COMPUTER SIMULATION OF THE OPTIMAL VAULTING MOTION DURING THE HORSE (TABLE) CONTACT PHASE

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The purpose of this research is to investigate how the kinematic factors during the horse (table) contact phase influence the post-flight performance in handspring vaulting. A six-segment planar simulation model comprising the lower arm, upper arm, head-trunk, thigh, shank, and foot was customized to an elite gymnast. The body segment parameters, maximum joint torques, and initial kinematic parameters from video analysis of the subject are required for the optimal matching computer simulation. The model was able to match a handspring vault after adjusting the visco-elastic characteristics of the arm-horse interface and joint activation time histories. The model was then used to determine the key factors which influence performance by varying the initial conditions. The objective function was the vertical velocity of the body center of mass at takeoff. The results suggest that smaller wrist angle, greater wrist angular velocity, straighter elbow, greater shoulder angular velocity, greater maximum shoulder torque, and smaller hip angle at horse contact were crucial in achieving the optimal performance. Compared with the five-segment model with a visco-elastic shoulder of a previous study, the six-segment model without a visco-elastic shoulder could still closely match the real performance, and better mimic the actual pushing movement of the arms.

KEY WORDS: gymnastics, modelling, optimization, muscular activation

INTRODUCTION: Most studies about gymnastic vaulting can be characterized into two approaches. One is to record the motions of vaults by cameras and identify the relationship between performance and kinematic parameters. The other is to predict the results by computer simulation. The strength of simulation is not only to examine the sensitivity of initial kinematic variables to give athletes and coaches advices, but also to reduce unnecessary trials/errors to avoid injury. Compared with video analysis, only a few studies employed computer simulation to investigate the vaulting skills. Dainis (1981) used a three-segment human model to describe the motion of handspring vault. The results indicate that the decrease of take-off velocity reduces the after-flight distance. Two-segment models without shoulder torque had also been developed for studying handspring vaults and the Hecht vault. It was found that when the model was limited to one segment by fixing the shoulder, the vault cannot be finished (Sprigings & Yeadon, 1997; King et al., 1999). Koh et al. (2003) used a five-segment model comprising the hand, upper limb, upper trunk, lower trunk, and lower limb to find out the key variables in the Yurchenko vault. The optimal vault displayed greater post-flight amplitude and angular momentum when compared with the gymnast's best trial, and the optimal parameter is within the capacity of the gymnast. King and Yeadon (2005) also used a five-segment model but consider the visco-elastic property of shoulder joint and arm–horse interface. The results show that factors such as shoulder elasticity and the hands which have previously been ignored also have a substantial influence on performance.

Although models of vaulting have been developed from two- to five-segment types with visco-elastic properties, the sensitivity of initial kinematic parameters at horse contact to post-flight performance is still not clear. The difficulty level of a vault is determined by extra spins/somersaults in addition to its basic form. Both greater take-off vertical velocity and post-flight amplitude are necessary for optimal performance. The purpose of this study is to develop a six-segment model for investigating how the initial kinematic factors during the horse contact phase influence the performance during post-flight in handspring vaulting.

METHODS: A six-segment (6S) planar human body model comprising the lower arm, upper arm, head - trunk, thighs, shanks, and feet was developed to simulate the vaulting motion during horse (table) contact. Movement was driven by torque actuators at the ankle, knee, hip, shoulder and elbow. The model was customized to an elite gymnast through subject specific length and strength parameters. Detailed inertia parameters were determined using the data of Taiwanese gymnasts by an MRI method (Chen & Ho, 2006). A high-speed camera operating at 200Hz was used to record the vaulting motion. The trail with the greatest CM velocity at take-off from horse was chosen for kinematical analysis and as the input values of the model. Equations of motion were generated by the software AUTOLEV (www.autolev.com). Each joint torque T was assumed as the product of 3 factors:

$$T = T_{\max}(\theta)h(\omega)A(t) \tag{1}$$

$T_{max}(\theta)$ depends on joint angle is the maximum isometric torque (effective torque for both extremities). The dependence on joint angular velocity is modeled by $h(\omega)$.

$$\begin{cases} h(\omega) = (\omega_0 - \omega)/(\omega_0 + \Gamma\omega), & \omega/\omega_0 < 1 \\ h(\omega) = 0, & \omega/\omega_0 \geq 1 \end{cases} \tag{2}$$

