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An essential performance factor in pole-vaulting

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Abstract

Most studies on pole-vaulting focus on energy transfer data but do not take into account all the actions exerted on the pole. Starting from experimental measurements, this study presents a three-dimensional mechanical model allowing the determination of the pole-vaulter's actions on the pole. The force and the moment exerted on the pole by the pole-vaulter during the last stride before take-off and during jump stage have been calculated. Then, a comparative study is carried out on two pole-vaulters having comparable morphologies and performing with the same pole, and points out the influence on performance of the moment applied to the pole. ***To cite this article: M. Mesnard et al., C. R. Mecanique 335 (2007).***

Résumé

Facteur essentiel de performance en saut à la perche. La plupart des publications relatives au saut à la perche considèrent des transferts d'énergie mais ne prennent pas en compte l'ensemble des actions exercées sur la perche. Cette Note propose un modèle mécanique tridimensionnel permettant à partir de mesures expérimentales de déterminer les actions de l'athlète sur la perche. L'effort et le moment exercés par l'athlète au cours du dernier appui précédant le décollage et au cours de la phase de saut ensuite, ont été calculés. Une analyse comparative, effectuée pour deux athlètes aux morphologies voisines, utilisant la même perche, souligne l'influence sur la performance du perchiste du moment appliqué sur la perche. ***Pour citer cet article : M. Mesnard et al., C. R. Mecanique 335 (2007).***

Keywords: Dynamics of rigid or flexible systems; Pole; Force, moment and wrench; Performance factor

Mots-clés : Dynamique des systèmes rigides ou flexibles ; Perche ; Force, moment et torseur ; Facteur de performance

Version française abrégée

McGinnis [1] développe un modèle plan (2D) de calcul de l'action exercée par l'athlète sur la perche. L'étude proposée, exploite une analyse vidéo tridimensionnelle (3D) des mouvements du perchiste, établie sur un modèle mécanique complet et une analyse dynamométrique [2] qui quantifie les actions extérieures exercées sur la perche et sur l'athlète.

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Afin de déterminer l'action du perchiste sur la perche, un modèle multicorps rigides 3D est appliqué au perchiste. L'action exercée par chacune des mains du perchiste sur la perche est globalisée au point médian. A partir de cette réduction et en couplant les mesures cinématiques et dynamiques, l'action 3D du perchiste est calculée lors du dernier appui précédant le décollage et durant la phase de saut.

Le modèle est ensuite appliqué à deux perchistes aux morphologies voisines, utilisant la même perche. Cette analyse comparative montre de faibles écarts sur les composantes verticales de l'effort et illustre également l'importance de la composante transverse – ou de flexion – du moment. Pour les deux athlètes, l'évolution de l'effort au cours du saut est très analogue. Cependant, le premier perchiste stocke une énergie supérieure, le retour élastique de la perche est ainsi plus rapide et la performance (hauteur maximale atteinte par le centre de gravité) améliorée. La composante transverse du moment diffère en revanche d'un athlète à l'autre et peut expliquer l'écart de performance. Elle constitue alors un facteur discriminant et sera essentielle lors de la conception et de l'optimisation des caractéristiques mécaniques de nouvelles perches de saut.

1. Introduction

In his study, McGinnis [1] developed a 2D calculation model of the wrench applied to the pole by the pole-vaulter's upper hand. The present study innovates with a 3D analysis of the movements that is built on a complete mechanical model of the pole-vaulter.

2. Experimental device

The pole-vaulters' movements were studied through a 3D video analysis system (Human Movement Analysis), developed in the 'Laboratoire de mécanique physique'. Two cameras (DVCam recording at 50 Hz) positioned on both sides of the track filmed the last stride before take-off. Two other cameras positioned slightly ahead of the first two, allowed the reconstruction of the gesture during the jump phase. The space partition into two parts made it possible to improve greatly the kinematic measurements. Moreover, the common space between the two volumes facilitated the rebuilding of the whole gesture. The acquisition dynamic device triggered a flash that ensured the synchronization of the cameras and the dynamometers.

3D displacement rebuilding requires a preliminary calibration of the filmed volume. The quality of the video measurements depends partly on the calibration that must match the vaulter's volume of evolution. Objects of calibration were placed on the track in order to calibrate the first volume. The second volume was gauged using the two posts plus a pole equipped with markers. More than thirty calibration points were necessary to obtain a precise calibration of each volume. Superimposing both volumes checked the calibration quality.

