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Preflight characteristics of Hecht vaults

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Abstract

This study reports the techniques used by gymnasts to perform the Hecht vault and compares them with techniques used for the handspring somersault vault (Takei and Kim, 1990). Data were obtained on 27 elite gymnasts performing the Hecht vault at the 1993 Canadian National Championships using two-dimensional video analysis with the Direct Linear Transformation (DLT) technique. The maximum height reached by the mass centre during postflight was significantly correlated ($p < 0.001$) with the vertical velocity of the mass centre and the body angle at horse contact. The backwards rotation of the body was significantly correlated ($p = 0.002$) with the shoulder angle at horse contact. The competition score was significantly correlated ($p = 0.031$) with the body angle at horse contact and the maximum height of the mass centre during postflight. For the Hecht vault the gymnasts had longer, lower and faster preflights with slower rotation at horse contact compared with the handspring somersault vaults.

Introduction

Vaults may be characterised by the directions of rotation during the preflight phase from Reuther board takeoff until initial horse contact and the postflight phase from horse takeoff until landing. There are two distinct groups (Takei, 1988): (a) continuous rotation vaults where the somersault rotation during preflight continues in the same direction during postflight (e.g. handspring vault), and (b) counter-rotation vaults where the direction of rotation in preflight is reversed during contact with the horse producing the opposite direction of rotation in postflight (e.g. Hecht vault). Previous research into the mechanics of vaulting has concentrated on continuous rotation vaults (Brüggeman 1987; Dainis, 1979, 1981; Dillman *et al.*, 1985, Kerwin *et al.*, 1993; Kwon *et al.*, 1990; Takei, 1988, 1989, 1991; Takei and Kim, 1990), reporting on the techniques used by gymnasts and identifying the characteristics for successful performance. For example Takei (1988) showed that a high horizontal velocity during the preflight onto the horse and a large gain in vertical velocity while in contact with the horse were important determinants for successful performance of the handspring somersault vault. The only research studies on Hecht vaults have been theoretical in nature using simulation models to investigate the necessary preflight characteristics. King *et al.* (1995) and Sprigings *et al.* (1994) used two segment simulation models to show that the preflight requirements for a Hecht vault are different from those for handspring somersault vaults with the Hecht requiring a longer preflight time, a low flight path and a near zero vertical velocity of the mass centre at horse contact. However no studies have reported on the actual techniques used by gymnasts performing the Hecht vault.

Since the introduction of the Hecht as the compulsory vault, there have been a number of amendments to the F.I.G. specifications for the vault. In the original version of the regulations governing compulsory exercises (F.I.G., 1993) the body angle above the horizontal at horse contact

was required to be at least 30°. Subsequently this criterion angle was reduced to 20° to facilitate more dynamic performances (Fink and Zschoke, 1994). This paper will investigate how the preflight characteristics of competitive performances of the Hecht vault influence the postflight performance.

Method

Data Collection

All Hecht vaults from the 1993 Canadian National Gymnastics Championships were video recorded using one Panasonic AG-160 portable camcorder operating at 60 fields per second with a 1 ms shutter. The camera was placed in the tiered seating and was inclined downwards at around 10 degrees, giving a side view of the vault. Prior to the competition a total of 12 spheres each of 0.04 m diameter were hung on nylon thread at heights of 0.2 m, 1.1 m and 2.15 m in four vertical columns spaced at intervals of 3.2 m, 1.9 m and 3.2 m in the plane of the vaulting horse. The columns were suspended over four points on the floor whose locations were measured with a steel tape. These calibration markers spanned the movement space of a typical vault from the hurdle step of the approach through to the final landing. The markers were video recorded and then removed. The camera was removed after calibration and replaced before competition the next day in the same location and with the same orientation.

Data Processing

The video was converted from 60 fps NTSC to 50 fps PAL and time code was added for digitising. A high resolution video digitising system based upon the Millipede Prisma III frame store was used to digitise each vault. Each of the 12 calibration points was digitised in four consecutive fields and the coordinate data was used together with the known locations of the points to obtain eight DLT parameters for planar reconstruction (Walton, 1981). In addition two control points in the background were digitised to correct for focal length and camera alignment changes that occurred when the camera was replaced. Unbiased estimates of the coordinate errors of the reconstructed locations of the calibration markers were calculated as root mean square differences between the known spatial coordinates of the calibration markers and the reconstructed coordinates.

