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The Hecht vault performed at the 1995 World Gymnastics Championships: Deterministic model and judges' scores

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The aim of this study was to determine the mechanical variables that govern success of the Hecht vault. The participants were 122 male gymnasts from 30 countries performing the vault at the 1995 World Gymnastics Championships. The vaults were filmed using a Photosonics 16-mm motion picture camera operating at 100 Hz. Approximately 80 frames were digitized for each vault analysed. The method of Hay and Reid was used to develop a theoretical model to identify the mechanical and physical variables that determine linear and angular motions of the vault. Correlational analysis was used to establish the strength of the relationship between the causal mechanical variables identified in the model and the judges' scores. Significant correlations ($P < 0.005$) indicated that the following were important determinants of success: large horizontal and vertical velocities at take-off from the board and the horse; large vertical and angular distances of pre-flight; large vertical impulses of high force and short duration exerted on the horse and the resulting large changes in vertical velocity on the horse; and large horizontal and vertical distances and long times of post-flight. Of the 18 significant variables identified in the present study, the angular distance of pre- and post-flights, the horizontal velocity and angular momentum at take-off from the horse, and the average moment of inertia and duration of post-flight collectively accounted for 57% of the variation in the judges' scores.

Keywords: biomechanics, deterministic model, gymnastics, Hecht vault, judges' scores.

Introduction

Of the events in gymnastics, the fewest skills are required in vaulting. All the vaults are categorized into either the continuous rotation or counter-rotation family of vaults. In the continuous rotation vaults, such as the handspring vault, the direction of body rotation about the somersaulting axis in the second flight phase (post-flight) is the same as that in the first flight phase (pre-flight). In counter-rotation vaults, the direction of body rotation in the post-flight is in the opposite direction from that in the pre-flight, as in the Hecht vault. In the performance of the Hecht vault, the original rules of compulsory exercises (Fèdèration Internationale de Gymnastique, 1993) required the body angle above the horizontal at hand contact on the horse to be at least 30°. Subsequently, this angle was reduced to 20° to promote more 'dynamic performances' (Fink and Zschoke, 1994). The gymnast leaves the take-off board with forward somersaulting rotation and continues to rotate forwards as the body travels forwards and upwards over the horse during the pre-flight and early horse contact phases to attain the required body angle of 20° above the horizontal (Fèdèration Internationale de Gymnastique, 1997). During the latter part of the horse contact phase, the gymnast reverses the direction of body rotation by blocking and pushing off the horse with the upper limb and shoulder muscles and flexing the trunk and hips slightly while on the horse (Kaneko, 1974). However, many gymnasts find it

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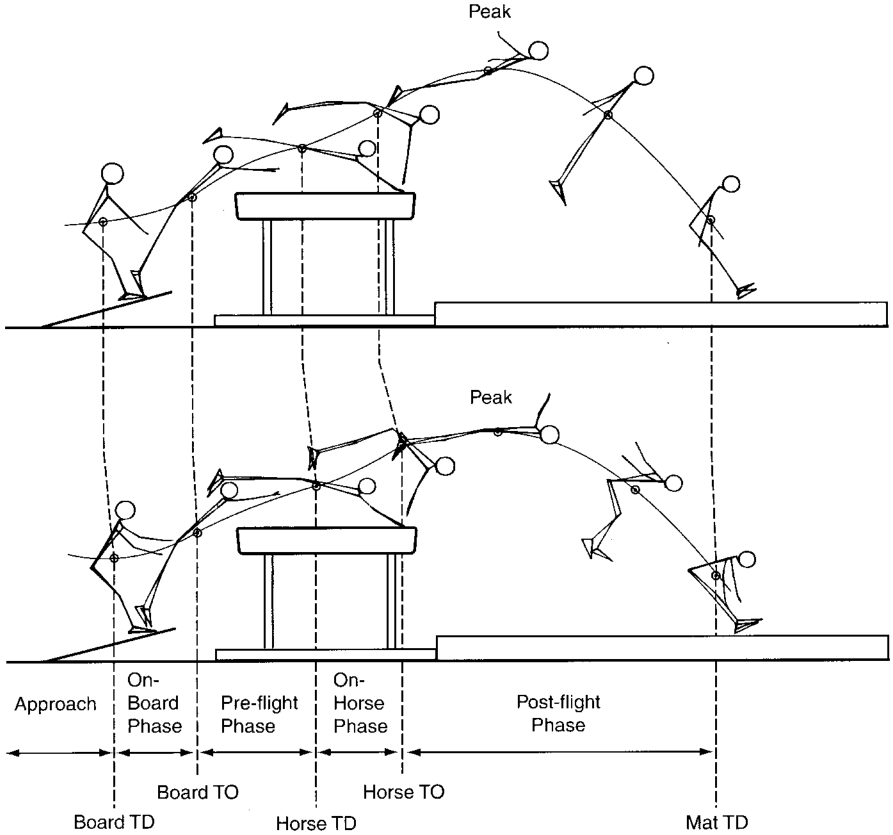

Fig. 1. The five phases of the Hecht vault: approach (run-up approach followed by a hurdle step onto the take-off board), on-board (foot contact on board to departure from the board), pre-flight (the first flight phase), on-horse (hand contact on horse to departure from the horse) and post-flight (the second flight). The vaults shown are the highest-scoring (upper, 9.65 points) and the lowest-scoring (lower, 7.975 points) Hecht vaults from the 1995 World Gymnastics Championships. TD = touchdown; TO = take-off.

difficult to execute this 'on-horse' reversal of direction with good form and technique, as shown by the lower sequence in Fig. 1. After departing from the horse, the gymnast must fulfil the post-flight height and distance requirements while continuing to travel forwards and upwards as the body rotates backwards (a distinct rise of the buttocks to at least 1 m above the horse and land at least 2.5 m beyond the far end of the horse in a standing position) (Fèdèration Internationale de Gymnastique, 1997). Exceeding the post-flight height and distance requirements and maintaining the fully extended body position throughout the post-flight, as seen in the upper sequence of Fig. 1, warrant possible bonus points, but these features are difficult to achieve when having to meet the body angle requirement of 20° at touchdown on the horse. In fact, 'bonus points can only be awarded for extremely high execution of the vault with a landing far beyond the normal distance of 2.5 m' (Fèdèration Internationale de Gymnastique, 1997).

The take-off board with a high coefficient of restitution, adopted since 1956, often causes 'excessive' body elevation and forward body rotation in pre-flight, resulting in an 'accidental body turnover' while on the horse (Kaneko, 1974). Therefore, it is a great challenge for the gymnast to control this reversal action by counteracting the undesirable 'excessive' forward rotation effect of today's springy take-off board. Risk of injury is great when the gymnast fails to reverse the direction of body rotation, which results in disastrous consequences such as landing upside down (Kaneko, 1974). Despite the seriousness of injuries, analysis of techniques of blocking and pushing off the horse when performing the counter-rotation vaults has been limited (Takei *et al.*, 1998; King *et al.*, 1999). The counter-rotation vaults are important in developing a foundation not only for the vaults of the same family, but also for the continuous rotation vaults (Kaneko, 1974).

