BIOMECHANICAL ANALYSIS OF THE HIGH JUMP AT THE VIth WCA IN ATHENS

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INTRODUCTION: The CM height during the high jump can be calculated using the following formula:

$$H = H_1 + \frac{v^2 \sin^2 a}{2g} \qquad (1)$$

It is clear from this formula that height (H) is dependent on the CM height at take-off, the CM take-off velocity and the take-off angle. H1 is strongly influenced by anthropometric measurements. The CM take-off velocity (v) and the take-off angle (a) characterize the vertical CM take-off velocity. Athletes produce their initial energy during the approach. During the take-off phase the athlete attempts to transform this energy into jump energy. This transformation always leads to a decrease in the athlete's total energy (Brüggemann and Arampatzis 1997). The correlation between the approach velocity and the vertical take-off velocity appears not to be linear, but rather to be individually determined (Dapena et al. 1990). This individual optimum can be influenced by the conditional abilities of the athlete (Dapena and Chung 1988, Dapena et al. 1990). In the international literature it has not yet been reported how this individual optimum can be determined. An understanding of this would be valuable for use in training and competition.
The purposes of this study are:

1. To examine the approach and take-off strategies of high jumpers at the world class level.
2. To determine how to estimate optimal take-off behavior from given initial characteristics.

METHODS:

Data collection: Twenty-six jumps by 12 finalists in the 1997 Track and Field World Championships high jump competition were analyzed. All the analyzed jumps were valid jumps. The movement of the athletes was recorded using 4 stationary cameras (2 for left jumpers and 2 for right jumpers) operating at 50 Hz. The cameras were calibrated using a 2x2x2 m^3 calibration cube. The origin of the coordinate system was at ground level at the middle point of the high jump cross bar. The Y axis was parallel to the cross bar and was positive to the left. The Z axis was oriented upward positive, and the X axis is perpendicular to the other two axes. The video data was digitized using a Peak-Motus system. The following parameters were calculated using a fast information program developed at the German Sport University of Cologne: CM position, body angle, CM velocities and total energy. The spatial coordinates (x, y, z) of the 19 digitized points per frame were calculated through DLT.

Data Analysis: Formula 1 can be converted to the following:

$$W = \frac{E_{k2}\sin 2a}{g} + \frac{2\cos a}{g}\sqrt{E_{k2}}(E_{p2} + E_{k2}\sin^2 a) \qquad (2)$$

$$E_{k2} = \frac{E_{kin\ 2}}{m}, \quad E_{p2} = \frac{E_{pot\ 2}}{m}, \quad E_{kin2} = \frac{1}{2}mv^2, \quad E_{pot\ 2} = mgh$$

The effective height (H) can be calculated as a function of the total CM energy at the end of the take-off phase and the take-off angle. During the take-off phase a loss of total CM energy always occurs during the transformation of the initial energy to jump energy. To quantify this transformation an index was created that shows the directional change of the movement dependent on energy loss. The transformation index is defined as the quotient of the take-off angle divided by the energy loss.

$$T_{Index} = \frac{a}{E_{Abnahme}} \qquad (3)$$

From formulas 2 and 3 the effective height (H) can be calculated as a function of the initial energy, energy loss and the transformation index. The potential energy difference among jumps was very small and can therefore be given a constant value for each jumper.

$$H = \frac{E_{p2}}{g} + \frac{(E_{t1} - E_{decrease} - E_{p2})\sin^2(T_{Index}.E_{decrease})}{g} \qquad (4)$$

The beginning energy represents the starting conditions for the jump and the energy loss and the transformation index represent the jump behavior. Using a cluster analysis two distinct groups were formed. The factors used in creating the groups were initial energy, energy loss and the transformation index. The difference between the two groups was tested using a T-test for a sample group.

RESULTS: Group 1 showed higher values ($p<0.05$) than group 2 for initial energy, as well as horizontal CM touch-down velocity. All other parameters up until touch-down, including trunk angle, touch-down and take-off angle, foot, knee and hip angle, as well as CM height, showed no significant difference. At take-off group 2 showed a higher ($p<0.05$) energy loss than group 1. The decrease in CM horizontal velocity was also larger in group 2. Group 1 produced a higher value ($p<0.05$) for the transformation index. The take-of parameters, final energy, take-off angle, CM flight height, horizontal and vertical CM velocity showed no significant differences. Also for jump height and effective height no significant ($p<0.05$) differences could be found.

The beginning energy and horizontal CM touch-down velocity show no significant ($p<0.05$) correlation with the effective height, the jump height or the CM take-off velocity. The decrease in total CM energy and the decrease in CM horizontal velocity during take-off also show no significant ($p<0.05$) correlation with the effective height, the jump height or the vertical CM take-off velocity. The decrease in CM total energy during the take-off phase did show a very high correlation with the transformation index (Fig. 1). This exponential correlation between the energy decrease and the transformation index shows that the maximum CM vertical velocity occurs at a specific value for energy loss (Fig. 1). A further reduction of total CM energy and the horizontal CM velocity does not result in an increase in vertical CM velocity (Fig. 1).

