Mechanical energetic processes in Long Jump and their effect on jumping performance

By Adamantios Arampatzis / Gert-Peter Brüggemann

The goal of this study was to find the optimal take-off characteristics for elite athletes with given starting conditions (initial energy). The data for this study was recorded at the 1997 Track and Field World Championships in Athens, Greece. The data was collected using three stationary video cameras (50 Hz). A total of 31 jumps performed by 12 athletes were analysed from both the men's and women's competitions.

It can be seen in both the men’s and women’s groups that athletes demonstrating different take-off parameters and different combinations of vertical and horizontal velocities attain the same jump distance. The total energy at touch down for the last approach stride determines the maximum jumping distance but most athletes fail to use this energy optimally.

The take-off parameters which are determined by the loss of the centre of mass (CM) energy during take-off and by the transformation of the approach energy to jump energy (transformation index) are very important for determining the jump distance. The transformation index shows a high correlation with both the start energy at touch down and the energy decrease during the take-off phase. The optimum energy loss at take-off for the athletes analysed was determined to be 5.5–6.0 J/kg for the women and 7.5–8.4 J/kg for the men.

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Introduction

Long jump performance is determined by the so-called "official distance". This is obtained by measuring the length of an imaginary perpendicular line from the front edge of the take-off board to the nearest mark that the athlete leaves in the sand. The flight distance was found to have the greatest influence on the jump distance (Hay et al., 1986; Lees et al., 1994). This distance is determined by the centre of mass (CM) take-off velocity, the take-off angle (the angle of projection) and the relative height of the CM from take-off to landing. The relative height of the CM depends on the CM height at the moment of both take-off and landing. The
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precise identification of the moment of landing and therefore the measuring of the exact landing height is somewhat difficult and insufficient. For further consideration and subsequent calculations, the "theoretical flight distance" will be included (CM's horizontal flight distance from take-off until the CM theoretically hits the ground. The "theoretical flight distance" \((W_{th})\) can be calculated using the following formula:

\[
W_{th} = \frac{v^2 \sin^2 \alpha}{2g} + \frac{v \cos \alpha}{g} \sqrt{\frac{b + \frac{v^2 \sin^2 \alpha}{2g}}{g}}
\]  

(1)

\(v\): CM-velocity at the end of the take-off phase (CM Take-off velocity)

\(a\): Take-off angle

\(b\): CM height at the end of the take-off phase

\(g\): acceleration of gravity

From the formula it is clear that the distance \((W_{th})\) is dependent on the height of the CM at the end of the take-off phase, and the horizontal and vertical take-off velocities. From this causal dependency various researchers over several decades (Ballreich, 1970, 1979; Hay et al., 1985; Koh and Hay, 1990; Hay and Nohara, 1990; Lees et al., 1993, 1994) have tried to identify which component (horizontal or vertical) of the take-off velocity plays a larger role in determining the jump distance. The results are often controversial and dependent on the performance level of the analysed jumpers. Koh and Hay (1990) reported that the goal of the take-off is not to minimise the loss of the horizontal CM velocity. This position was supported by the observation that a loss in horizontal velocity often leads to an increase in vertical velocity (Hay et al., 1986; Hay and Nohara, 1990; Koh and Hay 1990; Lees et al., 1993, 1994).

For both, men and women, a loss of total energy has been reported (Witters et al., 1992; Lees et al., 1993, 1994; Müller and Brüggemann, 1997). This means that during the transformation of approach energy to jump energy, a loss in total energy is to be expected. This also means that a decrease in horizontal CM velocity does not always lead to an increase in vertical CM velocity. Witters et al. (1992) found that the conversion efficiency was dependent on the horizontal CM touchdown velocity. The conversion factor varied among athletes. It is commonly believed (Ballreich and Brüggemann, 1986; Möser, 1990; Dieß and Pfeifer, 1991) and has been proven by the scientific community (Hay et al., 1985; Hay et al., 1986; Prause, 1990; Nixdorf and Brüggemann, 1990; Hay and Nohara, 1990) that the horizontal CM touchdown velocity has a positive effect on the various jump parameters. This correlation becomes smaller at higher levels of performance (Hay et al., 1985; Nixdorf and Brüggemann, 1990). All of these observations indicate that a) an optimum combination of jump parameters exists which allow for a maximum jump distance, and b) the jump distance and the optimal jump parameters are dependent on the physical capabilities of the athlete.

The goal of this study was to find the optimal take-off characteristics for elite athletes with given starting conditions (initial energy).

