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METHODS OF ESTIMATING ATHLETE INERTIAL PROPERTIES AND THEIR IMPLICATIONS FOR THE STUDY OF SOMERSAULTS

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Eleven methods of estimating the inertial properties of an athlete based on anthropometric measurements were compared. Four parameters were chosen to reflect the practical implications of using different estimation methods in the study of the somersault, along with sets of appropriate postures. There was considerable variation between the parameter values produced by each method. Nevertheless there was agreement across all methods on the order of arm actions producing tilt, and the tilt produced by twisting-related postures. For these techniques and postures a coach may use the order to select one technique or posture in preference over another, without knowing the inertial properties exactly.

INTRODUCTION: During a somersault angular momentum is effectively constant; however, by changing posture an athlete may alter the speed of the somersault or add twist. The inertial properties of the body segments are constant in the equations of motion, yet their value affects the rotational changes observed for any particular technique.

To estimate the inertial properties of the body segments of an athlete, non-invasive methods are required. Since a somersault is a whole body activity these methods must also be applicable to all body segments. For a coach the most accessible methods are based on regression equations and geometric modelling, since they require only minimal equipment for taking anthropometric measurements. Such measurements may be taken directly or extracted from photographs (Hanavan, 1964; Woolley, 1972; Baughman, 1983; Yeadon, 1984; Yeadon & Morlock, 1989; Zatsiorsky, 2002; Hatze, 2005).

Which is the simplest method that provides 'sufficiently accurate' estimates of the inertial properties for the study of somersaults? Currently there is no answer to this question since multiple methods of estimating inertial properties of the same individual have not been compared systematically, and the influence of the different values obtained on numerical predictions of somersault performance have not been previously studied.

METHODS: Body segment dimensions were extracted from a side and a front photograph of an athlete standing in anatomical position. Height and weight were measured directly.

The published inertial property estimation methods compatible with such measurements are the average percentages, linear regression equations and non-linear regressions presented in Zatsiorsky (2002) and the geometric models presented in Baughman (1983)—the 'GOBD model', Hanavan (1964), Woolley (1972) and Yeadon (1984). Hanavan and Woolley use identical geometry but the method of determining segment mass differs slightly.

The GOBD, Hanavan and Yeadon geometric models differ in both geometry and the method of estimating segment mass. Differences in the estimates they produce could therefore be due to geometric differences, mass distribution differences or both. To separate the effects of geometry and mass, two composite methods using the mass distribution method of Yeadon applied to both the geometry of Hanavan's model and the GOBD model were compared. These will be denoted as Hanavan-Y and GOBD-Y respectively. To assist in understanding which aspects of the geometric differences are the most significant, a model based on Hanavan's geometry but splitting the lower torso segment into two, which will be denoted as Hanavan3, and a reduced Yeadon model combing sub-segments of Yeadon's model that have the same shape and density were also considered. Yeadon's approach for mass estimations was used in both cases.

This gave a total of eleven methods of estimating inertial properties for comparison.

The significance to a coach of the differences between inertial parameter estimates depends on how they would influence choices of technique and posture, and expectations of the achievable somersault speed and the twist-to-somersault ratio (Frohlich, 1979; Yeadon, 1984). To quantify the effect of each estimate on somersaults and hence allow comparison of the methods, the following parameters were calculated:

1. The ratio of I_{yy} in the current posture to I_{yy} in the layout posture, I_{yy}/I_{yy_Layout}. This ratio is the multiplier that gives the flight time required to complete a somersault if the current posture was used instead of the layout posture. The inverse ratio gives the relative speeds.
2. The inertial property multiplier in the steady twisting somersault twist-to-somersault ratio equation given in Yeadon (1984) is $(I_0 - I_{zz})/I_{zz}$, where $I_0 = (I_{xx} + I_{yy})/2$. The larger the multiplier the greater the number of twists per somersault for the same angle of 'tilt'.
3. The 'tilt' due to the posture held, which corresponds to the angle between the longitudinal axis of the pelvis and I_{zz} The presence of 'tilt' will cause twisting to occur in a somersault (Frohlich, 1979; Yeadon, 1984). Thus in non-twisting somersaults tilt should be minimised and in twisting somersaults it may be used to increase the twist-to-somersault ratio.
4. The angle of tilt of the longitudinal axis of the body due to the following 'textbook' actions:
   a. a symmetrical 'diver' arm action, were the arms start outstretched to the sides and move to a position with one arm raised and the other lowered (Frohlich,1979)
   b. one arm is lowered in the frontal plane from a raised position
   c. one arm is raised in the frontal plane from a lowered position.

Tilt was calculated rather than the (directly related) twist-to-somersault ratio to focus on the effect of the inertial property estimates on the initiating action. Any posture may then be selected for the twist phase and it will determine how the tilt is translated into a twist.

