DYNAMIC MODELLING FOR THE SECOND FLIGHT PHASE OF THE YURCHENKO LAYOUT VAULT BASED ON MSC. ADAMS

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Original article

Abstract
Gymnasts attempt to increase the angles of rotation about transversal and longitudinal axes during the post-flight of vaulting, and these angles are related to different mechanical properties. The present study uses a 3D angle-driven computer simulation model of a gymnast who performs Yurchenko layout vault using ADAMS software. Simulation initial conditions are horizontal and vertical velocities of gymnast's pelvis center and angular velocities about the transversal and longitudinal axes which can be easily measured. The initial linear and angular velocity conditions of the simulation model are each changed in certain increments from measurement data collected from an elite woman gymnast. Increasing initial horizontal velocity results in an increased horizontal flight distance, but has no connection with the duration of flight and angle of twists. The overall angle of twists is concerned with initial vertical velocity and angular velocities about the transversal and longitudinal axes. Also, increasing initial vertical velocity and angular velocity about transverse axis leads to increase in touchdown angle between ground's horizontal axis and gymnast's longitudinal axis.

Keywords: *vault, aerial movement, multibody dynamics, ADAMS.*

INTRODUCTION

Gymnasts get marks which consist of difficulty and performance values of their vaulting in artistic gymnastics. The vault difficulty values are already defined at FIG Code of Points. These difficulty values depend on body configuration and rotation angles about transversal and longitudinal body axes in gymnast's flight performance (Atiković, 2011). The rotations around the transversal and longitudinal body axes are mainly performed in the second flight phase and the gymnasts change body configuration purposely for rotation in this phase.

The second flight of gymnast is related to various mechanical initial conditions at take-off from table and gymnast's body configuration during flight. The elements of successful vaults are vertical velocity at takeoff from the table, angular momentum about the mass center, and moment of inertia about the mass center (Čuk & Karacsony,2004; Prassas, 2002; Takei, 1998).

To simulate human movement, a human body can be divided by several rigid segments which are connected with various joints (Yeadon & King, 2008). Huang (1998) presented a three dimensional human body model to simulate human response within rear-end impact vehicle. This model consisted of 15 rigid bodies which were connected with spherical and revolute joints. King and Yeadon (2015) presented various simulation models of different sports movements with their detailed information. Angle-driven models were simpler to control human body configuration than torque-driven models, so these models were used to simulate complex movements having many degree of freedoms (DOFs). Yurchenko layout vaults include rotations about transversal and longitudinal axes in the second flight phase. Koh (2003a, 2003b) studied optimized performance at table contact phase by using a five segment model of a gymnast in order to obtain maximum flight height and good performance vault. This five segment model was driven by joint angles and angular velocities. Rotations about longitudinal axis can be produced during contact phase at table and during the flight phase by means of asymmetric movements of arm and hip. To simulate this kind of aerial movements, an angle-driven model that comprised four leg segments, four arm segments and three body segments was used (Yeadon 1990, 1993c, 1999).

The study of human movements needs to find joint angles from video data applying inverse kinematics theory. The measured global Cartesian coordinates should be transferred to generalized coordinates including all joint angles by the methods of inverse kinematics. Yeadon and Hiley (2003) collected the global position of the joint centers from two synchronized video data and determined joint angle histories using the Direct Linear Transformation method. Reinbolt (2011) presented an inverse kinematics method to minimize weighted square error between experimental and simulated global positions of markers. Also, Koh and Jennings (2003) used an optimization procedure to solve the inverse dynamics problem for Yurchenko layout vault. This objective function was composed of differences between computed and measured segment angles and between computed and measured center of mass (CM) positions of a gymnast.

MSC. ADAMS is a widely used software based on multibody dynamics, and it can help to simulate kinematics, statics and dynamics problems with its convenient interface. It has the capability to import various types of geometry files such as SolidWorks, IGES and Parasolid files. Once a simulation model is given by users, it builds a dynamic equation of the model automatically, and so users can simulate easily by inputting only simulation duration and interval. Liu and et al (2013) analyzed inverse and forward dynamic problems of bicycle riding human model using LifeMOD and ADAMS software, and presented the effect of bicycle suspension systems to human body.