Yeadon *et al.* (1998) investigated the relationship of pre-flight characteristics to post-flight performance in 27 elite gymnasts performing the Hecht vault at the 1993 Canadian National Championships. They found that the maximum height of post-flight was positively

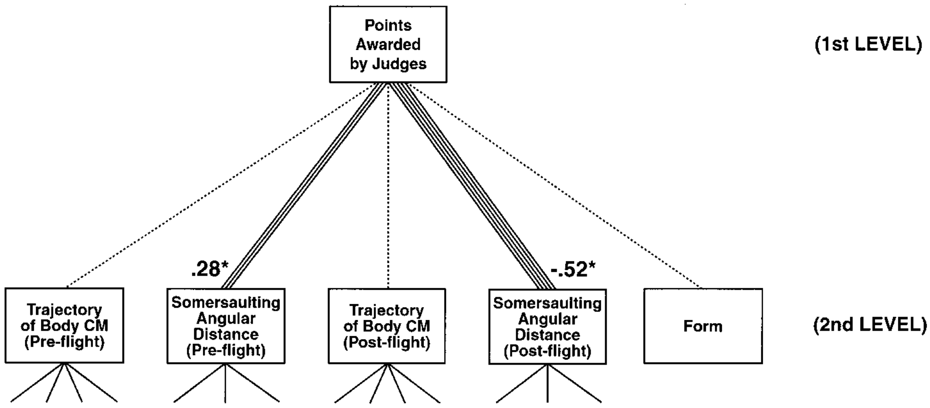

Fig. 2. Model showing five factors that determine the linear and angular motions and aesthetic performance of the Hecht vault, and zero-order correlations with the judges' score (* denotes significance). The number of lines linking variables indicates the magnitude of the relationship (e.g. 5 lines indicate $r = 0.50$). The dotted lines indicate a possible (untested) relationship involving a non-quantifiable variable.

correlated with the vertical velocity and the body angle at horse contact. The 1995 World Gymnastics Championships provided an opportunity to study the techniques of elite performances of this vault, 3 years after its introduction into the compulsory competitions. The World Championships include far more participating countries and gymnasts than the Olympic Games, in which the participants are limited only to those from the qualifying nations. Consequently, the championships provided a good opportunity to study the Hecht vault with a sample of gymnasts exhibiting a relatively wide range of skill. Takei *et al.* (1998) investigated the 25 highest- and 25 lowest-scoring vaults of the 122 Hecht vaults filmed during the championships to identify the kinematic and kinetic differences in the techniques used by the two groups. The results of *t*-tests used to compare group means indicated that the vaults receiving high scores demonstrated greater horizontal velocity at take-off from the board, larger vertical velocity at take-off from the horse, and a longer duration of post-flight than those receiving low scores. Although these differences are important for improving performance, they do not indicate the strength of the relationship between these variables and successful performance of the Hecht vault as rated by the judges. However, Takei *et al.* (1998) noted a trend towards a significant positive relationship between the judges' score and the aforementioned mechanical variables, in which larger mean values were found for the high-scoring vaults. The present study was designed to determine the strength of the relationship between the causal mechanical variables of the vault and the judges' scores. We wished to identify the mechanical variables (through development of a deterministic model and subsequent correlational analysis) that are crucial for achieving success in the performance of the Hecht vault.

Methods

Deterministic model

A deterministic model was developed to systematically guide the analysis between the mechanical variables and the judges' score. The model consists of five factors (two pre-flight factors, two post-flight factors and form), which are identified in the second level and linked, from below, to the 'points awarded by judges' shown in the first level (Fig. 2). In developing a model to analyse the pre-flight, two factors must be considered: (1) the linear motion reflected in the path of the centre of mass and (2) the angular motion reflected in the angular distance through which the gymnast rotates about the somersaulting axis. As shown in Fig. 3, the trajectory of the centre of mass in pre-flight is governed by the resultant velocity at take-off from the board, the relative height of take-off, the air resistance encountered in flight and the acceleration due to gravity. The resultant velocity at take-off from the board is the vector sum of the horizontal and vertical velocities at take-off (4th level). The somersaulting angular distance of the gymnast in pre-flight depends on the time of pre-flight, the average moment of inertia of the gymnast in pre-flight and the angular momentum of the gymnast at take-off from the board, as described by Hay and Reid (1988). The time of pre-flight is determined by the height of the centre of mass and the vertical velocity at take-off from the board, the height of the centre of mass at touchdown on the horse, the air resistance and the acceleration due to gravity (4th level). With these variables identified, the final form of the model for the pre-flight is shown in Fig. 3.

As shown in Fig. 4, the mechanical variables that govern the trajectory of the centre of mass and the

