INTERACTION BETWEEN THE POLE AND THE HUMAN BODY AND ITS EFFECT ON THE POLE VAULTING PERFORMANCE

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The purposes of this study were: (a) to examine the utilization of pole elasticity by the athletes through muscular work and to develope performance criteria throughout the pole vault and (b) to examine the reproducibility and the athlete's specificity of the developed criteria. In the study, 6 athletes performed from 4 to 11 trials each, at 90% of their respective personal best performance. All trials were recorded using four synchronized, genlocked video cameras operating at 50 Hz. The ground reaction forces exerted on the bottom of the pole were measured using a planting box fixed on a kistler force plate (1000 Hz). The interaction between athlete and pole may be split into two parts. During the first part of the interaction, energy is transferred into the pole and the total energy of the athlete decreases. The difference between the energy decrease of the athlete and the pole energy indicates if the athletes are producing additional energy by means of muscular work (criterion 1). In the second part of the interaction, energy is transferred back to the athlete and the total energy of the athlete increases. The difference between the returned pole energy and the amount of energy increase of the athlete defines criterion 2. The criteria are reproducible, specific to each athlete, capable of identifying deficits or strengths of the athlete's performance during his interaction with the pole; they can therefore estimate the quality of the technique during each of the phases of the interaction athlete-pole.

KEY WORDS: mechanical energy, strain energy, elasticity, energy conversion.

INTRODUCTION: Many physical and sport activities are characterised by the interaction between the human locomotor system and elastic or viscoelastic surfaces (Zamparo *et al.*, 1992; Ferris and Farley, 1997; Arampatzis and Brüggemann, 1998, 1999, 2001; Farley *et al.*, 1998; Ferris *et al.*, 1999). It has been precisely the sport context, where modifying the interactions between athlete and elastic or viscoelastic surfaces led to considerable performance improvements, Pole vault. is an impressive example. The implementation of elastic poles caused a fast boost in the performance of jumps. The pole, which in pole vaulting is representing the mechanical interface between the moving athlete and the environment, is able to store strain energy and deliver it back later in time. Sport events where relatively large deformations of the interface are inherent to performance, may benefit from the concept of energy storage and return. Furthermore, as it is possible to store energy in the pole, the athlete may produce muscular work and use this as additional energy during the vault. Hubbard (1980) and Ekevad and Lundberg (1995, 1997) reported that the exchange of energy between the athlete and the pole is very important for the jumping performance. Nevertheless, no study considering the exchange of energy and especially the importance of muscular energy delivery during the interaction between the athlete and the pole could be found. Therefore, the purposes of this study were: (a) to examine the utilization of pole elasticity by the athletes through muscular work and to develope performance criteria during the pole vault and (b) to examine the reproducibility and the athlete's specificity of the developed criteria.

METHOD: Six experienced pole vaulters (5 male, height: 1.84 ±0.04 m, weight: 80.3 ±4.99 kg, 1 female, height: 1.69 m, weight: 62.5 kg) were studied. One of the male subjects was a decathlete. The best performance of the four pole vaulters varied between 5.30m and 5.60m. The best performance of the decathlete was 4.35m and that from the female pole vaulter 4.25m. Each athlete had to perform from 10 to 15 pole vaults at 90% of their respective personal best performances. From these trials between 4 and 11 valid vaults per athlete were analysed. The trials were recorded by four genlocked video cameras operating at 50 fields per second. The three dimensional co-ordinates of a 12 segment model were calculated using the DLT method; hand and lower arm were regarded as one single segment. Kinematic data were smoothed using a forth order low-pass Butterworth filter with