The purpose of this study is to build a 3D angle-driven simulation model using ADAMS software and simulate the second flight movement of Yurchenko layout vault in various initial conditions. This model has an exclusive user interface to change initial conditions and joint angle trajectories for gymnasts and coaches.

METHODS

A computer simulation model has been built for an elite woman gymnast who performed Yurchenko layout vault using SolidWorks and ADAMS software. This model was driven by joint angle trajectories which were obtained from video data of gymnast's movement. To verify this model, the measured CM positions were compared with computed CM positions presented by simulation under measured initial conditions. Then, the model was repeatedly simulated to find how each of initial conditions influences the angle of twists and somersaults.

A 15 segment simulation model was built comprising head, torso, pelvis, hands, foot and the upper and lower arm and leg segments. During aerial flight phase, twist can be generated by asymmetric arm of hip movement, so the upper and lower arms and hands are each considered as a different segment, and the upper and lower legs and foot are also different segments (Yeadon, 1993c).

Each segment was built from measured geometric properties of the gymnast and combined into a whole body geometric model using SolidWorks software. Then, this whole body model was imported to ADAMS, and inertia properties of the model were calculated automatically by density of segments (Winter, 2005).

The bodies (parts of ADAMS model) should be connected with suitable joints. Generally, the multibody model of human body is considered as tree-type system whose root is the pelvis and each body connects its parent bodies with a joint. Table 1 shows the joints of model and their DOFs. As the pelvis body has 6 DOFs, this model has 36 DOFs.

Table 1
Type of joint used for the model

Position	Adjoining bodies	Type of Joint	DOF
Spine	Pelvis-Torso	Spherical	3
Neck	Torso-Head	Spherical	3
Shoulder(L, R)	Torso-Upper Arm	Spherical	3
Elbow(L, R)	Upper Arm-Lower Arm	Revolute	1
Wrist(L, R)	Lower Arm-Hand	Spherical	3
Pelvis(L, R)	Pelvis-Upper Leg	Spherical	3
Knee(L, R)	Upper leg-Lower leg	Revolute	1
Ankle(L, R)	Lower leg-Feet	Revolute	1

Generally, angles of joints are determined from global positions of markers which are attached to the body (Delbridge, 2015). These markers disturb aerial movement of gymnasts, so they cannot complete their vault to the best of their own physical abilities. Therefore, the movement was recorded using two video cameras (1920×1080 pixels, 400Hz), and global positions of joint points were determined by analyzing video data (Fig 1). As the revolute joint has only one rotational DOF, the angles of elbows and knees can be easily determined. But the spherical joint has three rotational DOFs and the angle coordinates of spherical joints are Cardan angles in ADAMS software. To determine Cardan angles of joints, nonlinear least square method in which Eq. (1) is a minimized objective function was used (Reinbolt, 2011).

$$\min_q \left[\sum_{i=1,\cdots,n} w_i \left\| x_i^{\exp} - x_i(q) \right\|^2 \right] \tag{1}$$

where w_i are weighted coefficients, $x_i^{\exp}$ are measured global coordinates of joint points, q are Cardan angles of spherical joints and calculated global coordinates of joint points $x_i(q)$ are functions of q.

These Cardan angles of joints are considered as nonstationary kinematical constraints using AKISPL function of ADAMS software.

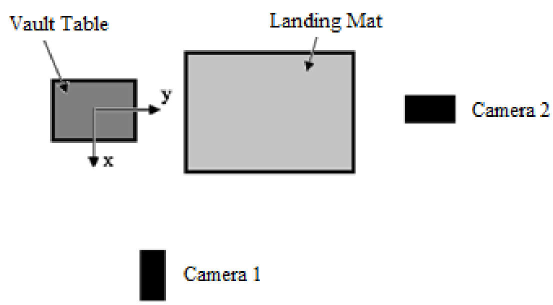

Figure 1. *Locations of Cameras*

Neglecting friction and resistance forces in the air, the external force acting on gymnast is only gravity, so the trajectory of mass center is closely approximated to a parabola. This parabolic movement is related to initial horizontal and vertical velocities (Takei, 1998). And the rotations around the transversal and longitudinal body axes are related to initial angular velocities (Čuk & Karacsony,2004; Prassas, 2002). The CM position of human body governed by CM positions of body segments cannot be directly measured. So, instead of CM velocity of whole human body, the CM velocity of pelvis segment is used as initial linear velocity conditions. And the angular velocities around the transversal and longitudinal body axes at take-off from table are also initial conditions.