27 of the 28 performances (one per gymnast) were digitised due to an incomplete recording of one competitor. The Hecht may be divided into an approach phase, in which the body does not preserve left / right symmetry and a vault phase in which symmetry is maintained. Different digitising protocols were adopted for these two phases. The vault phase may be subdivided into preflight, contact, postflight and landing phases. The landing was not digitised as the view was obscured by a television camera. Throughout the approach and vault phases every second field was digitised in order to reduce the amount of digitisation. In addition every field was digitised for one vault to establish the effect of digitising every second field.

Anthropometric measurements available on 11 elite gymnasts from previous studies and the mathematical model of Yeadon (1990) were used to calculate segmental masses and mass centre locations. The inertia data were then normalised to a total body mass of 62.88 kg and a standing height of 1.67 m corresponding to the average gymnast from the 1988 Olympic Games (Takei and Kim, 1990), using the procedure of Dapena (1978) in which segment mass is assumed to be proportional to body mass, and segment length proportional to standing height. In addition the normalised inertia data were averaged to give an average inertia data set.

The approach phase started at the first airborne video field of the hurdle step and ended one field before contact with the Reuther board. Fifteen points on the body were digitised: wrist, elbow, shoulder, hip, knee, ankle centres and toes on the left and right sides of the body plus the centre of the head. The segmental masses and relative mass centre locations were used to determine the whole body mass centre location throughout the approach. The approach velocity at contact with the Reuther board was calculated from the displacement of the mass centre during the hurdle step of the vault using projectile equations.

The vault phase started during contact with the board and ended just before landing. Eight points on the body were digitised: wrist, shoulder, hip and ankle centres on the left and right sides of the body. The segmental masses and relative mass centre locations were used to determine the whole body mass centre location in each digitised frame. To define the orientation and configuration of the gymnast, the body angle ϕ above the horizontal, the shoulder angle α between the arms and trunk and the pike angle β between the legs and trunk were used.

For the vault in which every field was digitised, the difference in horizontal location of the mass centre between fields was plotted against the field number. It was found that during the flight phases the mass centre travelled horizontally approximately twice as far between fields at every fifth field. From this it was concluded that during the conversion from 60 Hz NTSC to 50 Hz PAL every sixth field was dropped resulting in an uneven time base for the PAL video. The field times of each digitised sequence were determined by inspecting the changes in the horizontal displacement of the mass centre and identifying where the missing fields occurred. Interpolating cubic splines were then fitted to the displacement data sets and were evaluated at intervals of 0.04s.

The vault in which every field was digitised was used to estimate the error associated with digitisation. A pseudo data set was generated by averaging coordinate values from adjacent fields. RMS digitisation error estimates were calculated as the root mean square differences between the real and pseudo data sets and were used as the standard error estimates for each point in the cubic splines (Reinsch, 1967) which were fitted to each set of displacement data in both preflight and postflight phases. Cubic rather than quintic splines were used due to the small number of fields digitised in preflight (average = 7).

Throughout the vault phase the wrist, shoulder, hip and ankle centres were digitised on both sides of the body. The side-on view of the camera and the left-right symmetry of the Hecht vault resulted in points on the right side of the body being obscured for some of the vault. Digitisation error estimates for the left and right sides of the body were compared, to assess whether the averaging of the left and right sides would give smaller errors than using the left data set. If the errors in the left and right data sets are each distributed normally with mean zero and variances σ_L^2 and σ_R^2 respectively then the errors in the averaged data set will have variance $\frac{1}{4}(\sigma_L^2 + \sigma_R^2)$. If $\sigma_R < \sqrt{3}\sigma_L$ the averaged data set will have a smaller error variance than the left data set on its own.

To determine the times of Reuther board takeoff, horse contact, horse takeoff and landing, the cubic splines used to fit the displacement data during preflight and postflight were extrapolated to known heights corresponding to takeoff and landing. For Reuther board takeoff the locations of the ankles were extrapolated until they were 0.20 m above the board. For horse contact and takeoff the wrist locations were extrapolated until the wrist centres reached their average level during contact with the horse. For landing the time was found for which the vertical displacement of the mass centre was one metre above the landing mat level as a television camera obscured the field of view at landing. The times for which the extrapolated splines reached the required heights were used as the times of Reuther board takeoff, horse contact, horse takeoff and landing.

