PREDICTION OF AN OPTIMUM TECHNIQUE FOR THE WOMEN'S YURCHENKO LAYOUT VAULT

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The purpose of this study was to identify an optimum technique for the women's Yurchenko layout vault through an application of optimal control theory on a five-segment model consisting of the hand, whole arm, upper trunk, lower trunk and whole leg. An optimum technique for the vault was determined which, compared to the data, had greater post-flight amplitude and a better layout posture throughout post-flight. However, it involved a larger angular velocity of the segments and greater shoulder extension by about 9º, than the data. The impact phase of the optimum technique was shorter than the data by 0.003 s, and served to increase both the angular momentum of the model as well as the vertical horse takeoff velocity. There is thus, evidence of a 'blocking technique' during impact.

KEY WORDS: optimum technique, optimal control theory

INTRODUCTION: Studies of the Yurchenko family of vaults have typically relied on the analysis of film or video data to understand the mechanics involved (Kwon *et al*., 1990; Elliott & Mitchell, 1991; Jiang *et al*., 1993; Bohne *et al*., 2000). These cinematographic studies have provided insights to the performance of the vault. However, they are limited to only the examples of each movement analysed and cannot investigate the effect of technique variation beyond the range of observed movement. Moreover, conflicting results have been reported with reference to the technique during horse impact in terms of impact duration, changes in angular momentum, and evidence of 'blocking' with the arms and shoulders to bring about a large change in vertical horse takeoff velocity. The conflicting findings may be attributed to the fact that the gymnasts used in the respective studies were of varying standards or that varying techniques were used for the Yurchenko layout vault.

It is inevitable that the complete control of vaulting studies is not possible experimentally, as changes in any aspect of the technique may inadvertently introduce other modifications in the movement that may have a large effect on the result obtained (Yeadon & Challis, 1994). There is also strong resistance from the gymnast or coach for fear of injuries. Therefore, vaulting studies that seek to determine an optimum technique are best carried out by computer simulations. A distinct advantage of computer simulation studies is the effective control and isolation of selected variables of an experiment without subjecting the gymnast to conditions that may be hazardous. Few studies have used the theoretical approach in the study of gymnastics vaulting. Dainis (1981) and Gervais (1994) investigated vaults from the handspring family, while other theoretical studies have concentrated on the counter-rotational Hecht vault performed by male gymnasts (Sprigings & Yeadon, 1997; King *et al*., 1999). To date, there has been no theoretical study of the women's Yurchenko layout vault.

The purpose of the study is to determine an optimum technique for the women's Yurchenko layout vault and to gain an understanding of the mechanics during horse impact. This is done by means of computer simulation and optimization through an application of optimal control theory. The implications of such simulation studies are of significance to the coach as it would provide insight into vaulting techniques that would predict optimal performance.

METHODS: The use of dynamic optimization techniques through an application of optimal control theory is ideal for the analysis of sports performance, as the system dynamics of the movement are enforced throughout the analysis. The software package MISER3 (Jennings *et* *al*., 2000) was chosen as it handled continuous state inequality constraints well and was able to solve optimal control problems with complex constraints.

Since any optimal solution was intimately dependent on the gymnast's current physical capacities and capabilities, subject specific anthropometric data and performance characteristics were measured. The subject was an elite Australian female gymnast who trained for the 2000 Sydney Olympic Games. Subject specific body segment parameters were obtained based on the procedures of Jensen (1978), commonly known as the elliptical zone modelling technique. Subject specific performance variables were measured using a Peak high speed camera (HSC 200P) operating at 200 Hz, with an exposure rate set to 1/500 s to prevent blurring of the images during impact. The camera was positioned so that its focal axis was perpendicular to the plane of motion of the vault (assumed planar). A three meter linear scale was also filmed in the plane of motion of the camera. A chalkboard used for indicating trial numbers was included in the field of view of the camera. During the filming, the subject performed four trials of the vault from her preferred run-up distance. Maximum effort was stressed for each vault and as much time as necessary was given for complete recovery between vaults. Each of the vaults was rated by an internationally qualified judge. Only vaults that scored 9.1 points and above were deemed sufficiently proficient by the code of points which gave the Yurchenko layout vault a start value of 9.3 points. Three of the four vaults scored above 9.1 points. However, as the purpose of the study was to determine an optimum technique, only the best trial (9.25 points) was analysed. This trial was captured into events, namely, pre-flight, impact and post-flight and digitized using the Motus 2000 software. Digitizing began with the first frame of pre-flight and ended at the last frame of post-flight. Symmetry of the skill was assumed and only the left side of the subject was digitized. Quintic splines were used to smooth the data (Vint & Hinrichs, 1996). The pre-flight trials were used to check on the center of mass trajectory of the gymnast to determine if it was still rising prior to impact with the horse. The kinematic data of the best vault were then used in conjunction with the anthropometric data to compute joint torque histories for a five- segment model (hand, whole arm, upper trunk, lower trunk and whole leg) by the method of inverse dynamics (Winter, 1990). The joint torque histories were used as initial torque estimates, together with the initial kinematic conditions at horse impact and horse takeoff for the dynamic optimization of the vault.

