Journal of Sports Sciences 23, 775-780, 2005

Why do high jumpers use a curved approach?

John C.C. Tan[1] and Maurice R. Yeadon[2]

[1]Physical Education and Sports Science, National Institute of Education, Nanyang Technological University, Singapore S637616
[2]School of Sport and Exercise Sciences, Loughborough University, Loughborough LE11 3TU, UK

Abstract

Currently all elite high jumpers use the Fosbury Flop technique with a curved approach. This suggests that the curved approach presents some clear advantage although there is no general agreement upon the mechanism or the mechanics. This study aimed to determine the characteristics of the approach curve and to investigate how it contributes to the generation of somersault rotation. A simple theoretical model was used to demonstrate that a tightening approach curve would change the inward lean towards the centre of the curve into outwards lean. Three-dimensional video analysis was conducted on performances of two elite male high jumpers in competition. It was found that in each case the radius of the approach curve and the inward lean angle both decreased towards the end of the approach ($p < 0.01$). The amount of outward lean angular velocity generated was shown to be a major proportion of the required somersault angular velocity for a jump. It was concluded that the main advantage of a curved approach was that it resulted in the generation of somersault velocity providing the curve tightened towards the end of the approach.

Keywords: high jump, curved approach, somersault rotation, biomechanics

Introduction

In present-day high jumping the Fosbury Flop is the sole technique used by competitive high jumpers throughout the world. The high jump comprises an approach phase, a takeoff phase and a flight phase. The approach phase consists of a straight run-up followed by a curved section during the last four to five steps prior to takeoff (Figure 1). During this phase the approach speed of the jumper builds up to between 6 and 8 ms^{-1} (Dapena, 1980a). The takeoff phase comprises the last foot-ground contact during which the horizontal velocity decreases, the vertical velocity increases and somersault momentum is generated (Dapena, 1980a; Dapena, 1980b). During the flight phase the jumper rotates as the mass centre rises in order to facilitate bar clearance. However, many of the characteristics of the flight phase are determined by the takeoff phase and are dependent on the characteristics of the approach phase.

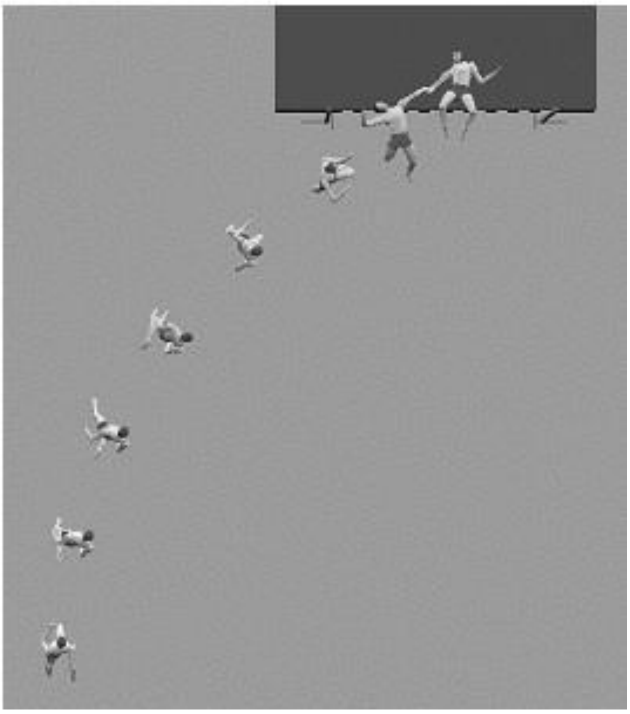

Figure 1. The curved approach in high jumping.

In the early days of the Fosbury Flop it was thought by some that the curved approach was nothing more than an idiosyncracy of Dick Fosbury (Fix, 1981). When running a curved approach the body must lean into the curve to provide the necessary centripetal force and so the takeoff will start with the body leaning inwards. Since the body will rotate towards the bar during the takeoff phase this initial orientation is advantageous since it permits the necessary rotation during takeoff without having excessive outwards lean (towards the bar) as the flight phase begins (Dapena, 1980b; Ecker, 1976). Leaning inwards at the start of takeoff and outwards at the end of takeoff means that the body will be close to the vertical throughout so that the reaction force from the ground will be more effective in producing vertical velocity (Jacoby, 1987). A curved approach has also been thought to be beneficial in lowering the mass centre prior to the takeoff phase (Heinz, 1974; Ae et al., 1986) as this allows the mass centre to move through an increased vertical distance during takeoff (Dapena, 1993; Jacoby, 1986) resulting in a greater time during which to develop a large vertical impulse (Dapena, 1987; Wagner, 1985; Jacoby, 1986).