an optimised cut off frequency for each point of the model ("Peak Motus" Motion Analysis System). The calibration cube was 5x5x1 m^3. The origin of the inertial co-ordinate system (ICS) was located above the deepest point of the planting box at ground level in the middle of the run up path. The x-axis was defined to be the horizontal axis in the main plane of movement. The y-axis was defined to be the vertical one. The z-axis results from the crossed product between the x and y axes. The masses and moments of inertia of the various segments were calculated using the data provided by Zatsiorsky and Seluyanov (1983).
The ground reaction forces exerted on the bottom of the pole were measured by fixing the planting box on a kistler force plate (1000 Hz). The force data were smoothed using a fourth-order low-pass Butterworth filter with a cut-off frequency of 40 Hz. The synchronization of the kinematic and dynamic data was achieved by using LEDs (light emitting diodes) and a synchronous TTL signal. For the calculation of the athlete's total mechanical energy see Schade *et al.* (2000). The strain energy of the pole was calculated as follows:

$$E_{pole} = \int F_p \cdot ds$$

F_p : force in direction of pole deformation
s : deformation of the pole

The deformation of the pole was determined through the variation of the distance between the deepest point of the planting box and the point digitised at the hand of the upper arm. The force in direction of pole deformation was calculated as follows:

$$F_p = F_x \cdot \cos\alpha + F_y \cdot \cos\beta + F_z \cdot \cos\gamma$$

$F_{x,y,z}$: components of the measured ground reaction forces at the planting box.
cosg, cos ,
cos : direction cosines of the position vector *r* ($r = \overline{OP}$)
O : deepest point of the planting box
P : point digitised at the hand of the upper arm

Differences between athletes were tested by applying a repeated measure one-way analysis of variance (ANOVA, post hoc test Tukey, $p<0.05$).

RESULTS: The results show that the energies of the athlete and the pole are very reproducible (fig.1). The intraclass correlation coefficients are very high ($r>0.92$) and there are no significant differences between the various trials of the same athlete. During the first part of the interaction between the athlete and the pole, energy is transferred into the pole and the total energy of the athlete decreases (fig.1). During the second part of the interaction, energy is transferred back to the athlete and the total energy of the athlete increases (fig.1). During this energy exchange between athlete and pole, there is an energy loss from about 7-10% of the energy transferred to the pole. Anyway, the energy of the athlete at pole release is higher compared to his initial energy.

DISCUSSION: All athletes, except athlete 3, are successfully using the elasticity of the pole during the first part of the interaction between athlete and pole, and the amount of energy transferred to the pole is bigger than the energy decrease of the total body energy (criterion 1, fig.2). This indicates that the amount of energy at the end of this phase is higher than the initial energy. This additional energy derives from the muscular work done during the rockback. For athlete three, criterion 1 is negative reflecting an energy loss in the whole system (athlete-pole). This indicates that the athlete absorbed energy by means of muscular work. Therefore, a clear energy was caused loss during the first part of the interaction with the pole. This subject was a decathlete and his behaviour might be explained by technical deficits of his execution.

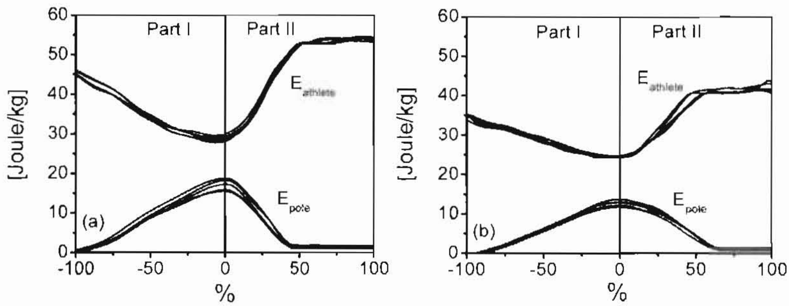

Figure 1. Mechanical energy of the athlete and of the pole during 5 trials (a: male athlete, b: female athlete). The x-axis is normalised as follows: -100% up to 0% represents the phase between the beginning of the vault and the maximum pole bend position; 0% up to 100% represents the phase between the maximum pole bend position and the instant of maximum center of mass height.

