FLEXIBILITY OF THE EXPERIMENTAL SIMULATION APPROACH TO THE ANALYSIS OF HUMAN AIRBORNE MOVEMENTS: BODY SEGMENT PARAMETER ESTIMATION

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The experimental simulation approach to the analysis of human airborne movements provides athletes, coaches, and investigators with unique advantages. However, its potential is not fully utilized due to the complex simulation procedures and it is essential to simplify the simulation procedures to improve its flexibility and applicability. One area that needs improvement & simplification is the body segment parameter (BSP) estimation. In this paper, some recent findings on the effects of the method of BSP estimation on the experimental simulation of complex human airborne movements, and the applicability of selected BSP estimation methods in the experimental simulation of these movements are presented.

KEY WORDS: simulation, human airbone movement, body segment paramenter

INTRODUCTION: Simulation of torque-free movements of the human body was originally initiated by space scientists (McCrank & Seger, 1964; Kane & Scher, 1970; Passerello & Huston, 1971). The main issue in these studies was the effectiveness of the proposed reorientation movements for astronauts in the space. Although the models employed and the movements studied were fairly simple, they laid a firm foundation for the simulation of more complex torque-free movements.

Later research (Miller, 1970; Huston & Passerello, 1971; Ramey, 1973; Pike, 1980; Ramey & Yang, 1981) reported on theoretical simulation studies dealing with sporting movements and Dapena (1981) introduced a new approach to simulation, the experimental simulation, in which the time history of the joint motions and the initial conditions of the airborne motion were obtained from actual trials. Yeadon, Atha and Hales (1990a) reported an experimental simulation study of selected trampoline maneuvers, which served as a milestone for this area of research.

Applying the simulation approach to the analysis of complex airborne movements can be beneficial to the athletes in terms of safety and performance enhancement. The probable results of new maneuvers can be predicted through simulation before the actual trial. The cause-and-effect relationships among different biomechanical performance factors can be identified for performance enhancement. In addition, the analysis techniques employed in the simulation process, such as the non-inertial reference frames, provide researchers with tools to investigate complex human movements more effectively. For example, Yeadon and associates (Yeadon, 1994, 1993, 1989; Yeadon, Lee & Kerwin, 1990b) quantified the contribution of body motions to the development of twists in various sports.

In spite of its potential advantages, the experimental simulation is still not popular and only a handful of simulation studies (Yeadon, 1994, 1993; Yeadon et al., 1990b; Kwon, 2000, 1993) have been reported since Yeadon et al. (1990a) published their work. This may be attributed to several factors, but it seems it is due mainly to the complex simulation procedures. The experimental simulation demands that investigators define and use local reference frames, perform extensive anthropometric measurements for inertial property estimation, compute the internal & external orientation angles from the transformation matrices, compute the airborne angular momentum, solve a set of differential equations for the external orientation angles, and modify the movements for further simulation.

There seem to be two main ways to improving the flexibility and applicability of the experimental simulation approach: (1) to develop a comprehensive & user-friendly experimental simulation software package which allows users to easily define the local reference frames and modify movements (Kwon & Sung, 1994); and (2) to simplify the inertial property computation procedures. It is meaningful to identify applicable body segment parameter estimation methods from the pool of readily available methods in an effort to simplify the simulation procedures and to improve the flexibility and applicability of the experimental simulation approach. In this paper, the findings of a series of papers dealing with the effects of the method of body segment parameter estimation on the angular momentum and experimental simulation accuracy were summarized.

