Experimental Simulation of an Airborne Movement: Applicability of the Body Segment Parameter Estimation Methods

Young-Hoo Kwon

The purpose of this study was twofold: (a) to investigate the effect of the method of body segment parameter (BSP) estimation on the accuracy of the experimental simulation of a complex airborne movement; and (b) to assess the applicability of selected BSP estimation methods in the experimental simulation. It was hypothesized that different BSP estimation methods would provide different simulation results. A sensitivity analysis was performed to identify the BSP items and segments responsible for the inter-method differences in the simulation accuracy. The applicability of the estimation methods was assessed based on the simulation results and the number of anthropometric parameters required. Ten BSP estimation methods classified into 3 groups (4 cadaver-based, 4 gamma mass scanning-based, and 2 geometric) were employed in a series of experimental simulations based on 9 double-somersault-with-full-twist H-bar dismounts performed by 3 male college gymnasts. The simulated body orientation angles were compared with the corresponding observed orientation angles in computing the simulation errors. The inclination and twist simulation errors revealed significant ($p < .05$) differences among the BSP estimation groups and methods. It was concluded that: (a) the method of BSP estimation significantly affected the simulation accuracy, and more individualized BSP estimation methods generally provided more accurate simulation results; (b) the mass items, and the lower leg and thorax/abdomen were more responsible for the intermethod differences in the simulation accuracy than other BSP items and segments, respectively; (c) the ratio methods and the simple regression methods were preferable in simulation of the somersaulting motion due to the fewer anthropometric parameters required; (d) the geometric models and the cadaver-based stepwise regression method were superior to the other methods in the simulation of the complex airborne motion with twist.

Key Words: orientation angles, simulation error, local reference frames, BSP perturbation, sensitivity analysis

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Introduction

The simulation approach to analysis of complex airborne movements can be beneficial to athletes in terms of safety and performance enhancement. Simulation of human movement was originally initiated by aerospace scientists (Kane & Scher, 1970; McCrank & Seger, 1964; Passerello & Huston, 1971) in studying the effectiveness of the proposed reorientation movements for astronauts in space. Later research (Huston & Passerello, 1971; Miller, 1970; Pike, 1980; Ramey, 1973; Ramey & Yang, 1981) reported theoretical simulation studies dealing with sports movement. Dapena (1981) introduced a new approach, the experimental simulation, in which the time-history of the joint motions and the initial conditions of the aerial motion were obtained from the actual trial. Yeadon, Atha, and Hales (1990) conducted an experimental simulation of selected trampoline maneuvers, which served as a milestone for the experimental simulation of sports movements.

To accomplish its full potential, the experimental simulation approach must be reliable and flexible. Factors that can affect the simulation accuracy include the models (body and simulation), the inertial properties of the body segments (BSP), and the experimental errors (anthropometric measurement and digitizing). It is possible to meet the practical body model and reliable simulation model requirements to a certain extent through careful modeling. The experimental errors are generally regarded as random, and repetition of the anthropometric measurements, careful digitizing, and data smoothing will reduce these errors somewhat. Although Yeadon et al. (1990) reported that the digitizing error considerably affected the simulation errors, it must be interpreted as the combined effects of several factors, not random digitizing error alone.

The body segment parameters (BSP) involved in the computation of kinematic and kinetic quantities, and in the simulation, can introduce systematic errors. One may obtain multiple sets of BSP by employing different direct and indirect BSP estimation methods available. Mungiole and Martin (1990) showed differences in BSP data computed from different methods, and Kwon (1996) reported that the method of BSP estimation significantly affected the airborne angular momentum of the gymnast. To improve the reliability and flexibility of the experimental simulation, it is essential to identify, from the existing pool of readily available methods, the BSP estimation methods that are applicable in the experimental simulation. The purpose of this study was to (a) investigate the effect of the method of body segment parameter (BSP) estimation on the accuracy of the experimental simulation of a complex airborne movement, and (b) assess the applicability of selected BSP estimation methods in the experimental simulation. Three research questions were identified: (1) Will different BSP estimation methods provide different simulation results? (2) Which BSP items and segments are more responsible for the intermethod differences in the simulation accuracy, if any, than others? (3) Which BSP estimation methods are more applicable than others in the experimental simulation of the airborne movements?