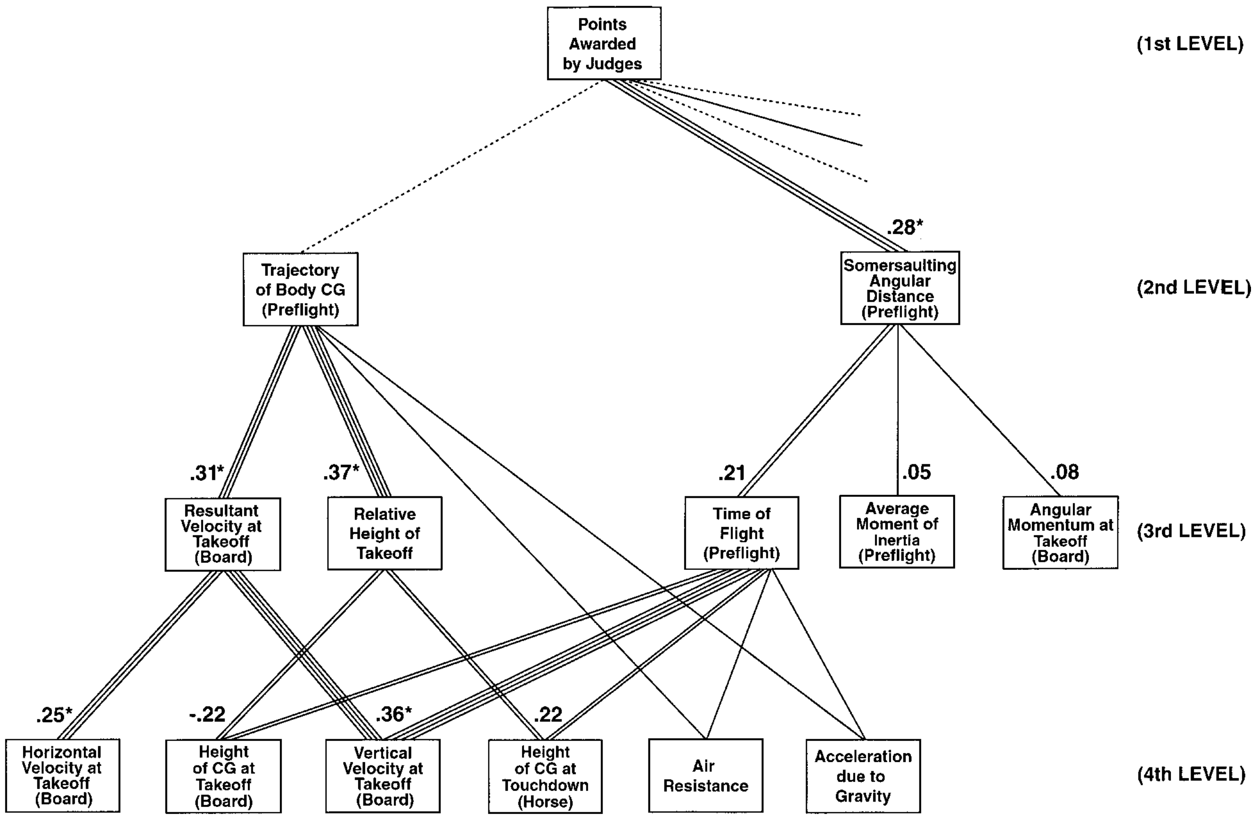

Fig. 3. Model showing mechanical variables that determine the linear and angular motions of the pre-flight phase of the Hecht vault, and zero-order correlations with the judges' score. Numerical and graphic displays of correlation coefficients are as described in the legend to Fig. 2. CM = centre of mass. *Note*: The correlation coefficient shown at the top of each box enclosing the quantifiable variable in the 3rd and 4th levels indicates its relationship with the judges' score, rather than the relationship with the variable linked immediately above.

somersaulting motion in the post-flight phase are similar to those identified in the third and fourth levels of the model for the pre-flight (Fig. 3). The variables that determine the performance of the blocking and pushing off the horse and subsequent post-flight are identified in the third to seventh levels of the model in Fig. 4. More specifically, the vertical velocity at take-off from the horse shown in the fourth level is the sum of the vertical velocity at touchdown on the horse and the change in the vertical velocity that occurs while on the horse (5th level). The change in the vertical velocity is determined by the gymnast's mass and the vertical impulse that the gymnast exerts (and that which the horse, in reaction, exerts on the gymnast) (6th level). The vertical impulse exerted on the gymnast is, in turn, determined by the average vertical force exerted and the time during which the force acts – that is, the time of support on the horse (7th level) (Hay and Reid, 1988). The horizontal motion variables were similarly identified (see Fig. 4). Form, the aesthetic characteristic of performance referred to as 'segmentation' by George (1980), includes the position of body parts and the manner in which they move from one position to another during the vault. However, Hay and Reid (1988) stated that, while form is important in determining the overall success of the vault, the effort required to identify all of its elements, define them mechanically and analyse them in a meaningful manner is much greater than any benefit that might be gained from doing so. Concurring with Hay and Reid, we believed the mechanical analysis of aesthetics or form to be beyond the scope of the present study, and thus the model was not developed in this direction.

Data collection

Male gymnasts ($n = 122$) from 30 countries were filmed using a Photosonics 16-mm motion picture camera operating at 100 Hz as they performed the Hecht vault at the 1995 World Gymnastics Championships. The camera was positioned 67.86 m from the long axis of the horse with its optical axis 90° to the gymnast's horizontal direction of motion (direction of runway) and 85° to his vertical direction of motion to record

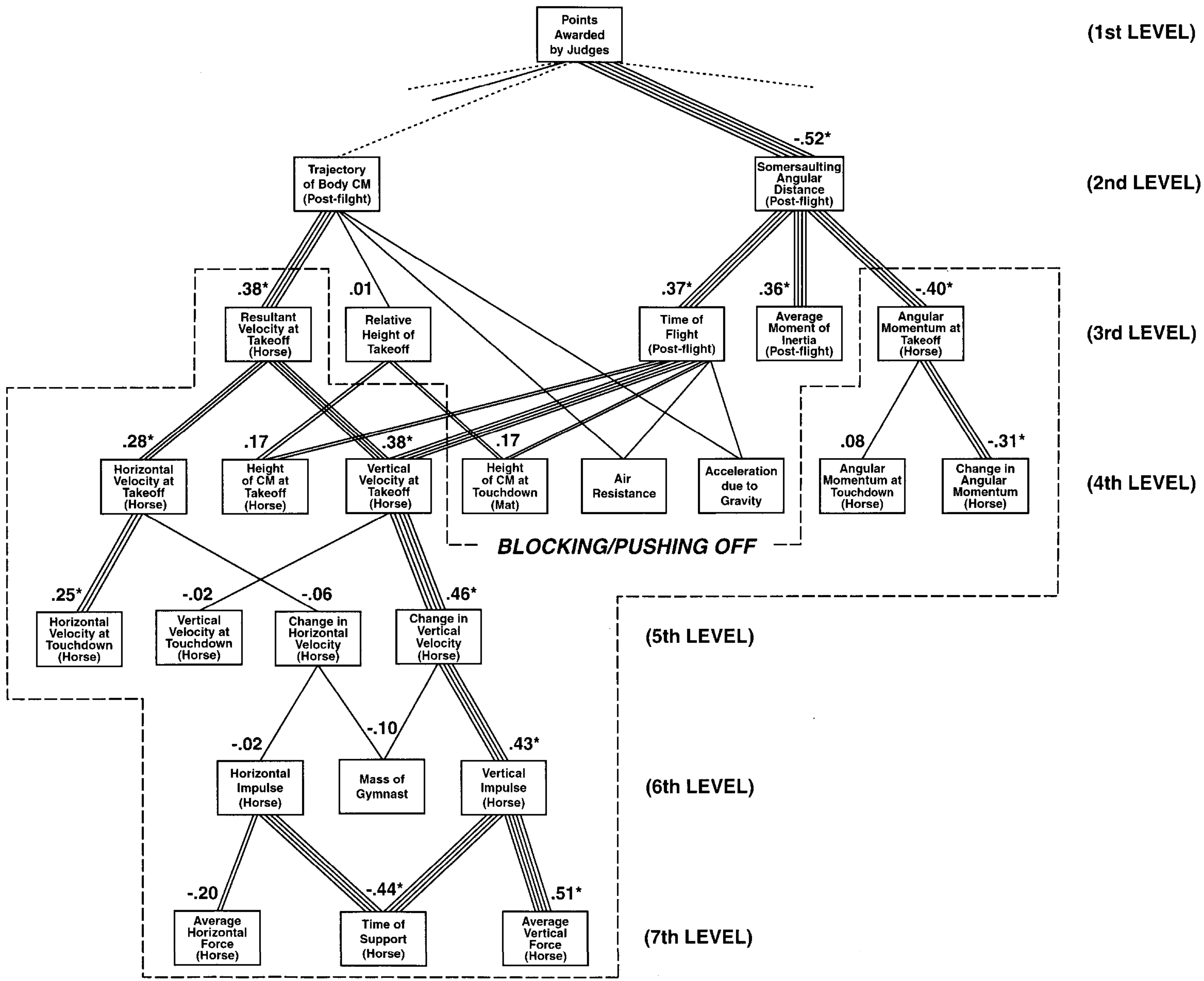

Fig. 4. Model showing mechanical variables that determine (a) the blocking/pushing off the horse during the on-horse phase and (b) the linear and angular motions of the post-flight phase of the Hecht vault, and zero-order correlations with the judges' score. *Note*: The correlation coefficient shown at the top of each box enclosing the quantifiable variable in the 3rd to 7th levels indicates its relationship with the judges' score, rather than the relationship with the variable linked immediately above.

the vault from the designated filming area. Angle verification of downward camera tilt of 5° below the horizontal was performed by determining the inverse sine of the horse height computed from its film image, divided by the actual height of the official horse used during the competition (1.35 m). Subsequently, using the method described by Takei (1991), the vertical coordinates of all the digitized body points were corrected for camera tilt before computing the whole-body centre of mass. The measured dimensions of the official vault apparatus included in each frame were used to establish a linear scale and horizontal reference. Internal timing lights pulsing at a frequency of 100 Hz were used to mark the sides of the film to provide a basis for determining appropriate temporal scales.