BSP ESTIMATION METHODS: There are several indirect & direct body segment parameter (BSP) estimation methods readily available. In the direct methods, one computes the BSPs directly from the subject using either medical imaging techniques, such as MRI (Mungiole & Martin, 1990) and CT (Rodrigue & Gagnon, 1983; Ackland, Henson & Bailey, 1988), or mass scanning techniques (Zatsiorsky & Seluyanov, 1983). Due to problems such as radiation, high cost, and the need for specialized equipment, however, it is difficult to apply these methods in practice. The geometric (mathematical) models (Hanavan, 1964; Huston & Passerello, 1971; Jensen, 1978; Yeadon, 1990a; Hatze, 1975) may also be classified as direct methods. Yeadon et al. (1990a) used a geometric model that requires a total of 95 anthropometric parameters (Yeadon, 1990). Yeadon et al. (1990b) and Yeadon (1993) later adopted alternative anthropometric measurement strategies since anthropometric measurements were not allowed in the competition settings. The BSP ratios, regression (prediction) equations, and scaling coefficients obtained from a group of living subjects (Zatsiorsky & Seluyanov, 1983, 1985; Zatsiorsky, Seluyanov & Chugunova, 1990; Plagenhoef, Evans & Abdelnour, 1983) or cadaver specimens (Dempster, 1955; Barter, 1957; Clauser et al., 1969; Chandler et al., 1975; Dapena, 1978; Hinrichs, 1985; Forwood et al., 1985) are commonly used in the indirect methods.
For a BSP estimation method to be used in the experimental simulation of airborne movements, it should at least fulfill the following criteria: (1) it must provide a complete set of BSPs including the 3 principal moments of inertia; and (2) the estimation procedures must be fairly simple, safe and inexpensive. The indirect methods based on the work of Chandler et al. (1975) and Zatsiorsky & associates (Zatsiorsky & Seluyanov, 1983, 1985; Zatsiorsky et al., 1990), and the geometric models (Hanavan, 1964; Hatze, 1975; Jensen, 1978; Yeadon, 1990a) generally suffice criterion 1. However, the Hatze model (Hatze, 1975) and the elliptical zone method (Jensen, 1978) among the geometric models do not fulfill criterion 2 since they require either an extensive anthropometric measurement (Hatze model; 242 parameters) or specialized equipment (elliptical zone method). Based on these criteria, Kwon (1996) selected a total of 10 BSP estimation methods classified into 3 groups: cadaver-based indirect methods, mass scanning-based indirect methods, and geometric models (Table 1). See Kwon (1996) for the details of these methods regarding the modifications and the required anthropometric parameters.

Table 1 Method of BSP Estimation Candidates for the Experimental Simulation

Group	Method	Description
Group C[1] (Cadaver-based)	C1	Ratios (9)[5]
	C2	Simple regression by mass (9)
	C3	Stepwise regression (36)
	C4	Scaling (18)
Group M[2] (Mass scanning-based)	M1	Ratio method (8)
	M2	Simple regression by mass & height (9)
	M3	Prediction equations (38)
	M4	Scaling (24)
Group G (Geometric models)	G1	Modified Hanavan[3] (24)
	G2	Modified Yeadon[4] (67)

[1]Based on Chandler et al. (1975)
[2]Based on Zatsiorsky and associates (Zatsiorsky & Seluyanov, 1983, 1985; Zatsiorsky et al., 1990)
[3]Modified version of Hanavan (1964)
[4]Modified version of Yeadon (1990)
[5]Number of anthropometric parameters required

BSP ESTIMATION VS. AIRBORNE ANGULAR MOMENTUM: Most experimental simulation studies (Dapena, 1981; Yeadon et al., 1990; Kwon, 2000) are based on the conservation of angular momentum. In an ideal situation, the angular momentum of a gymnast's body about its center of mass (CM) remains constant during the airborne phase. However, the computed angular momentum fluctuates due to errors and the average value is used in the simulation as the initial condition along with the time history of the joint motions. The discrepancy in the angular momentum between the actual value and the one used in the simulation appears to be the main cause of the simulation error. Kwon (1996) investigated the effect of the method of BSP estimation on the airborne angular momentum.

Subjects and trials. Nine double-somersault-with-full-twist horizontal-bar dismounts performed by 3 male collegiate gymnasts were analyzed. Each gymnast repeated the maneuver three times with varying postures. See Kwon (1996) for details of the subject & trial data.

