APPLICATIONS OF BIOMECHANICS CINEMATOGRAPHY TO RESEARCH AND COACHING ASPECTS OF THE POLE VAULT

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Pole vaulting is one of the most complex skills in Track and Field. To the biomechanist the analysis of the movement pattern "fiberglass vaulting technique" and the interaction of the athlete and the flexible pole present a challenge.

Among the approaches to an analysis of the event, the following are seen as being prevalent:

1. Investigators try to isolate independent variables and estimate their empiric-statistic performance relevance based on a criterion such as the maximum vertical displacement of the vaulter's center of mass. Primary kinematic input data are obtained from a cinematographic record of the event (12,14). The statistical approach ultimately led to the construction of non-deterministic models (17), which improve the understanding of the event and provide "normal" data indicative of trends for the sample under investigation. To the individual athlete, especially on the higher-performance level, however, these findings are of limited value.

2. Computer models, based on deterministic models of the event have been presented. Through the use of digital (15) and analog (8) computers, it is potentially possible to isolate the influence of independent variables on the performance, to optimize the technique of a specific vaulter, to select the optimum pole for any given set of input data, and to predict the performance potential of an athlete. This approach is very promising. In the near future, models that do describe the entire vault adequately should be accessible to the coach and help him devise and monitor an individual athlete's training.

3. Several researchers have reported kinematic and/or kinetic data. The performance's relevant parameters are, in general, quantified from cinematographic procedures (1,2,6,10) and, in one case, through the use of a force plate under the takeoff area and a strain gauge instrumented vaulting box (1,2). The initially available energy and its efficient use throughout the vault were

found to be closely related to vaulting success. Dillmann (et al) (1968) operationally defined the "predicted height" (the height the vaulter would attain if all the kinetic energy at take-off was completely utilized in the vault), and the "adjusted predicted height" (the predicted vertical rise of the center of mass accounting for the final kinetic energy at the peak of the flight). The angular momentum of the vaulter was identified as a crucial parameter (3,15), but has not been previously quantified.

Scope Of The Paper

This paper has been extracted from a comprehensive study of the pole vault (10) and concentrates on the quantification of performance parameters through biomechanics-cinematography data collection and analysis procedures, as well as on possible ways to interpret the results for coaching purposes. Due to the limited number of analysed vaults in this study, no general statements are made. The graphs do not represent an "ideal" performance, but rather are typical and serve to illustrate how the data can aid an individualized analysis of an athlete's performance.

Method

A cinematographic record of the vault was obtained from a Photo-Sonics IPL camera operating at 100 FPS with an exposure time of 1/2400 sec. The film data was digitized on a Bendix Platen interfaced to an HP9825B desk-top computer. For the analysis, the MIT Humanscale data (5) for the relative segment masses and the locations of the segmental centers of mass with respect to the proximal end point of each segment were used. Moments of inertia for each segment about the transverse axis through the respective segmental centers of mass were taken from Dapena (1978).

The validity of the cinematographic analysis was determined through a comparison of the changes in momentum of the vaulter to the concomitant impulses measured in the vaulting box (9,10).

The following performance-relevant parameters were quantified:

