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19:3; 43-54, 2004

Technical and conditioning aspects of the women's pole vault

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Translated from the original German by Jürgen Schiffer

ABSTRACT

The aim of this study was to obtain basic knowledge of the performance-determining aspects of the women's pole vault. One focus was on the mechanical and energetic aspects of the movement process in the event. This examination was conducted using female athletes of a very high performance level. It was found that 86% of the variance in the height of the CM (centre of mass) achieved by a vaulter could be explained by the combination of two factors: initial energy (the total of the body's level of energy at the time of the last touchdown of the take-off foot) and energy gain (the increase in the body's energy through muscular work during the course of the vault). The second focus was on the special physical abilities that are needed for coping with the demands of the pole vault. For this part of the work, female athletes of various levels of ability were studied and compared. Standard tests of sprinting ability (with and without a pole) and jumping strength, and experimental tests of trunk strength (mechanical output in both the rockback and extension movements) were used in an effort to develop a diagnostic procedure. It was found that on average the better vaulters achieved higher values in most, but not all, of the tests used. Finally, the extent to which female pole vaulters exploit their potential was examined and factors that can lead to better vaulting performances were identified.

AUTHOR

Stefanie Grabner was awarded a Ph.D by the German Sports University in Cologne, Germany in 2003. Her dissertation, entitled Production and Exchange of Mechanical Energy in the Women's Pole Vault Under Particular Consideration of Individual Physical Prerequisites (published by Shaker in Aachen/ Germany), has been used as the basis for this article.

Problem

Over the course of the last decade, athletics disciplines that had previously been reserved for men have become established in the women's competition programme. The triple jump, hammer throw and the pole vault for women are all now included in the programmes of World Championships in Athletics, European Championships and Olympic Games.

In the case of the pole vault, inclusion on the international level has led to the event's popularity with female athletes in a number of countries and a steady improvement of both performance levels and performance density. There is a high and continuously increasing demand for consolidated sport science knowledge of this still young event as athletes and coaches question the causes of these improvements and seek ways to make training more effective and achieve even better results in competition.

A complex performance diagnosis in a sports discipline should include both a sound analysis of the the athlete's technique, with the identification of performance-determining characteristics of the movement process, and an extensive analysis of the athlete's physical condition.[1,2] In the context of the pole vault, the latest biomechanical findings emphasise the special significance of energetic aspects in the technique analysis.[3,4,5,6,7,8,9,10,11,12,13] However, there is a fundamental deficit of this type of information on the women's pole vault. Moreover, as yet there has not been an extensive study of the physical prerequisites for women in the event.

Mechanical-energetic analysis

Methodology

Using a three-dimensional kinematic analysis two questions were examined:

1 To what extent are the athletes able to create kinetic energy during the approach?
2 To what extent are the athletes able to utilise this kinetic energy throughout the rest of the vault or to transform it into potential energy?

The subject sample included the first ten placed vaulters at the 1998 German Indoor Championships in Sindelfingen. At the time of the investigation, eight of these athletes were ranked among the top twenty on the yearly world list. In this competition, the sample athletes achieved a mean maximum height of their centre of mass (h_{CM}(max)) of 4.17m (s=0.18) on their best valid attempt.

Video recordings were made with four shutter cameras (two Hi-8 and two S-VHS cameras), which were synchronised through Genlock and LEDs (Light Emitting Diodes). The frame rate was 50Hz with a shutter time of 1/1000sec.

Cameras 1 and 3 recorded the vaulters' movements from the penultimate ground contact to shortly after the maximum flexion of the pole, while cameras 2 and 4 recorded the movements from the position of maximum pole flexion until the completion of bar clearance. This division of the movement recording into two phases is necessary to guarantee a sufficiently great spatial resolution of the video material. The area covered by each camera was about 6m x 4m.

All cameras were placed above the terraces of the stadium, in an elevated position relative to the pole vault facility. Cameras 1 and 2 were positioned next to each other and recorded the movements in the direction of the vault from the right at an angle of about 70° to the main movement plane. To make a three-dimensional evaluation possible, cameras 3 and 4, which were also positioned next to each other, recorded the vaults diagonally from behind at an angle of about 90° to cameras 1 and 2.

A reference cage with a length of 4m in the direction of the vault, 2m in the take-off area and 4m in the area of the further course of the vault was used for scaling.