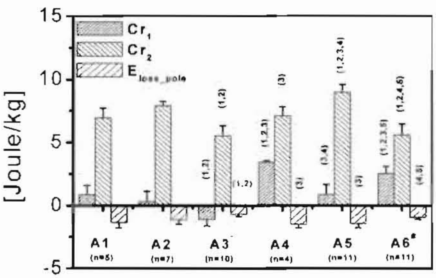

Figure 2. Both criteria (Cr_1 and Cr_2) and energy loss in the pole (E_{loss_pole}) analyzed for trials of six athletes (*: decathlete, #: female athlete).
[1]: statistically significant ($p<0.05$) difference to athlete1
[2]: statistically significant ($p<0.05$) difference to athlete2
[3]: statistically significant ($p<0.05$) difference to athlete3
[4]: statistically significant ($p<0.05$) difference to athlete4
[5]: statistically significant ($p<0.05$) difference to athlete5

In the second part of the interaction between athlete and pole, the energy stored in the pole flows back to the athlete. The energy recovered from the pole is about 7-10% lower than the maximal strain energy of the pole. This value is low when compared to other viscoelastic interfaces used in sport (i.e. gymnastic floor, Arampatzis *et al.* 2001) and might be explained by the lesser viscosity of the pole. In this phase, all studied subjects demonstrate an increase in total body energy that is higher than the amount of energy delivered back from the pole (criterion 2, fig.2). This indicates that during the second part of the interaction the athletes are producing additional muscular energy and this way increase the energetic level of the system athlete-pole. Despite the variance in criterion 2 is very low within one athlete, there are clear statistically significant differences between athletes (fig.2). So it can be assumed that the behaviour of the athletes during this phase, which is estimated by criterion 2 is specific to each athlete and also reproducible. Both criteria are able to identify deficits and strengths of the athletes within the whole interaction phase with the pole (parts 1 and 2) and this way of explaining the differences in final energy of the athlete (fig.3). In fig.3(a) both athletes show the same initial energy, but the final energy is higher for athlete 5. This difference results from the better behaviour of athlete 5 during the second part of the interaction (criterion 2 is statistically significant higher, fig.3a). During the first part, despite athlete 1 has a higher amount of energy stored in the pole, criterion 1 has similar values for athlete 5. This indicates that the higher amount of energy transferred to the pole by athlete 1 does not come from muscular work, but rather from a passive decrease in the total energy of the body (fig.3a). Contrary to that in fig.3(b) the reason for a higher final energy of athlete 4 is to be found during the first part of the interaction between athlete and pole (criterion 1 is higher for athlete 4). This athlete shows a higher energy transfer to the pole than athlete 2 and what is most important, this is done actively by means of muscular work. Both examples show that differences in final energy of the athletes may have been originated during different phases of the energy exchange. Furthermore, it is possible that different athletes use different energy storage and return strategies during their interaction with the pole while reaching similar amounts of energy at the end of the pole phase.

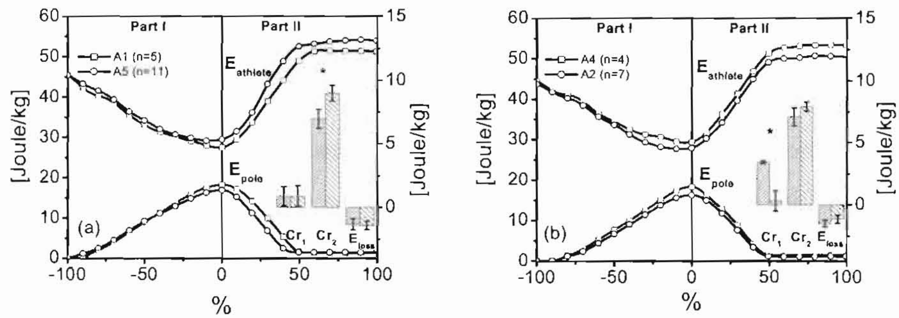

Figure 3. Mechanical energy of the athlete, of the pole, criterion 1 (Cr1), criterion 2 (Cr2) and energy loss in the pole (E_{loss}). The x-axis is normalised as follows: -100% up to 0% represents the phase between the beginning of the vault and the maximum pole bend position; 0% up to 100% represents the phase between the maximum pole bend position and the instant of maximum center of mass height.

*: statistically significant ($p<0.05$) difference between athletes

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