In order to reach a horizontal orientation near the peak of the flight over the bar, the jumper needs to develop sufficient somersault angular momentum during takeoff (Dapena, 1995). This angular momentum is typically about an axis parallel to the bar (Dapena, 1980b). A number of coaches have suggested that the curved approach is useful in developing this somersaulting motion during the takeoff phase (Fix, 1981; Jacoby, 1986; Paolillo, 1989) or during the penultimate contact phase as well (Heinz, 1974). Dapena (1980b) used three-dimensional cinematography to analyse the approach, takeoff and flight phases of six Flop jumpers and found that the majority of the somersault angular momentum was generated during the takeoff phase. He thought that the data suggested that a curved approach might favour the production of somersault angular momentum during the takeoff phase but did not speculate on the mechanism.

A number of researchers and coaches have described the curved section of the high jump approach as a 'circular arc' or even as 'a quarter of a circle' (Chu and Humphrey, 1981; Martin, 1982). Dapena et al. (1997) fitted an arc of a circle to four of the last five foot locations omitting the penultimate foot placement which typically lay outside this curve. Kerssenbrook (1974) analysed Dick Fosbury's approach and noted that the curvature increased as he approached the bar.

While there is some agreement that a curved approach may aid the production of somersault rotation the mechanism whereby this is achieved and the characterisation of the approach curve are not well-established. It is the aim of this study to determine the characteristics of the approach curve and investigate how it contributes to the generation of somersault rotation.

Methods

Theoretical considerations of the mechanics of skating a curve or cornering on a bicycle suggest that a tightening curve will produce outwards lean rotation. It was therefore hypothesised that high jumpers generate somersault rotation by tightening the foot placement curve. To test this hypothesis a case study approach was used in which a number of performances by each of two elite jumpers were analysed.

Theory

A simple mathematical point mass model can be used to demonstrate how the tightening the approach curve will produce straightening-up of the inwards lean. The model comprises a point mass m at one end G of a massless rigid rod FG of length h, inclined at θ to the vertical. The foot F of the rod moves along a curve of variable radius R and the rod is free to rotate about F in a vertical plane perpendicular to the curve (Figure 2). While this model more closely resembles a cyclist cornering or an ice skater gliding around a curve, since F remains in contact with the ground continuously, it is also an approximation to running a curve where the centripetal force is intermittent and the contact points are discrete.

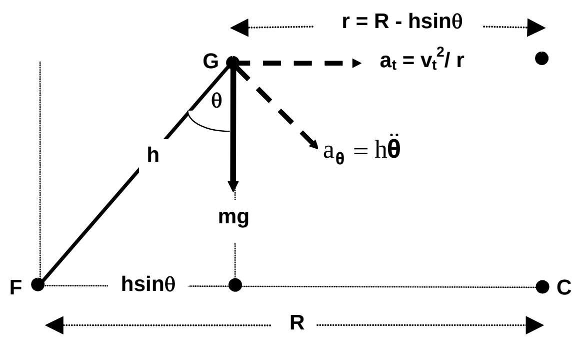

Figure 2. A point mass model of running a curve. The foot F is constrained to follow a curved path while the mass centre G is free to rotate about F. G has horizontal velocity v_t and acceleration a_t due to the motion of F and velocity $v_\theta = h\dot{\theta}$ and acceleration a_θ due to the rotation about F.