For the convenience of users, the customized simulation dialog box was built using the ADAMS Dialog-Box Builder (Fig 2). Users can change initial conditions, trajectories of angle joints and simulation settings in this dialog box. A trajectory of angle joint was defined as a spline curve, so users can change configurations of body in the air by changing it. Also, this dialog box has animation controls and a graph display button to display simulation results such as the total rotation angle of twists, CM position and velocity trajectories of whole body using ADAMS View command language.

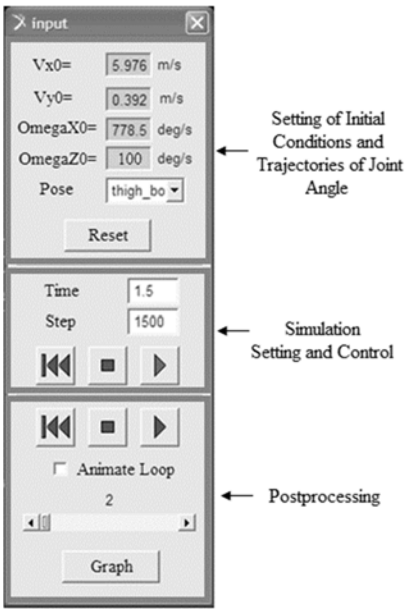

Figure 2. Customized Simulation Dialog Box.

Computer simulation result of the Yurchenko layout vault is shown in Fig. 3. The gymnast performed Yurchenko stretched with 2/1 turns. At the take-off from table, the horizontal velocity of gymnast's pelvis center is 3.0m/s and vertical velocity is 4.3m/s. The angular velocities around longitudinal and transversal axes are respectively 525°/s and 250°/s.

Figure 3. Computer graphics result of the model used in evaluation.

The flight durations of video and simulation are 1.0575s and 1.068s, respectively. The difference of flight duration is 10.5ms and its relative error is about 1%. Fig. 4 shows a comparison between CM position trajectories obtained from simulation result and video. The marker 'o's are CM positions which were calculated from video sequences. It can be seen from Fig. 4 that the simulation result closely matches the video result and its relative error is 8.6%. This error may partly occur in measuring marker positions of body segment to calculate whole body CM position from video sequences, and also partly in inertial parameters of body segments which were determined by their densities.

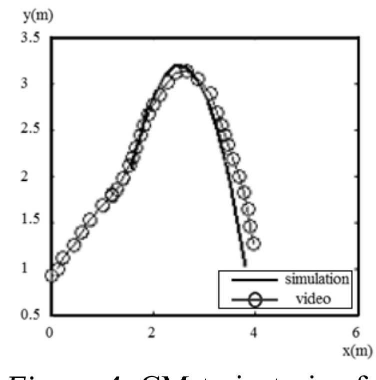

Figure 4. CM trajectories from simulation and video.

$X_{\max}$ and height $Y_{\max}$, touchdown twist angle about longitudinal axis of body Φ_T and touchdown somersault angle between horizontal axis of ground and longitudinal axis of body at flight end time θ_{end}. To compare simulation results in various initial conditions, simulations are terminated when the distance from CM position of pelvis to ground is 0.9 meter.

In this simulation model, the orientation angles of the human body can be determined by measuring the CM marker's orientation of the torso segment. Fig. 5 shows the trajectory of the body's somersault, tilt and twist angles when initial velocity conditions are $V_x = 3m/s, V_{y0} = 4.3m/s, \omega_{z0} = 525°/s, \omega_{x0} = 250°/s$