Data Analysis

For the preflight phase five variables (u , v , ϕ , α , ω) were selected which describe the conditions at contact with the horse, and for postflight three variables (h , d , ψ) were chosen which describe the performance of the vault (Table 1).

Table 1. Variables used in regression

Preflight independent variables at horse contact	symbol	Postflight dependent variables	symbol
horizontal velocity of the mass centre	u	maximum height of the mass centre	h
vertical velocity of the mass centre	v	landing distance of the mass centre	d
body angle	ϕ	rotation potential	ψ
shoulder angle	α		
angular velocity of the body	ω		

The "rotation potential" was calculated as a measure of how much backwards rotation was a direct result of the preflight characteristics, by removing the effect of circling the arms and piking during postflight.

Equation (1) shows how the rotation potential was calculated as a function of the angle the arms rotated through relative to the body and the average pike angle during postflight.

$$\psi = \phi_a [1 - 0.216 (\pi - \beta_p)^2] + 0.05 \theta \quad (1)$$

where all angles are measured in radians and:

ψ = rotation potential in the layout position

ϕ_a = actual rotation observed

β_p = average pike angle in postflight

θ = angle the arms rotate through relative to the body during postflight

The constants for the equation were calculated from simulations using the model of Yeadon *et al.* (1990). For example if the actual rotation observed was 120° , with the arms rotating through one revolution relative to the body and with an average pike angle of 150° , then the body would rotate by 18° less without the arm rotation and 7° less if the body remained straight giving a rotation potential of 95° .

Linear regression was used to seek a relationship between each preflight variable and each postflight variable using the statistical package 'MINITAB' (Sevin, 1992). In addition individual regressions of the competition score were carried out against the body angle at horse contact, the maximum height of the mass centre in postflight, the landing distance of the mass centre past the end of the horse, and the rotation potential. In cases where there was a significant correlation ($p < 0.05$) with an independent variable, this variable was used to detrend both the dependent variable and the other independent variables by obtaining the residuals when regressed against the highly

correlated variable. The dependent variable residuals were then regressed against the residuals of each of the remaining independent variables.

Results

Error estimates

Unbiased estimates of the coordinate errors of the reconstructed locations of the calibration markers were found to be 6 mm and 11 mm in the horizontal and vertical directions respectively. For the vault in which every field was digitised, horizontal and vertical RMS digitisation error estimates were 22 mm and 24 mm for the eight joint centres digitised throughout the vault phase. The joint digitisation errors are larger than the errors found for the calibration markers due to the difficulty of visually estimating the joint centres. The calibration markers were fixed and clearly visible whereas the joint centres were moving and sometimes obscured from view.

Since averaging left and right sides of the body resulted in a smaller error estimate than just using the left data set, the averaged data set was used. For the averaged data set the RMS digitisation error estimates were 16 mm and 17 mm in the horizontal and vertical directions respectively.

Digitising every other field resulted in times for takeoff from the Reuther board, horse contact, horse takeoff and landing accurate to the nearest frame. Extrapolation was used to improve these times. Table 2 shows the differences in calculated times for the different methods used. If the time calculated for the vault in which every field was digitised and extrapolation used is assumed to be the most accurate, then by digitising every other field and extrapolating gives times of contact and takeoff within 0.01s.

Table 2. Times of takeoff, contact and landing using the different data types [s]

Data type used	Time of spring board takeoff	Time of horse contact	Time of horse takeoff	Time of landing
25 Hz	0.10 / 0.08	0.42 / 0.44	0.46 / 0.48	—
25 Hz + extrapolation	0.13 / 0.12	0.43 / 0.42	0.50 / 0.49	1.22 / 1.22
50 Hz	0.12	0.42	0.50	—
50 Hz + extrapolation	0.12	0.43	0.50	1.21

Note: There are two sets of times for the 25 Hz data since two data sets were generated from the 50 Hz data.