1. Horizontal, vertical and linear velocities of the vaulter's center of mass.

2. Translational and rotational kinetic energies, as well as gravitational potential energy.

3. The angular momentum of the vaulter.

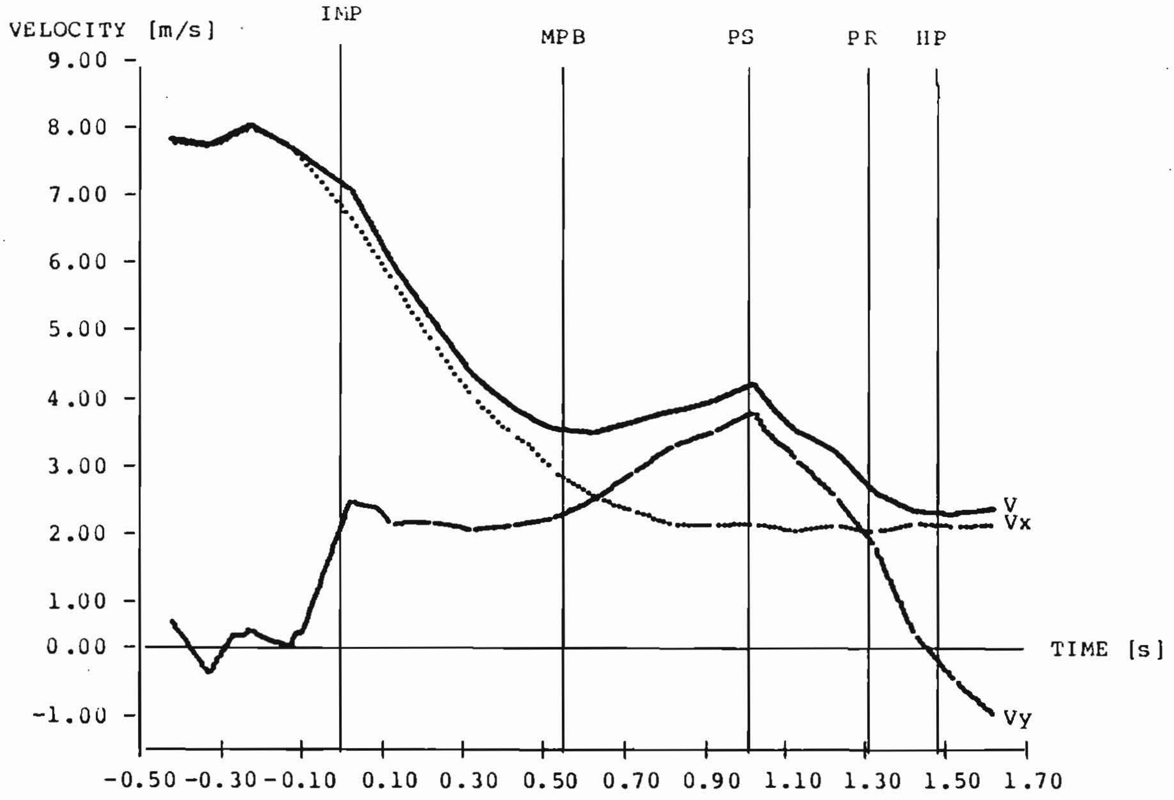

FIGURE 7

LINEAR VELOCITY OF THE VAULTER'S CENTER OF MASS AND ITS HORIZONTAL (V_x) AND VERTICAL (V_y) COMPONENTS

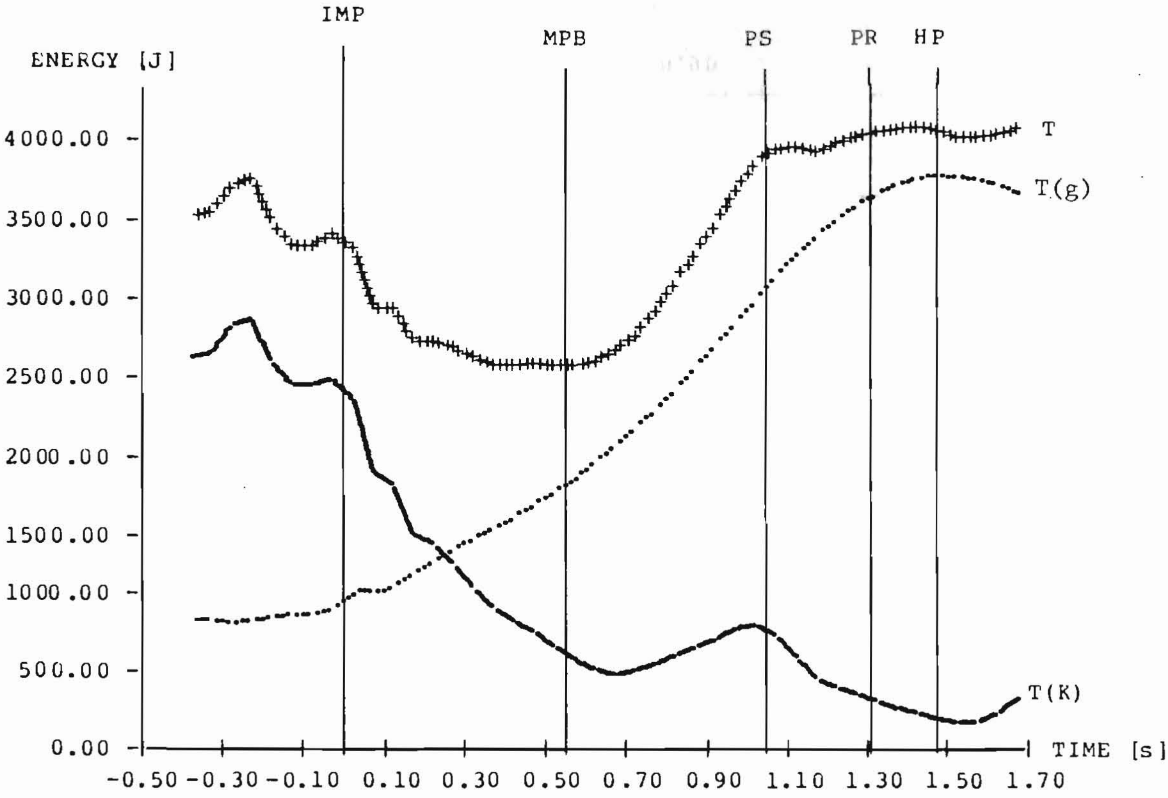

FIGURE 8

KINETIC ENERGY ($T_{(K)}$), GRAVITATIONAL POTENTIAL ENERGY ($T_{(g)}$) AND TOTAL ENERGY (T)