Methods

This study was performed on data from 9 double-salto-with-full-twist horizontal-bar (H-bar) dismounts performed by three male college gymnasts (mass = 69.3 ± 5.4 kg, height = 176.0 ± 3.7 cm, age = 21.7 ± 0.6 yr). The research protocol was approved by the Institutional Review Board and informed consents were obtained from the par-
Participants. One gymnast performed the H-bar dismounts in two distinct positions (lay-out and tuck) while the others performed in tuck position only. A 15-segment body model including two trunk segments (thorax/abdomen and pelvis) was employed. Kwon (1996) provides details of the participant and trial data, the body model, and the general experimental and data processing procedures.

Ten BSP estimation methods were employed: Group C (cadaver-based) – C1 (ratio); C2 (simple regression by mass); C3 (stepwise regression); and C4 (scaling); Group M (mass scanning-based) – M1 (ratio); M2 (simple regression by mass and height); M3 (prediction equation); and M4 (scaling); Group G (geometric models) – G1 (modified Hanavan); and G2 (modified Yeadon). Group C was based on the work of Chandler et al. (Chandler, Clauser, McConville, Reynolds & Young, 1975), while Group M was based on the work of Zatsiorsky et al. (Zatsiorsky & Seluyanov, 1983, 1985; Zatsiorsky, Seluyanov & Chugunova, 1990). Methods G1 and G2 were modified versions of the models reported by Hanavan (1964) and Yeadon (1990), respectively. See Kwon (1996) for details of the estimation methods, modifications, and method selection criteria.

The experimental simulation procedures outlined by Ramey and Yang (1981) and Yeadon et al. (1990) were adopted in this study with modifications in the local reference frame definition and orientation angle computation. First, the relative orientation of a segmental reference frame to its linked proximal frame (Figure 1) was consistently described by three Eulerian angles of XYZ type. The unit vectors of the segmental reference frames were computed from the 3-D marker coordinates. See Kwon (1993) for definitions of the segmental reference frames. Second, the unit vectors of the whole-body reference frame (WB-frame), fixed to and rotating with the body, were defined as follows:

\[
\hat{z}_{WB} = \frac{R_U - R_L}{|R_U - R_L|} \\
\hat{y}_{WB} = \hat{z}_{WB} \times \hat{x}_{TA} + \hat{x}_P \\
\hat{x}_{WB} = \hat{y}_{WB} \times \hat{z}_{WB}
\]

where \( \hat{x}_{wb}, \hat{y}_{wb}, \) and \( \hat{z}_{wb} \) = the transverse, anteroposterior, and longitudinal unit vectors of the WB-frame, respectively; \( R_U \) and \( R_L \) = the position vectors of the CM of the upper body (head, thorax/abdomen, and arms) and the lower body (pelvis and legs) respectively, and \( \hat{x}_{TA} \) and \( \hat{x}_P \) = the transverse unit vectors of the thorax/abdomen and pelvis, respectively. The Z-axis of the inertial frame was aligned vertically with the Y-axis being the direction of dismount.

The angular velocities and angular momenta of the segments were computed through the procedures presented by Kwon (1996). The initial position and velocity of the body CM, the average airborne angular momentum, and the time history of the relative orientation angles of the segments obtained from the actual trial were used as the input variables of the simulation. The three orientation angles (somersault, inclination, and twist) of the WB-frame to the global frame were updated as the output of the simulation based on a group of differential equations derived from the principle of angular momentum conservation (Kwon, 1993; Ramey & Yang, 1981; Yeadon et al., 1990):
Figure 1 — The relative orientation relationships among the segments: The pelvis is the most proximal while the head, hands, and feet are the most distal. A total of 35 degrees of freedom (DOF) were assigned to the relative motions among the segments including 3 DOF for the relative orientation of the two shoulder lines and the neck line to the thorax/abdomen. Three additional DOF were assigned to the relative orientation of the whole-body reference frame (WB-frame) to the global (inertial) frame. See Kwon (1993) for definitions of the local reference frames.