Equation of motion

The gravitational torque **T** about F is equal to the rate of change of angular momentum **L**.

$$\mathbf{T} = d\mathbf{L}/dt \quad (1)$$

The gravitational torque T = mghsin θ is in a direction tangential to the foot curve. The angular momentum **L** about F of a point mass may be calculated as the cross-product moment of momentum **h** x m**v** so that **L** has a component $mv_t h\cos\theta$ directed along the horizontal inward radius, where v_t is the horizontal velocity of the mass centre in the direction of the tangent to the foot curve, and a tangential component $mv_\theta h$ parallel to v_t where v_θ is the velocity due to rotation about F. The rate of change of these vector components gives rise to two components of the rate of change of angular momentum about F in the direction of a tangential axis through F:

$$d\mathbf{L}/dt = ma_\theta h + ma_t h\cos\theta \quad (2)$$

where $\mathbf{a}_\theta = \dot{\mathbf{v}}_\theta$ and $\mathbf{a}_t = \dot{\mathbf{v}}_t$. Equation (1) becomes:

$$mgh\sin\theta = ma_\theta h + ma_t h\cos\theta$$

Substituting $r = R - h\sin\theta$, $a_\theta = h\ddot{\theta}$ and $a_t = v_t^2/r$ and rearranging gives:

$$h\ddot{\theta} = g\sin\theta - (v_t^2 \cos\theta) / (R - h\sin\theta) \quad (3)$$

In equation (3), it can be noted that if the value of R decreases (as the curve tightens) then the term on the left side will become more negative. If the foot contacts lie on an arc of a circle initially and the lean angle θ is constant then reducing the radius R will decrease the inward lean and produce an outwards angular velocity as the rod straightens up. In the case of intermittent contact with the ground, as in the case of running a curve, the same considerations will apply so that running a tightening curve will produce an outwards lean angular velocity that will manifest itself as somersault once the jumper becomes airborne.

Data Collection

Two elite high jumpers (A and B) participated in this study. A was 1.96 m tall with a mass of 79 kg and a personal best competition performance of 2.32m while B was 1.86 m tall with a mass of 73 kg and a personal best competition performance of 2.37m. Informed consent was obtained from the participants in accordance with procedures approved by the Ethical Advisory Board of Loughborough University.

A total of 17 jumps were video-recorded in two competitions: seven jumps from jumper A and ten from jumper B. Prior to competition, anthropometric measurements were taken on the athletes in order to calculate segmental inertial parameters using the mathematical inertial model of Yeadon (1990).

Two Panasonic MS2 sVHS video cameras were positioned beyond the perimeter of the track, approximately 45 metres from the centre of the bar and with optical axes of the cameras intersecting at approximately 45° as shown in Figure 3. The recordings of the jumps were carried out at 50 fields per second with a shutter speed of 1/250 s.

The athletes were consulted prior to competition so that the locations of their foot placements in their approach runs were obtained. A volume measuring 12 m long x 3 m wide x 2.3 m high, which included the last five steps of the approach run, was spanned using markers on 10 vertical poles and the two high jump uprights. The calibration markers were video-recorded to effect camera calibration using the Direct Linear Transformation (DLT) method of Karara (1980).

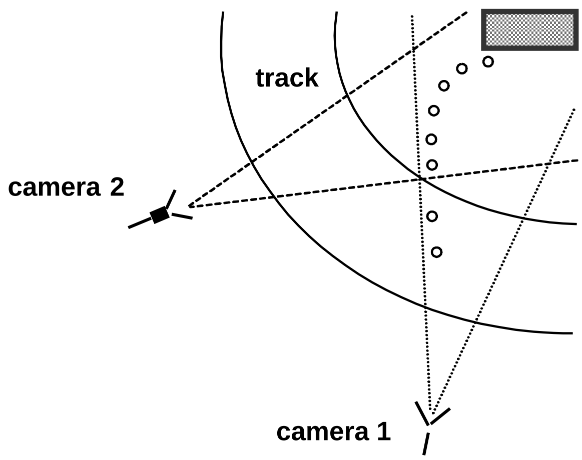

Figure 3. Camera positions relative to approach run of jumper A.

In the video recordings of the jumps 15 body landmarks (wrist, elbow, shoulder, hip, knee, ankle and toe on both sides of the body plus the centre of the head) were digitised manually for the last five steps of the approach and the flight over the bar. Interpolating quintic splines were fitted to the digitised coordinate data in order to obtain coordinate values at times between the fields (Wood and Jennings, 1979). A DLT reconstruction (Karara, 1980) was then carried out to synchronise the digitised data (Yeadon and King, 1999) and obtain 3D coordinate time histories of each digitised body landmark.