Data reduction

For each vault analysed, approximately 80 frames of film were digitized. These included every frame from four frames before take-off from the board to four frames after take-off from the horse, then every third frame until touchdown on the mat and four additional consecutive frames. An M-16C Vanguard projection head and HIPAD Plus 9200 digitizer linked on-line to a microcomputer were used for digitizing. The horizontal and vertical coordinates of 21 points defining a 14-segment model of the human body described by Clauser *et al.* (1969) were recorded for each frame analysed. When using the cubic spline technique for data smoothing, a minimum of three additional data points are required for padding at the beginning and end of the sample to ensure there is no distortion of the data to be analysed. Therefore, we digitized the four consecutive frames before take-off from the board and those after touchdown on the mat. These data were then used as input to a computer program designed to display the curves of the digitized body points (Hay and Nohara, 1990). Any gross outliers identified were aligned manually to the curves or redigitized, after which the cubic spline smoothing procedure (Hutchinson, 1986) was applied to these position data. Subsequently, the location of the centre of mass in each digitized frame was computed using the segmental mass proportion and segmental centre of mass location data of Clauser *et al.* (1969) and the basic segmental procedure described by Hay (1993).

The time of contact was defined as the time from the first frame when the gymnast contacted the board or horse to the first frame when he lost contact with the board or horse. The time of flight was defined as the time from the first frame when the gymnast lost contact with the board or horse to the first frame when he contacted the horse or landing mat. The frames depicting the instants of touchdown on and take-off from the board and the horse as well as touchdown on the mat were identified. From these critical instants, the on-board, pre-flight, on-horse and post-flight phases were defined (Fig. 1). The horizontal velocity at take-off from the board was determined by dividing (a) the horizontal displacement of the centre of mass from the first frame showing the gymnast off the take-off board to the last frame showing the gymnast in the air before contact with the horse, approximately 20 frames later, by (b) the elapsed time between these two instants. The vertical velocity at take-off from the board (v_{VTO}) was computed using the vertical displacement of centre of mass (Δy) from the first frame showing the gymnast off the board to the last frame before contact with the horse, and the elapsed time (Δt) between these two frames:

$$v_{VTO} = [\Delta y + 4.905(\Delta t)^2]/\Delta t$$

The vertical velocity at touchdown on the horse (v_{VTD}) was computed using the following equation of uniformly accelerated motion:

$$v_{VTD} = v_{VTO} - 9.81(\Delta t)$$

The velocities at take-off from the horse and touchdown on the landing mat were computed in a similar fashion.

The height and mass of 79 of the 122 gymnasts had to be estimated, as this information was not available. The missing height data were estimated using a method similar to that used by Hay and Nohara (1990), which was based on the segment lengths obtained from digitized data. The missing mass data were estimated using the following regression equation derived from the known masses and heights of the 67 male gymnasts competing in the 1992 Olympic Games (Takei, 1998):

$$\text{mass} = \text{height}\ (86.73) - 82.45 \qquad (r = 0.86,\ r^2 = 0.73)$$

The angular distance the gymnast rotated during the flight phase was defined as:

$$\theta = (\bar{H}\bar{I}^{-1})t$$

where $\bar{H}$ = the somersaulting angular momentum, $\bar{I}$ = the average moment of inertia of the gymnast about the same axis and t = time (Takei, 1992; Takei and Dunn, 1997). The angular momentum of the gymnast about the transverse axis through the mass centre during the pre-flight and post-flight were calculated using the method described by Hay *et al.* (1977) and the segment moment of inertia data of Whitsett (1963). The angular momentum of pre-flight was the arithmetic mean of approximately 20 angular momentums from all the frames analysed for the pre-flight phase. The angular momentum of post-flight was similarly obtained by computing the mean of approximately 45 post-flight angular momentums. To facilitate comparisons among gymnasts, the angular momentums and moments of inertia of the whole body about the somersaulting axis were normalized using the method described by Hinrichs (1987):

$$\text{normalized value} = (\text{absolute value})[(\text{mass})(\text{height}^2)]^{-1}$$

The error estimates (mean $\pm$ s) of normalized angular momentums for the pre-flight and post-flight phases in the 122 gymnasts were 0.017 ± 0.0055 and 0.013 ± 0.0027, respectively. Body angles were determined by a horizontal reference line extending backwards through the gymnast's lateral malleolus, and a line connecting the lateral malleolus and the base of the mid-neck (the midpoint between the manubrium and the seventh cervical vertebra). They were measured from the horizontal reference line in a clockwise direction (Fig. 5).

The impulses and average forces exerted during the on-horse phase were determined by the impulse–momentum relationship (Hay and Reid, 1988; Takei, 1998). For example:

$$(\bar{F}_V - W)t = m(v_{VTO} - v_{VTD})$$

where $\bar{F}_V$ = average vertical force exerted, W = body weight, t = time of horse support, m = body mass, v_{VTO} = vertical velocity at take-off from the horse and v_{VTD} = vertical velocity at touchdown on the horse. This equation, when rearranged, yields an expression for $\bar{F}_V$ for each gymnast:

$$\bar{F}_V = [m(v_{VTO} - v_{VTD})/t] + W$$

Data analysis

To identify the mechanical variables that are crucial for success, Pearson product–moment correlations were computed between (a) each quantifiable variable in the second level of the model and the judges' score, and (b) the judges' score and the variables in the next lower (3rd) level that were linked to the significant variable immediately above. Step (b) was then repeated to advance the analysis to progressively lower levels of the model. Correlational analysis was chosen to establish the strength of the relationship between the known causal mechanical variables identified in the model and the score awarded by the judges. A value of $P < 0.005$ was chosen to indicate significance and to control the potential increase in Type I error rate (where variables indicate a significant relationship merely by random chance) as a result of performing multiple correlations. To evaluate the practical significance of the variables, the coefficient of determination (r^2) was computed for each variable that was found to be significantly correlated with the judges' score.