Results and Discussion

Figure I presents the velocities of the center of mass from the penultimate stride to post-bar clearance. The horizontal velocity reaches a maximum of 8 m/s. This is slow compared to several competitive vaults (5.5-5.7 m) where run-up velcities of up to 9.6 m/s were attained. During take-off the horizontal velocity drops to 6.8 m/s, caused by the transformation of horizontal to vertical momentum, which is reflected in the vertical take-off velocity of 2.4 m/s. From a comparative study of two vaults that resulted in pole breakage, it appears as if the active vertical take-off action is essential for a successful vault. Also, it is interesting to note that the vertical velocity remains positive throughout the last stride and take-off: the center of mass is lowest in the support phase of the penultimate stride. Thereafter the center of mass continues to rise, most significantly during the take-off. Shortly after the pole is maximally bent, the vertical velocity exceeds horizontal velocity: the center of mass moves at an angle greater than 45° to the horizontal. This is also the point at which pole failure occurred in the previously-mentioned unsuccessful vaults. By the time the pole is fully uncoiled, the horizontal velocity reaches a near-constant value of 1.8 m/s. Since approximately 1 m/s suffices for the bar clearance, this value already indicates inefficient energy utilization. As the pole straightens, the vaulter's vertical velocity is increased from 2.3 m/s to 3.8 m/s. Until the vaulter releases the pole, the mean vertical acceleration is $-7.5\ m/s^2$: the vaulter thus continues to apply force through the pole after the pole is straight. However, in this vault, the "push-off" action is not well-timed, the vaulter allows his body to drop before initiating the "push".

Translational and rotational kinetic energies, the gravitational potential energy and the total energy of the vaulter are plotted in figure 2.

The initial kinetic energy at take-off, the efficient utilization of the energy and the work done by the vaulter are important parameters for a successful vault. For the analyzed vault, the initial kinetic energy was 2444 J. This value compares unfavorably to the 3240 J measured in a competitive vault (5.5m) of the same subject, and must be considered as a partial explanation for the difference in the achieved height. Efficient use of initially-available energy menas that the vaulter must keep the difference between the total energy and the gravitational potential energy at the high point small. This is achieved by reducing the kinetic energy at this time to the smallest possible value required for bar clearance. Data reported by Dillman (1968) and the analysis of a world-record performance by the author(Gros, 1981) suggest that a horizontal velocity of approximately 1 m/s is sufficient for bar clearance. In the analysed vault, the