The location of the whole body mass centre was calculated from the 3D coordinates of the body landmarks and the segmental masses and the relative mass centre locations. The backward lean angle ϕ was calculated as the angle between the vertical and the projection of the line joining the mid-foot F (the mid-point of the ankle and the toe) and the body mass centre G on the vertical plane through the horizontal approach velocity (Figure 4).

The inward lean angle θ of the body was calculated as the angle between the vertical and the projection of FG on the vertical plane perpendicular to the horizontal approach velocity (Figure 4). The inward lean angle was evaluated for each foot contact at the time for which the backward lean angle was zero (mid-stance) so that the mass centre was “alongside” the foot.

The mid-foot locations at these times were used to calculate the radii of circles through a given foot location and the previous two. This gave radii for the last four foot contacts since there were video data for the last six foot contacts. The changes in the inward lean angles and the radii of the curves were investigated using analysis of variance with repeated measures. If the changes were significant, post hoc Tukey tests were used to analyse the differences.

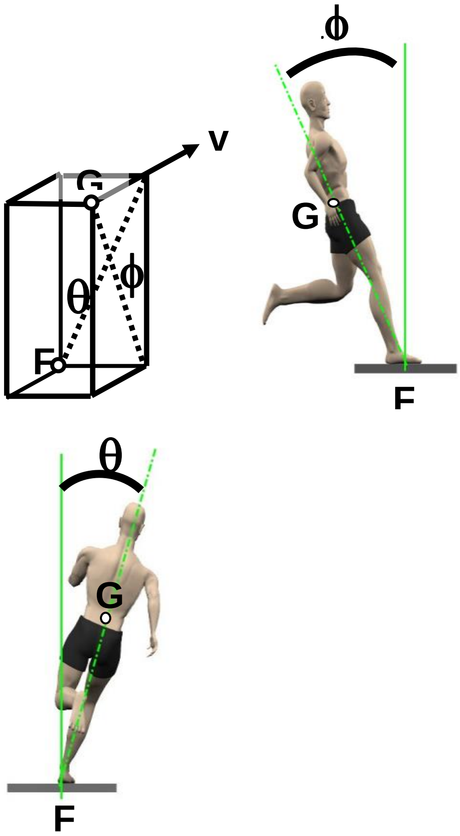

Figure 4. Backward lean angle ϕ and inward lean angle θ are the angles made with the vertical by projections of the foot – mass centre line FG on vertical planes parallel and perpendicular to the horizontal velocity v.

Results

In Figure 5 the mean locations of the foot placement and mass centre when jumper A was in mid-stance are shown in a plan view of the curved approach. From this view the curve described by the foot placements is seen to have 'tightened' to meet the mass centre curve at the end of the approach (C0). Figures 6 and 7 show that the corresponding radius of the mean foot placement curve decreased from about 12 m to 7 m for each jumper. The changes in radius of the foot placement curves were found to be significant ($p < 0.01$) for both the jumpers. For jumper A, the radius of the foot placement curve at C0 (last foot contact) was found to be smaller ($p < 0.01$) than the other radii at C1, C2 and C3. For jumper B, the radius at C2 of the foot placement curve was larger ($p < 0.01$) than the other radii at C3, C1 and C0. The radii of the foot placement curves at the different foot contacts indicate that jumper A tightened the foot placement curve at C0 while jumper B tightened the curve at C1.

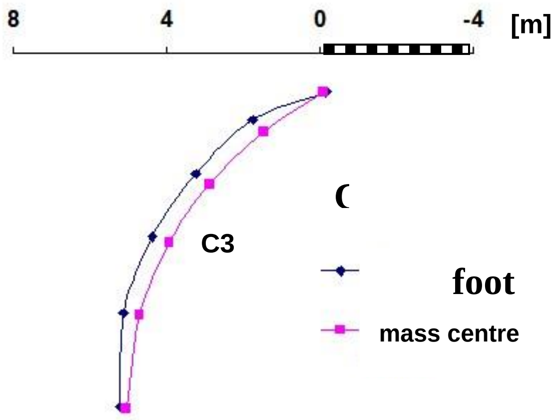

Figure 5. Mean foot and mass centre paths for jumper A.