Descriptive data

Horizontal and vertical approach velocities of the mass centre were calculated at board contact and are compared with corresponding values for handspring somersault vaults performed during the 1988 Olympic Games (Takei and Kim, 1990) in Table 3. The mean horizontal approach velocity for the Canadian gymnasts was 7.14 m.s⁻¹ which is considerably less than the 7.93 m.s⁻¹ for the Olympic gymnasts, but the mean vertical velocities were similar (-0.97 m.s⁻¹ and -1.02 m.s⁻¹ respectively).

At takeoff from the Reuther board the mean horizontal velocity for the Hecht was 5.56 m.s⁻¹ which is higher than the mean of 5.31 m.s⁻¹ for the handspring somersault vault. Average vertical

velocities at takeoff from the Reuther board for the Hecht and handspring somersault were 3.48 m.s⁻¹ and 3.76 m.s⁻¹ respectively. At horse contact the mean vertical velocity of the mass centre was 1.00 m.s⁻¹ for the Hecht which is much smaller than the mean 2.36 m.s⁻¹ for the handspring vault (Table 3). The angular velocity of the body at horse contact for the Hecht was 3.40 rad.s⁻¹ which is much lower than the mean preflight angular velocity of 7.37 rad.s⁻¹ for the handspring somersault.

The postflight variables: maximum height of the mass centre, landing distance and rotation potential were used to evaluate each performance (Table 4). For the Hecht vault, the mean values for height, distance and rotation potential were 2.31 m, 2.49 m and 80° respectively.

Table 3. Horizontal and vertical velocities of the mass centre [m.s⁻¹]

	Hecht				handspring			
	[present study]				[Takei and Kim, 1990]			
	mean	S.D.	min	max	mean	S.D.	min	max
horizontal approach velocity	7.14	0.27	6.47	7.74	7.93	0.34	7.11	8.51
vertical approach velocity	-0.97	0.25	-1.44	-0.54	-1.02	0.21	-1.47	-0.51
horizontal velocity at board takeoff	5.56	0.36	4.87	6.13	5.31	0.32	4.61	6.05
vertical velocity at board takeoff	3.48	0.18	3.00	3.95	3.76	0.30	3.20	4.52
horizontal velocity at horse contact	5.56	0.36	4.87	6.13	5.31	0.32	4.61	6.05
vertical velocity at horse contact	1.00	0.38	0.42	2.01	2.36	0.41	1.66	3.50

Table 4. Mean values of preflight and postflight variables

preflight and postflight variables	mean value	σ
horizontal velocity of the mass centre at horse contact	5.56 m.s ⁻¹	0.36
vertical velocity of the mass centre at horse contact	1.00 m.s ⁻¹	0.38
body angle at horse contact	1°	6
shoulder angle at horse contact	140°	9
angular velocity of the body at horse contact	3.40 rad.s ⁻¹	1.34
maximum height of the mass centre	2.31 m	0.11
landing distance of the mass centre	2.49 m	0.29
rotation potential	80°	13

Regression analysis

Each of the postflight variables was regressed against each of the preflight variables. Table 5 shows the significance levels (p values) and R² values for the single variable linear regressions.

Table 5. Single variable linear regressions [* indicates $p < 0.05$]

preflight (independent) variables	Postflight (independent) variables					
	maximum		landing		rotation	
	height h		distance d		potential ψ	
	p	R ²	p	R ²	p	R ²
horizontal velocity of the mass centre u	0.601	0.012	0.001*	0.372	0.814	0.002
vertical velocity of the mass centre v	0.001*	0.384	0.682	0.006	0.839	0.002
body angle ϕ		0.704	0.006	0.125	0.090	0.553
shoulder angle α	0.415	0.026	0.610	0.010	0.015	0.214
angular velocity of the body ω	0.002	0.314	0.121	0.900	0.716	0.005

The maximum height h of the mass centre during postflight was found to be significantly correlated with the vertical velocity v of the mass centre ($p = 0.001$, $R^2 = 0.38$) and the angular velocity ω of the body ($p = 0.002$, $R^2 = 0.31$) at horse contact. The landing distance d of the mass centre past the end of the horse was significantly correlated with the horizontal preflight velocity ($p = 0.001$, $R^2 = 0.37$). The rotation potential was found to be significantly correlated with the shoulder angle α at horse contact ($p = 0.015$, $R^2 = 0.21$). Table 6 shows the significance levels (p values) and R^2 values for the single variable linear regressions for the competition score. The score was significantly correlated with the body angle at horse contact ($p = 0.043$, $R^2 = 0.152$).

