Optimum takeoff angle in the standing long jump

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ABSTRACT: The aims of this study were to identify the optimum takeoff angle in the standing long jump and to understand the underlying biomechanics that produce the optimum angle. Five subjects performed maximal-effort standing long jumps using a wide range of takeoff angles, and the takeoff, flight, and landing variables were measured from a video analysis of the jumps. A simple model of force generation in the takeoff phase was able to explain the observed decrease in takeoff speed with increasing takeoff angle, and the takeoff and landing configurations of the jumper were explained by geometrical models. The decrease in takeoff speed with increasing takeoff angle substantially reduced the optimum takeoff angle below the 45° expected for a projectile activity. Although the calculated optimum takeoff angles (about 23°) were slightly lower than the athlete’s preferred takeoff angles (about 35°), a jumper may achieve a near-maximal jump distance by using a takeoff angle anywhere in the range from 15° to 35°.

INTRODUCTION

In a standing long jump the athlete aims to project the body for maximum horizontal distance beyond a takeoff line. The jumper starts from a static standing position, then generates a large takeoff speed by using a countermovement coupled with an arm swing and a double leg takeoff. The standing long jump is often used as a functional test to assess an athlete’s leg power, but the test may underestimate the athlete’s true potential if she does not use the best possible jumping technique. In ‘projectile’ events such as the standing long jump, one of the most important technique variables is the projection angle. The purpose of the present study was to examine the effects of changes in projection (takeoff) angle on performance in the standing long jump, and to identify and explain the optimum takeoff angle.

Performance in the standing long jump is evaluated by the total jump distance, \( d_{\text{jump}} \), which is the horizontal distance from the takeoff line to the mark made by the heels at landing. The total jump distance is the sum of three component distances (Figure 1):

\[
d_{\text{jump}} = d_{\text{takeoff}} + d_{\text{flight}} + d_{\text{landing}}
\]  

(1)
where $d_{\text{takeoff}}$ is the takeoff distance, $d_{\text{flight}}$ is the flight distance, and $d_{\text{landing}}$ is the landing distance (Hay and Reid, 1988). The longest component distance is usually the flight distance, and the jumper may be considered as a projectile in free flight because air resistance has little effect on the trajectory of the jumper. The horizontal range (flight distance) of a jumper in free flight is given by

$$d_{\text{flight}} = \frac{v^2 \sin 2\theta}{2g} \left[ 1 + \left( 1 + \frac{2gh}{v^2 \sin^2 \theta} \right)^{1/2} \right]$$  \hspace{1cm} (2)$$

where $v$ is the takeoff speed, and $\theta$ is the takeoff angle. The relative takeoff height, $h$, is given by

$$h = h_{\text{takeoff}} - h_{\text{landing}}$$  \hspace{1cm} (3)$$

where $h_{\text{takeoff}}$ is the takeoff height and $h_{\text{landing}}$ is the landing height. In most jumps the athlete’s centre of mass is slightly lower at landing than at takeoff (Figure 1).

The jumper’s optimum takeoff angle may be obtained by using equation 2 to calculate the angle at which the flight distance is greatest. It is well known that when takeoff speed is held constant the optimum takeoff angle is just under 45°. However, in projectile-related sports activities the athlete is not expected to be able to achieve the same speed at all projection angles (Hay, 1973). That is, $v$ is not expected to be a constant. To calculate the optimum projection angle the athlete’s expression for $v(\theta)$ must be measured and substituted in equation 2 (Linthorne, 2001).

In studies of shot-putters and javelin throwers, the maximum projection speed the athletes could achieve decreased with increasing projection angle (Red and Zogaib,
The relative projection height also varied with projection angle, but this had a small effect on the optimum projection angle. Optimum projection angles in the shot put ranged from 28 to 38º, mainly because of individual differences in \( v(\theta) \) due to differences in strength and throwing technique.