The digitising equipment of the PEAK-MOTUS system was used for evaluation of the data collected. A Butterworth filter with at cutoff frequency of 5Hz was used for smoothing the data. To obtain 3D coordinates from the camera set-ups mentioned, the DLT (Direct Linear Transformation) method was used. The calculation of the coordinates of the CM is based on data provided by ZATSIORSKY et al.[14]

From the available three-dimensional data material, the body's total energy (E_{tot}) was calculated as the sum of the potential energy (E_{pot}) and the kinetic translatory and rotatory energy (E_{kin}). This was done as follows:

$$E_{tot} = \sum_{i=1}^{12} m_i\, g\, h_i + \sum_{i=1}^{12} \frac{m_i\, v_i^2}{2} + \sum_{i=1}^{12} \frac{\theta_{iTR}\, \omega_{iTR}^2}{2} + \frac{\theta_{TLO}\, \omega_{TLO}^2}{2}$$

In this equation m_i is the mass of the i-th segment, g is gravity, h_i the height of the CM of the i-th segment, v_i the velocity of the CM of the i-th segment, θ_{iTR} the mass inertia moment of the i-th segment about its transversal axis, ω_{iTR} the angular velocity of the longitudinal axis of the i-th segment, θ_{TLO} the mass inertia moment of the trunk about its longitudinal axis and ω_{TLO} the angular velocity of the trunk about its longitudinal axis.

To facilitate the comparability of the athletes, the total energy was normalised to the body mass.

Results

Consideration of the body's energy reveals both how much energy athletes create during the approach and to what extent they are able to add energy through muscular work on the pole during the course of the vault.

At the time of the last touchdown of the take-off foot (t_{TD}), ie at the end of the approach, which is the main phase of energy creation, a mean total energy of 39.93 J/kg (joule per kilogram of bodyweight) was measured for the subject group. This means that by this point in the vault, 91.8% of the energy that the athletes exhibit at the time of the maximum CM height (t_{HP}) has been achieved. The peak value of 42.97 J/kg was not reached by N.R., the winner of the competition, but by M.G., the vaulter who placed second.

All the vaulters studied could significantly increase the total energy of their body during the course of the vault, ie from the time of the last touchdown of the take-off foot (t_{TD}) until the time of the maximum CM height (t_{HP}). On average the "energy gain" was 3.58 J/kg (Figure 1). The highest energy value at the time of the maximum CM height, 46.26 J/kg, was achieved by Y.B., the vaulter placed third, while A.S., the vaulter placed tenth, could only reach 40.71 J/kg. As an example, Figure 2 shows the energy course of the athlete N.R. during her vault over 4.25m.

Significant or highly significant correlations of the body's total energy with the height of the bar cleared as well as with the maximum CM height (h_{CM}(max)) can be verified at the following points in time: t_{TD} (time of the last touchdown of the foot), t_{PS} (time of the complete pole extension), t_{PR} (time of leaving the pole), and t_{HP} (time of the maximum CM height).

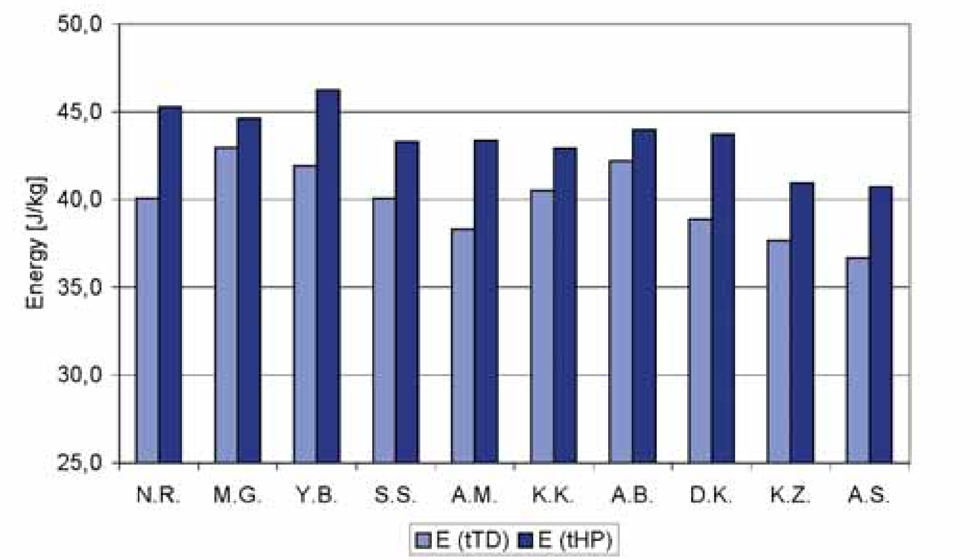

Figure 1: Total energy of the body at the time of the last touchdown of the foot (t_{TD}) and of the highest point of the CM (t_{HP}).

