Determination of Model Complexity in Simulation of Flight Phase Dynamics and Joint Control Prior to Landing

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Introduction

Prior to landing, humans must effectively prepare for the impending load by controlling the body's moment of inertia prior to contact. The ability of an individual to prepare for contact may be influenced by the preparation time (Lees, 1981), segment kinematics (McNitt-Gray, 1991), flight phase task complexity, and visual conditions prior to contact (Sidaway, et al., 1989). To advance our understanding of landing dynamics and test hypotheses regarding multijoint control prior to landing, an experimentally validated dynamic model that can include control elements needs to be developed. The purpose of this study is to determine the level of model complexity needed to capture the salient features of the dynamics and multijoint control used by gymnasts when landing from a layout salto. We hypothesized that a 5-segment planar model would adequately simulate the flight phase dynamics of a layout salto performed during competition as assessed by experimental data and conservation laws.

Methods

Layout saltos dismounts from asymmetrical bars performed by female gymnasts (n=6) during the 2000 Olympics Artistic Gymnastics Competition were videotaped (200Hz, 2-NAC C2S). Prior to the competition, a vertical calibrated pole with reflective markers was placed at known locations within the dismount area. 2D body landmarks (deLeva, 1996) were manually digitized and 3D data were computed (Motus, Peak Performance). Sagittal plane kinematics were digitally filtered and differentiated using quintic splines (Woltring, 1986). Kinematics of the left and right limbs was analyzed to test for symmetry and planar motion.

Consider a human body model that consists of \( n \) rigid segments interconnected by frictionless revolute joints actuated by moments about the joint centers (Figure 1).

\[
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{q}_i} \right) - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial q_i} = Q_i, \quad i = 1 \ldots N \quad (N=n+2) \quad (1)
\]

where \( \dot{q} = [q_1 \ q_2 \ q_3 \ldots q_N]^T \) are the generalized coordinate, \( Q = [0 \ 0 \ \tau_3 \ldots \tau_N]^T \) are the generalized forces, \( T \) is the total kinetic energy, \( V \) is the total potential energy. For \( i = 1,2 \) in (1) are non-actuated degrees of freedom that requires conservation laws to be satisfied. These conservation equations were expressed in terms of position (0th order form), velocities (1st-order form), and forces or accelerations (2nd order form). These conservation equations can be considered as constraints on the system dynamics. These constraints, which express basic physical characteristics independent of any control law, were used to test the accuracy of the multijoint model.

Figure 1: Planar Model

The differential equations describing the flight phase dynamics of an \( n \)-segment model were automatically formulated using symbolic mathematics software (MapleSoft, Waterloo, Can.). The symbolic equations were converted into a programming algorithm using Matlab/Simulink (Mathworks, Natick, MA) and ADAMS (Mechanical Dynamics, Ann Arbor, MI). Input parameters to the computer algorithm included segment lengths, masses, center of mass, and moment of inertia. Body segment parameters determined from gamma scans of female...
athletes (deLeva, 1996; Zatsiorksy and Seluyanov, 1983) were used to define the model segment inertial properties. Generalized coordinates ($q$) from digitized data, as well as their first ($\dot{q}$) and second ($\ddot{q}$) derivatives were used as input into the algorithm. In this study, the conservation laws, expressed in $0^{th}$-order form, $1^{st}$-order form, and $2^{nd}$-order form constraints were calculated for the 8-segment (8-S), 5-segment (5-S), 4-segment (4-S), and 3-segment (3-S) models and compared with the expected results. The absolute error $|\epsilon|$, the root mean squares errors $\text{RMS}\epsilon$, and the gravitational constant error $g\epsilon$ were compared between models to determine the complexity of a model that can accurately simulate the dynamics of human layout dismount.

**Results and Discussion**

A comparison of left and right limb joint kinematics about the flexion/extension axis confirmed bilateral symmetry while identical shoulder and hip landmark coordinates indicated the absence of twist. This suggests that a planar model of the gymnast can adequately reproduce the dynamics of the layout salto. Based on the model-calculated linear and angular values and their error from expected conservation equation values from a trial, the 5-S model generated the least error (Table 1). Further reduction beyond 5-S led to increased error, particularly in the calculation of the higher order constraint equations (e.g. velocity and accelerations).

<table>
<thead>
<tr>
<th>Performance Index</th>
<th>8-S</th>
<th>5-S</th>
<th>4-S</th>
<th>3-S</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{CG}$ [m]</td>
<td>8.0E-03</td>
<td>7.0E-03</td>
<td>8.4E-03</td>
<td>5.2E-03</td>
</tr>
<tr>
<td>$y_{CG}$ [m]</td>
<td>4.2E-03</td>
<td>2.7E-03</td>
<td>3.7E-03</td>
<td>4.1E-03</td>
</tr>
<tr>
<td>$\dot{x}_{CG}$ [m/s]</td>
<td>4.6E-01</td>
<td>3.6E-01</td>
<td>4.1E-01</td>
<td>3.1E-01</td>
</tr>
<tr>
<td>$\dot{y}_{CG}$ [m/s]</td>
<td>3.4E-01</td>
<td>2.4E-01</td>
<td>3.3E-01</td>
<td>3.1E-01</td>
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<tr>
<td>$H_{CG}$ [ratio]</td>
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<td>0.035</td>
<td>0.040</td>
<td>0.042</td>
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<tr>
<td>$Q_1$ [BW]</td>
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<td>1.97</td>
<td>2.01</td>
<td>2.03</td>
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<td>$Q_2$ [BW]</td>
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<td>$M_{CG}$ [BW*m]</td>
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<td>1.39</td>
<td>1.72</td>
<td>1.85</td>
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<tr>
<td>$g\epsilon$ [m/s^2]</td>
<td>1.809</td>
<td>0.713</td>
<td>0.723</td>
<td>1.418</td>
</tr>
</tbody>
</table>

Table 1: Model complexity analysis performance indices RMS$\epsilon$ and $g\epsilon$.

Also, the 5-S model-calculated angular momentum about the total body center of gravity ($H_{CG}$, normalized to mean value) had the least absolute error ($|\epsilon|$) while greater in the 4-S and 3-S models (Figure 2).

**Figure 2**: Angular momentum about the total body center of gravity ($H_{CG}$) and absolute error ($|\epsilon|$) from expected values.
From these results, we determined that a 5-S model might provide the best trade-off between accuracy and simplicity for simulating the layout salto landings. Inclusion of the neck joint in the 5-S model (in contrast to 4-S and 3-S models) may be important not just in increasing the accuracy of the model but also in facilitating visual feedback control mechanism in preparation for landing (Lee et al., 1992; Berthoz and Pozzo, 1994).

A method for developing an accurate model for simulating the landing mechanics preceding contact was presented and the model complexity needed to simulate a particular task was determined. The flight phase conservation laws were utilized to quantify performance of the model. Development of such a model is a crucial step to testing hypothetical scenarios in motor control analysis, musculoskeletal loading consequences, and enhancement of sports performance. The use of experimentally based joint trajectory will facilitate future hypothesis testing regarding multi-joint control strategies and allow development of distributed control logic for examination of highly complex skills. Examination of flight phase control using a multi-segment model will enable us to determine how and when humans modify their control strategy to accommodate for less than ideal initial condition at landing.

References
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