\[
\begin{align*}
H^{(WB)} - H^{(WB)}_{rel} &= I^{(WB)}_{CM} \cdot \\
&= \begin{bmatrix}
\cos \Theta \cdot \cos \Psi & \sin \Psi & 0 \\
-\cos \Theta \cdot \sin \Psi & \cos \Psi & 0 \\
\sin \Theta & 0 & 1
\end{bmatrix} \\
&= \begin{bmatrix}
\Phi \\
\dot{\Theta} \\
\dot{\Psi}
\end{bmatrix}
\end{align*}
\]

where \(H^{(WB)}\) = the airborne angular momentum of the gymnast described in the WB-frame, \(H^{(WB)}_{rel}\) = the relative angular momentum of the body parts to the WB-frame, \(I^{(WB)}_{CM}\) = the inertia tensor of the gymnast about his whole-body CM, and \((\phi, \Theta, \Psi)\) = the somersault, inclination, and twist angles of the WB-frame, respectively. The simulation program (KSIMUL) was tested with several null configurations to screen out flaws in the simulation model and the logical errors in the simulation program (Kwon & Sung, 1994).
The simulated orientation angles of the WB-frame were compared with those computed from the actual trial for the entire airborne phase. The maximum deviations in the orientation angles of the WB-frame were identified as the simulation errors. The ratios of the simulation errors to the corresponding orientation angle ranges were defined as the relative simulation errors. The relative simulation errors were compared among the BSP estimation methods and method groups through one-way ANOVA ($p < .05$) to assess the effects of the method of BSP estimation on simulation accuracy. Although each participant repeated the H-bar dismount three times, all trials were treated as independent and the repeated-measures design was not adopted. The repetition was considered not random since body posture could systematically affect the simulation results.

In order to identify the source of the intermethod differences in simulation accuracy, a sensitivity analysis was performed with the BSP systematically perturbed: (a) the mean normalized BSP (mass ratios, CM location ratios, and 3 radius-of-gyration ratios) of the segments were computed; (b) in each trial, the airborne angular momentum, and subsequently the simulation error (criterion error), were computed based on the mean normalized BSP; (c) in each trial, each BSP item was perturbed independently within its standard deviation (mean + $SD$ and mean – $SD$) and the deviations in the simulation error from the criterion value were computed; (d) the RMS deviation in the simulation error was computed for each BSP item and for each segment.

The applicability of the BSP estimation methods was assessed based on the simulation accuracy and the number of anthropometric parameters required.

**Results**

No intergroup or intermethod difference was observed in the somersault simulation error with all methods demonstrating equally accurate results (2.7–3.1%) (Table 1). However, Group G revealed a lower mean inclination simulation error than Group C. In Group C, Method C3 resulted in a lower mean inclination simulation error than Method C2. Methods C3, G1, and G2 generally produced lower mean inclination simulation errors than the other BSP estimation methods. Although the relative inclination simulation error was much larger than the relative somersault simulation error, the actual mean inclination simulation error was fairly small (8.2°). In the twist simulation (twist range = 335.8 ± 28.6°), Group G provided a lower mean simulation error than the others. Method C3 resulted in a smaller twist simulation error than the others in Group C. Method M4 produced a smaller mean error than Method M2 in Group M. Methods C3 and G1 demonstrated significantly smaller twist errors than Methods C1, C2, C4, M1, and M2, while Method G2 resulted in smaller error than Methods C1, C2, C4, M1, M2, and M3. Method M4 also revealed a smaller twist error than Method C2.