The dynamometric analysis [2] aims at measuring the external efforts being exerted on the pole-vaulter and the pole; two six-component dynamometers were set along the track:

– The first one, integrated into the running track at 3.60 meters from the pole vault box, made it possible to measure the effort exerted by the pole-vaulter on the ground at the time of the last stride before take-off;
– The second one, placed under the pole vault box, determined the effort developed by the 'pole-athlete' system in the pole vault box.

3. Mechanical model

Fig. 1 presents the reference frame R_0 chosen for this study and fixed on the running track. The centre of the pole vault box defines point O, the origin. The axes are selected in the following way:

– x is the axis of the running track;
– z is the ascending vertical axis;
– y is chosen to build a direct reference frame.

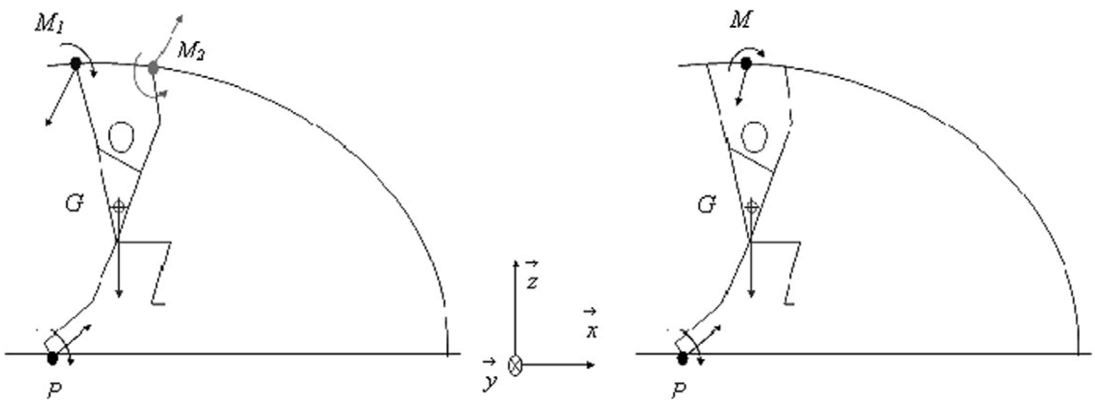

Fig. 1. Mechanical model and equivalent wrenches.

Fig. 1. Modèle mécanique et torseur équivalent.

Fourteen articulated rigid solids and mechanical joints modelled the pole-vaulter. A solid including a revolution axis represented each elementary solid or body segment. De Leva's anthropometric table was used to define the mass and the inertial parameters of each body segment [3].

The next paragraph deals with the equations that determine the wrench action of the pole-vaulter on the pole. Four external actions are applied to the pole-vaulter and are represented by the four wrenches:

- The Pole-vaulter's weight in point G, $\{W\}$;
- The pole action exerted on the pole-vaulter at M_1, $\{\tau_1\}$;
- The pole action exerted on the pole-vaulter at M_2, $\{\tau_2\}$;
- The ground action on the pole-vaulter in P, $\{I\}$.

In order to evaluate the pole-vaulter's global action exerted on the pole, called $\{T\}$, the wrenches, $\{\tau_1\}$ and $\{\tau_2\}$ are carried at point M, the middle of $[M_1, M_2]$ (Fig. 1).

As, $-\{T\} = \{\tau_1\} + \{\tau_2\}$, applying the Fundamental Principle of Dynamics to the pole-vaulter at point G, it comes: $\{D_{\text{pole-vaulter}/R_0}\} = -\{T\} + \{W\} + \{I\}$. Finally, if (S) is the pole-vaulter, the pole-vaulter's action (force and moment of the wrench) on the pole can be written:

$$\begin{cases} \vec{F} = -m\left[g\vec{z} + \vec{a}(G/R_0)\right] + \vec{I} \\ \vec{M}_T(M) = -\dfrac{\mathrm{d}_0\vec{\sigma}_{S/R_0}(G)}{\mathrm{d}t} - \left(\overrightarrow{GM_1} + \dfrac{1}{2}\overrightarrow{M_1M_2}\right) \wedge \left\{-m\left[g\vec{z} + \vec{a}(G/R_0)\right] + \vec{I}\right\} + \vec{M}_I(P) + \overrightarrow{GP} \wedge \vec{I} \end{cases} \tag{1}$$

The pole-vaulter's angular momentum in his centre of gravity, $\vec{\sigma}_{S/R_0}(G)$, is computed using Dapena's method [4]. In these equations, during the jump stage, $\{I\} = \{0\}$.