Each of these parameters needs to be linked to a posture so that they may be evaluated in the context of a somersault. For this purpose 19 postures were chosen:

- Ten symmetric postures used in non-twisting somersaults were linked with the first parameter only: 'layout' (L), 'arch' (A), 'just layout' (JL), 'open pike' (OP), 'pike' (P), 'tight pike' (TP), 'tuck' (T), 'tight tuck' (TT), and 'cowboy tuck' (CT);
- Four postures associated with twist initiation were linked with the first and third parameter: 'layout with arms above head' (LAU), 'layout with arms in the frontal plane and perpendicular to the body' (LAS), 'entry pike' (EP), 'lateral hip flexion' (LHF)
- Five postures often held during a twist were linked with the first three parameters: 'layout with one arm up and one down' (L1U1D), 'layout with one arm in high V the other in low V' (LHVLV), L1U1D with both arms bent 90o' (LB1U1D), LB1U1D allowing lateral hip flexion' (LHF1U1D), and 'puck' (PU).

Of these, three postures were selected to be linked with the fourth parameter group: L, EP, and P. These postures were reduced to planar models and the tilt produced by each arm action was calculated. Comparison of the tilt produced will indicate the most effective arm action and suggest the best body posture to hold while performing these actions.

RESULTS and DISCUSSION:

Ordering: Ordering techniques and postures by the numerical values of parameters allows a coach to select one technique and posture in preference to another based on whether a greater or lesser parameter value is required. If all methods of estimating inertial properties give the same order, a coach may simply use this order and not need to determine inertial properties. Inertial property estimation is, however, required to determine the actual parameter values when establishing expectations of a posture or technique.

The order of postures by $I_{yy}/I_{yy\ Layout}$ is very similar across all methods (Figure 1), generally agreeing with expectations that increases in hip and knee flexion reduce the ratio, and greater extension of the arms above the head increases the ratio. On more careful examination there are differences in the ordering according to the estimation method. For order refinement and specific technique selection the method of estimating inertial properties is therefore crucial. Of particular interest for non-twisting somersaults is that, despite CT being commonly used to

maximise rotational speed, it does not give the minimum $I_{yy}/I_{yy\ Layout}$ value for all methods; in three of the eleven methods TT gives the minimum. In addition even though P is considered more difficult there is disagreement as to if P or T gives a lower ratio. For twisting somersaults there is agreement that using PU has the lowest $I_{yy}/I_{yy\ Layout}$ value and so will allow the somersault to be completed in the minimum flight time. In addition LHVLV and LB1U1D were found to have lower $I_{yy}/I_{yy\ Layout}$ values than L1U1D and so can reduce flight time, however which gives the lowest ratio depends on the estimation method.
Examining the values of $(I_0 - I_{zz})/I_{zz}$ the LHVLV posture produces the lowest result for all methods except GOBD-Y. This is likely due to its large I_{zz} value. As a result LHVLV should not be used if attempting to maximise the twist-to-somersault ratio. The LB1U1D position produces a larger ratio than L1U1D in nine of the eleven methods. This suggests that LB1U1D may not only be used for reducing the flight time required but also for increasing the number of twists that can be completed compared to L1U1D.
The order of the tilt produced by each posture is constant across all methods. A positive tilt is a tilt to the left. LHVLV with the left arm low produced the most tilt to the right. Lateral hip flexion to the left in LHF1U1D produced tilt in the opposite direction to the asymmetry of the arms, but by far produced the most tilt. Unfortunately the tilt produced by LHF1U1D is in the opposite direction to the tilt that would be produced by any of the arm actions in parameter 4. Lateral flexion towards the lowered arm should thus be avoided. Lateral flexion in the opposite direction could be investigated for the possibility of boosting tilt.
The order of arm actions that produce tilt is consistent across all estimation methods. Inspecting the order indicates that raising one arm will produce more tilt than the symmetrical action, which produces more tilt than dropping one arm, for all three postures. The entry pike position increases the tilt produced by each action. This agrees with Frohlich (1979) who suggested that its use would boost tilt since the entry pike has a smaller I_{xx} value than layout. Even though the puck position had a lower planar I_{xx} value, it produced less tilt than the entry pike. Clearly the other inertial constants are also important and must be considered.
Due to the spread of the parameter values produced by each method, expected parameter values depend strongly on the method of estimating inertial properties.
Mass distribution choices: Across all parameters the difference between GOBD and GOBD-Y is small: < 0.01 for $I_{yy}/I_{yy\ Layout}$, < 0.6 for $(I_0 - I_{zz})/I_{zz}$, < 0.2^o tilt due to a posture and < 0.5^o tilt due to an arm action. These differences are negligible considering the practical effects and the size of the ratios and tilt angles predicted. This is an interesting result since the average density used in GOBD was 1.49 g/cm^3 while the densities used in GOBD-Y were in the range 1.01–1.16 g/cm^3. It thus appears that within these ranges the geometrical distribution of mass is more important than the actual mass.
For the three Hanavan based methods the difference for $I_{yy}/I_{yy\ Layout}$ is moderately small (< 0.06), although it is similar to the difference between Hanavan and reduced Yeadon. The differences for the other parameters varied considerably and equally were not clearly less than differences between models with different geometry.
Geometry Choices: Hanavan-Y and Hanavan3 differ mostly in postures where bending occurs in the torso, reflecting the differences in the way that this bending is modelled. Such differences, for example, resulted in up to 0.06 difference in $I_{yy}/I_{yy\ layout}$ for a tuck. In addition, by splitting the lower torso an additional waist measurement was included, which means that even in postures not involving bending of the torso parameter values differed. For example in layout posture the tilt produced by the arm actions differed by up to 0.36^o. The number of torso segments used in the inertial property estimation method is thus significant.
Comparing Hanavan3, Yeadon, reduced Yeadon and GOBD-Y which all use Yeadon's mass distribution approach shifts the focus of comparisons to geometry. Of particular interest was the observation that $I_{yy}/I_{yyLayout}$ for GOBD-Y and Yeadon are within 0.04 of each other with 13 of the 18 postures within 0.01. The similarity does not hold for the other somersault parameters. This is an intriguing result since the geometry of these two models is quite

