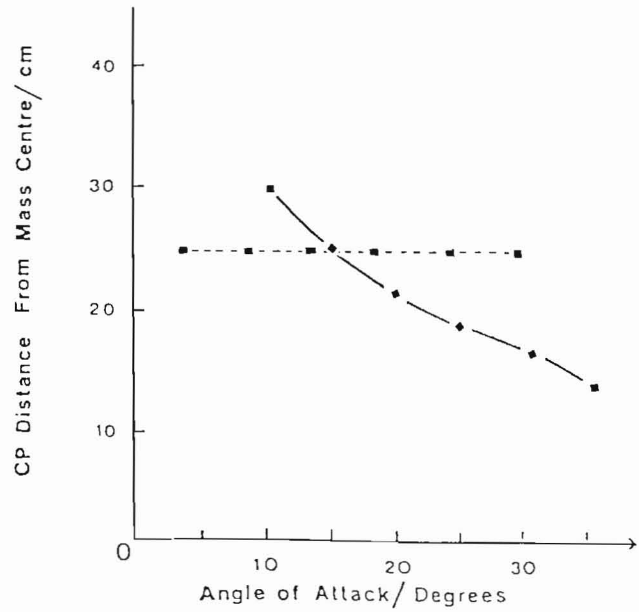

Fig. 4 CP distance (d) versus Angle of Attack (b)
—— Authors' Data
------ (9)

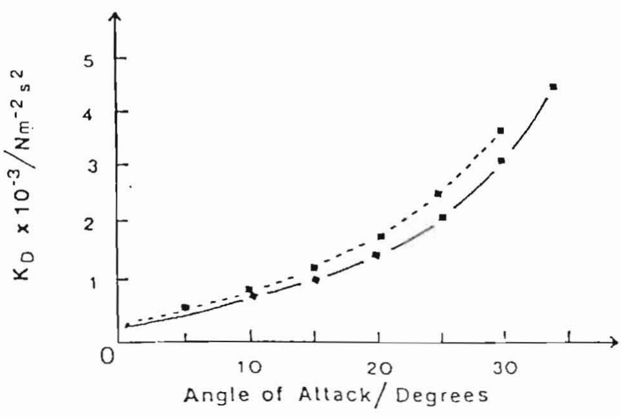

Fig. 5 K_D versus Angle of Attack (b)
—— Authors' Data
------ (9)

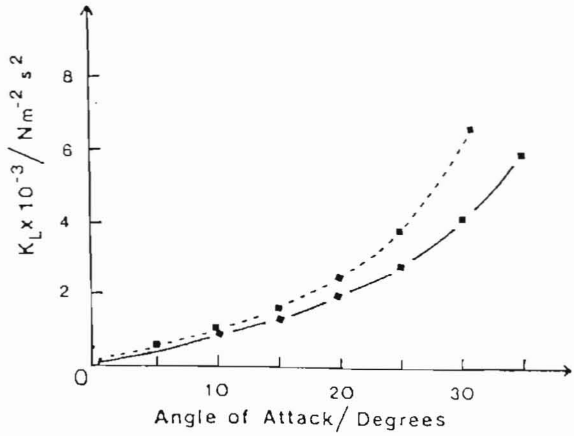

Fig. 6 K_L versus Angle of Attack (b)
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------ (9)

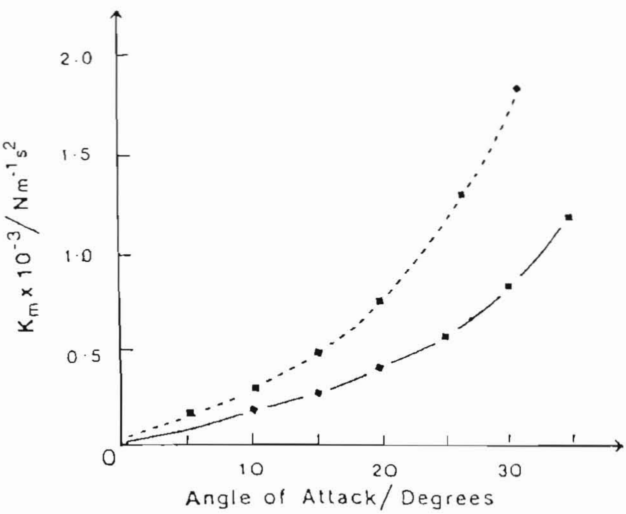

Fig. 7 K_m versus Angle of Attack (b)
—— Authors' Data
------ (9)