Table 6. Correlations between individual performance variables and score [* indicates $p < 0.05$]

independent variables	score	
	p	R ²
body angular at horse contact ϕ	0.043*	0.152
maximum height of the mass centre h	0.081	0.116
landing distance d	3.393	0.003
rotation potential ψ	0.598	0.011

The maximum height of the mass centre during postflight was found to be significantly correlated with the body angle at horse contact ($p = 0.014$, $R^2 = 0.22$) and with the angular velocity of the body at horse contact ($p = 0.028$, $R^2 = 0.18$) once the effect of the vertical velocity at horse contact had been removed (Table 7). The competition score was found to be significantly correlated with the maximum height of the mass centre during postflight ($p = 0.083$, $R^2 = 0.12$) and

with the landing distance of the mass centre past the end of the horse ($p = 0.092$, $R^2 = 0.11$) once the effect of the body angle at horse contact had been removed (Table 7).

Table 7. Regressions of residuals after adjusting for highly correlated variable

regression equation	highly correlated variable	F value	significance level	R^2
$h_r = 0.000 + 0.007878\phi_r$	v	7.05	0.014	0.22
$h_r = 0.000 + 0.0005191\omega_r$	v	5.43	0.028	0.18
$\text{score}_r = 0.000 + 0.8191h_r$	ϕ	3.26	0.083	0.12
$\text{score}_r = 0.000 + 0.3407d_r$	ϕ	3.06	0.092	0.11

Note: r = residual values
 h = maximum height of the mass centre during postflight
 v = vertical velocity of the mass centre at horse contact
 ϕ = body angle at horse contact
 ω = angular velocity of the body at horse contact

Discussion

This study has examined the techniques used by gymnasts to perform the Hecht vault and has compared them with techniques used in handspring somersault vaults (Takei and Kim, 1990). The preflight phases are similar in the sense that the gymnast has forwards rotation at horse contact. The postflight phases of the two vaults differ since the direction of rotation is reversed during contact with the horse in the Hecht whereas the direction of rotation is unchanged during horse contact in the handspring somersault.

Using a passive two segment model King *et al.* (1995) showed that the conditions at horse contact determine the type of vault. It was found that for the Hecht vault a long, low flight path of the mass centre with slow rotation during preflight was best, compared with a short, high flight path of the mass centre with fast rotation for the handspring somersault vault. Comparing the mean preflight characteristics for the Hecht vault (present study) and the handspring somersault vault (Takei and Kim, 1990) highlights a number of clear differences in the techniques used (Fig. 1). During preflight the average horizontal velocity of the mass centre was higher for the Hecht vault (5.56 m.s^{-1} compared with 5.31 m.s^{-1}) even though during the approach phase the horizontal velocity was higher for the handspring vault (7.93 m.s^{-1} compared with 7.14 m.s^{-1}). For the Hecht vault there was therefore only a 22% reduction in horizontal velocity during contact with the Reuther board compared with a 33% reduction for the handspring vault. The differences in velocity components at contact and takeoff with the Reuther board were accompanied by differences in body angle at takeoff. For the Hecht vault the mean takeoff angle was 23° past the vertical compared with 14° for the handspring somersault vault.