Body model. A 15-segment body model based on 21 body points with at most 38 degrees of freedom was defined. The trunk was sectioned into two segments at the navel level: thorax-abdomen and pelvis. The location of the inter-torso link (center of the trunk cross-section at the navel level) was computed through a geometric method described in Kwon (1993).

Data collection. The 3-D DLT method (Abdel-Aziz & Karara, 1971) was used in camera calibration and subsequent 3-D reconstruction. Four range poles (487.68 cm long each) were used as the calibration frame. A digital theodolite was used to measure the horizontal angular positions of the range poles and the vertical positions of the control points marked on the pole (32 control points). The 3-D coordinates of the control points were computed from the angular position data. Four S-VHS video camcorders (Panasonic AG-450) were used for videotaping with the frame rate and the shutter speed being 60 Hz and 1/250 s, respectively. The Z-axis of the global (inertial) reference frame was aligned vertically with the Y-axis being in the direction of dismount. See Kwon (1996) for detailed information on equipment setup.

Results. A summary of the results of the airborne angular momentum computation is presented in Table 2. All the average angular momentum components (a_x, a_y & a_z) and their respective standard deviations (SDs; s_x, s_y & s_z) were subject to normalization to facilitate comparisons among the BSP estimation methods. a_x was normalized among the methods (100% = a_x of method G2) while a_y & a_z were normalized by their corresponding a_x (a_y/a_x & a_z/a_x). s_x, s_y & s_z were all normalized by their corresponding a_x (s_x/a_x, s_y/a_x & s_z/a_x). The X component of the airborne angular momentum was the main component with a_y and a_z being approximately 5.2 ± 1.6% and 5.2 ± 3.3% of a_x, respectively. The minor components showed large SD-to-average ratios, 103.2% (Y) & 99.6% (Z).

Table 2 Mean Angular Momentum Ratios (in Percentages) of the BSP Estimation Methods (n = 9) (Kwon, 1996)

Group	Method	a_x ratio*	a_y ratio	a_z ratio
C	C1	89.5 ± 2.1	5.3 ± 1.4	5.3 ± 3.5
	C2	88.7 ± 2.9	5.2 ± 1.5	5.3 ± 3.5
	C3	99.1 ± 2.0	5.4 ± 2.2	5.3 ± 3.5
	C4	91.3 ± 2.3	5.3 ± 1.6	5.3 ± 3.5
	Mean	92.2 ± 4.8**	5.3 ± 1.6	5.3 ± 3.4
M	M1	91.0 ± 2.3	5.3 ± 1.6	5.3 ± 3.6
	M2	93.2 ± 3.0	5.2 ± 1.8	5.2 ± 3.5
	M3	96.4 ± 2.2	5.3 ± 1.5	5.3 ± 3.5
	M4	96.7 ± 3.8	4.9 ± 1.4	5.2 ± 3.6
	Mean	94.3 ± 3.6**	5.2 ± 1.5	5.3 ± 3.4
G	G1	92.6 ± 1.8	5.0 ± 2.0	4.8 ± 3.5
	G2	100.0[1]	4.7 ± 1.7	4.9 ± 3.5
	Mean	96.3 ± 4.0**	4.9 ± 1.8	4.9 ± 3.4

*Inter-group difference was observed ($p < .05$). **Inter-method difference was observed ($p < .05$). [1]a_x values of the BSP estimation methods were normalized by a_x of method G2.

The mean a_x ratios of the BSP estimation methods except G2 (100%) ranged from 88.7% to 99.1% with the maximum range being 10.4%. Significant inter-group difference (G > C) and significant inter-method differences in all groups (C3 > C1, C2 & C3; M3 & M4 > M1; G2 > G1) were observed. The overall mean a_y & a_z were 5.16 ± 1.62% & 5.18 ± 3.34% of a_x, respectively. The maximum ranges of the method means were 0.65% (a_y) and 0.52% (a_z), showing no inter-group or inter-method difference. All components resulted in very similar s-to-a_x ratios among the methods: 7.4-7.9% (X), 4.7-5.4% (Y), and 4.8-5.6% (Z). Based on the observation that a_x ratio revealed significant inter-method differences and a_y, a_z, s_x, s_y, and s_z showed similar ratios to a_x among the methods, Kwon (1996) concluded the method of BSP estimation significantly changed the magnitude and fluctuation of the airborne angular momentum.