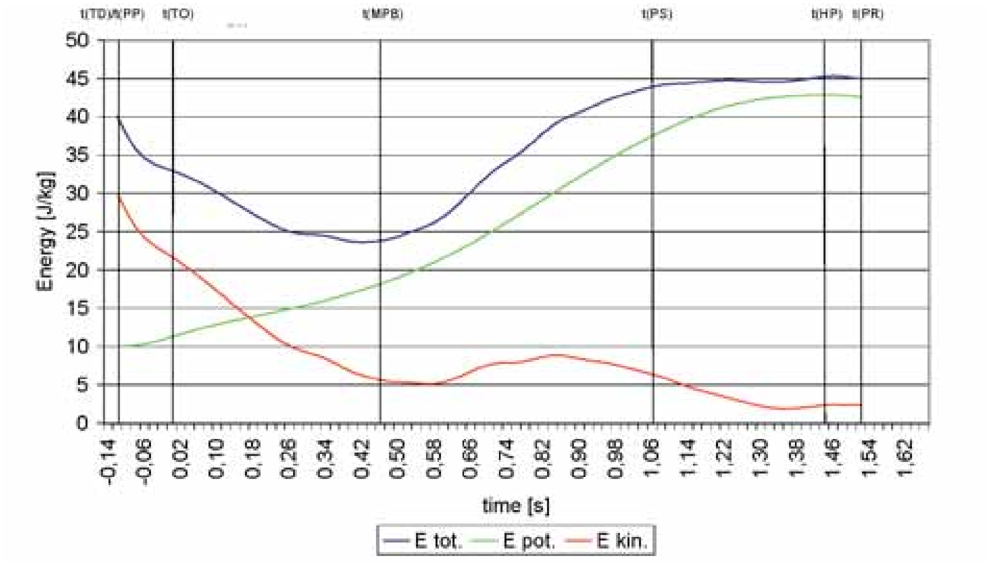

Figure 2: Energy course of the 4.25m vault by N.R.

Using multiple linear regression analysis, the relationships between the predictor variables initial energy ($E(t_{TD})$) and energy gain ($E(t_{HP})-E(t_{TD})$) and the criterion variable $h_{CM}(max)$ have been analysed in more detail. The results show that with the exclusive integration of the variable $E(t_{TD})$ into the model, only 55.3% of the variance of $h_{CM}(max)$ can be explained. Here, the correlation coefficient is 0.744. However, if the factors $E(t_{TD})$ and $E(t_{HP})-E(t_{TD})$ are considered together, the multiple correlation coefficient is R = 0.927. Using both factors, 86.0% of the variance of $h_{CM}(max)$ can be explained.

As a function of the selected variables $E(t_{TD})$ and $E(t_{HP})-E(t_{TD})$, $h_{CM}(max)$ can be calculated as follows:

$$h_{CM}(max) = -0.09431 + 0.09866\,(E(t_{TD})) + 0.09176\,(E(t_{HP}))-E(t_{TD}))$$

In Table 1, the relative influence of the variables initial energy and energy gain on the criterion variable $h_{CM}(max)$ is quantified making it possible to weight the influence of the individual factors on the dependent variable. For this purpose the mean value of each factor is varied by the amount of a standard deviation, with the other factor being kept constant in the regression equation. The estimations of the degree of influence of the different factors are comparable because in each case the variation is made within an interval including 68% of the measuring values of the sample examined. In the present study, with medium values of the influencing factors initial energy (39.92 J/kg, s=2.06) and energy gain (3.58 J/kg, s=1.32), a maximum CM height ($h_{CM}(max)$) of 4.17m can be calculated. If the mean values are varied by one standard deviation each, the values presented in Table 1 are obtained.

	$E(t_{TD})$	$E(t_{HP})-E(t_{TD})$
$\Delta h_{CM}(max)$ [m]	0.20	0.12

Table 1: Relative influence on $\Delta h_{CM}(max)$ of the predictor variables initial energy ($E(t_{TD})$) and energy gain ($E(t_{HP})-E(t_{TD})$).

The considerably greater effect of the factor initial energy, as compared to energy gain, can be clearly seen. The increase of the initial energy by one standard deviation can cause an increase of the maximum CM height by 0.20m. On the other hand, with an increase of the energy gain by one standard deviation an increase in height of only 0.12m can be expected.

Conditional prerequisites

Methodology

Analysis of the conditional abilities in the areas of sprinting, jumping, and trunk strength (rock-back and extension test) was made of female pole vaulters from three different performance categories. Group 1 (G 1), which included world-class athletes, had an average PB (personal best performance) of 4.39m (s=0.12); Group 2 (G 2) had an average PB of 4.15m (s=0.06) and Group 3 (G 3), which consisted of young female pole vaulters, had an average PB of 3.22m (s=0.13).

The data on the young pole vaulters (G 3) was collected in March 2000, while the conditional tests on the other two groups were conducted in March 2001. All test series were conducted in the athletics hall of the German Sport University in Cologne.

To assess sprinting ability, test runs were conducted over a distance of 20m from a "flying" start. The velocities over the first and second 10m sections were measured by means of double light barriers. The athletes' sprint velocity without a pole and then with a pole were measured. By comparing these results with the approach velocities measured during competitive vaults one can see whether the athletes have reserves, eg whether they exploit their velocity potential during competition or not.

For further evaluation, the maximum velocity reached over a 10m section was considered in each case.