Details of the generic formulation of the combined optimal control and optimal parameter selection problem can be found in the MISER3 manual (Jennings *et al*., 2000). In brief, the objective is to minimize over the set of control functions (**u**) and system parameters (**z**), an objective function expressed as: $G_0(\mathbf{u},\mathbf{z}) = \phi_0(\mathbf{x}(t_f), \mathbf{z}) + \int g_0(t, \mathbf{x}(t), \mathbf{u}(t), \mathbf{z})\, dt$, where the states (**x**) are governed by a set of differential equations $\mathbf{x} = \mathbf{f}(t, \mathbf{x}(t), \mathbf{u}(t), \mathbf{z})$, with initial conditions $\mathbf{x}(0) = \mathbf{x}_0(\mathbf{z})$. The minimization is subject to any constraints involving the state functions, system parameters and control functions expressed canonically in a form similar to the objective function. This is intentional as such a formulation allows problems with multiple complex constraints imposed simultaneously to be tackled readily. This generality thus greatly facilitates the actual computation of the problem and reduces the complexity of the user-supplied program immensely. For the present study, 14 states, 4 controls (wrist, shoulder, mid-trunk and hip torques) and 12 system parameters were set up in MISER3 for a five segment model comprising the hand, whole arm, upper trunk, lower trunk and whole leg. The model parameters and the corresponding MISER3 states are described in Table 1.

Based on the evaluation scheme of the vault, the likelihood of points deduction was determined to be greater in the post-flight than during impact or the pre-flight. As the aim in vaulting is to acquire maximal points through post-flight amplitude and minimizing points deductions, the objective function (G_0) was thus formulated such that it represented the aim of maximising performance score during post-flight. This consisted of a terminal cost (ϕ_0) of meeting the 2 m distance requirement; and attaining the landing angle given by data (z_{12}); and a cost of maintaining the layout position throughout post-flight while keeping the arms close to the body. The minimization was subject to an equality constraint imposed on the duration of the vault (z_{11}); an inequality constraint imposed on the amplitude of post-flight (hip height 1 m above horse); and an inequality constraint that the horizontal reaction force on the horse is positive during impact. The forward dynamics of the five- segment model was then optimised for the controls and the initial values of the states as well as the impact time to determine if an optimum technique existed given the present performance characteristics of the gymnast. Tight bounds were placed on the system parameters so that any optimum solution would be attainable by the gymnast.

Table 1 Model Parameters Used in MISER3

MISER3 states	Model parameters
X_1	(hand) θ_1
X_2	(arm) θ_2
X_3	(upper trunk) θ_3
X_4	(lower trunk) θ_4
X_5	(leg) θ_5
X_6	ω_1
X_7	ω_2
X_8	ω_3
X_9	ω_4
X_{10}	ω_5
X_{11}	[1]CM_X or [2]x_E
X_{12}	[1]Cm_y or [2]y_E
X_{13}	[1]velocity CM_X or [2]velocity x_E
X_{14}	[1]velocity CM_X or [2]velocity y_E

System parameters	Initial value
Z_1	θ_1 (0)
Z_2	θ_2 (0)
Z_3	θ_3 (0)
Z_4	θ_4 (0)
Z_5	θ_5 (0)
Z_6	ω_1 (0)
Z_7	ω_2 (0)
Z_8	ω_3 (0)
Z_9	ω_4 (0)
Z_{10}	ω_5 (0)
Z_{11}	duration of vault
Z_{12}	body lean

Controls	Joint torques
U_1	wrist
U_2	shoulder
U_3	mid-trunk
U_4	hip

1 denotes impact phase; 2 denotes post-flight phase;
(x_E , y_E) - coordinates of the proximal end of segment 1; (CM_X,CM_Y) - coordinates of system CM;
θ_i (i = 1,…,5) - segment angle with respect to the horizontal axis; ω_j (j = 1,…,5) - segment angular velocity.

RESULTS AND DISCUSSION: Results of the optimisation show that the constraints were satisfied, that is, the 2 m distance requirement was attained at the end of post-flight; and the duration of the vault was the same as the data. The optimised vault was superior in post-flight amplitude compared with the data and demonstrated a better layout throughout the post-flight. This means less likelihood of any points deduction under the penalty items, 'insufficient layout' and 'lack of stretch before landing' and provides the opportunity for bonus points in the judging. Overall, the optimised vault would score better than the data. The results of the optimisation also indicate that the initial impact configuration was different to the data; namely an increased shoulder extension by 9º and an increased hip flexion by 8º. It is not clear if the hip flexion is a consequence of the increased shoulder extension due to limited joint mobility of the gymnast. However, the increased shoulder extension was consistent with the observations by Bohne *et al*. (2000) who noted that better Yurchenko layout vaults were performed by gymnasts who contacted the horse with a larger shoulder joint extension, as a result of reaching early for the horse, than those who did not.

As the system parameters were constrained by narrow bounds ($\pm$ 0.1 rad for θ, $\pm$ 0.1 rad$\cdot$s^{-1} for ω), the optimum parameters were consequently close to the present performance capabilities (data) of the gymnast. Thus, the optimum vault is attainable. However, to execute it, a higher angular velocity at impact with the horse than the data was required. In addition, the total angular momentum of the system must also be increased during impact with the horse, contrary to the data, in which pre-flight angular momentum was only maintained during impact with the horse. This difference in technique is due to the higher angular momentum demands of the optimum technique. A `blocking' technique was also observed. This is manifested by an increase in vertical takeoff velocity and a reduction in horse contact time by 0.003 s compared with the data.

CONCLUSION: An optimum Yurchenko layout vault technique was identified that was superior to the data but still within the capability of the gymnast. The technique requires a higher angular velocity at impact with the horse and a greater shouder extension than the data. In addition, a 'blocking' technique during horse impact was identified which served to increase both the pre-flight angular momentum as well as the vertical horse takeoff velocity. As a consequence of the increased angular velocity of the gymnast at horse impact, there was a decrease in horse contact time compared with the data. The observations suggest that an effective 'blocking' technique, a high pre-flight angular velocity, and an appropriate body segment configuration at horse impact are key ingredients for a high scoring Yurchenko layout vault. The implication to the coach is to work on the roundoff technique of the gymnast as the latter converts forward linear momentum to angular momentum and simultaneously orientates the gymnast for the backflip entry of the vault.

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