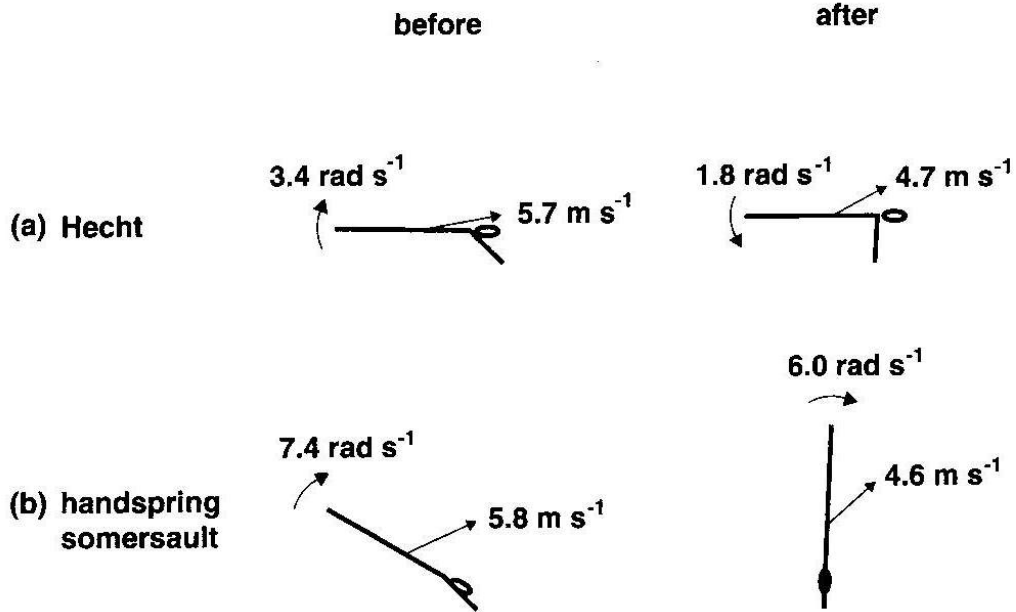


Fig. 1. Mean conditions just before and after contact with the horse in (a) the Hecht (present study) and (b) the handspring somersault (Takei and Kim, 1990).

For the Hecht vault the average vertical velocity was 1.00 m.s^{-1} at horse contact which is much lower than the 2.26 m.s^{-1} reported for the handspring somersault vault. This difference in vertical velocity at horse contact is due to the difference in vertical velocity at takeoff from the Reuther board and to the longer preflight time for the Hecht vault. The average preflight time for the Hecht was 0.25s compared with 0.16s for the handspring somersault vault. This resulted in a 71% reduction in vertical velocity for the Hecht vault during preflight compared with only 37% reduction for the handspring somersault vault. The angular velocity of the body at horse contact was also very different for the two vaults. For the Hecht the mean angular velocity was 3.40 rad.s^{-1} compared with a mean preflight angular velocity of 7.37 rad.s^{-1} for the handspring somersault vault. The low angular velocity of the body at horse contact in the Hecht is due to the longer preflight time and the lower body angle at horse contact. For the Hecht vault the average body angle at horse contact was 1° above the horizontal compared with 30° for the handspring somersault vault.

To understand the techniques employed for the two vaults, the mechanics of the contact phase with the horse must be considered. If the contact with the horse is modelled as a passive rebound of a two segment model contacting a rigid horse (King *et al.*, 1995; Sprigings *et al.*, 1994) then by using the conservation of angular momentum about the point of contact, equations can be written which explain how the conditions at horse contact dictate which type of vault is produced in postflight.

$$\text{Before impact:} \quad h_0 = I_g \omega_g + M_g v_g d_g \quad (2)$$

$$\text{After impact:} \quad h_0 = I_a \omega_a + I_b \omega_b + M_a \omega_a d_a^2 + M_b v_b d_b \quad (3)$$

where:

h_O = angular momentum about the point of contact O with the horse

I = moment of inertia about a transverse axis through the mass centre

ω = angular velocity

M = mass

d = distance from mass centre to O

v = velocity component perpendicular to the line joining the mass centre to O

The subscripts g, a and b represent the whole body, the arm segment and the body segment respectively.

Fig. 1 shows the conditions before and after contact with the horse for the Hecht vault and the handspring somersault vault. Using equation (2) with the conditions at horse contact gives a much lower angular momentum value for the Hecht vault due to the low angular velocity of the body, the low vertical velocity of the mass centre and the smaller moment arm for the horizontal component of velocity. For the Hecht a lower angular momentum value during preflight is required to facilitate the reversal of rotation during horse contact. For the handspring somersault a high angular momentum value is required so that a high angular velocity of the body can be achieved in postflight. Equation (2) shows that a high angular velocity of the body and, a high vertical velocity of the mass centre produce a high angular momentum value. For the direction of the typical \mathbf{v}_g shown in Fig. 1b a high body angle will increase d_g and hence will increase the angular momentum contribution from the second term in equation (2).