For the assessment of take-off effectivity, standard jumping-strength diagnostics, which consist of the squat jump, countermovement jump and drop jump (from a height 22cm), were selected.[15,16] Using this procedure, it is possible to analyse the vaulters' purely concentric strength abilities and particularly their ability to develop strength during the stretch-shortening cycle.

The recording of the external ground reaction force for the standard jumping-strength diagnostics was made using a piezoelectric force plate manufactured by KISTLER.

In order to check the athletes' prerequisites for performing muscular work on the pole, a special measurement procedure, based on knowledge about the movement execution under competitive conditions, was developed. This method makes it possible to analyse the vaulters' specific trunk-strength abilities during both the hip–flexion phase (the rock-back movement until approximately the time of maximum pole flexion) and the hip-extension phase (the extension movement during the pole straightening phase). To facilitate dynamic strength measurement, the M3 strength diagnosis equipment manufactured by SCHNELL, which allows the execution of the desired hip-

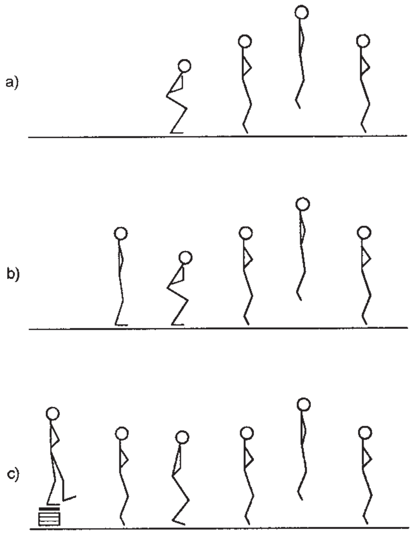

Figure 3: Standard jumping-strength diagnostics: a) squat jump, b) countermovement jump, c) drop jump.

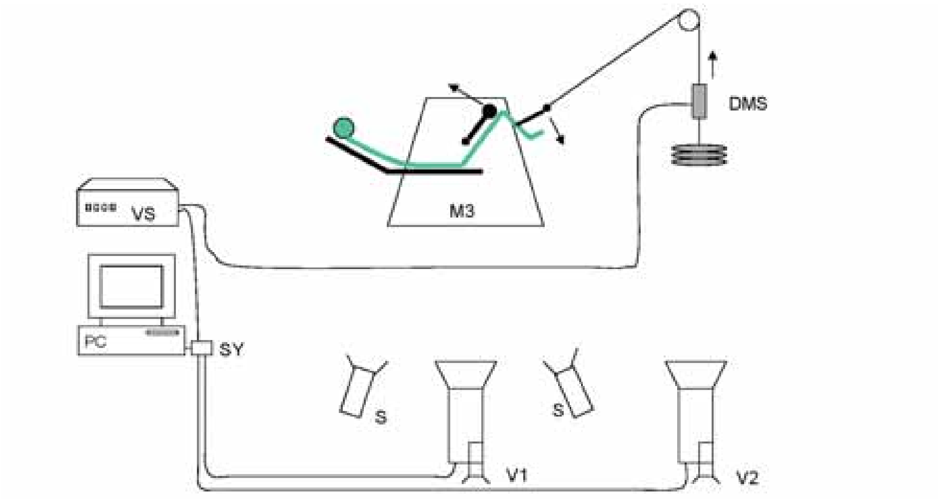

Figure 4: Experimental setup for the hip-flexion exercise (rock-back test). M3: M3 strength training and diagnostics equipment manufactured by SCHNELL, DMS: DMS force sensor, VS: DMS amplifier, SY: synchronisation unit, PC: measuring computer, V1+V2: video cameras (Hi 8), S: spotlights.

flexion and hip-extension movement in a way similar to that which takes place during the pole vault, was expanded by several components (Figs. 4 and 5). The angle area defined for the test exercises was determined using the results of the analysis of the complex pole vault movement under competitive conditions. As a result, the movement range during the hip-flexion test was 152° - 63° and 48° - 152° during the hip-extension test. When selecting the weight resistances (5kg, 10kg and 15kg in the hip-flexion test, and 15kg, 20kg and 25kg in the hip-extension test), special care was taken that the movement could still be executed at a high velocity.

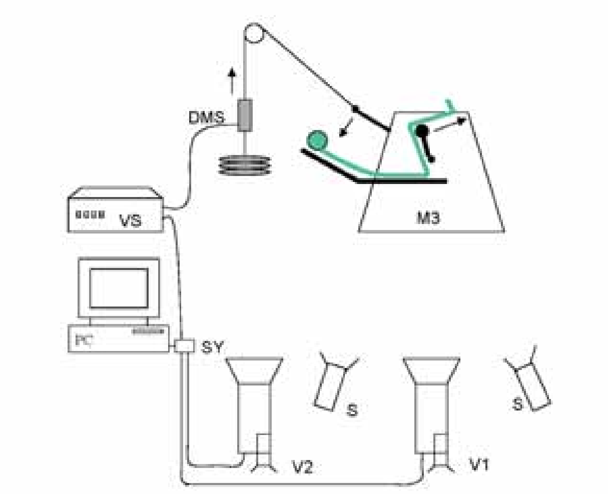

Figure 5: Experimental setup for the hip-extension exercise (extension test). M3: M3 strength training and diagnostics equipment manufactured by SCHNELL, DMS: DMS force sensor, VS: DMS amplifier, SY: synchronisation unit, PC: measuring computer, V1+V2: video cameras (Hi 8), S: spotlights.