The inward lean angles at the last four foot contacts of the approach are presented in Figures 6 and 7. For jumper A the inward lean angle at C0 (the last foot contact) was found to be smaller ($p < 0.01$) than the inward lean angles at C1, C2 and C3. Thus the inward lean angle decreased at the final foot contact C0. The mean inward lean at C1 was less than 1^o greater than that at C2 and this difference was not significant ($p > 0.1$).

For jumper B the inward lean angle at C0 was again smaller ($p < 0.01$) than the inward lean angles at C1, C2 and C3. The mean inward lean increased by 2^o from C3 to C2 ($P < 0.05$). The mean inward lean at C1 was less than 1^o smaller than that at C2 and this difference was not significant ($p > 0.1$).

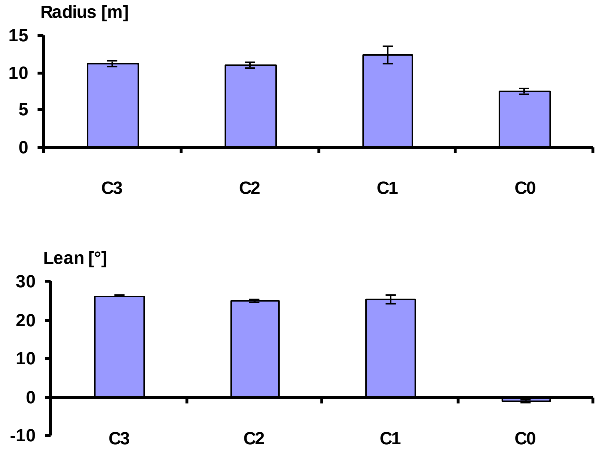

Figure 6. Radii of circles through the last four foot locations and inward lean angles for jumper A. C0 is the final foot contact.

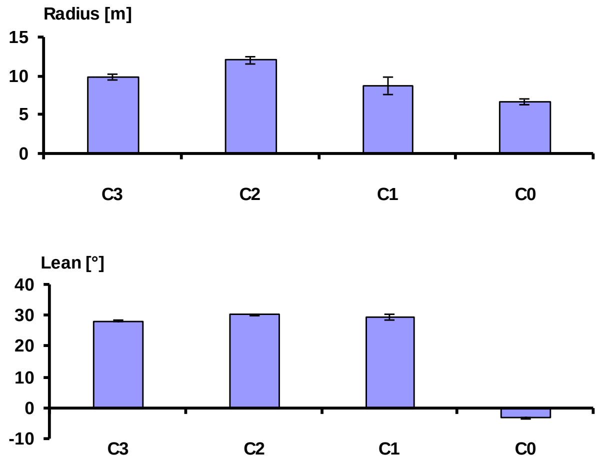

Figure 7. Radii of circles through the last four foot locations and inward lean angles for jumper B. C0 is the final foot contact.

Discussion

The results of the video analysis indicated that the foot curve tightened towards the end of the approach for each jumper. For jumper A the curve tightened at the last foot contact while for jumper B the curve tightened over the last two foot contacts. This is consistent with the analysis by Kerssenbrook (1974) of Dick Fosbury's high jump approach. Dapena (1997) fitted circles to four of the last five foot contacts (omitting the penultimate contact) for the approaches of 15 jumpers in the finals of the 1991 World Championships. In 13 cases the penultimate foot contact lay outside the fitted circle and this is indicative of a tightening curve. It would appear, therefore, that the approach of an elite high jumper is characterised by a foot contact curve that tightens towards the end of the approach.

The theoretical analysis of running a curved approach indicated that tightening a curve of constant radius with a fixed lean angle leads to an outwards lean angular velocity and a decrease in the inward lean angle. This may be understood by considering the example of a cyclist cornering. Suppose that the cyclist has a constant speed, constant lean and constant radius while cornering. For a given velocity and lean angle, equation (3) gives a value for the radius that maintains a steady state. For a larger radius than this value the inward lean will accelerate and increase while for a smaller radius the inward lean will decrease. Thus a tightening curve will inevitably lead to an increasing outward lean velocity. So towards the end of the cornering the cyclist turns the handlebars more into the curve and the bicycle straightens up (Figure 8) so that as it reaches the vertical the handlebars are turned straight and the bicycle proceeds in a straight line. In a running approach the contact with the ground is intermittent and the mass centre moves on a sequence of curves during foot contact interspersed with straight lines during flight when viewed from above (Dapena, 1980a). Nevertheless the same mechanics apply giving the same steady state lean angle for given foot placement radius and mass centre velocity (equation (3)). As a consequence the inward lean angle will decrease if the curve tightens towards the end of the approach.