Equation (2) shows that the angular momentum about the hands is the sum of the angular momentum about the mass centre and the angular momentum of a point moving with the mass centre. On impact with the horse this second term increases causing a decrease in the angular momentum about the mass centre which leads to a decrease in the angular velocity of the body. In the Hecht vault the reduction in angular velocity results in a reversal in the direction of rotation compared with just a slowing down of the angular velocity for the handspring somersault vault.

The relationships between the preflight characteristics and the postflight performance of the Hecht vaults analysed in this study will now be discussed.

Each Hecht vault was evaluated using three dependent postflight variables: the maximum height reached by the mass centre, the distance of the mass centre past the end of the horse at landing, and the rotation potential. For a good Hecht vault the horizontal distance past the end of the horse must be at least 2.5 m with bonus points for distances greater than 3.5 m. The height needs to be sufficient for the feet to miss the end of the horse, and the rotation potential needs to be large enough so that sufficient backwards rotation can be achieved.

The distance travelled by the mass centre past the end of the horse was positively correlated with the horizontal velocity of the mass centre at horse contact: the faster the velocity the greater the distance travelled ($p = 0.001$). The other preflight variables were also positively correlated with the distance travelled but these relationships were not statistically significant ($p > 0.05$). Equations (2) and (3) together with constant acceleration equations can be used to explain the above findings. Greater body and shoulder angles at horse contact give a higher mass centre location at contact which results in a higher mass centre location at takeoff. From constant acceleration equations, a higher mass centre location at takeoff gives a longer flight time and therefore a greater distance travelled. Higher horizontal, vertical or angular velocities at contact with the horse give higher

angular momentum at horse contact and therefore give higher velocities at takeoff (equations (2) and (3)) which also result in a greater distance travelled.

The maximum height of the mass centre during postflight was positively correlated with the vertical velocity of the mass centre at horse contact ($p = 0.001$). Once maximum height and the remaining preflight variables had been adjusted for their linear relationship with vertical velocity, it was found that body angle and angular velocity were each significantly ($p < 0.05$) correlated with maximum height (Table 7). In both cases the higher the body angle or angular velocity the greater the height reached in postflight by the mass centre. Constant acceleration equations indicate that for a given vertical velocity a higher mass centre location will result in a greater height being reached. A higher body angle at contact results in a higher body position at takeoff and therefore a greater height is reached. Equations (2) and (3) show that higher vertical and angular velocities at horse contact result in a greater angular momentum value before impact and therefore a greater angular momentum value at takeoff which allows a higher vertical velocity at takeoff (equation (3)).

The rotation potential was significantly correlated with the shoulder angle at horse contact ($p = 0.015$) with the smaller the shoulder angle the greater the backwards rotation produced. If the shoulder angle is too large (e.g. 180°) the gymnast will behave like a single rigid segment and the whole body will rotate forwards as in a handspring vault. If the shoulder angle is too small (e.g. 90°) there will be little change in the velocity of the mass centre and the reduction in the angular velocity of the body will only arise from the increase in arm angular velocity. The mean shoulder angle at impact with the horse was $140^\circ \pm 9^\circ$ which is consistent with the simulation findings of King *et al.* (submitted) who found an optimum shoulder angle of 137° for a horizontal body position at horse contact.

Relationships have been found between the preflight and postflight variables of the Hecht vault. This vault requires the correct combination of the preflight variable values at horse contact in order to produce height and distance in postflight along with the correct amount of rotation.

The techniques used to perform the Hecht vault have been shown to be different from those for the handspring somersault vault. For the Hecht vault the gymnasts had longer and lower preflights with slower rotation compared with the handspring somersault vaults. The Canadian gymnasts did not manage to achieve high body angles at horse contact. This was probably due to the competition being soon after the Hecht had been introduced as the compulsory vault. It may be expected that techniques used in the 1996 Olympic Games will have improved to achieve higher body angles at horse contact. To reach body angles close to 20° above the horizontal at horse contact gymnasts must have preflight characteristics which allow the direction of rotation to be reversed from such high angles. In order to achieve this gymnasts may require higher horizontal preflight velocities with longer preflight times giving a low angular momentum value at horse contact and sufficient horizontal velocity to clear the horse.