The aim was to find out how much total energy the athletes were able to create (because in the course of the complex pole vault movement they must create, through muscular work, as much energy as possible during the pole phase) and the speed at which this energy is created (because to utilise the energy exchange with the vaulting pole as effectively as possible, the energy must be created during a relatively short period of time). The results of these measurements give a value for the particularly significant parameter of mechanical output (work/time).

Results

During the conditional test series conducted with the vaulters of different performance categories, numerous biomechanical parameters particularly in the area of jumping and trunk strength diagnostics were collected. In the following, the results of those parameters taken from the present study[17] which are of special interest to the coaches of performance-oriented female pole vaulters will be presented. Apart from the results of the sprint test, these are the jumping heights as performance criterion in the squat jump and countermovement jump as well as the mean mechanical output in the drop jump. From the trunk-strength diagnostics (rock-back and extension test), the mean mechanical output achieved by the athletes in each test is presented.

With regard to sprinting ability, the vaulters of the strongest group (G 1) achieved a mean value of 8.18m/s without pole and a mean velocity of 7.78m/s with pole. It is notable that the performances of this group were very heterogeneous. While the strongest sprinter of this group, S.S. (PB in the pole vault: 4.30m) could reach velocities of 8.73m/s without and 8.29m/s with pole, N.H. (PB: 4.56m) only reached velocities of 7.76 and 7.39m/s respectively. This means that she is clearly below the mean values of G 2 (8.06m/s without pole and 7.46m/s with pole). The vaulters of the youth group (G 3) reached mean velocities in the sprint test of 7.96m/s without pole and 7.39m/s with pole (Figure 6).

When considering the sprint results it also emerges that the strongest athletes (G 1) show a significantly lower loss of velocity (0.41m/s) caused by carrying the pole than the other vaulters (0.61m/s in G 2 and 0.58m/s in G 3).

The correlation statistics do not show a significant relationship between the sprint parameters and the PB in the pole vault.

In the squat jump the athletes of G 1 reached a higher maximum jumping height on average than the athletes of G 2 (29.3cm as compared to 26.8cm). However, the latter group showed a very marked scattering of results (Figure 7). The average maximum jumping height of the vaulters of the youth