The optimum takeoff angle in the standing long jump is also expected to be well below 45º. However, the standing long jump is slightly different from the shot put and javelin throw in that the takeoff distance and landing distance make a relatively large contribution to the total jump distance (Figure 1). The optimum takeoff angle may therefore be influenced by the relation between takeoff distance and takeoff angle, \( d_{\text{takeoff}}(\theta) \), and between landing distance and takeoff angle, \( d_{\text{landing}}(\theta) \). Also, typical projection speeds in the standing long jump are much lower than in the shot put and javelin throw. The relation between height difference and takeoff angle, \( h(\theta) \), may therefore play a more important role in determining the optimum takeoff angle.

METHODS

Five physically active males (age 24 ± 3 years; height 177 ± 8 cm; weight 79 ± 5 kg) volunteered to participate in the study. Each subject performed five maximal-effort standing long jumps at his preferred takeoff angle, and then twenty-five maximal-effort jumps at five other takeoff angles. All jumps were recorded at 50 Hz using two video cameras placed perpendicular to the jump direction and about 10 m away from the takeoff line and landing pit. An Ariel Performance Analysis System was used to determine the takeoff speed, takeoff angle, takeoff height, landing height, takeoff distance, landing distance, and flight distance for each jump. The optimum takeoff angle for each subject was calculated by substituting the expressions for \( v(\theta) \) and \( h(\theta) \) into equation 2, and the calculated optimum projection angle was compared to the subject’s preferred takeoff angle.

RESULTS

For all five subjects, the takeoff speed decreased with increasing takeoff angle (Figure 2). This decrease was explained by a simple physical model of the takeoff phase of the jump. The jumper was assumed to exert a constant muscular force over a straight-line range of leg extension (pushoff). The force and range were also assumed to be the same for all takeoff angles. During the pushoff, the force generated by the jumper must overcome both the weight of the jumper’s body and the inertia of the jumper’s body. As the takeoff angle is raised, the jumper spends a greater fraction of their muscular force in overcoming the weight of the body, and so less force is available to accelerate the body. The takeoff speed at high takeoff angles is therefore not as great as at low takeoff angles, and the relation between takeoff speed and takeoff angle is given by (Linthorne, 2001)

\[
v(\theta) = \sqrt{\frac{2Fl}{m} - 2gl \sin \theta + v_r^2}
\]  

(4)
where $F$ is the average muscular force exerted by jumper, $l$ is the pushoff range (the acceleration path length of the jumper’s centre of mass during the leg extension phase), $m$ is the mass of the jumper’s body, $g$ is the acceleration due to gravity, and $v_i$ is the speed of the jumper’s centre of mass at the start of the pushoff phase.

![Figure 2](image-url) Takeoff speed as a function of takeoff angle (Subject 1).

**Table 1** Values of force and pushoff range obtained from fitting equation 4 to plots of takeoff speed as a function of takeoff angle. (value ± standard error)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Force (N)</th>
<th>Pushoff range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1754 ± 63</td>
<td>0.32 ± 0.02</td>
</tr>
<tr>
<td>2</td>
<td>1709 ± 115</td>
<td>0.34 ± 0.03</td>
</tr>
<tr>
<td>3</td>
<td>1750 ± 207</td>
<td>0.34 ± 0.06</td>
</tr>
<tr>
<td>4</td>
<td>1979 ± 182</td>
<td>0.29 ± 0.04</td>
</tr>
<tr>
<td>5</td>
<td>2427 ± 327</td>
<td>0.21 ± 0.04</td>
</tr>
</tbody>
</table>

Fitting a curve of the form of equation 4 to the takeoff speed versus takeoff angle plots gave realistic values for the force and pushoff range (Table 1). The pushoff ranges obtained from the model were in good agreement with values measured directly from the video data, and the average forces exerted by the jumpers were consistent with values measured from force platform studies (Ridderikhoff *et al.*, 1999).
Figure 3 The takeoff height ($h_{\text{takeoff}}$), landing height ($h_{\text{landing}}$), and height difference between takeoff and landing ($h_{\text{difference}}$) as a function of takeoff angle (Subject 1).