The twist simulation error was found most sensitive to the mass items among the BSP types: lower leg (RMS deviation = 26.3°), head (9.6°), thorax/abdomen (7.2°), and foot (7.2°) (Figure 2). Among the segments, the lower leg (13.3°) and the thorax/abdomen (10.5°) produced the largest simulation error fluctuations. The mass of the lower leg revealed the largest fluctuation, followed by the longitudinal moments of inertia of the thorax/abdomen (18.7°). CM location of the pelvis (9.2°) and transverse moments of inertia of the thorax/abdomen (7.4°) also caused relatively large fluctuations.
Discussion

Since no intergroup or intermethod difference was observed in the somersault simulation error and the magnitude of the inclination simulation error was fairly small, the twist simulation error may be identified as the discriminating measure of the simulation accuracy. Methods C3, G1, and G2 generally produced smaller twist errors than other methods. Different BSP estimation methods indeed provided different simulation results.

The BSP estimation methods employed in this study represent different method pools. Methods C1 and M1 (ratio methods) and Methods C2 and M2 (simple regression methods) are the least individualized ones among the estimation methods used in this study. Eight to nine anthropometric parameters were required in these methods (Table 1) to secure the compatibility between the original methods (Chandler et al., 1975; Zatsiorsky & Seluyanov, 1983) and the body model used in this study. On the other hand, Methods C3, M3, G1, and G2 are the most individualized ones among the

<table>
<thead>
<tr>
<th>Group</th>
<th>Method</th>
<th>Somersault</th>
<th>Inclination*</th>
<th>Twist*</th>
</tr>
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<tbody>
<tr>
<td>C</td>
<td>C1 (9)</td>
<td>3.0 ± 0.5</td>
<td>44.8 ± 12.8</td>
<td>21.1 ± 5.0</td>
</tr>
<tr>
<td></td>
<td>C2 (9)</td>
<td>2.7 ± 0.7</td>
<td>59.2 ± 20.6</td>
<td>25.9 ± 3.2</td>
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<td></td>
<td>C3 (36)</td>
<td>2.7 ± 0.7</td>
<td>33.8 ± 9.5</td>
<td>9.7 ± 3.9</td>
</tr>
<tr>
<td></td>
<td>C4 (18)</td>
<td>2.7 ± 0.9</td>
<td>54.7 ± 20.6</td>
<td>21.3 ± 5.0</td>
</tr>
<tr>
<td></td>
<td>Group mean</td>
<td>2.8 ± 0.7</td>
<td>48.1 ± 18.7**</td>
<td>19.5 ± 7.4**</td>
</tr>
<tr>
<td>M</td>
<td>M1 (8)</td>
<td>2.9 ± 0.7</td>
<td>41.5 ± 12.9</td>
<td>19.4 ± 4.8</td>
</tr>
<tr>
<td></td>
<td>M2 (9)</td>
<td>2.8 ± 0.7</td>
<td>46.0 ± 13.6</td>
<td>22.9 ± 6.7</td>
</tr>
<tr>
<td></td>
<td>M3 (38)</td>
<td>3.1 ± 0.7</td>
<td>40.3 ± 10.6</td>
<td>18.3 ± 3.2</td>
</tr>
<tr>
<td></td>
<td>M4 (24)</td>
<td>3.1 ± 0.7</td>
<td>41.1 ± 10.8</td>
<td>15.9 ± 2.1</td>
</tr>
<tr>
<td></td>
<td>Group mean</td>
<td>3.0 ± 0.7</td>
<td>42.3 ± 11.7</td>
<td>19.1 ± 5.1**</td>
</tr>
<tr>
<td>G</td>
<td>G1 (41)</td>
<td>2.8 ± 0.3</td>
<td>34.3 ± 12.5</td>
<td>10.1 ± 5.5</td>
</tr>
<tr>
<td></td>
<td>G2 (67)</td>
<td>2.7 ± 0.6</td>
<td>30.7 ± 5.9</td>
<td>7.1 ± 2.5</td>
</tr>
<tr>
<td></td>
<td>Group mean</td>
<td>2.7 ± 0.5</td>
<td>32.5 ± 9.7</td>
<td>8.6 ± 4.4</td>
</tr>
<tr>
<td>Overall mean</td>
<td>2.9 ± 0.7</td>
<td>42.7 ± 15.6</td>
<td>17.2 ± 7.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(16.1 ± 3.7°)</td>
<td>(8.2 ± 2.5°)</td>
<td>(57.4 ± 23.9°)</td>
<td></td>
</tr>
</tbody>
</table>