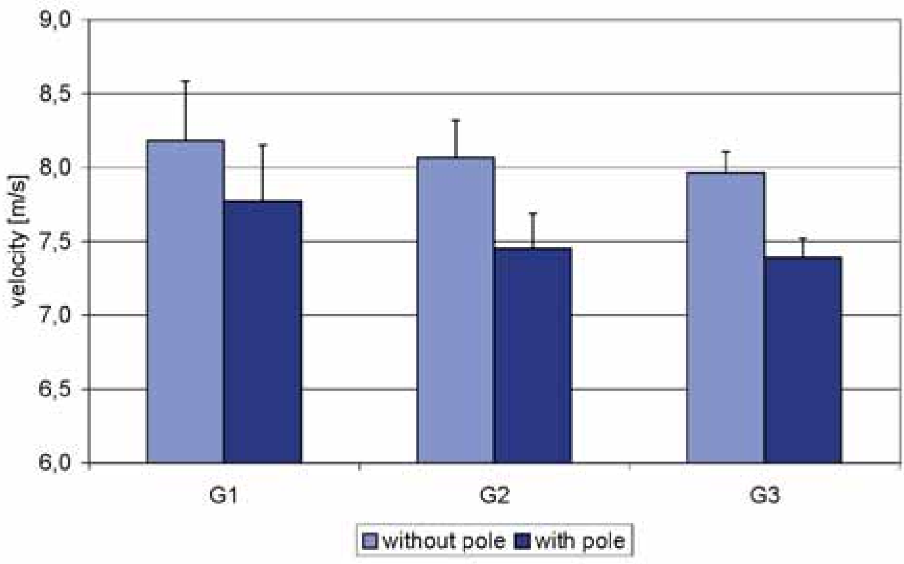

Figure 6: Overview of the sprint velocities without and with pole

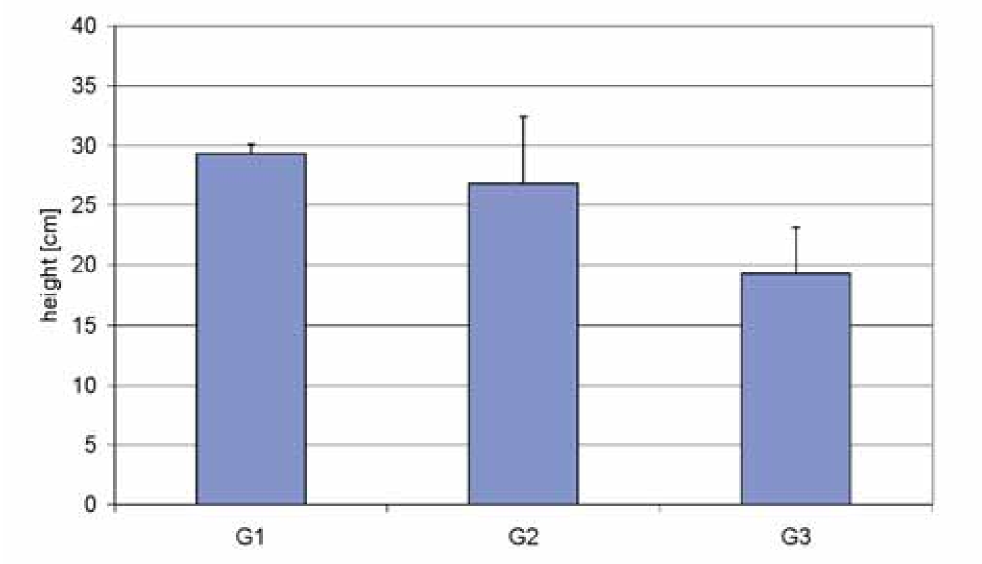

Figure 7: Jumping heights in the squat jump

group (G 3) was only 19.2cm. Significant differences between the mean values could only be found in G 1 and G 3.

When executing an introductory swinging movement the vaulters of the top group could increase their average maximum jumping height from the squat jump by 2.9cm to 32.2cm, while in G 2 the average increase in jumping height was 2.1cm (to 28.9cm). However, the greatest increase in average jumping height (7.2cm) was observed in G 3. The athletes of this group reached 26.4cm in the countermovement jump, while in the squat jump they could only reach 19.2cm (Figure 8). As far as the jumping height is concerned, significant differences in the mean values only exist between the top group (G1) and the youth group (G 3).