**Methods**

Data was recorded from 31 jumps completed by male jumpers and 31 jumps achieved by female jumpers. The jumps were performed by the 12 finalists in both the men's and women's long jump finals at the 1997 World Championships. Only legal jumps were analysed. To capture the data three stationary cameras (50 Hz) were used.

Equation 1 can be rewritten in the following form:

\[
W_{th} = \frac{E_{kin2} \sin\alpha}{g} + \frac{2 \cos\alpha}{g} \sqrt{E_{kin2}(E_{pot2} + E_{kin2} \sin^2\alpha)}
\]  

(2)

\(E_{kin2}\) = \(E_{pot2}\)

\(E_{kin2}\) CM kinetic energy at the end of the take-off phase.

\(E_{pot2}\) CM potential energy at the end of the take-off phase.

\(m\): athlete mass

This means that the distance \((W_{th})\) can be calculated as a function of the total CM en-
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gery at take-off and the take-off angle. The distance, which can be calculated using equation 2, shows a positive correlation with the official distance (r=0.70, p<0.001 for the men and r=0.71, p<0.001 for the women) and also with the effective distance* (r=0.80, p<0.001 for the men and r=0.75, p<0.001 for the women). During the take-off phase a decrease in the CM total energy always occurs. During the take-off phase a transformation of approach energy to jump energy also occurs. To quantify this transformation, an index was created which shows the relationship of the directional change of the movement during the take-off phase with regard to the energy loss at take-off. The transformation index is defined as the quotient of the take-off angle divided by the energy loss.

\[ T_{\text{index}} = \frac{\alpha}{E_{\text{decrease}}} \]  

**E_{\text{decrease}}**: decrease in the athlete's total energy during the take-off phase

The total CM energy at the end of the take-off phase can be ascertained by the following equation:

\[ E_{T2} = E_{T1} - E_{\text{decrease}} \Rightarrow \]

\[ E_{p2} + E_{k2} = E_{T2} - E_{\text{decrease}} \Rightarrow \]

\[ E_{k2} = E_{T1} - E_{\text{decrease}} - E_{p2} \Rightarrow \]

\[ E_{T1} = \frac{E_{\text{tot1}}}{m}, \quad E_{T2} = \frac{E_{\text{tot2}}}{m} \]

**E_{\text{tot1}}**: total energy at the beginning of the take-off phase (Start Energy)

**E_{\text{tot2}}**: total energy at the end of the take-off phase (End Energy)

The differences in the athlete's potential energy at the end of the take-off phase are very small and can therefore be represented for each athlete by a constant value.

From equations (2), (3) and (4) the distance (Wtfl) can be calculated as a function of the starting energy, energy loss and the transformation index.

\[ W_{\text{tfl}} = \frac{(E_{T1} - E_{\text{decrease}} - E_{p2})\sin(2T_{\text{index}}E_{\text{decrease}})}{g} \]

\[ + \frac{2\cos(2T_{\text{index}}E_{\text{decrease}})}{g} \sqrt{E_{k2}(E_{T1} - E_{\text{decrease}} - E_{p2})} \]

\[ (+E_{T1} - E_{\text{decrease}} - E_{p2})^2 \sin^2(2T_{\text{index}}E_{\text{decrease}}) \]

**Jump characteristics.**

Using a cluster analysis, groups were created on the basis of starting energy, energy loss and the transformation index. For both the men and the women, 3 relatively homogeneous groups could be identified. An independent group t-test was used to measure the differences among the groups.

**Results and Discussion.**

From the results it is clear that both the men's and women's groups can be divided into two primary jumping styles which demonstrate the same starting characteristics and achieve the same effective jump distance and official jump distance. Groups 1 and 2 from the men and groups 1 and 3 from the women produced the same starting energy (tables 1 and 2). During the take off, the energy loss for group 1 from the men and group 3 from the women was more than for the other groups (tables 1 and 2). The importance of this observation is that both groups showed less energy and a larger take-off angle at the end of the take off phase in comparison to groups 2 (men) and 1 (women, tables 1 and 2). The relationship between the horizontal and vertical velocities in groups 1 (men) and 3 (women) also varied. Group 3 from the men had the farthest jump distance and group 2 from the women had the shortest jump distance (tables 1 and 2). Group 3 (men) had the largest energy loss and the lowest transformation index (table 2).