4. Results

The GCVS algorithm [5] was used to derive the trajectory from the pole-vaulter's gravity centre. The cut-off frequencies obtained are: 6 Hz for x and z axis, 5 Hz for y axis. The relationship between the displacement amplitude and the measurement uncertainty influences the choice of the cut-off frequency. The displacement along y axis remains lower than along the two other axes. Consequently, the choice of a lower cut-off frequency is essential.

During the first part of the jump, the calculation undertaken to determine the action developed on the pole, jointly implements the results of the video analysis and those obtained from the dynamometric measurements. Fig. 2 presents the force and the moment results.

Fig. 2 illustrates the stage (from 0.1 to 0.25 s) during which the pole-vaulter is still in contact with the ground. The force applied to the pole is almost exclusively localized in the plane (x, z). Fig. 2 indicates that the pole-vaulter seems to try to resist take-off by fighting the pole's action.

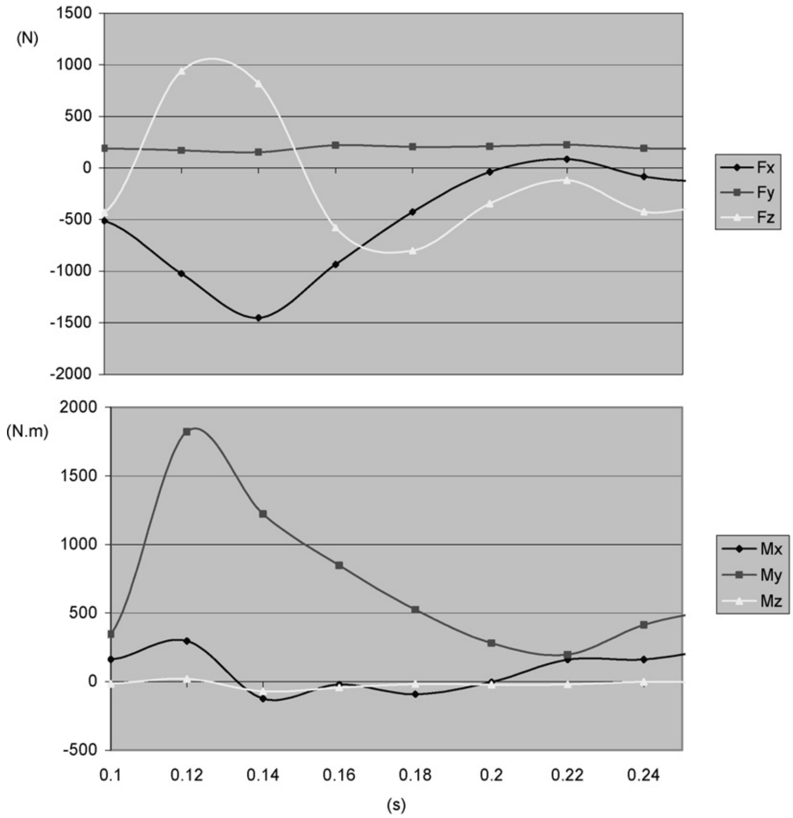

Fig. 2. Pole-vaulter's force and moment exerted on the pole during the last stride before the take-off at point M.

Fig. 2. Force et moment exercés par l'athlète sur la perche lors du dernier appui précédent le décollage au point M.

The study shows that a longer last contact makes it possible to deform the pole in a much more significant way. Therefore, the pole-vaulter undergoes less effort.

The assumption of plane effort during the first stage of the jump is confirmed by the results in Fig. 2. This figure shows the very low values of components x and z of the pole-vaulter's moment applied to the pole. Moreover, the pole-vaulter tries to resist the pole's effort by applying a significant positive moment around the transverse axis y. This effort also makes it possible to increase the initial angle of the pole with the stop bottom. This parameter influences clearly the pole's deformation and thus, the deformation energy stored in the pole.