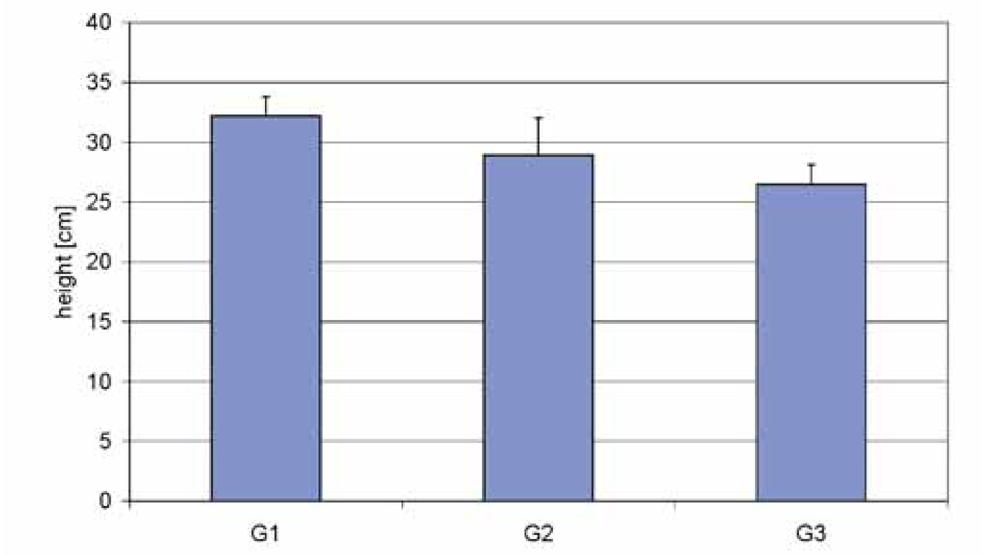

Figure 8: Jumping heights in the countermovement jump

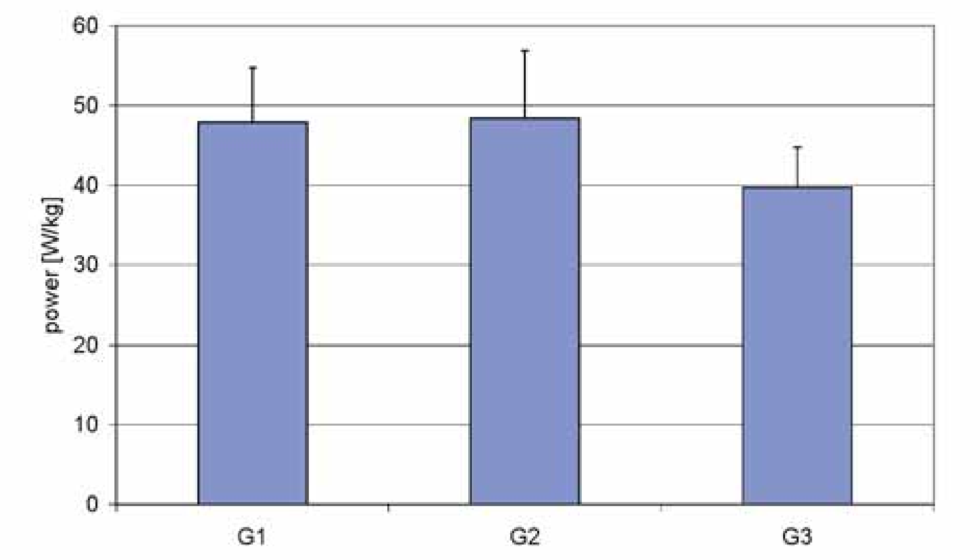

Figure 9: Mean mechanical output of the athletes in the drop jump

Regarding the mean mechanical output in the drop jump (Figure 9), it turned out that the vaulters of G 2 achieved slightly higher values on average (48.32W/kg) than the athletes of the top group (47.89W/kg). Once again, in both groups the performances were very heterogeneous. The athletes of the youth group reached a mean mechanical output of 39.71W/kg. Statistically significant differences between the mean values could not be found between the groups.

However, it emerged that significant correlations existed between both the jumping height in the squat jump and countermovement jump and the mean mechanical output in the drop jump and the best pole vault performances of the athletes.

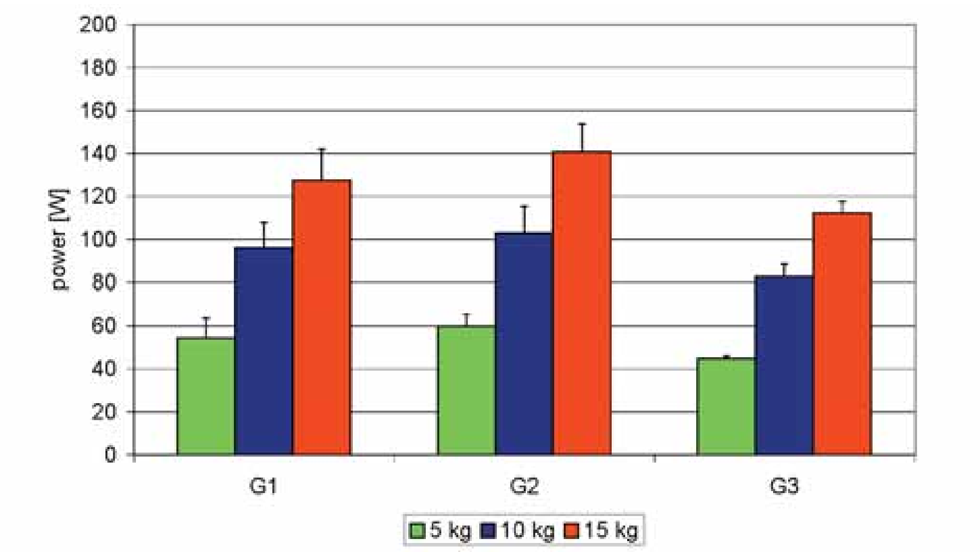

Figure 10: Comparison of the mean mechanical output of the athletes in the rock-back test (hip flexion) with a mass of 5kg, 10kg and 15kg

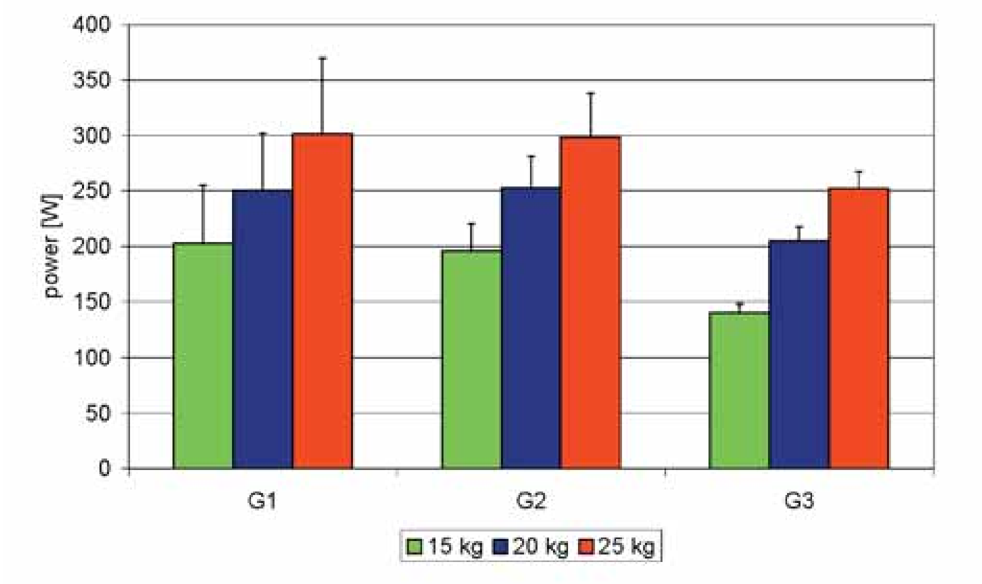

Figure 11: Comparison of the mean mechanical output of the athletes in the extension test (hip extension) with a mass of 15kg, 20kg and 25kg