With group 3 producing the highest starting energy as well as the highest energy loss, the athletes were able to achieve a higher end energy than group 1 and a higher take-off angle than group 2 (table 2). Group 3 al-
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Table 1: Energy, transformation index, distances, take-off angles, horizontal and vertical CM velocities during the take-off phase for the women's groups

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(n=9)</td>
<td>(n=11)</td>
<td>(n=11)</td>
</tr>
<tr>
<td>Beginning energy (Joule/kg)</td>
<td>55.73 (1.01)</td>
<td>52.38 (1.13)*</td>
<td>55.90 (1.08)*</td>
</tr>
<tr>
<td>Energy decrease (Joule/kg)</td>
<td>5.40 (1.04)</td>
<td>5.21 (0.92)</td>
<td>7.83 (0.71)*</td>
</tr>
<tr>
<td>Transformation index (Grad/Joule/kg)</td>
<td>3.61 (0.69)</td>
<td>4.21 (0.72)</td>
<td>2.70 (0.32)*</td>
</tr>
<tr>
<td>Endenergy (Joule/kg)</td>
<td>50.32 (1.70)</td>
<td>47.17 (1.31)*</td>
<td>48.07 (1.10)*</td>
</tr>
<tr>
<td>Take-off angle (Grad)</td>
<td>18.96 (1.54)</td>
<td>21.41 (1.73)*</td>
<td>20.97 (1.66)*</td>
</tr>
<tr>
<td>Effective distance (m)</td>
<td>7.01 (0.17)</td>
<td>6.76 (0.15)*</td>
<td>6.98 (0.26)*</td>
</tr>
<tr>
<td>Official distance (m)</td>
<td>6.82 (0.13)</td>
<td>6.60 (0.12)*</td>
<td>6.73 (0.17)*</td>
</tr>
<tr>
<td>Horizontal touch down velocity</td>
<td>9.62 (0.09)</td>
<td>9.53 (0.11)*</td>
<td>9.65 (0.14)*</td>
</tr>
<tr>
<td>Horizontal take-off velocity</td>
<td>8.29 (0.23)</td>
<td>7.83 (0.24)*</td>
<td>7.97 (0.21)*</td>
</tr>
<tr>
<td>Vertical take-off velocity</td>
<td>2.84 (0.18)</td>
<td>3.05 (0.19)*</td>
<td>3.07 (0.23)*</td>
</tr>
</tbody>
</table>

* Statistically significant difference between groups 1 and 2, and between groups 1 and 3 (p<0.05)
1 Statistically significant difference between groups 2 and 3 (p<0.05)

so had the highest horizontal touch down velocity and the highest vertical take off velocity (table 2). Group 2 of the women demonstrated similar attributes during the take off phase (similar energy loss and transformation index). Due to the fact that group 2 produced the lowest starting energy, the athletes also showed a lower end energy than their counterparts in group 1 (table 1).

It is clear at this level of competition that the starting energy, which is determined by the horizontal velocity at touch down, plays an important role in jump performance. It cannot be concluded that the start energy alone determines the official jump distance. There is a significant (p<0.05) correlation be-

Table 2: Energy, transformation index, distances and take-off angles, horizontal and vertical CM velocities during the take-off phase for the men's groups

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(n=12)</td>
<td>(n=6)</td>
<td>(n=13)</td>
</tr>
<tr>
<td>Beginning energy (Joule/kg)</td>
<td>64.19 (1.43)</td>
<td>64.33 (1.16)</td>
<td>67.78 (1.13)*</td>
</tr>
<tr>
<td>Energy decrease (Joule/kg)</td>
<td>9.12 (0.72)</td>
<td>7.03 (0.52)*</td>
<td>11.02 (1.12)*</td>
</tr>
<tr>
<td>Transformation index (Grad/Joule/kg)</td>
<td>2.20 (0.24)</td>
<td>2.69 (0.18)*</td>
<td>1.91 (0.17)*</td>
</tr>
<tr>
<td>End energy (Joule/kg)</td>
<td>55.07 (1.51)</td>
<td>57.30 (1.11)*</td>
<td>56.76 (1.56)*</td>
</tr>
<tr>
<td>Take-off angle (Grad)</td>
<td>19.98 (1.50)</td>
<td>18.85 (0.24)*</td>
<td>20.78 (1.49)*</td>
</tr>
<tr>
<td>Effective distance (m)</td>
<td>8.10 (0.18)</td>
<td>8.17 (0.04)</td>
<td>8.37 (0.18)*</td>
</tr>
<tr>
<td>Official distance (m)</td>
<td>7.94 (0.17)</td>
<td>7.95 (0.09)</td>
<td>8.08 (0.22)*</td>
</tr>
<tr>
<td>Horizontal touch down velocity</td>
<td>10.51 (0.14)</td>
<td>10.49 (0.10)</td>
<td>10.81 (0.10)*</td>
</tr>
<tr>
<td>Horizontal take-off velocity</td>
<td>8.75 (0.23)</td>
<td>9.01 (0.13)*</td>
<td>8.84 (0.20)</td>
</tr>
<tr>
<td>Vertical take-off velocity</td>
<td>3.18 (0.19)</td>
<td>3.08 (0.05)</td>
<td>3.35 (0.21)*</td>
</tr>
</tbody>
</table>