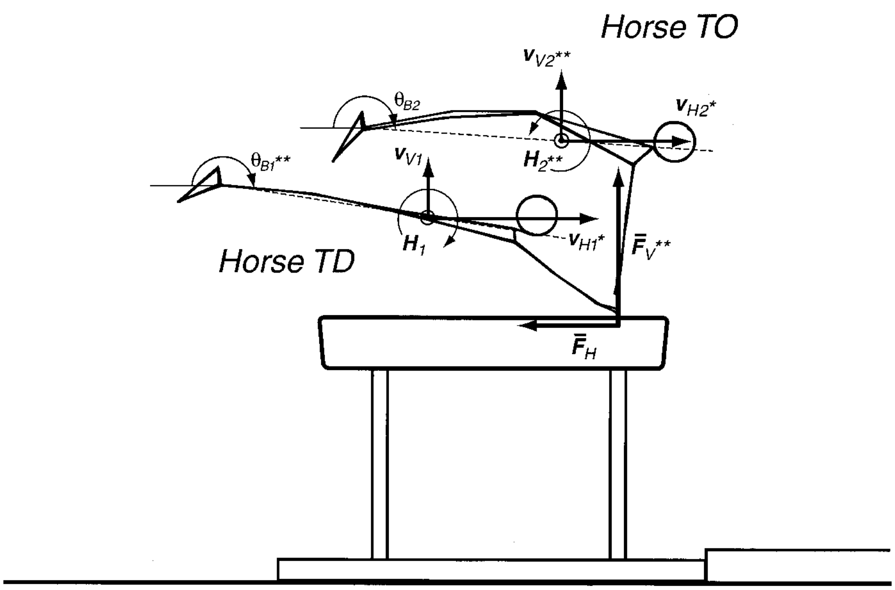

Fig. 5. The body angle (θ_B), velocities and angular momentum (H) at touchdown (TD) and take-off (TO) from the horse. The significant variables (* $P < 0.005$; ** $P < 0.001$) are indicated by asterisks. During the course of blocking and pushing off the horse, the vertical reaction force ($\bar{F}_V$) exerted by the horse tends to increase the gymnast's vertical velocity (v_V) while simultaneously decreasing forward angular momentum, enabling a reversal of direction of body rotation while on the horse. On the other hand, the horizontal reaction force ($\bar{F}_H$) tends to decrease horizontal velocity (v_H) while simultaneously increasing forward angular momentum and the chance of accidental 'body turnover' while on the horse.

Results

In this section, we present the model, significant correlations and our interpretation of the results. The analysis and interpretation of the results begins with the variables in the second level of the model and advances to those in the lower levels, one phase or branch at a time.

Pre-flight mechanical variables and judges' score

Two variables were identified in the second level of the model (Fig. 3), of which only the somersaulting angular distance was quantified because it was impossible to describe the 'trajectory of body centre of mass' with a single number for the purpose of analysis. The significant correlation between somersaulting angular distance and the judges' score indicated that the greater the forward body rotation in pre-flight, the higher the score awarded by the judges. However, none of the three variables that determine the somersaulting angular distance of pre-flight was significantly correlated with the judges' score (Tables 1 and 2).

The four variables that determine the trajectory of the body's centre of mass in pre-flight were identified in the third and fourth levels of the model (Fig. 3). The resultant velocity at take-off from the board ($r = 0.31$; Table 3) and the relative height of take-off ($r = 0.37$; Table 2) yielded a significant correlation coefficient of similar magnitude in each case with the judges' score. This meant that they were almost equally important, as they accounted for similar variances with the judges' score. The significant correlation for the resultant velocity at take-off meant that the greater the resultant velocity at take-off from the board, the higher the judges' score. Subsequent analysis of the horizontal and vertical velocities at take-off from the board (4th level of the model in Fig. 3) yielded a significant correlation coefficient with the judges' score in each case (vertical, $r = 0.36$; horizontal, $r = 0.25$; Table 3). These correlations indicated that the greater the horizontal and vertical velocities at take-off from the board, the higher the score awarded by the judges. However, the vertical velocity at take-off from the board was more important than the horizontal velocity at take-off in achieving success because it accounted for twice the variance with the judges' score.

Finally, the significant correlation reported above for the relative height of take-off indicated that the greater the vertical distance travelled by the body centre of mass in pre-flight, the higher the judges' score. However, neither the height of centre of mass at take-off from the board nor the height of centre of mass at touchdown on the horse yielded a significant correlation coefficient with the judges' score (Table 2). The differences in the

Table 1. Descriptive statistics and correlations (r) with the judges' score for somersaulting angular motion variables in the Hecht vault

Variables	Mean ± s	Min	Max	r
Normalized angular momentum (s^{-1})				
pre-flight	0.34 ± 0.03	0.28	0.42	0.08
change on horse	−0.43 ± 0.03	−0.51	−0.33	−0.31**
post-flight	−0.09 ± 0.02	−0.14	−0.03	−0.40**
Normalized average moment of inertia				
pre-flight	0.076 ± 0.003	0.060	0.084	0.05
post-flight	0.054 ± 0.003	0.044	0.062	0.36**
Body angle at critical instants (°)				
horse touchdown	178 ± 9	157	206	0.32**
change on horse	−7 ± 4	−20	4	−0.40**
horse take-off	172 ± 8	154	203	0.11
Angular distance (°)				
pre-flight	54 ± 8	33	85	0.28*
post-flight	−67 ± 13	−93	−25	−0.52**
Average angular velocity (degrees per second)				
pre-flight	258 ± 21	216	318	0.06
post-flight	−91 ± 18	−138	−32	−0.38**

* $P < 0.005$; ** $P < 0.001$.

Table 2. Descriptive statistics and correlations (r) with the judges' score for temporal and linear motion variables in the Hecht vault

Variables	Mean ± s	Min	Max	r
Time (s)				
pre-flight	0.21 ± 0.04	0.11	0.33	0.21
on-horse	0.16 ± 0.02	0.12	0.22	−0.44**
post-flight	0.74 ± 0.05	0.59	0.90	0.37**
Horizontal displacement of CM (m)				
pre-flight	1.30 ± 0.22	0.76	1.86	0.37**
post-flight	3.44 ± 0.42	2.16	4.28	0.44**
official distance of post-flight	3.39 ± 0.48	2.09	4.37	0.49**
Height of CM at critical instants (m)				
board take-off	1.28 ± 0.04	1.18	1.37	−0.22
horse touchdown	1.75 ± 0.07	1.51	1.93	0.22
horse take-off	2.08 ± 0.06	1.88	2.21	0.17
peak of post-flight	2.33 ± 0.11	2.07	2.70	0.36**
mat touchdown	1.03 ± 0.07	0.84	1.19	0.17
Relative height of take-off (m)				
board TO to horse TD	0.47 ± 0.07	0.27	0.65	0.37**
horse TO to mat TD	−1.05 ± 0.08	−1.35	−0.82	0.01

** $P < 0.001$. CM = centre of mass; TO = take-off; TD = touchdown.
Note: The height of CM at peak of post-flight was calculated using the vertical velocity at take-off from the horse. The heights of CM were measured from the floor.