RESULTS

The simulation results are flight duration T_{end}, maximal flight distance

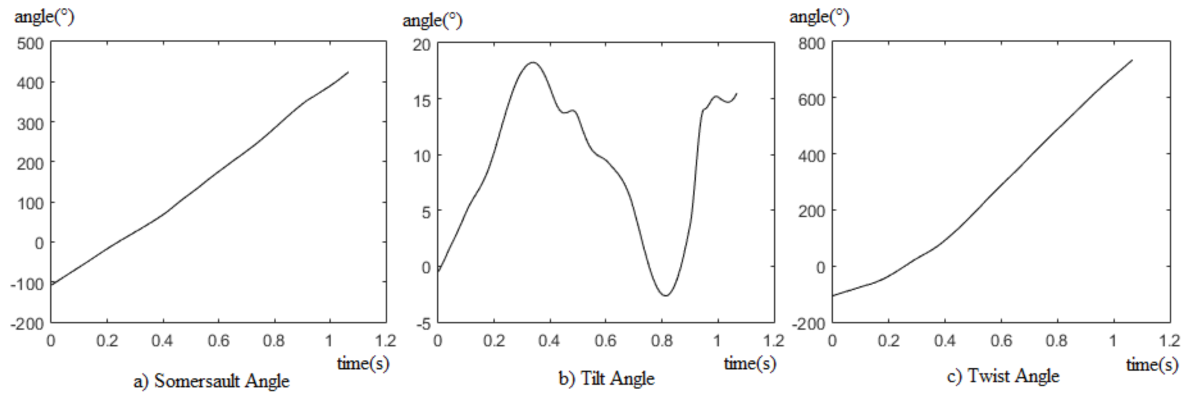

Figure 5. The trajectory of the body's orientation angles during simulation when initial conditions are $V_x = 3m/s, V_{y0} = 4.3m/s, \omega_{z0} = 525°/s, \omega_{x0} = 250°/s$.

Table 2 shows simulation results when initial horizontal velocity V_{x0} varies from 2.6m/s to 3.2m/s with an increment of 0.2m/s. Increasing initial horizontal velocity results in an increased maximal flight distance $X_{\max}$, but has no connection with T_{end}, $Y_{\max}$, Φ_T and θ_{end}.

Table 2

Simulation results with the variation of V_{x0} $V_{y0} = 4.3m/s, \omega_{z0} = 525°/s, \omega_{x0} = 250°/s$

V_{x0}	T_{end}	$X_{\max}$	$Y_{\max}$	Φ_T	θ_{end}
2.6	1.068	2.087	2.906	740.7	60.09
2.8	1.067	2.299	2.906	740.2	60.09
3	1.068	2.514	2.906	740.7	60.09
3.2	1.068	2.727	2.906	740.9	60.15

The flight duration of a particle is related with its vertical velocity in parabolic movement. Simulation results show the initial vertical velocity of pelvis segment V_{y0} effects on every five resultant variables (Table 3).

Table 3

Simulation results with the variation of V_{y0}.

$V_{x0} = 3m/s, \omega_{z0} = 525°/s, \omega_{x0} = 250°/s$

V_{y0}	T_{end}	$X_{\max}$	$Y_{\max}$	Φ_T	θ_{end}
3.9	1.007	2.398	2.7485	698.3	30.36
4	1.022	2.431	2.7842	704.4	38.03
4.1	1.037	2.461	2.822	713.3	45.5
4.2	1.052	2.488	2.863	725.3	52.68
4.3	1.068	2.514	2.906	740.7	60.09
4.4	1.084	2.542	2.9525	756.4	66.93
4.5	1.101	2.569	2.9995	769.5	74.24
4.6	1.12	2.603	3.0473	782.2	82.68
4.7	1.135	2.628	3.096	796.2	92.29

The simulation results, as changing the other two initial angular velocity conditions, are shown in Table 4 and 5, respectively. If the initial angular velocity about transversal axis ω_{z0} increases, the flight duration T_{end}, maximal flight distance $X_{\max}$ and maximal flight height $Y_{\max}$ are decreased., but the twist angle Φ_T and touchdown angle θ_{end} are increased. Also, the total rotation angle Φ_T is related with initial angular velocity about longitudinal axis ω_{x0}.

Table 4

Simulation results with the variation of ω_{z0}.