EXPERIMENTAL SIMULATION OF AIRBORNE MOVEMENTS: Torque-free motion of a gymnast in the air is governed by the conservation of angular momentum. A set of differential equations for the rotation of the body can be obtained from this law (Ramey & Yang, 1981; Yeadon et al., 1990a; Kwon, 2000):

$$\mathbf{H}^{(WB)} - \mathbf{H}_{rel}^{(WB)} = \mathbf{I}_{CM}^{(WB)} \cdot \begin{bmatrix} \cos\theta \cdot \cos\psi & \sin\psi & 0 \\ -\cos\theta \cdot \sin\psi & \cos\psi & 0 \\ \sin\theta & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \quad (1)$$

where **H** = the average airborne angular momentum, $\mathbf{H}_{rel}$ = the relative angular momentum of the body parts to the whole body reference frame (the WB-frame), $\mathbf{I}_{CM}$ = the inertia tensor of the whole body, [ϕ, θ, ψ] = the somersault, inclination, and twist angles of the body with respect to the global reference frame (the external orientation angles). Note that all the vectors and matrices in equation 1 are described in the WB-frame. The translation of the body CM (**R**) can be described as (Kwon, 2000):

$$\mathbf{R} = \mathbf{R}_o + t\mathbf{V}_o + \frac{1}{2}t^2\mathbf{g} \quad (2)$$

where $\mathbf{R}_o$ & $\mathbf{V}_o$ = the initial position & velocity of the body CM, respectively, t = the time in flight, and **g** = the gravitational acceleration.

The input variables of the simulation include the airborne angular momentum (**H**), the initial orientation of the body (ϕ_o, θ_o, ψ_o), the initial position and velocity of the body CM ($\mathbf{R}_o$ & $\mathbf{V}_o$), the time history of the relative orientation angles among the segments (the internal orientation angles), the BSPs, and selected anthropometric parameters. The inertia tensor ($\mathbf{I}_{CM}$) of the body and the relative angular momentum of the body to the WB frame ($\mathbf{H}_{rel}$) are to be computed from the time history of the internal orientation angles, the BSPs, and the anthropometric parameters. The external orientation of the body (ϕ, θ, ψ) and the position of the CM (**R**) are the output of the simulation. The internal and external orientation angles determine the number of degrees of freedom (DOFs) of the system. See Kwon (1993) for detailed description of the simulation procedures including the local reference frame definition.

The BSPs are involved in the **H**, $\mathbf{H}_{rel}$, & $\mathbf{I}_{CM}$ computation, having a potential to affect the outcome of the simulation. Different from the random experimental errors, the BSPs can introduce systematic errors to the system.

BSP ESTIMATION VS. SIMULATION ACCURACY: A summary of results of the simulations performed by Kwon (2000) on data from 9 double-somersault-with-full-twist horizontal-bar dismounts is presented in Table 3. The maximum discrepancies between the observed external orientation angles (somersault, inclination, and twist) and the simulated angles were used as the simulation errors. The simulation errors were normalized by the maximum

external orientation angle ranges, respectively, to obtain the relative errors.
The overall mean somersault simulation error was 2.9 ± 0.7% (16.1 ± 3.7°; mean maximum somersault range = 559.8°). All estimation methods demonstrated equally accurate somersault simulations (2.7 - 3.1%), showing no inter-group or inter-method difference. The overall mean inclination simulation error was 42.7 ± 15.6% (8.2 ± 2.5°; mean maximum inclination range = 20.1°). Inter-group difference (G < C) and inter-method difference in group C (C3 < C2) were observed. Methods C3, G1 & G2 generally produced smaller inclination errors than the other BSP estimation methods. The overall mean twist simulation error was 17.2 ± 7.3% (57.4 ± 23.9°; mean maximum twist range = 335.8°). Inter-group difference (G < C & M) and inter-method differences in groups C and M (C3 < C1, C2 & C3; M4 < M2) were observed. Methods C3, G1 & G2 scored smaller twist errors than other estimation methods. Method M4 also revealed a smaller twist error than method C2. The twist simulation error was identified as the discriminating measure of the simulation accuracy and Kwon (2000) concluded the method of BSP estimation affected the simulation accuracy.