Table 3. Descriptive statistics and correlations (r) with the judges' score for the velocity variables in the Hecht vault

Variables	Mean ± s	Min	Max	r
Resultant velocity ($m \cdot s^{-1}$)				
board take-off	7.07 ± 0.53	5.71	8.44	0.31**
horse take-off	5.15 ± 0.45	3.59	6.09	0.38**
Horizontal velocity ($m \cdot s^{-1}$)				
board take-off (pre-flight)	6.25 ± 0.58	4.44	7.68	0.25*
change on horse	−1.60 ± 0.37	−2.99	−0.90	−0.06
horse take-off (post-flight)	4.65 ± 0.45	3.23	5.70	0.28*
Vertical velocity ($m \cdot s^{-1}$)				
board take-off	3.28 ± 0.19	2.73	3.65	0.36**
horse touchdown	1.32 ± 0.36	0.29	2.65	−0.02
change on horse	0.87 ± 0.30	−0.23	1.78	0.46**
horse take-off	2.20 ± 0.35	0.93	3.13	0.38**

* $P < 0.005$; ** $P < 0.001$.

gymnasts' physiques may have been a confounding factor in the above relationship. Therefore, partial correlations were computed with the effect of the gymnast's standing height removed. The results of the relative height of take-off ($r = 0.36$, $P < 0.001$), the height of centre of mass at take-off from the board ($r = -0.21$, $P = 0.02$) and the height of centre of mass at touchdown on the horse ($r = 0.24$, $P = 0.008$) with the judges' score were nearly identical to the zero-order correlation, although the last variable approached significance.

On-horse and post-flight mechanical variables and judges' score

Two variables were identified in the second level of the model (Fig. 4). Of these, only the somersaulting angular distance could be quantified, as stated earlier. The somersaulting angular distance correlated significantly with the judges' score ($r = -0.52$; Table 1). This correlation indicated that the greater the backward body rotation in post-flight, the higher the score awarded by the judges. Subsequent analysis of the time of flight ($r = 0.37$), the average moment of inertia of the gymnast in post-flight ($r = 0.36$) and the gymnast's angular momentum at take-off from the horse ($r = -0.40$) yielded a significant correlation coefficient with the judges' score in all three cases (Tables 1 and 2). These correlations indicated that the higher the score awarded by the judges, the longer the duration of post-flight, the greater the average somersaulting moment of inertia in post-flight and the greater the backward somersaulting angular momentum at take-off from the horse. They also indicated that these three variables were equally important in achieving success because they accounted for similar variances with the judges' score. The analysis of the angular momentum at touchdown on the horse ($r = 0.08$) and the change in angular momentum while on the horse ($r = -0.31$) (4th level of the model in Fig. 4), which together determine the angular momentum at take-off from the horse, yielded a significant correlation coefficient with the judges' score only for the latter variable. This correlation indicated that the greater the change in the angular momentum while on the horse, the higher the score awarded by the judges.

The five variables that determine the time of post-flight were identified in the fourth level of the model. Similarly, the four variables that determine the trajectory of body centre of mass in post-flight were identified in the third and fourth levels of the model in Fig. 4. Of these, only the resultant velocity at take-off from the horse ($r = 0.38$) yielded a significant correlation coefficient with the judges' score (Table 3). This correlation indicated that the greater the resultant velocity at take-off from the horse, the higher the score awarded by the judges. Since the differences in the gymnasts' physiques may have been a confounding factor in the analysis of the relative height of take-off – that is, the height of the centre of mass at take-off from the horse relative to its height at touchdown on the landing mat – partial correlations were computed with the effect of the gymnast's standing height removed. However, the results of the relative height of take-off ($r = -0.01$, $P = 0.97$), the height of centre of mass at take-off from the horse ($r = 0.22$, $P = 0.01$) and the height of centre of mass at touchdown on the mat ($r = 0.20$, $P = 0.03$) with the judges' score were nearly identical to the zero-order correlation (Table 2).

Subsequent analysis of the horizontal ($r = 0.28$) and vertical ($r = 0.38$) velocities at take-off from the horse (4th level of the model in Fig. 4), which together determine the resultant velocity at take-off, yielded a significant correlation coefficient with the judges' score in both cases (Table 3). These correlations indicated that the greater the horizontal and vertical velocities at take-off from the horse, the higher the score awarded by the judges. Of these two variables, however, the vertical velocity at take-off from the horse was more important than the horizontal velocity at take-off in achieving success because it accounted for a greater variance with the judges' score. Analysis of the variables that determine the horizontal and vertical velocities at take-off from the horse, identified in the fifth level of the model in Fig. 4, yielded significant correlation coefficients with the judges' score for the horizontal velocity at touchdown on the horse ($r = 0.25$) and the change in vertical velocity on the horse ($r = 0.46$), but not for the other two variables (Table 3). These correlations indicated that the higher the score of the Hecht vault, the greater the horizontal velocity at touchdown on the horse and the greater the change in the vertical velocity while on the horse. Of these variables, however, the change in the vertical velocity on the horse was far more important than the horizontal velocity at touchdown on the horse in achieving success because it accounted for more than three times as much variance with the judges' score. As for the variables that determine the change in the vertical velocity on the horse, the vertical impulse on the horse, identified in the sixth level of the model in Fig. 4, yielded a significant correlation coefficient ($r = 0.43$) with the judges' score (Table 4). This correlation indicated that the greater the vertical impulse exerted while on the horse, the higher the score awarded by the judges. Finally, the time of horse support ($r = -0.44$) and the average vertical force on the horse ($r = 0.51$) (7th level of the model in Fig. 4), which together determine the vertical impulse on the horse (Hay and Reid, 1988), yielded a significant correlation coefficient in each case with the judges' score (Tables 2 and 4). These correlations indicated that the higher the score of the Hecht vault, the shorter the time of hand support on the horse and the greater the normalized average vertical force exerted while on the horse. The result also indicated that these two variables were equally important in achieving success of the vault because they accounted for similar variances with the judges' score.

In short, the higher judges' scores were negatively related to the time of contact on the horse and positively related to: (1) the horizontal and vertical velocities at take-off from the board; (2) the vertical displacement of body centre of mass and the angular distance of forward body rotation in pre-flight; (3) the vertical impulse exerted on the horse and the change in vertical velocity and angular momentum while on the horse; (4) the horizontal and vertical velocities and the backward somersaulting angular momentum at take-off from the horse; and (5) the angular distance of backward body

Table 4. Descriptive statistics and correlations (r) with the judges' score for forces and impulses during the on-horse phase of the Hecht vault

Variables	Mean ± s	Min	Max	r
Horizontal impulse (N·s)	−10 ± 126	−198	−51	−0.02
Vertical impulse (N·s)	55 ± 19	−14	112	0.43**
Average horizontal force ($\bar{F}_H$) (N)	−640 ± 181	−1347	−296	−0.18
Average vertical force ($\bar{F}_V$) (N)	967 ± 152	493	1361	0.42**
Normalized $\bar{F}_H$	−1.04 ± 0.29	−2.17	−0.44	−0.20
Normalized $\bar{F}_V$	1.57 ± 0.22	0.82	2.21	0.51**

** $P < 0.001$.

rotation, the average moment of inertia and the duration of post-flight.