$V_{x0} = 3m/s, V_{y0} = 4.3m/s, \omega_{x0} = 250°/s$

ω_{z0}	T_{end}	$X_{\max}$	$Y_{\max}$	Φ_T	θ_{end}
450	1.087	2.758	2.937	692.6	-20.22
475	1.08	2.683	2.923	704.2	0.63
500	1.073	2.6	2.912	714.8	34.24
525	1.068	2.514	2.906	740.7	60.09
550	1.07	2.442	2.9053	753.3	82.54
575	1.058	2.318	2.9059	774.1	109.1
600	1.059	2.212	2.907	803	142.7

Table 5

Simulation results with the variation of ω_{x0}.

$V_{x0} = 3m/s, V_{y0} = 4.3m/s, \omega_{z0} = 525°/s$

ω_{x0}	T_{end}	$X_{\max}$	$Y_{\max}$	Φ_T	θ_{end}
200	1.066	2.489	2.9079	691.7	63.03
225	1.067	2.505	2.9076	712.5	58.98
250	1.068	2.514	2.906	740.7	60.09
275	1.067	2.517	2.9057	756.4	58.62
300	1.068	2.525	2.9059	756.2	52.92
325	1.068	2.527	2.9065	761.7	51.01

From simulation results for various initial conditions, the cross correlation coefficients between initial conditions and flight results are obtained (Table 6). If the variation of flight result, when changing an initial condition was very small, this correlation coefficient was neglected (marker '- 's).

Table 6
The cross correlation coefficients between initial conditions and flight results.

	T_{end}	$X_{\max}$	$Y_{\max}$	Φ_T	θ_{end}
V_{x0}	-	1.000	-	-	-
V_{y0}	1.000	1.000	0.999	0.995	0.999
ω_{x0}	-0.961	-0.996	-0.838	0.937	0.999
ω_{z0}	-	0.958	-	0.937	-0.936

DISCUSSION

The aim of the present study was to build a simulation model of the gymnast who performed Yurchenko layout vault by using ADAMS software and to study relations between initial conditions and flight results in the second flight phase. The customized dialog box was designed for gymnasts and coaches to use the simulation model easily and conveniently.

Initial conditions of second flight are related to linear and angular velocities at vault table touchdown and their changes in contact with the table. Among these initial conditions, the linear velocities and angular velocity about transversal axis are concerned with the first flight phase, while the angular velocity about longitudinal axis is related with body configuration during table contact phase (Yeadon 1993a, b).

The results show that the initial horizontal velocity does not affect a gymnast's vaulting performance, but it is related to maximal flight distance in second flight phase. When the gymnast lands on mat, the landing position should be at appropriate distance from the vault table to avoid accidents, so this horizontal velocity condition cannot be reduced to zero.

The one of important flight results is the rotation angle about longitudinal axis of body which is associated with initial vertical velocity and angular velocities (Table 6). Consequently, the flight duration gets increased by an average of 16 ms and the twist angle about longitudinal axis by an average of 12°, as the initial vertical velocity gets increased by 0.1m/s. And the twist angle gets almost increased by 28°, when both initial angular velocities about transversal and longitudinal axes are increased by 50°/s.

Simulation results also shows that the flight duration was decreased with increase of initial angular velocity about transversal axis. Generally, the flight duration is related with the initial vertical velocity of a body's CM. The linear initial velocities used in this paper are horizontal and vertical velocities of gymnast's pelvis CM, not those of the whole human body's CM. The vertical velocity of the whole human body's CM can be determined by pelvis CM velocities and angular velocity about transversal axis, hence the flight duration may be related with this initial angular velocity.

The landing on mat is a final phase of vault and the suitable touchdown angle is important for successful landing. The touchdown angle is increased with increase of initial vertical velocity and angular velocity about transversal axis of gymnast, but when the angular velocity about longitudinal axis increases, this angle is decreased slightly.

CONCLUSION

From these results, it can be seen that the important technique on vault table is to change the linear horizontal momentum of the first flight phase to the linear vertical momentum of the second flight.

Through the simulation model in this paper, the twist somersaulting flight result can be shown by intuition, as the initial conditions and flight body configurations are changed by users. Gymnasts and coaches can get the sufficient initial conditions and correct their own shortcomings in body configuration to perform any aerial movements including Yurchenko layout vaults.

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