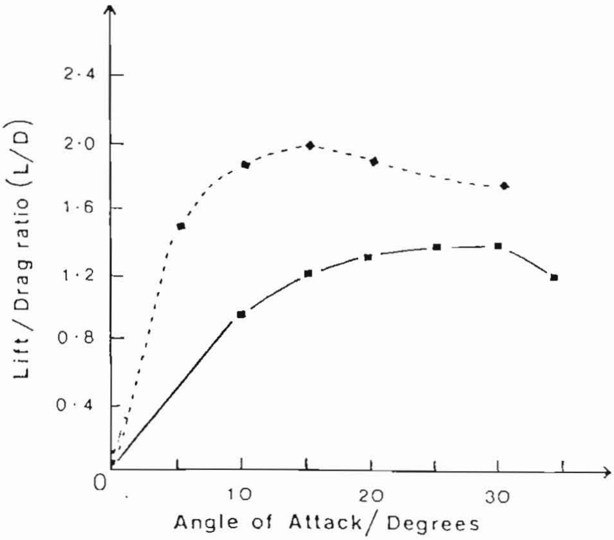

Fig. 8 Lift/Drag Ratio versus Angle of Attack (b)
—— Authors' Data
------ (9)

The overall volume of the ladies' javelin, being far below that of the men's javelin, would suggest that D, L and M would be smaller for the ladies' javelin. This is indeed so as can be seen in figures 5, 6 and 7. Interestingly the ratio of the drag forces on the ladies' javelin to those for the men's javelin (9) is far greater than corresponding ratios of the lift and pitching moment. Hence the lift / drag (L/D) ratio values are smaller for the ladies' javelin (Figure 8). The lift / drag ratios are within the reasonable range expected from previous aerodynamic literature concerning bodies of high fineness ratio (14). The low L/D ratio (Figure 8) for the ladies' compared with the men's javelins (9) should mean that the distances thrown in the ladies' event will be considerably less than the ballistic ranges. The men's new rules javelins travel approximately 3% less than their ballistic range with more effective L/D ratios. Essentially, the drag / mass ratio is much higher for ladies' javelins and will thus reduce the implement's speed more than for men's javelins. Figure 6 shows that the ladies' javelin begins to stall at b = 35°, consistent with earlier results found for this shape of body (3).

The aerodynamic data are now in a form to be entered into a computer flight simulation program (Figure 3). The first, and most surprising result from this program predicts that the ladies' javelin would travel approximately, but consistently, 20% short of its ballistic range under normal throwing conditions. This compares with the men's new rules javelin which is predicted to travel 2-3% short of its ballistic range (10). The reduced 'aerodynamic effectiveness' of the ladies' javelin can be explained almost entirely by the relatively large drag forces discussed above.

Release Height (zo) and Release speed (vo)

The program shows that both dR/dzo and dR/dvo are always positive when keeping other variables constant (7, 8, 10, 11, 12). For example, a 1m increase in release height under global optimum conditions (discussed later) increases range by 1.17 m for the ladies' javelin, i.e. dR/dzo = 1.17, the same value found previously for men's new rules javelins (10). However, any attempt to increase zo above a thrower's 'norm' will have negative effects on other parameters, notably vo, and hence will have a negative net effect on range (7, 10, 12). Under optimal release conditions (discussed later) increasing vo by 1 m/s increases range by 4.72 m, i.e. dR/dvo = 4.72 s. This result was obtained with the same nominal release speed (v_n = 30.48 m/s, discussed later) used for men's javelins, where dR/dvo = 5.64 s (10). Although dR/dvo for ladies' javelins is considerably smaller than for men's javelins, owing to the relatively larger drag/mass ratios associated with ladies' javelins, release speed is still by far the most important determinant of range. As with the men's javelin, the athlete with the greatest potential to develop release speed will have a considerable advantage over other throwers.

Release speed can be considered as the sum of two contributions (12). Firstly, the speed of the implement developed by the athlete during a maximum controllable run-up and, secondly, the additional speed imparted by the athlete during delivery. Since both the former speed and the sum, vo, have been shown to have rank order correlations with range (e.g. 2, 15) the technique contributing to achieving these is important and has been discussed elsewhere (12).