Finally, the pole-vaulter's objectives just before he takes off are:

– To prolong contact duration and to resist the pole effort;
– To increase the angle between the pole extremity and the stop bottom.

The calculation of the pole-vaulter's action during the jump phase requires knowledge of the 3D trajectories provided by the video analysis and the athlete's model. Fig. 3 allows one to observe the three components of the force and the moment developed on the pole during the jump phase.

The bi-directional model of the effort remains valid during the first jump stage. However, during the reversal stage (pull-up and turnover) starting at 0.7 s, the displacement of the pole-vaulter's centre of gravity is not contained in plane (x, z) as before.

Furthermore, it can be observed, that the force component along x remains positive during the jump: it represents the continuous negative acceleration of the pole-vaulter. Lastly, the force component along the z axis that comes from the acceleration of the pole-vaulter's centre of gravity remains an important performance criterion. It seems much more representative of the gesture than the component along x axis which depends strongly on the pole used.

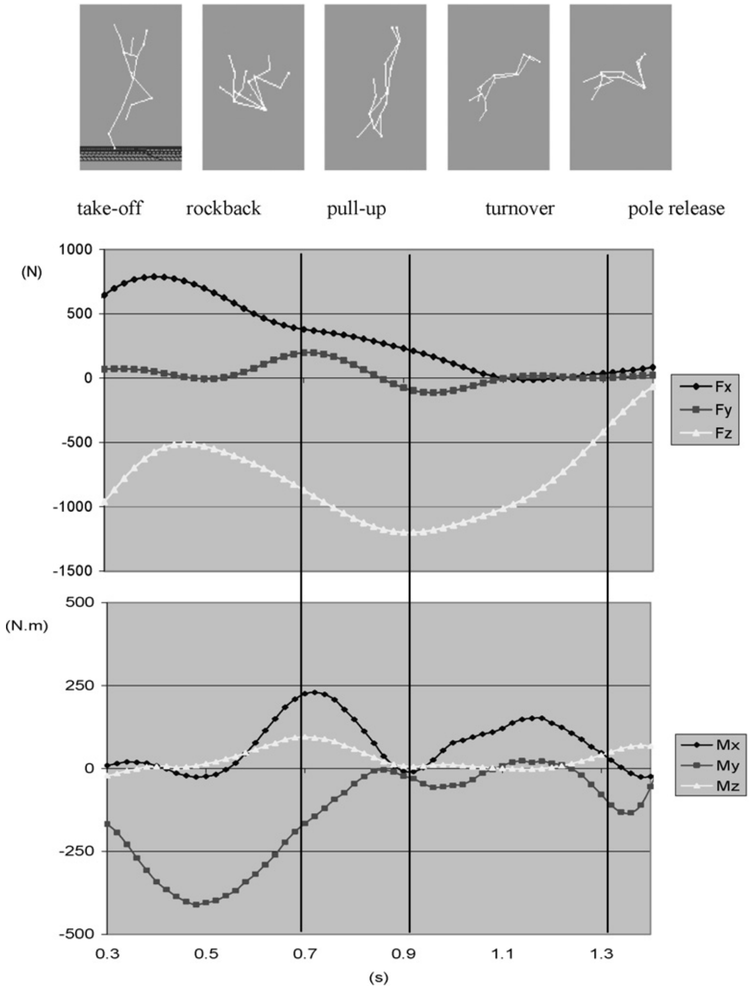

Fig. 3. Pole-vaulter force and moment at point M exerted on the pole during the jump phase.

Fig. 3. Forces et moment au point M exercés sur la perche par l'athlète durant le saut.

The observations carried out on the pole-vaulter's force can also apply to the moment (Fig. 3). Indeed, during the first jump stage, the moment is primarily applied in the transverse direction y. The assumption of action contained in plane (x, z) is then totally justified. During this stage (from 0.3 to 0.7 s), the pole-vaulter rotates around his hips (rock back). This makes it possible to apply a negative moment around axis y to the pole.

Then, the pull-up (from 0.7 to 0.9 s) and turnover (from 0.9 to 1.3 s) stages authorize the pole-vaulter's rotations around the two other axes. Therefore, the components around the two axis x and z are not equal to zero but remain low compared to the y component.