As far as the mean mechanical output in the rock-back test (Figure 10) is concerned, the vaulters of G 2 achieved higher average values (60.02W with a weight load of 5kg, 102.98W with 10kg and 140.64W with 15kg) in all three exercises than the athletes of G 1, who reached 54.41W (5kg), 95.87W (10kg) and 127.53W (15kg). Here, too, the performances within the groups were very heterogeneous. The youth vaulters achieved a mean mechanical output of 45.08W in the rock-back test with 5kg, 82.86W with 10kg and 112.24W with 15kg. Significant differences were found between G 2 and G 3 regarding the mean values in the test exercises with 5kg as well as with 15kg.

As far as the mechanical output is concerned, the mean values of the two strongest groups in the extension test (Figure 11) differ only slightly. The athletes of G 1 reached an average value of 202.39W in the exercise with 15kg, 250.57W with a load of 20kg and 300.94W in the test with 25kg, while the vaulters of the G 2 reached 195.77W (15kg), 252.41W (20kg) and 298.55W (25kg). Members of the youth group, with 140.68 W (15 kg), 204.48 W (20 kg) and 251.97 W (25 kg) achieved significantly lower values of medium mechanical output in the hip-extension test than the world-class athletes in G 1. Statistically significant differences regarding the mean values only exist between G 1 and G 3 in the test exercise with 15kg.

The correlation statistics show verifiable relationships between the athletes' PB in the pole vault and the mechanical output in the rock-back test with 5kg and 15kg as well as in in the extension test with 15kg and 25kg.

Summary and conclusions

The results of the mechanical-energetic analysis of the world-class vaulters very clearly show the enormous significance of the energetic parameters to the total vaulting performance. The factors "initial energy" ($E(t_{TD})$) and "energy gain in the further course of the vault" ($E(t_{HP})$-$E(t_{TD})$) together explain 86% of the variance of the maximum CM height ($h_{CM}(max)$). For the two factors mentioned a multiple correlation coefficient R = 0.927 was calculated.

As far as the conditional prerequisites are concerned, statistically significant differences regarding the mean values were identified between G 1 and G 3 (for the squat jump and countermovement jump as well as the extension test with a weight load of 15kg) and G 2 and G 3 (particularly for the rock-back test). However, between the two stronger groups there are no differences with the exception of the sprint with pole as compared with the sprint without pole. To some extent, this could be caused by the heterogeneity within the groups.

While under competitive conditions a highly significant relationship could be verified between the velocity of the CM during the last step and the maximum vaulting height, as far as the conditioning test is concerned the correlation statistics do not show any relationships between the sprint velocities (with or without pole) and the athletes' best pole vault performance. It is possible that not all vaulters can realise their sprint-performance potential in the competitive situation.

On the other hand there are significant correlations between almost all parameters of the jump-strength diagnostics, particularly jumping heights as well as medium and maximum mechanical output, and the complex pole vault performance. Regarding the rock-back and extension test, there are also correlative relationships between various strength, work and performance characteristics and the athletes' PB in the pole vault.

Most of the relationships within the parameter-groups "sprint test", "jumping-strength diagnostics" and "rock-back and extension test" are significant. Because of the highly significant correlations between the rock-back test exercises with various weight loads as well as the extension tests with different masses, it is possible to restrict oneself to one singular test each in the two areas for reasons of economy. Here the rock-back test with 15kg and the extension test with 25kg are selected because in these two exercises the highest amount of mechanical work is done and the highest mean mechanical output is achieved. In spite of the relatively great masses, a high movement velocity can be maintained.

When considering the correlations between the conditional parameters, the close connections between the sprinting and jumping-strength parameters are striking. Contrary to this, there are almost no relations between the sprinting and trunk-strength parameters and only a few relations between the jumping-strength and trunk-strength diagnostics (here especially concerning the extension test).

The individual analysis of selected female pole vaulters regarding the relationships between energetic and conditioning parameters leads to the following conclusions: The initial energy of the athletes analysed during the competitive vault can mostly be explained by their ability to sprint while carrying the pole. On the other hand, the good jumping and trunk-strength abilities of some vaulters at the time of the investigation did not manifest themselves in their energy balance during the complex pole vault movement.

Finally it can be said that the exploitation of the performance reserves in all areas or the optimisation of the conditional prerequisites in connection with improvements of the vaulting technique will certainly lead to further increases in the women's pole vault performance in the coming years.

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