Since zo can be discarded as an unimportant variable in terms of range, a value of 2 m was used throughout the study since it is a 'top of range' value for ladies and will enable the authors to afford a useful comparison with the men's event. Similarly, the authors have utilized the data of (5) for variation of release speed with angle. This has been used in previous men's javelin simulation studies (7, 8, 10):

$$vo = 30.48 - [0.127\ (ao-35)]$$
with speeds in ms^{-1} and angles in degrees

No accurate values are available for the release speed of the very best female throwers (see 12). Therefore, the relevance of this relationship cannot be properly assessed, although considering the difference in mass, male / female differences, the data of Kunz (16) showing the effect of implement mass and release speed, and the data of Komi and Mero (17) showing no significant differences between run-up speeds of male and female throwers, there seems no reason why the above relationship should not apply to top female throwers.

Release angle (ao), pitch (wo) and angle of attack (bo)

Throwing the ladies javelin directly through the long axis (i.e. wo = 0) allows a maximum possible range of 74.07 m at ao = 36.2°. Allowing ao and bo to vary but keeping wo = 0 increases maximum range by 8 cm to 74.15 m at new suboptimal ao = 36.2° (no change) and bo = −2.8°. Allowing ao and wo to vary but keeping bo = 0 increases range to 74.73 m at ao = 37.1° and wo = −17.4°/s. Finally, the global optimum solution (where dR/dao = dR/dbo = dR/dwo = 0 and any deviation causes a reduction in range) produces a range of 74.75 m at ao = 37.2°, bo = 0.7° and wo = −17.2°/s. This is 16 m less than the global optimum range for the men's javelin at a 0.7° greater release angle (10). Interestingly, the optimum angle of attack is +7° for the ladies' javelin compared with −2.8° for the men's javelin (10). The optimum wo = −18.2°/s found here compares with −8.3° for the men's javelin (10). Both of these values may be considerable overestimates of the true optima owing to the vibration effects that may be incurred at such a release pitch (7, 10, 11, 12). The suboptimal data presented earlier and movements away from the optimum conditions suggest that, for the ladies' javelin, wo is the most important parameter discussed in this section. This contrasts with the conclusions for menn's new rules javelins (10) but confirms results for men's old rules javelins (7). It must be stressed that ao, bo and wo all have optimal values and thus would be expected to exhibit some form of inverted-U relationship with range and vo (10, 12). The simple rank order correlations that often appear in the literature for these variables are therefore, not surprisingly, non-significant.

Other considerations

There is a great scope for manufacturers to attempt to reduce the relatively large aerodynamic drag forces acting on ladies' javelins. There appears to have been little research into the aerodynamics of these implements which is evident simply by the shape of all of the ladies' javelins on the market showing no attempt at optimising the plan area distributions of these javelins. Furthermore, the transverse moment of inertia (I_G) has been shown for men's javelins (10) to cause significant differences in range, yet only one manufacturer appears to be making use of this fact. The differences between the Apollo javelin used here and the Sandvik ladies' javelin causes only a 2 cm change in predicted range, but until the full range of I_G values is assessed, the potential for manufacturer manipulation will not be evident.

The effects of wind on ladies' javelins are fairly small, with a 2 m/s tailwind increasing range by only 8 cm. The simulations showed a tailwind to be optimal, although some athletes prefer headwinds. This may best be explained by personal preferences since the effects of such wind speeds on range are so small.

Finally, the effects of other variables not considered here are likely to be greater than for the men's javelin. For example, the smaller aerodynamic forces and transverse moment of inertia of ladies' javelins is likely to affect the degree of gyroscopic stability (12, 18). Although these facts have not been investigated, simple observation of flight reveals their importance clearly, especially when the angle of attack is close to zero and the aerodynamic forces, therefore, are at their lowest. These factors can also explain the higher than expected landing attitude angles attained in this simulation study at around 30°-40° since this gyroscopic stability might be expected to reduce the total change in pitch during flight. It was not possible under reasonable throwing conditions to simulate flat landings. There is obviously a strong need to look into such unexplored and complex areas, as the effects of javelin spin, in future research.

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