The above summary is reflected in the results of a comparison of the technical characteristics of the 25 highest- and 25 lowest-scoring vaults in the present sample. The 25 highest-scoring vaults had significantly:

- larger horizontal and vertical velocities at take-off from the board;
- greater horizontal and vertical distances travelled by mass centre and greater forward body rotation in pre-flight;
- higher body angle at touchdown on the horse, shorter time of contact on the horse and yet greater average vertical force and greater vertical impulse exerted while on the horse, and greater change in both the vertical velocity and angular momentum while on the horse;
- larger horizontal and vertical velocities and greater backward somersaulting angular momentum at take-off from the horse (Table 5).

Discussion

Board take-off techniques and pre-flight performance

The results of the present study are similar to those reported for the continuous rotation vaults, such as the handspring (Takei, 1989), handspring and salto forward tucked (Takei, 1988; Takei and Kim, 1990) and handspring with full turn (or twist) (Takei, 1998), in which a large horizontal velocity at take-off from the board is an important determinant of success. However, it was not only the large horizontal velocity at take-off but also the large vertical velocity at take-off from the board that determined success of the Hecht vault. The differences in techniques between the continuous rotation vaults and the Hecht vault became more distinct in the performance of the pre-flight. In the handspring vault (Takei, 1989), the higher judges' scores were negatively related to the duration of pre-flight, the vertical distance travelled by mass centre, and the height of body mass centre and the body angle at touchdown on the horse. In the handspring with full turn (or twist) vault (Takei, 1998), the higher judges' scores were negatively related not only to the first three variables mentioned above for the handspring vault, but also the degree of forward body rotation in pre-flight. However, for the Hecht vault, the higher judges' scores were positively related to the vertical distance travelled by the mass centre and forward body rotation in pre-flight. In the present study, reflecting the above results, the 25 highest-scoring Hecht vaults had a significantly higher body angle (181° or 1° above horizontal) than the 25 lowest-scoring vaults (173° or 7° below horizontal). These differences may be due, in part, to the difference in the blocking and pushing-off technique required to achieve the desired changes in the horizontal and vertical velocities and angular momentum while on the horse and, subsequently, to depart from the horse with appropriate body position and orientation to enable the required somersaulting or twisting rotation in a timely manner to achieve successful performance. These differences in technique may also be attributed to the fact that a body angle of 200° or 20° above the horizontal at touchdown on the horse is required for the Hecht vault. In fact, failure to achieve the required body angle results in a loss of a performance point, while exceeding this angle warrants a bonus point. However, there is no such requirement nor bonus point assigned to the continuous rotation vaults of any variation.

Blocking/pushing-off technique and post-flight performance

In the present study, the large vertical force and large vertical impulse exerted while on the horse, the large change in the vertical velocity and angular momentum while on the horse, and the short time of contact on the horse were important determinants of success (Fig. 5). Similar results have been reported for the handspring vault (Takei, 1989) and the handspring and salto forward tucked vault (Takei, 1988; Takei and Kim, 1990).

Table 5. Comparisons of mechanical variables between the highest-scoring and lowest-scoring Hecht vaults (mean)

Variable	Highest-scoring vaults (n = 25)	Lowest-scoring vaults (n = 25)	t
Horizontal velocity ($m \cdot s^{-1}$)			
board take-off	6.64	6.02	4.06**
change on horse	−1.70	−1.56	−1.36
horse take-off	4.93	4.46	3.80**
Vertical velocity ($m \cdot s^{-1}$)			
board take-off	3.44	3.18	5.75**
change on horse	1.02	0.61	5.40**
horse take-off	2.48	2.00	4.97**
Normalized angular momentum (s^{-1})			
board take-off	0.35	0.34	1.69
change on horse	−0.44	−0.41	−3.58**
horse take-off	−0.09	−0.07	−3.04*
Displacements of CM in pre-flight (m)			
horizontal	1.40	1.14	4.24**
vertical	0.50	0.42	4.45**
Body angle at touchdown on horse (°)	181	173	3.10*
Angular displacement (°)			
pre-flight	56	49	2.94*
post-flight	−71	−55	4.40**
Angular velocity of post-flight (degrees per second)	−91	−78	−2.50
Time (s)			
horse contact	0.15	0.17	−4.93**
post-flight	0.79	0.71	5.73**
Force and impulse on horse			
normalized vertical force	1.72	1.36	6.49**
vertical impulse ($N \cdot s$)	63	39	4.81**

* $P < 0.005$; ** $P < 0.001$. CM = centre of mass.

For coaches and gymnasts, the present findings suggest that the blocking and pushing off the horse should be done ‘forcefully and rapidly’ to bring about the desired large changes in the vertical velocity and angular momentum while on the horse.

The large vertical velocity at take-off from the horse was an important determinant of success in the performance of both the handspring (Takei, 1989) and the handspring with full turn (or twist) (Takei, 1998) vaults. On the other hand, both the large horizontal and vertical velocities at take-off from the horse were the important variables in achieving success of the handspring and salto forward tucked vault (Takei and Kim, 1990). In the present study, not only the large horizontal and vertical velocities at take-off but also the large backward angular momentum at take-off from the horse determined success of the Hecht vault.

All gymnasts in the present study contacted the horse with a body angle of less than 26° above the horizontal and departed from it with a body angle of less than 23° above the horizontal. This caused the body mass centre to remain posterior and superior to the point of hand contact throughout the course of blocking and pushing off the horse (Fig. 5). The large upward vertical impulse exerted on the gymnast by the horse caused a large change in the vertical velocity on the horse. This enabled the gymnast to depart from the horse with a large vertical velocity even though the time of contact was very short. The vertical force simultaneously tends to reduce the gymnast’s forward angular momentum while on the horse (Fig. 5). In the present sample, the effect of the vertical reaction force – that is, exerting a counter-clockwise moment on the gymnast – was far greater than that of the horizontal reaction force exerting a clockwise moment (Fig. 5). Consequently, all gymnasts not only decreased the forward angular momentum to zero by means of 'blocking', but also generated the backward angular momentum by 'pushing-off' the horse to reverse the direction of body rotation while on the horse. In fact, the 25 highest-scoring vaults of the 122 Hecht vaults analysed had similar normalized forward angular momentum at touchdown on the horse, a significantly greater change of this variable while on the horse, and significantly greater backward angular momentum at take-off from the horse compared with the 25 lowest-scoring vaults (Table 5).

A large gain of vertical velocity on the horse is almost always accompanied by large reductions in both horizontal velocity and angular momentum (Takei, 1992; Takei *et al.*, 1996). Therefore, maximizing vertical velocity at take-off results in a high trajectory of the mass centre and helps the gymnast to fulfil the post-flight height requirement. If everything else is equal, the larger the vertical velocity at take-off from the horse, the greater the maximum height of mass centre and the longer the duration of post-flight. Furthermore, in the continuous rotation vaults, maximizing the vertical velocity at take-off tends to decrease the forward angular momentum and forward somersaulting potential in post-flight (Takei, 1992; Takei *et al.*, 1996) and thus increase the danger of stalling in mid-air. On the other hand, a large gain in vertical velocity and a simultaneous decrease in forward angular momentum, large enough to cause a reversal of body rotation while on the horse, positively influence the post-flight performance of the counter-rotation vaults. A large vertical impulse, which causes a large change in the vertical velocity and angular momentum while on the horse, is therefore an important determinant of success (Fig. 5). In coaching terms, it aids the gymnast not only to prevent 'accidental body turnover' and to perform an 'impressive' on-horse reversal of body rotation from the body angle well in excess of the required 20° above the horizontal at touchdown, but also to achieve large backward body rotation, great maximum height of mass centre and long duration of post-flight which the judges seek in awarding bonus points.