As a general conclusion, it can be said that the pole-vaulter's moment applied to the pole in the direction y introduces a bending moment into the structure that can be used as a significant performance criterion.

5. Discussion

In order to illustrate the importance of the moment applied to the pole, a comparative study was carried out on two pole-vaulters having comparable morphologies and performing with the same pole. Moreover, the two pole-vaulters did not have the same technical level and did not accomplish the same performance. During this test, pole-vaulter 1 achieved a 4.9 m jump versus 4.49 m for pole-vaulter 2.

Fig. 4 aims to clarify the weak variation observed in the values of the force developed on the pole in the direction z.

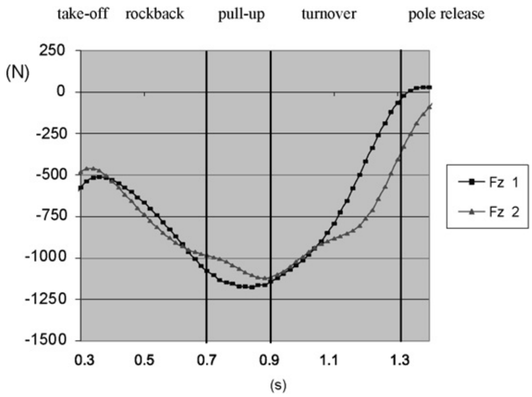

Fig. 4. Vertical component of the force exerted on the pole.

Fig. 4. Composante verticale de la force exercée sur la perche.

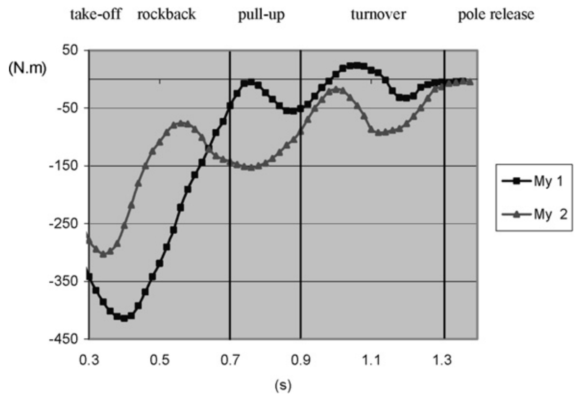

Fig. 5. Moment at point M applied to the pole around y.

Fig. 5. Moment au point M appliqué à la perche selon y.

A variation of 6% on the maximum values of the force was observed. The evolution of that force during the jump is completely similar for the two pole-vaulters. Nevertheless, as pole-vaulter 1 stored more deformation energy in the pole, the straightening of the pole was faster (from 1.1 to 1.3 s).

The analysis of the forces developed on the pole does not make possible to distinguish the performances of these two pole-vaulters. Then, it is necessary to determine the moment applied to the pole. All the slight force differences are in the same direction of the performance index: pole-vaulter 1 has achieved a higher jump than pole-vaulter 2.

Fig. 5 presents the results for the transverse component around axis y of the moment applied to the pole. These values are essential because they describe the pole-vaulter's ability to apply a bending moment to the pole.

The moment analysis leads to trying to define an essential performance criterion. In this example, the variations of the forces were too low to allow a clear distinction between the two gestures. At the same time, the differences between the moments appear much more sensitive.

During the first part of his jump, the pole-vaulter uses the rotation of his legs around his hips to bend the pole and thus to store deformation energy. One notes, during this first phase (rockback), that the transverse component of the moment is very different from one pole-vaulter to another. The better pole-vaulter applies a more significant negative moment. The difference between the maxima rises up to 27%. In the second phase of the jump (pull-up and turnover), the pole-vaulter uses the pole energy to clear the bar. There, the y component of the moment must be weak not to slow down the elastic return of the pole. It is noted that pole-vaulter 1 uses this possibility whereas pole-vaulter 2 generates a more significant moment which slows down the pole and limits performance.

This result confirms the pole-vaulter's ability to bend the pole and then to apply a significant bending moment.

In conclusion, the present study shows that the moment applied to the pole is an essential performance factor as well as the vertical component of the force exerted on the pole. Moreover, this stage is essential to simulate the dynamic behaviour of the pole under chosen efforts in order to optimise the mechanical characteristics for each type of pole-vaulter.

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