Table 3 Mean Simulation Errors (in Percentages) of the BSP Estimation Methods (n = 9) (Kwon, 2000)

Group	Method	Somersault	Inclination*	Twist*
C	C1	3.0 ± 0.5	44.8 ± 12.8	21.1 ± 5.0
	C2	2.7 ± 0.7	59.2 ± 20.6	25.9 ± 3.2
	C3	2.7 ± 0.7	33.8 ± 9.5	9.7 ± 3.9
	C4	2.7 ± 0.9	54.7 ± 20.6	21.3 ± 5.0
	Mean	2.8 ± 0.7	48.1 ± 18.7**	19.5 ± 7.4**
M	M1	2.9 ± 0.7	41.5 ± 12.9	19.4 ± 4.8
	M2	2.8 ± 0.7	46.0 ± 13.6	22.9 ± 6.7
	M3	3.1 ± 0.7	40.3 ± 10.6	18.3 ± 3.2
	M4	3.1 ± 0.7	41.1 ± 10.8	15.9 ± 2.1
	Mean	3.0 ± 0.7	42.3 ± 11.7	19.1 ± 5.1**
G	G1	2.8 ± 0.3	34.3 ± 12.5	10.1 ± 5.5
	G2	2.7 ± 0.6	30.7 ± 5.9	7.1 ± 2.5
	Mean	2.7 ± 0.5	32.5 ± 9.7	8.6 ± 4.4

*Inter-group difference was observed ($p < .05$). **Inter-method difference was observed ($p < .05$).

ANGULAR MOMENTUM OPTIMIZATION: Modeling of a simple system of rigid bodies and intentional perturbation of the BSP items (mass, CM location and moments of inertia) easily reveals that the errors in the BSPs does not generate random effects on the airborne angular momentum, which implies that the average airborne angular momentum may not be the most representative measure to be used in the simulation, and that the average angular momentum may also contribute to the simulation error. This is especially probable in the case of the minor angular momentum components (a_y & a_z) since they showed large SD-to-average ratios: 103.2% (Y) & 99.6% (Z) (Kwon, 1996). In addition, the external orientation of the gymnast is to be updated in each frame based on the previous orientation and the posture. Therefore, the simulation errors are orientation & posture-dependent and the error propagation scheme involved in the experimental simulation becomes quite complex.
Based on the argument that the average airborne angular momentum may not be the most representative measure to be used in the simulation, Kwon (2000) intentionally manipulated (optimization) the airborne angular momentum components. He manipulated only the minor components (a_y & a_z) (within ±55% of their respective SDs, with the increment being 1%) for two reasons: (1) since the minor components showed high SD-to-average ratios (Kwon, 1996), a more effective optimization was expected with the minor components; and (2) there was a need to limit the extent of optimization to prevent the nature of the trial from being altered extremely. The Y and Z angular momentum pair that provided the smallest combined

simulation error (inclination + twist) was identified as the optimal angular momentum. The simulation errors obtained from the optimal angular momentum were regarded as the optimized simulation errors (Figure 1a & b).
It was reported that the angular momentum optimization produced mean decreases in the simulation errors of 11.9% (somersault), 28.1% (inclination), and 76.0% (twist). The optimized errors of the BSP estimation methods ranged 2.2-2.7% (somersault), 28.9-32.4% (inclination), and 3.6-4.7% (twist) showing no significant inter-method difference. All methods except C3, G1 & G2 showed significant decrease in the inclination error while all methods exhibited significant decrease in the twist simulation error. It was clearly demonstrated that the angular momentum optimization substantially improved the simulation accuracy.