Here ω is the instantaneous joint angular velocity, ω_0=±20 rad/s is maximum angular velocity (positive in extension), and constant Γ=2.5 is a shape factor. Joint activation level $A(t)$ characterizing the coordination strategy corresponds to the effective activation of muscles across the joint. The activation level $-1 \leq A(t) \leq 1$ represents maximum effort for flexion and extension respectively. Linear interpolation was used to get the value at every time instant. The visco-elastic properties of the interface between the model and the vaulting horse (arm-horse interface) were modeled by a non-linear spring force F (King & Yeadon, 2005).

$$F = S \times D^2 + K \times D \times V \tag{3}$$

Here S is the stiffness, D is joint displacement, K is the damping coefficient, and V is the joint velocity. This force F is applied in both horizontal and vertical directions. The objective was to maximize the vertical velocity of the center of mass (CM) at takeoff from the horse. The optimization algorithm adopted was the downhill simplex method. Varying initial guesses and re-starting the optimization from a newly found optimum are employed. The model was validated when the averaged angular difference between the model and actual performance was < 5%. Next, the elbow joint was fixed to develop a five-segment (5S) model. By varying the initial kinematic parameters and repeating the optimum calculation, the likelihood of finding the global rather than a local optimum was increased.

RESULTS AND DISCUSSION: The averaged difference between actual performance and model was 4.10%, which met the criterion of model validity in this study. The elbow angle changed from 2.98 to 3.14 rad in the horse contact phase (Fig.1, 2).

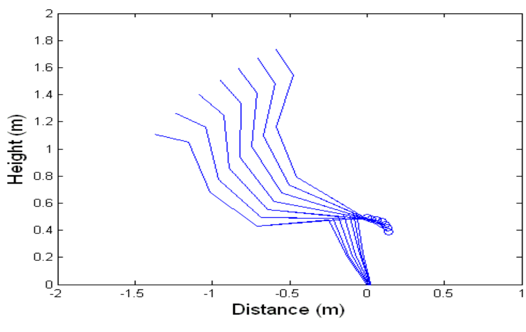

Figure 1: Motion in the horse contact phase of the 6S model

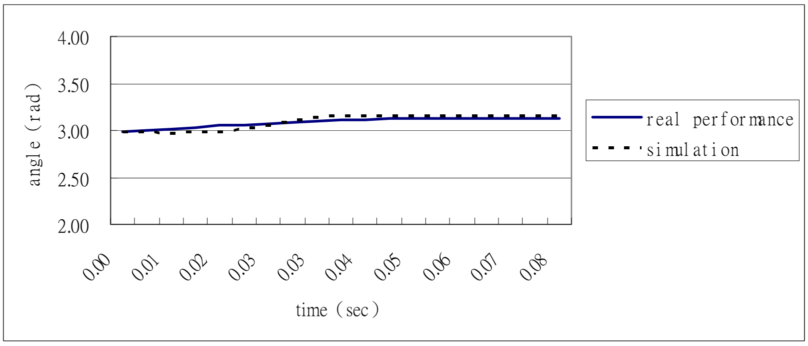

Figure 2: Elbow angle in the horse contact phase

Table1：Parameters of visco-elastic property at the arm-horse interface. Letter h and v represents the horizontal and vertical direction, respectively.

	6S	5S
Sh	130Nm^{-2}	130 Nm^{-2}
Sv	25284000 Nm^{-2}	1264200 Nm^{-2}
Kh	146000 Nsm^{-2}	146000 Nsm^{-2}
Kv	900000 Nsm^{-2}	900000 Nsm^{-2}

Table 2：Influence of initial parameters on the vertical velocity at take-off

	parameter	Initial value	adjustment	Vertical velocity of the CM (Vv-cm) at take-off	Comparison with the nominal 6S results
wrist	angle (rad)	0.9	-10%	5.70	9.08%
		1.1	＋10%	4.86	-7.13%
	angular velocity (rad/s)	6.42	-10%	4.88	-6.60%
		7.84	＋10%	5.73	9.47%
elbow	angle (rad)	2.68	-10%	3.14	-39.94%
		3.14	＋5%＊	5.66	8.23%
	angular velocity (rad/s)	0.9	-10%	5.32	1.68%
		1.1	＋10%	5.25	0.41%
shoulder	angle (rad)	1.7	-10%	5.39	2.99%
		2.08	＋10%	5.03	-3.76%
	angular velocity (rad/s)	5.34	-10%	5.06	-3.24%
		6.52	＋10%	5.53	5.70%
hip	angle (rad)	3.53	-10%	5.73	9.62%
		4.31	＋10%	4.50	-13.99%
	angular velocity (rad/s)	1.62	-10%	5.28	0.96%
		1.98	＋10%	5.14	-1.73%
maximum shoulder joint torque (Nm)		108	-10%	-10%	-2.35%
		132	＋10%	＋10%	2.00%

＊Here a 5% increase is used because a 10% increase will exceed the range of motion.