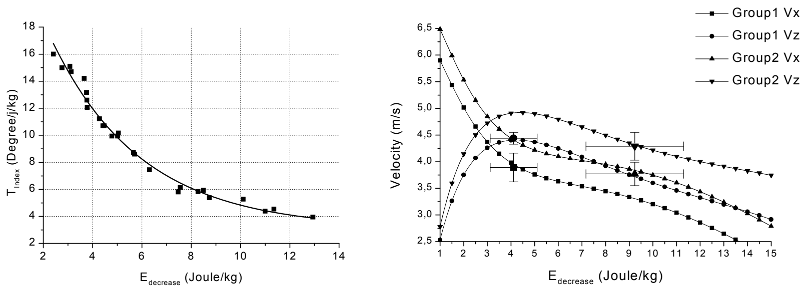

Fig. 1: Transformation index as a function of the energy decrease, horizontal and vertical CM-velocity as a function of the energy at touch down and energy decrease

DISCUSSION: The two groups demonstrated varying initial conditions and varying jump behavior. Group 2 had both a higher beginning energy and a higher energy loss during the take-off phase. The transformation index for group 2 is lower and so the two groups show approximately the same final energy and take-off angle at the end of the take-off phase. This leads to the fact the two groups show no significant difference in the effective or jump heights. This observation shows that the energy loss of group 2 is too large and therefore gives group 2 no advantage. Through a lower energy loss and a higher transformation index Group 1 was able to make up its deficit in initial energy in relation to group 2. The large energy loss demonstrated by group 2 seems to be an important mistake. The horizontal CM velocity of group 2 was reduced more than that of group 1 without producing a further increase in the vertical CM velocity. The question that naturally arises is why the energy decrease of the two groups is different in spite of the fact that body positioning at touch-down showed no clear differences. One possible explanation for this is that the muscle stiffness of the two groups varied. Muscle stiffness affects the coordination of the muscle-tendon complex and can therefore change the amount of energy lost. The exact effects of muscle stiffness on energy loss cannot be quantified in this study. Furthermore it seems that during the take-off phase the initial energy influences the energy loss. These two factors show a high correlation ($r=0.93$, $p<0.05$).

The transformation index showed a very close relationship with energy loss (Fig. 1). The transformation index can be estimated using an exponential function of energy loss. This makes it possible to calculate the effective height as a function of the initial energy using formula 4. Figure 2 shows the possible effective heights of the two groups. Group 1 showed a near optimal take-off and therefore reached almost 100% of its potential height. In contrast, group 2 had a less effective take-off and could have achieved an effective height approximately 10% higher than actually achieved. The optimal energy loss would be between 4 and 5 J/Kg and the take-off angle between 47.8 and 49.3 degrees. Figure 1 illustrates that the vertical CM velocity increases with a decrease in horizontal velocity. This relationship has an optimal point, after which a greater horizontal velocity loss doesn't result in a greater vertical velocity gain. In contrast, with an excessively high horizontal

velocity loss the resultant vertical velocity also decreases. The optimum horizontal approach velocity for group 1 is 3.13 – 3.35 m/s and for group 2 it is 3.40 – 3.61 m/s. This indicates that those athletes who produce a higher approach velocity also require a larger energy loss to achieve their optimum take-off velocity.
It is also possible to diagnose to what extent the athletes are taking advantage of their starting energy (Fig. 2). Particularly interesting to examine are the three jumps from Partyka (Fig. 2). He demonstrated optimal take-off characteristics only during his best jump (2.35m). Through the examination of the initial energy and the take-off characteristics of the athlete we can gather important information that can be used during training sessions to improve the take-off phase. Or if an athlete already demonstrates favorable take-off characteristics, an effort can be made to increase his initial energy. Further research needs to done to determine the effect of muscle stiffness on energy loss during the take-off phase.

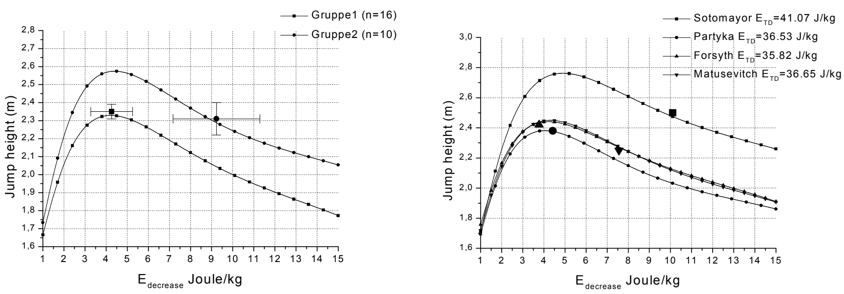

Fig. 2: Jump height as a function of the energy at touch down and energy decrease

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