Additional factors of significance

According to Hay and Reid (1988), errors or faults in performance revealed during the latter phase of a skill are likely to be caused by the performance of the earlier phases. This means that the outcome of post-flight performance is largely influenced by what took place during the preceding on-horse phase, which in turn is dependent upon the pre-flight performance, which in turn is governed by what took place during the preceding on-board phase. Therefore, on-board mechanical variables are likely to have an important 'causal influence' on the subsequent three sequential phases of the vault and overall outcome of performance. In this regard, the vertical velocity at take-off from the board yielded significant correlation coefficients with the body angle at horse contact ($r = 0.49$, $P < 0.001$), the time of horse support ($r = -0.40$, $P < 0.001$), the vertical velocity at horse take-off ($r = 0.35$, $P < 0.001$) and the maximum height of post-flight ($r = 0.46$, $P < 0.001$). These correlations meant that the greater the vertical velocity at take-off from the board, the higher the body angle at touchdown on the horse, the shorter the time spent on the horse, the greater the vertical velocity at take-off from the horse and the greater the maximum height of the body centre of mass attained in post-flight. Mechanically speaking, if everything else is equal, the greater the vertical velocity at take-off from the horse, the greater the maximum height of post-flight, the larger the horizontal distance travelled in post-flight and the longer the duration of post-flight and, thus, the easier it is to control the body for display of 'form' for bonus points and simultaneously prepare for landing on the mat.

In the present study, the average angular speed of post-flight correlated significantly with the judges' score (Table 1), indicating that the faster the backward rotation of the body in post-flight, the higher the score awarded by the judges. This contrasts with previous findings for the handspring and salto forward tucked vault (Takei, 1992) and the handspring with full turn (or twist) vault (Takei, 1998), which indicated that the slower the somersaulting rotation of the body in post-flight, the higher the judges' score. As odd as it may seem, these contrasting differences are in accord with the performance guidelines of the respective vaults. As stated earlier, a body angle of 20° above the horizontal at horse contact is required for the Hecht vault, and exceeding this body angle warrants a bonus point. On the other hand, there is no such requirement nor bonus points in the handspring category vaults. High-scoring handspring and salto forward tucked vaults (Takei, 1991) and high-scoring handspring with full turn (or twist) vaults (Takei *et al.*, 1996) displayed similar angular distance of somersaulting rotation in post-flight and significantly longer time of post-flight compared with their respective low-scoring vaults. A combination of comparable angular distance of somersaulting body rotation and the longer duration of post-flight in the high-scoring vaults resulted in significantly smaller average angular speed of forward somersaulting rotation compared with the low-scoring vaults. The present findings on the Hecht vault are consistent with its performance guidelines; that is, the higher the body angle at touchdown on the horse, the greater the backward body rotation required during the subsequent on-horse and post-flight phases to bring the gymnast's body back to an upright position for a controlled landing on the mat. In fact, as seen in Table 5, the 25 highest-scoring Hecht vaults in the present sample had significantly greater angular distance of post-flight and longer duration of post-flight than the 25 lowest-scoring vaults. A combination of the greater backward body rotation required for successful landing and the longer time of post-flight in the 25 highest-scoring vaults resulted in a greater average angular speed (non-significant) than that of the 25 lowest-scoring vaults (Table 5). In short, for the Hecht vault, the better vaulters rotate through a greater angular distance and, therefore, must rotate faster than the low-scoring vaulters. In the handspring category vaults, most gymnasts rotate through a similar angular distance, with the better vaulters rotating more slowly than low-scoring vaulters as they have more time in the air.

The angular distance of post-flight (ANGDPST) was the best single predictor of the judges' score and accounted for 27% of variation in the judges' score. The equation was:

$$\text{judges' score} = 8.445 - (\text{ANGDPST}) \quad (r = 0.52,\ r^2 = 0.27)$$

The results of the stepwise regression analysis of the 18 significant variables in the present study indicated that six variables are important in predicting successful performance as rated by the judges: the angular distance of post-flight, the time of post-flight (TIMEPST), the horizontal velocity at take-off from the horse (VHTOHRS), the angular distance of pre-flight (ANGDPRE), the normalized average moment of inertia of post-flight (NAVIPST) and the normalized angular momentum at take-off from the horse (NHTOHRS). These six predictor variables collectively account for 57% of the variation in the judges' score. The equation is:

$$\text{judges' score} = 4.909 - 0.045\,(\text{ANGDPST}) - 1.48\,(\text{TIMEPST}) + 0.179\,(\text{VHTOHRS}) + 0.012\,(\text{ANGDPRE}) + 65.85\,(\text{NAVIPST}) + 30.55\,(\text{NHTOHRS}) \quad (r = 0.75,\ r^2 = 0.57)$$

Finally, we tried to develop a multiple regression equation useful to coaches in predicting the judges' score by entering the additional variables that are typically used by the judges in evaluating the vault. Three variables – the official horizontal distance of post-flight, measured from the far-end of the horse to the heel of the gymnast at touchdown on the mat (OFFDPST), the body angle at touchdown on the horse (ANTDHRS) and the time of post-flight (TIMEPST) – were identified as important in predicting the judges' score. These three predictor variables in the equation collectively account for 39% of variation in the judges' score and are relatively easily measured by the coaches during daily training sessions on the field or in the gymnasium. The equation useful to coaches is:

$$\text{judges' score} = 5.580 + 0.266\,(\text{OFFDPST}) + 0.012\,(\text{ANTDHRS}) + 0.893\,(\text{TIMEPST}) \quad (r = 0.63,\ r^2 = 0.39)$$

Conclusions

Based on the results of the present study, success of the Hecht vault is most likely when the emphasis is on achieving:

- Large horizontal velocity at touchdown on the board by sprinting the approach and departing from it with large horizontal and vertical velocities.
- Large vertical distance travelled by mass centre and large forward body rotation in pre-flight by reaching as far forward as possible towards the far end of the horse with the hands and arms (flexion of the humerus) upon leaving the take-off board.
- Large change in the vertical velocity and angular momentum while on the horse, and resulting large vertical velocity and large backward somersaulting angular momentum at take-off from the horse, by exerting large vertical impulse of high force and short duration via blocking and pushing off the horse 'forcefully and rapidly' using the muscles of the shoulders and shoulder girdle.
- Large average moment of inertia by extending the body fully to display Hecht or fish-like body position throughout the post-flight, while simultaneously preparing for a controlled landing on the mat.

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