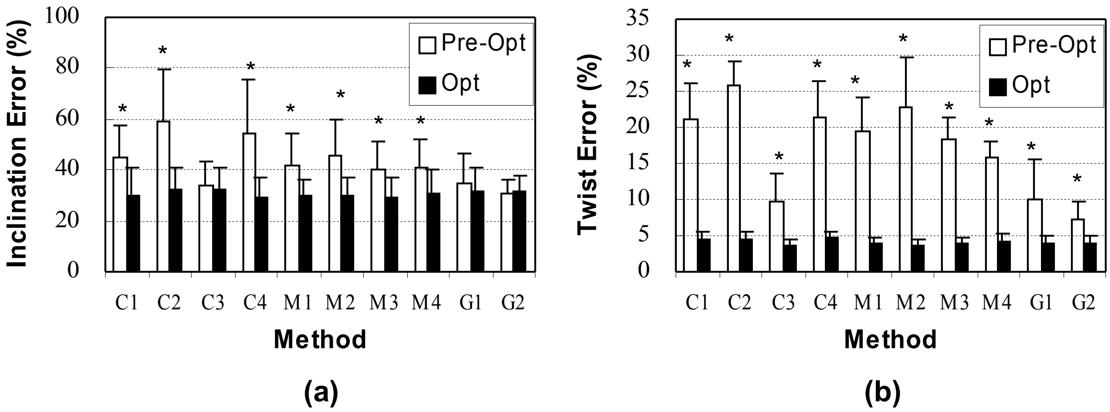

Figure 1 – Comparison between the optimized and the pre-optimization simulation errors: (a) inclination, and (b) twist (Kwon, 2000).
***denotes a significant ($p < .05$) decrease in the simulation error due to the angular momentum optimization.**

APPLICABILITY OF THE BSP ESTIMATION METHODS: Based on the results of a series of simulations with 10 BSP estimation methods, Kwon (2000) assessed the applicability of the BSP estimation methods. When the main focus of simulation is on the somersault, all methods are equally applicable. The ratio methods (C1 & M1) and the simple regression methods (C2 & M2), however, are preferred since they require a considerably smaller number of anthropometric parameters (8-9), but still provide equally accurate simulation results. In simulating a complex motion with twist, the geometric models (G1 & G2) and the cadaver-based stepwise regression method (C3) are the only applicable methods. These methods require 67 (G2), 41 (G1) or 36 (C3) anthropometric parameters. The gamma mass scanning-based scaling method (M4) requires a smaller number of parameters (24) and may be used for the simulation of a complex movement of relatively short duration.
In methods C1 and C2, the anthropometric parameters were required to compute the BSPs of the subtrunk segments and to convert the BSP data compatible to the body model used by Kwon (1996 & 2000). Similarly, 8-9 anthropometric parameters were required in methods M1 and M2 to secure the compatibility and to combine the BSPs of the thorax-abdomen. With additional modeling and/or assumptions, the number of required parameters can be reduced. Use of simple methods (C1, C2, M1 & M2) in conjunction with the angular momentum optimization strategy would substantially improve the flexibility of the experimental simulation approach.

SUMMARY: While most of the experimental simulation procedures can be incorporated into a well-structured user-friendly software package, one area that needs a special attention is the BSP estimation. The BSP estimation requires measurement of anthropometric parameters, and the complexity of the measurement and the method limits the flexibility of the experimental simulation approach. Among the 10 BSP estimation methods applicable in the experimental simulation of airborne movements, the geometric models and the cadaver-based stepwise regression method demonstrated superior applicability to others. All methods were equally applicable in simulating the somersault motion. The angular momentum optimization strategy developed by Kwon (2000), based on the minor angular momentum components, would substantially improve the applicability of the simpler methods such as the ratio & simple regression methods.

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