*Intergroup difference observed, \( p < 0.05 \); **Intermethod difference observed, \( p < 0.05 \).  
\(^1\)C = cadaver-based; M = mass scanning-based; G = geometric models.  
\(^2\)C1 = ratio method; C2 = simple regression by mass; C3 = stepwise regression; C4 = scaling; M1 = ratio method; M2 = simple regression by mass and height; M3 = prediction equation; M4 = scaling; G1 = modified Hanavan; G2 = modified Yeadon.  
\(^3\)Number of anthropometric parameters required.
estimation methods used in this study since they rely heavily on the anthropometric measurements taken from the gymnast (36 to 67 parameters). Methods C4 and M4 are somewhat individualized estimation methods since they use both anthropometric measurements taken from the gymnast (18 to 24 parameters), and mean BSP ratios (C4) or scaling factors (M4). Methods C3, G1, and G2 generally provided more accurate simulation results than other methods, while Method M4 provided a smaller error than Method C2 (Table 1). This may be generalized to mean that more individualized BSP estimation methods generally provided more accurate simulations.

Since each mean normalized BSP item was perturbed within its standard deviation obtained from 10 BSP estimation methods, the sensitivity analysis results can be interpreted as the contribution of the BSP items to the intermethod difference in the simulation accuracy. However, the fluctuation in the twist simulation error caused by perturbation of a particular BSP is the combined effect of the magnitude of its standard deviation and the intrinsic sensitivity of the simulation error to it. In other words, a large fluctuation in the twist simulation error is expected if a BSP item is very different among the estimation methods and/or the simulation error is intrinsically sensitive to this particular item. Although the tradeoff between these two factors is not fully understood, one could conclude that the main source of the intermethod differences in simulation accuracy was the mass estimates among the BSP, and the lower leg and thorax/abdomen among the segments.

Figure 2 — Summary of the sensitivity analysis results (CM = CM location ratio; m = mass ratio; IT = transverse radius-of-gyration ratio; IL = longitudinal radius-of-gyration ratio). The mean normalized BSP over the BSP estimation methods were intentionally perturbed within their respective standard deviations and the fluctuation in the twist simulation error was computed. For simplicity, the results from the anteroposterior and the mediolateral moments of inertia perturbation were combined together (IT).
When the main focus of simulation is on the somersault, Methods C1, C2, M1, and M2 are preferable since they require considerably fewer anthropometric parameters (8 to 9) than other methods but provide equally accurate simulation results. In simulating a complex motion, Methods C3, G1, and G2 are superior to the others. Method M4 may be used for simulation of a complex movement of relatively short duration. Although Methods G1, G2, and C3 overall provide more accurate simulation results than others, they require extensive anthropometric measurements. Measuring an extensive set of anthropometric parameters from athletes during competition is generally impossible, thus these methods become inapplicable. In order to increase the overall reliability and flexibility of the experimental simulation, it is necessary to develop ways to improve the applicability of the relatively simple BSP estimation methods such as C1, C2, M1, and M2. Dapena (1981) introduced the concept of “period of validity” to confine the time period for which the simulation error remains within an acceptable range, but this is not the ultimate solution.

It was concluded from the simulation error analysis that the method of BSP estimation significantly affected the simulation results. The mass estimates, and the lower leg and thorax/abdomen were more responsible for the intermethod differences in simulation accuracy than other BSP items and segments, respectively. Although all BSP estimation methods were equally applicable to the simulation of somersaulting motion, the ratio methods and simple regression methods were preferred due to the fewer anthropometric parameters required. In simulating a complex airborne motion that involves twists, the geometric models and the cadaver-based stepwise regression method were identified as the preferable methods.

References


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