FIGURE 12

ANGULAR MOMENTUM (H_{CM}) ABOUT THE CENTER OF MASS

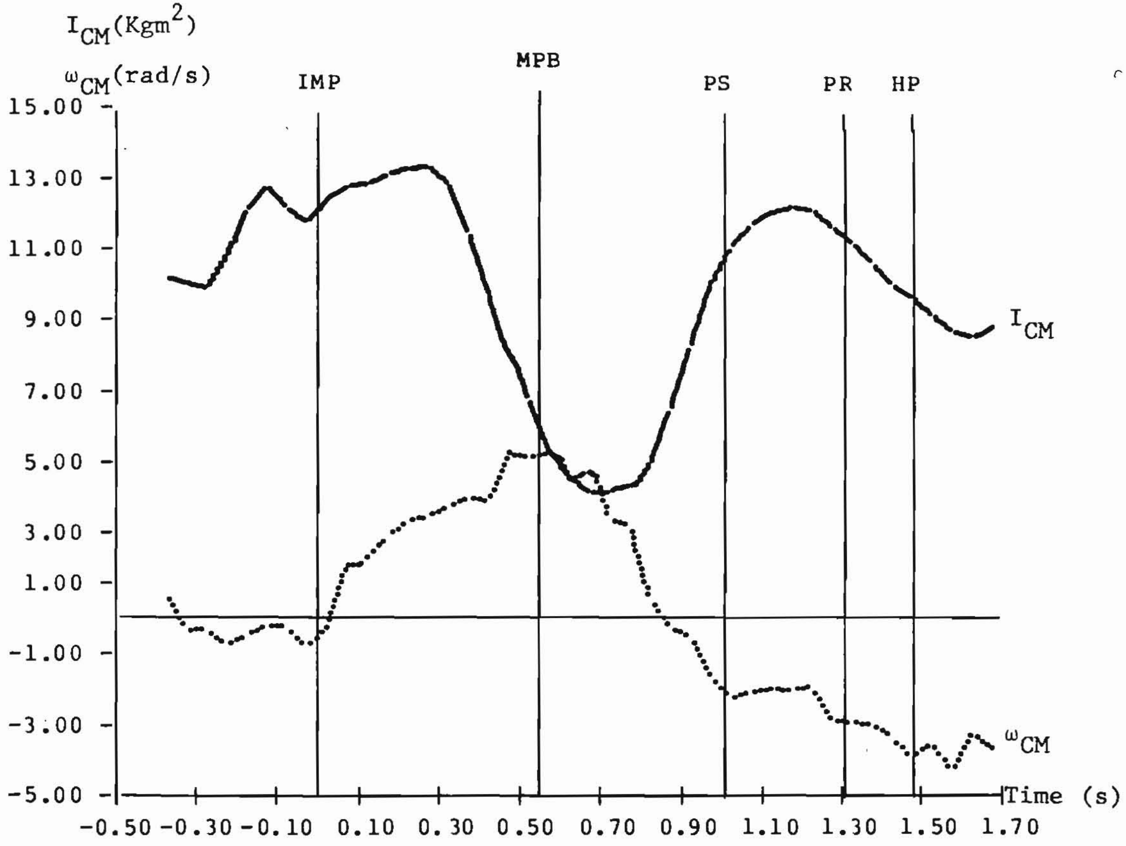

FIGURE 13

MOMENT OF INERTIA (I_{CM}) AND ANGULAR VELOCITY (ω_{CM})

ABOUT THE CENTER OF MASS

athlete had a final kinetic energy of 220 J. This is equivalent to an 0.27 m vertical displacement. The subject could gain 0.21 in height through more efficient energy utilisation. The net work done by the vaulter can be estimated by subtracting the total initial kinetic energy from the total final energy of the system. The net work done by the vaulter in the specific vault under investigation was 621 J, which is equivalent to a vertical rise of the center of mass of 0.76 m. All three parameters -- the kinetic energy, the efficient energy utilisation, and the work done by the vaulter, combined, can be used to evaluate a vault and detect factors that limit performance.

The angular momentum of the vaulter about the center of mass and its components, namely moment of inertia and angular velocity are indicative of the vaulter's behavior on the pole (Figures 3 and 4). Changes in body configuration such as extension or tuck, as well as the result of those movements, become transparent. In the analysed vault, the moment of inertia ($I=13.3\ Kgm^2$) versus time graph clearly shows the hang phase, the shortening of the pendulum where the upper hand is considered to be the axis of rotation and the body-tuck or rock-back position ($I=3.5\ Kgm^2$). Since angular momentum data has not been reported in the literature to date, a comparison to other vaults is not possible. The subject of the present study does not reach a fully-inverted position, which could be caused by a late or insufficient decrease of the moment of inertia, or too-early leg extension into the J position after rock-back. The center of mass is not directly in line with the axis of rotation; thus the legs and upper body drop, which finds its ultimate expression in a very low push-off angle of 127°. Bergemann (1978) reported values of 132°, 165°, and 164°. The subject of the present study reached 145° in a competetive vault (5.5 m); 150° was measured in a 5.7 m vault (11).

Selected References

1. Barlow, D.A. Kinematic and Kinetic Factors Involved in Pole Vaulting. Ph.D. Thesis, Indiana University, 1973.

2. Barlow, D.A. "Kinematic and Kinetic Factors Involved in Pole Vaulting". Track and Field Quarterly Review '79 (1979) 1, pp. 19-21.

3. Bergemann, B.W. "Contribution of Research to the Pole Vault". Science In Athletics, J. Terauds (Ed.), Academic Publishers, Del Mar, California, 1978.

4. Dapena, Jesus. "A Method to Determine the Angular Momentum of a Human Body about Three Orthogonal Axes Passing Through its Center of Gravity". Journal of Biomechanics, Vol.11, (1978), pp. 251-256.

5. Diffrient, N. et.al. Humanscale, The MIT Press, Cambridge, Massachusetts, 1974.

6. Dillmann, J.D., Nelson, R.C. "The Mechanical Energy Transformations of Pole Vaulting with a Fiberglass Pole". Journal of Biomechanics, Vol 1, pp. 175-183.

7. Ganslen, Richard V. Mechanics of the Pole Vault, John Swift and Company, St. Louis, Missouri (1970).

8. Fidelius, K., Morawski, J., Wiklik, K. "Analoge Simulation in Sport", Biomechanische Untersichungsmethoden im Sport; Marhold (ed.).

9. Gros, H.J., Terauds, J. "Comparison of data derived from Biomechanics Cinematography and direct force measurements" Proceedings of the International Society for Optical Engineering, Vol. 291 (1982) pp. 58-61.

10. Gros, H.J. "Computerized Analysis of the Pole Vault Utilizing Biomechanics Cinematography and Direct Force Measurements". Unpublished Ph.D. Thesis, The University of Alberta, Canada, 1982.