different. If the trend holds, and is not merely due to chance, for a range of athletes GOBD-Y, which requires less measurement, could be used instead of Yeadon.

Regression equations: The published regression equations were based on athletes that were considerably taller than the athlete studied here; the current athlete is 2.88 standard deviations below the mean. In addition the estimated inertial properties did not obey two known conditions for all segments: mass is positive and the sum of two principal moments of inertia exceeds the third. As a result the validity of using the regression equations is questionable for this athlete. Nevertheless the regression equations are still in general agreement with the geometric methods when ordering techniques and postures. This suggests that even rough estimates can assist a coach in ordering, and so selecting, techniques and postures.

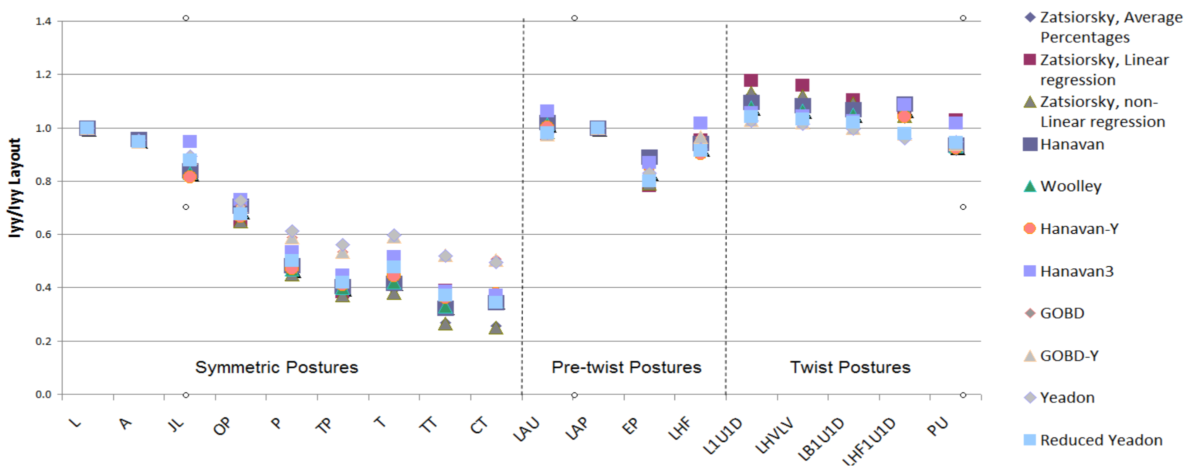

Figure 1: The ratio Iyy to Iyy in the layout posture.

CONCLUSIONS: Considerable variation in the values of the somersault parameters was observed across the eleven inertial property estimation methods compared. The method of distributing mass and the geometry affects the values. Further investigation is required to determine if GOBD-Y and Yeadon models will produce similar results for $I_{yy}/I_{yy\ layout}$, across a broad range of athletes. If so, the simpler GOBD-Y model could be used when studying non-twisting somersaults.

Although values of the parameters varied considerably, the order of postures and techniques does provide some insight into which to use. For a coach seeking to maximise twist production, it is advisable to teach athletes to initiate their twist by raise one arm in an entry pike position as this gives maximum tilt. In addition, laterally flexing towards the lowered arm should be discouraged since the lateral flexion will cancel some of the tilt produced by any arm action. After the throw for the twist instructing athletes to bend the arms to use the posture LB1U1D over L1U1D has potential for reducing the flight time required and increasing the number of twists that can be completed.

Future work will involve applying the estimation methods to multiple athletes to determine if trends hold. Predictions will also be compared to actual performances to determine the accuracy of each method.

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