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References

- Bruggeman, G.-P. (1987). Biomechanics in gymnastics. In *Current research in sports biomechanics. Medicine and Sports Science*, **25** (edited by B. van Gheluwe and J. Atha), pp. 142-176. Basel: Karger.

- Dainis, A. (1979). Cinematographic analysis of the handspring vault. *Research Quarterly*, **50**, 341-349.
- Dainis, A. (1981). A model for gymnastic vaulting. *Medicine and Science in Sports and Exercise*, **13**, 34-43.
- Dapena, J. (1978). A method to determine the angular momentum of a human body about three orthogonal axes passing through its centre of gravity. *Journal of Biomechanics*, **11**, 251-256.
- Dillman, C.J., Cheetham, P.J. and Smith S.L. (1985). A kinematic analysis of men's Olympic long horse vaulting. *International Journal of Sport Biomechanics*, **1**, 96-110.
- Fédération Internationale de Gymnastique. (1993). Compulsory Exercises: MEN 1993-1996. Switzerland: FIG.
- Fink, H. and Zschoke, K.H. (1994). New criteria for the performance of the compulsory vault. Memorandum to all Gymnastics Federations from the Men's Technical Committee.
- Kerwin, D.G., Harwood, M.J. and Yeadon, M.R. (1993). Hand placement techniques in long horse vaulting. *Journal of Sports Sciences*, **11**, 329-335.
- King, M.A., Yeadon, M.R., Kerwin, D.G. and Sprigings, E.J. (1995). Computer simulation of the Hecht vault. In *XVth Congress of the International Society of Biomechanics Book of Abstracts* (edited by K. Hakkinen, K. Keskinen, P.V. Komi and A. Mero), pp. 478-479. University of Jyväskylä. ISBN 951-34-0563-X.
- King, M.A., Yeadon, M.R. and Kerwin, D.G. (submitted). A torque-free two segment simulation model of long horse vaulting. *Journal of Sports Sciences*.
- Kwon, Y.-H., Fortney, V.L. and Shin, I.-S. (1990). 3-D analysis of Yurchenko vaults performed by female gymnasts during the 1988 Seoul Olympic Games. *International Journal of Sport Biomechanics*, **6**, 157-176.
- Reinsch, C.H. (1967). Smoothing by Spline Functions. *Numerische Mathematik*, **10**, 177-183.
- Sevin, A. (1992). *Minitab manual to accompany general statistics*. New York: John Wiley and Sons.
- Sprigings, E.J., Yeadon, M.R., Watson, G. and King, M.A. (1994). Passive rebound technique for the Hecht vault: An exploratory simulation approach. In *Canadian Society for Biomechanics: Proceedings of the Eighth Biennial Conference and Symposium* (edited by W. Herzog, B. Nigg and T. van den Bogert), pp. 224-225. Calgary: Canadian Society for Biomechanics.
- Takei, Y. (1988). Techniques used in performing handspring and salto forward tucked in gymnastic vaulting. *International Journal of Sport Biomechanics*, **4**, 260-281.
- Takei, Y. (1989). Techniques used by elite male gymnasts performing a handspring vault at the 1987 Pan American Games. *International Journal of Sport Biomechanics*, **5**, 1-25.
- Takei, Y and Kim, E.J. (1990). Techniques used in performing the handspring and salto forward tucked vault at the 1988 Olympic Games. *International Journal of Sport Biomechanics*, **6**, 111-138.
- Takei, Y. (1991). A comparison of techniques used in performing the men's compulsory gymnastic vault at the 1988 Olympics. *International Journal of Sport Biomechanics*, **7**, 54-75.
- Walton, J.S. (1981). Close-range cine-photogrammetry: a generalised technique for quantifying gross human motion. Unpublished doctoral dissertation. Pennsylvania State University.
- Yeadon, M.R. (1990). The simulation of aerial movement-II. A mathematical inertia model of the human body. *Journal of Biomechanics*, **23**, 67-74.

Yeadon, M.R., Atha, J. and Hales, F.D. (1990). The simulation of aerial movement-IV. A computer simulation model. *Journal of Biomechanics*, **23**, 85-89.