Figure 4 Total jump distance and the three component distances as a function of takeoff angle (Subject 1). The optimum takeoff angle is about 23°.

The takeoff height and takeoff distance data (Figures 3 and 4) were explained by a simple geometrical model of the athlete at takeoff. All the athletes had approximately the same body configuration at takeoff, and so the takeoff height and takeoff distance were determined mainly by the athlete’s size and angle of forward lean (Figure 1).
The angle of forward lean was not exactly the same as the takeoff angle, but there was a consistent linear relation between the two angles.

The landing height and landing distance (Figures 3 and 4) were determined by the requirement that the jumper must maintain balance during the landing. When jumping at low takeoff angles the athlete has a high horizontal speed at landing, and so he may thrust his feet far ahead of his body at landing to gain extra distance, without the risk of falling backward after landing (Figure 1). When jumping with a high takeoff angle, the athlete has a lower horizontal speed at landing, and so cannot safely thrust the feet very far ahead of the body.

**OPTIMUM TAKEOFF ANGLE**

The optimum takeoff angle for each jumper was calculated by substituting the athlete’s expressions for $v(\theta)$ and $h(\theta)$ into equation 2. The takeoff angle that maximised the flight distance was about 33° (Figure 4). Both $v(\theta)$ and $h(\theta)$ were influential in reducing the optimum takeoff angle to below 45°. In the standing long jump the calculation of the optimum takeoff angle must also include the effects of the takeoff and landing distances. Both distances decreased with increasing takeoff angle and so further reduced the calculated optimum takeoff angle to about 23° (Figure 4).

**DISCUSSION**

For all five subjects in this study, the jumper’s preferred takeoff angle was slightly higher than the calculated optimum takeoff angle (Table 2). However, the jumpers did not suffer any significant reduction in performance through using a sub-optimal takeoff angle. Even if the takeoff angle was 10° higher than the optimum angle, the jumper would still achieve within 7 cm of the maximum jump distance (Figure 4).

**Table 2** Comparison of the calculated optimum takeoff angle with the subjects’ preferred takeoff angle. (value ± standard error)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Calculated optimum takeoff angle (°)</th>
<th>Preferred takeoff angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.6 ± 0.9</td>
<td>33.3 ± 1.1</td>
</tr>
<tr>
<td>2</td>
<td>21.6 ± 1.6</td>
<td>34.3 ± 2.3</td>
</tr>
<tr>
<td>3</td>
<td>27.7 ± 3.7</td>
<td>39.1 ± 2.4</td>
</tr>
<tr>
<td>4</td>
<td>22.6 ± 2.8</td>
<td>31.4 ± 2.8</td>
</tr>
<tr>
<td>5</td>
<td>21.2 ± 2.7</td>
<td>35.1 ± 1.9</td>
</tr>
</tbody>
</table>

Jumpers may subconsciously prefer to use a higher than optimal takeoff angle because jumping with a very low takeoff angle can produce catastrophic failure. At low takeoff angles the athlete has an extreme forward lean at takeoff, and so the feet
may slip, resulting in a very poor performance and possibly injury. Jumps at low takeoff angles also require the athlete to use a tight tuck of the legs when swinging the feet through for landing. If the leg tuck is insufficient, the jumper’s feet may strike the ground midway through the flight phase, again resulting in a poor performance and possibly injury.

CONCLUSION

Each of the five athletes in the study had a unique optimum takeoff angle that depended on the athlete’s strength, technique, and physique. The jump distance was insensitive to takeoff angle. Similar jump distances were produced using a takeoff angle anywhere in the range from 15° to 35°. A simple model of force generation in the takeoff phase was used to explain the decrease in takeoff speed with increasing takeoff angle, and the takeoff and landing configurations of the jumper were explained by geometrical models.

REFERENCES