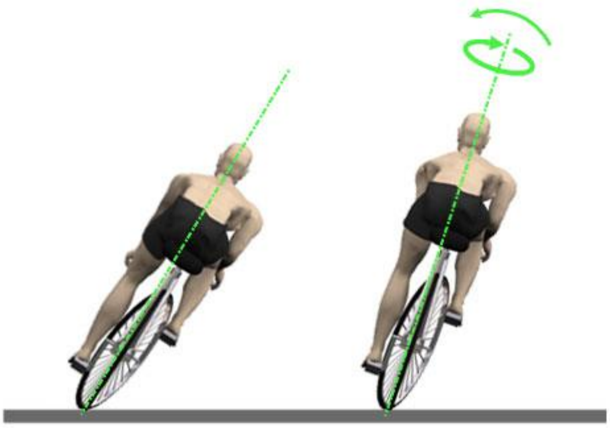

Figure 8. When the front wheel turns more into the curve, the cyclist will straighten-up.

The video analysis confirmed that the inward lean angle decreased towards the end of the approach. This occurred primarily during the final foot contact for both jumpers. The inward lean angle decreased from around 30^o in the penultimate foot contact to around 0^o in the final foot contact (Figures 6 and 7). This change occurred over a time interval of close to 0.3 s and so the mean outward lean angular velocity was approximately $100^o s^{-1}$. Even if the change started during the penultimate foot contact the angular velocity at takeoff would still have to be around twice the mean value, that is about $200^o s^{-1}$. Since the high jumper rotates through approximately half a somersault during the flight phase, which lasts for about 0.8 s, the mean somersault velocity during flight will be around $220^o s^{-1}$. These calculations indicate that the outwards angular velocity generated by tightening the curve accounts for a major part of the total somersault angular velocity.

For jumper A the mean lean angle did not change significantly from C3 to C2 to C1 so that the lean angle was essentially constant (Figure 6) with close to zero angular velocity. For the same three contacts there were no significant differences between the radii of the foot curves so that the radius was essentially constant (Figure 6). At C0 the radius decreased ($p < 0.01$) and the lean angle also decreased ($p < 0.01$) as predicted by the theoretical model.

For jumper B the radius at C2 of the foot placements was larger ($p < 0.01$) than the radii at C3, C1 and C0 so that the radius started to decrease at C1 (Figure 7). This might be expected to lead to a decrease in the lean angle from C2 to C1. The lean angle, however, increased by 2^o ($p < 0.05$) from C3 to C2 (Figure 7) so that there would have been a lean angular velocity at C2 tending to increase the lean angle since the radius increased at C2. As a consequence the outward acceleration induced by the reduction in radius from C2 to C1 reduced the the inward lean velocity but did not reduce the lean angle significantly (0.7^o, $p > 0.1$). The subsequent further decrease in the radius at C0 ($p < 0.01$) accentuated the large decrease in lean from C1 to C0.

Thus the data obtained from the two jumpers, although showing individual characteristics, are consistent with the hypothesis that a tightening of the approach curve leads to an outwards lean rotational velocity. In order to apply the theoretical model quantitatively to an analysis of running a curve, further development is needed in which the intermittent nature of ground contact is included. Using such a simulation model it should be possible to compare model output with actual performance and to assess more accurately how much of the somersault rotation can be accounted for by this mechanism.

The tightening of the curve may also be expected to contribute to the development of vertical velocity since the lean is inwards at the start of the final foot contact and the mass centre will rise even though the knee is flexing (Dapena and Chung, 1988). In addition starting the final foot contact with a lean away from the bar will also be beneficial to the jump but the main advantage of the curved approach is that it provides the somersault angular velocity.

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