In order to match with the duration of horse contact, the vertical stiffness (Sv) of the 5S model had to be about half of the 6S model. It is probably because the 5S model lacks the cushioning effect provided by the elbow, and Sv should be smaller to lengthen the contact time. In addition, elbow angle changed slightly in the horse contact phase. The results demonstrate that model 6S can reproduce the actual motion more precisely.

At the wrist joint (contact point), Vv-cm increased by 9.08% if the joint angle was reduced by 10% to be 0.9 rad, implying that the wrist angle of the individual is somewhat too big. This result agrees with the optimal contact angle of 0.87 rad in the previous study (King et al.,1999). Besides, if the angular velocity increased by 10%, Vv-cm also increased by 9.47%. When the elbow angle decreased to 2.68 rad, Vv-cm decreased considerably by 39.94%, resulting in the motion far different from the actual performance. But if the elbow became straight, Vv-cm increased by 8.23%. This result proves the general strategy of keeping the whole arm straight to get more reaction force from the horse. When the shoulder angle increased to 2.08 rad, Vv-cm decreased by 3.76%. This trend disagrees with the optimal simulation shoulder angle of 3.13 rad (King et al., 1999) and 2.27 rad of two elite gymnasts (Xu et al., 2004) in other studies. The wrist angle of the individual was already much greater than the optimal value, so the shoulder angle should be smaller to avoid over-shortened contact time. Actually, the contact time of this simulation is less than that of the real performance. When the shoulder angular velocity increased by 10%, Vv-cm increased by 5.70%. As for maximum shoulder joint torque, 10% increase caused about 2% increase in Vv-cm. Although King and Yeadon（2005）indicated minor difference between simulations with and without shoulder torque, this torque should have certain influence on the performance of handspring vaults. When the hip angle was reduced to 3.53 rad, Vv-cm increased by 9.62%. Compared with the hip angle of 2.69 rad. and 3.40 rad. of the two elite gymnasts (Xu et al., 2004), this initial angle used by our subject was not large enough.

CONCLUSION: The six-segment model can describe the real motion of vault more exactly than models with less segments, and more closely mimics the actual pushing movement of the arms. Although the visco-elastic property was not contained in shoulder joint, the model closely matched the real performance. From the optimal simulations, the suggestion to the individual is to have a smaller wrist angle, greater wrist angular velocity, straighter elbow, greater shoulder angular velocity, greater maximum shoulder torque, and smaller hip angle at horse contact.

REFERENCES:

Chen, K.-H. & Ho, W.-H. (2006). An analysis of kehr with 1/1 turn on 1 pommel: The case of Tsai-Chih Hsiao. *Journal of Physical Education in Higher Education.* 8-1, 201-212.

Dainis, A. (1981). A model for gymnastic vaulting. *Medicine and Science in Sports and Exercise*, 13, 34-43.

King, M. A. & Yeadon, M.R. (2005). Factors influencing performance in the Hecht vault and implications for modeling. *Journal of Biomechanics*, 38, 145-151

King, M.A., Yeadon, M.R., & Kerwin, D.G. (1999). A two segment simulation model of long horse vaulting. *Journal of Sports Sciences*, 17, 313-324.

Koh, M., Jennings, L., Elliott, B., & Lloyd, D. (2003) A predicted optimal performance of the Yurchenko layout vault in women's artistic gymnastics, *Journal of applied biomechanics*, 19, 187-204.

Sprigings, E.J. & Yeadon, M.R. (1997). An insight into the reversal of rotation in the Hecht vault. *Human Movement Science*, 16, 517-532.

Xu, Yuan-yu, Yao, Xia-wen, Ji, Zhong-qiu, Huang, Yu-bin, & Chen, Xiong (2004). *China Sport Science and Technology.* 40, 73-77.

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