* Statistically significant difference between groups 1 and 2, and between groups 1 and 3 (p<0.05)
1 Statistically significant difference between groups 2 and 3 (p<0.05)
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Table 3 Measured and optimal values of the effective jump distance, the energy decrease and the take-off angles

<table>
<thead>
<tr>
<th></th>
<th>Eff. Distance (m)</th>
<th>Energy Decrease (J/kg)</th>
<th>a (Grad)</th>
<th>Opt. Distance (m)</th>
<th>Opt. Energy Decrease (J/kg)</th>
<th>Opt. a (Grad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drechsler</td>
<td>7.13</td>
<td>4.38</td>
<td>16.9</td>
<td>7.22</td>
<td>5.30 - 5.80</td>
<td>18.60 - 19.00</td>
</tr>
<tr>
<td>Tiedtke</td>
<td>6.98</td>
<td>6.71</td>
<td>21.4</td>
<td>7.06</td>
<td>5.40 - 5.90</td>
<td>20.88 - 21.47</td>
</tr>
<tr>
<td>Jaklofsky</td>
<td>6.64</td>
<td>8.47</td>
<td>20.2</td>
<td>7.13</td>
<td>5.50 - 5.70</td>
<td>20.14 - 20.40</td>
</tr>
<tr>
<td>Galkina</td>
<td>7.17</td>
<td>5.88</td>
<td>19.5</td>
<td>7.16</td>
<td>5.56 - 5.80</td>
<td>19.96 - 20.18</td>
</tr>
<tr>
<td>Walder (3)</td>
<td>8.58</td>
<td>10.35</td>
<td>19.5</td>
<td>8.79</td>
<td>7.45 - 8.30</td>
<td>19.12 - 19.75</td>
</tr>
<tr>
<td>Walder (4)</td>
<td>8.43</td>
<td>11.03</td>
<td>21.2</td>
<td>8.83</td>
<td>7.70 - 8.30</td>
<td>19.25 - 19.60</td>
</tr>
<tr>
<td>Sosunov (6)</td>
<td>8.46</td>
<td>12.05</td>
<td>22.3</td>
<td>8.57</td>
<td>7.40 - 8.30</td>
<td>19.23 - 19.87</td>
</tr>
<tr>
<td>Sosunov (3)</td>
<td>8.18</td>
<td>6.41</td>
<td>18.5</td>
<td>8.30</td>
<td>7.50 - 8.20</td>
<td>20.31 - 20.92</td>
</tr>
<tr>
<td>Sosunov (2)</td>
<td>8.05</td>
<td>9.87</td>
<td>20.7</td>
<td>8.22</td>
<td>7.70 - 8.30</td>
<td>20.75 - 21.19</td>
</tr>
<tr>
<td>Sosunov (5)</td>
<td>8.12</td>
<td>6.81</td>
<td>19.0</td>
<td>8.20</td>
<td>7.35 - 8.30</td>
<td>20.35 - 21.24</td>
</tr>
</tbody>
</table>

between start energy and official jump distance but the correlation coefficients for the women (r=0.57) and the men (r=0.54) are very low.

This indicates that the jump technique of the athletes plays an important role in the jump distance. During the take off phase there is always a decrease in energy. The results (comparison between men's groups 1 and 2 and women's groups 1 and 3) indicate that an energy loss does not necessarily result in a decrease in jump performance.

It has already been mentioned in the methods section that the distance \(W_{\text{run}}\) achieved can be calculated as the function of the starting energy, the energy loss and the transformation index (equation 5). Figure 1 shows the distance \(W_{\text{run}}\) as a function of energy loss with various transformation indexes and a given starting energy \(E_{\text{beg}}=56.12\) Joule/kg, start energy from Galkina's best jump. It's important to note that an improvement in jump distance \(W_{\text{run}}\) can be achieved through a higher transformation index with the same energy loss or with a greater energy loss and the same transformation index.

The examination of figure 2 shows that there is a relationship between energy loss and the transformation index. The correlation coefficient of the two parameters is \(r=-0.91\), \(p<0.001\) for both the men's and women's groups. This means that a higher energy loss with a lower transformation index can be achieved.

The transformation index appears also to be dependent on the start energy. A significant \((r=-0.67, p<0.001\) for the men and \(r=-0.63, p<0.001\) for the women) correlation between the two parameters was found. This finding coincides with the results from Witters et al. (1992). They found that, with an increase in approach velocity, the conversion efficiency at take off was decreased. All

![Figure 1: Distance in relation to energy decrease with various transformation indexes and a constant initial energy](image-url)
of these relationships indicate that a) an optimal combination of energy loss and the transformation index exists and b) the optimal combination is dependent on the starting energy.

With the use of a multiple regression equation, it was possible to calculate the relationship between the transformation index and both the start energy and the energy loss during the take-off phase for both the men's and women's groups. In both cases the multiple correlation coefficients were very high ($r=0.94$ for the women and $r=0.91$ for the men). The formula (5) can be altered so that the distance ($W_{m}$) can be calculated as a function of start energy and the energy loss. Then it is possible to individually diagnose whether the start energy is effectively used to create the optimal take-off characteristics (figure 3 and table 3). For example, Drechsler has the highest start energy and therefore the potential to jump the farthest. In comparison to Galkina however, her take-off phase is not as effective and therefore the jump distance of Drechsler is less than that of Galkina. Were Drechsler to achieve an energy loss of about 5.3-5.8 J/kg, she could jump 7.22 m with a take-off angle of 18.6-19 degrees. Galkina, in contrast, demonstrates almost optimal take-off characteristics and effectively uses the start energy that she produces.

On the other hand, Tiedtke and Jaklofsky showed too much energy loss during the take-off phase and were quite a long way from attaining their optimal technique. Jaklofsky could jump farther than Tiedtke if she had an energy loss from 5.5 to 5.7 J/kg and therefore a take-off angle from 20.14 to 20.4 degrees (figure 3).

In the men's group, Walder had a starting energy of 69.5 J/kg, which would allow him to jump 8.83 m if his take-off was optimal. An optimal take-off for him would be an energy loss from 7.7 to 8.3 J/kg (figure 3) and a take-off angle of 19.25 to 19.60 degrees. Sosunov demonstrated both too much energy loss (jumps 6 and 2) as well as too little energy loss (jumps 3 and 5). On his last jump he pro-
duced a starting energy of 67.35 J/kg which in the best case scenario would produce an energy loss of 7.5-8.1 J/kg, a take-off angle of 19.32 to 19.80 degrees and a jump distance of 8.57. With this information we can explain the results of the various groups (figure 4).

Groups 1 and 2 for men produced the same amount of start energy and neither group demonstrated an optimal take-off phase.

Group 1 demonstrated too much energy loss and group 2 too little. Both groups could have produced jumps of 8.24 m with an energy decrease of 7.7 to 8.0 J/kg and a take-off angle between 20.44 and 20.74 degrees.

Group 3 demonstrated an even worse take-off phase. They could have jumped 28 cm further if they had managed an energy loss between 7.4 and 8.4 J/kg and a take-off angle from 19.38 to 20.14 degrees.

**Conclusion**

Using a simple model, it was shown that athletes belonging to the absolute top level rarely utilize their starting conditions (initial energy) in an optimal way. In addition, the initial energy limits the distance achieved. During contact time the transformation index defines the quality of the take-off. These phenomena could have the following implications for practical training:

**Long-term strategies**

It was shown that the distance can be defined as the function of initial energy and energy reduction. With identical energy reduction and a higher transformation index the distance increases (Figure 1). This means that a long-term training strategy should aim at a shift of the curve in Figure 2 to the top. Training aiming at a shift to the top has direct effects on the competition performance. Exactly which training forms could lead to such a shift remain to be examined.

**Short-term strategies**

The short-term strategy should aim at finding and training the optimal take-off characteristics or behaviour. Given that the dependence of the transformation index is determined experimentally in an athlete from energy reduction, it is possible to determine an athlete's optimal take-off behaviour. This behaviour can therefore be controlled and improved through training.

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