COMPUTER SIMULATION OF PLANAR AIRBORNE HUMAN MOTIONS

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Dedication

I would like to dedicate this thesis to my parents, George and Luella Lemaire, who have given me support and encouragement above and beyond the normal limits of parenthood.

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Abstract

The airborne phases of a standing broad jump, dive front roll, front somersault, layout dive, reverse 2.5 pike dive, front 3.5 tuck dive, and long jump were used as the target skills for validation of a computer simulation model. These events were filmed in either a laboratory or competitive setting to determine the take-off velocities, take-off angles, total body angular momenta, relative angle histories, initial body positions, and segment lengths (for competitive situations) of the subjects. The segment lengths (10 segments) for the laboratory trials and the total body weights were determined by direct measurement. The absolute positions of the segments were predicted by the simulation model and compared to the original motion (obtained from film) on the basis of trunk angle and trajectory.

All but one of the simulated activities were found to be valid for rotation (under 10% error). The long jump, which did not meet the validation criteria, exceeded the validation zone by only 1%. For translation all but the 2.5 and 3.5 dives were valid (under 10% error) but it was shown that error in the criterion center of gravity values were likely the source of failure for these skills. It is expected that this simulation will be of use for research, education, and training of planar airborne human movements.

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INTRODUCTION

Validation is an important, though often neglected, component in the development of biomechanical tools and methods. In most cases it is extremely difficult or impossible to measure accurately the mechanical characteristics or properties of human movements. The problem increases in complexity as one moves out of the laboratory and into the field or into a competitive sport environment. Problems such as; obtaining valid body segment parameters, internal forces, and external forces; identifying the positions of musculo-skeletal structures; recording the movement patterns without disturbing the motion; and integrating the results into a form which is meaningful to the practitioner, present the researcher with formidable obstacles. The simulation of human motion is one area in which attempts have been made to produce a functional tool to aid researchers and practitioners in the prediction of human motion. Unfortunately, these simulations have shown substantial variation when validation has been attempted; were only validat d under specific, highly controlled conditions; or were not validated at all (i.e., no validation information reported). With the development of a valid simulation model, one would be able to determine the orientation of the human body after changes have been made to the body's anthropometric, kinematic, and kinetic parameters. This would lead to many practical applications for the teaching, visualization, and development of complex human movements.

Airborne activities have constituted a significant part of the simulation research involved with human motion. Sports such as diving, gymnastics, and athletics have been subjected to a variety of approaches aimed at representing, mathematically, the activity in question. The flight phase of these activities constitutes a period over which the only external forces being applied to the body are conservative (air resistance is assumed negligible), thereby allowing for the application of the law of conservation of angular momentum to the system (Miller, 1970; Ramey, 1974; Frohlich, 1979; Nissinen, Preiss, and Bruggemann, 1985). Kane and Scher (1970) used these principles to examine the airborne motion the human body. It was dynamically shown that a body's orientation in space can be changed when there is no (or a constant) angular momentum through the use of twists and "torque-free" somersaults. By combining these principles with kinematic data the position of a body over designated airborne time intervals could be determined.

Miller (1973) applied these principles in her simulation of planar non-twisting dives. A four segment model (based on Hanavan's computerized model), take-off velocity, take-off angle, body mass, angular momentum, and the histories of relative joint angles were combined to determine the body's absolute orientation in space. This information was then used to display the final result. It was recommended that the model be used to examine the effects of different anthropometric measures and style changes on total body motion. Although this simulation was valid, the use of a four segment model limited the application to layout and pike dives. This model also failed to recognize the contribution of the head or to allow motion at the knee or elbow (the head alone accounts for 8.1% of the body weight as compared to 5.0% for an entire arm).

Ramey (1973) designed a simulation for the long jump which was similar to Miller's except for two factors. Ramey used a model with 8 hinge joints and the 9 corresponding segments (the head and the neck were combined with the trunk). The other variation occurred with the use of the angular momentum term (Ho). Whereas Miller calculated the angular momentum and observed the resultant orientation, Ramey used an estimated value. An iterative approach was utilized to determine the angular momentum needed to produce a successful long jump. The simulation was not validated but the researcher did indicate a "very good approximation of the activity". Ramey's model failed to acknowledge an effect from the head-neck segment on the resultant motion, thereby encountering the same limitations as Miller (1973). Also, a trial and error approach was used to determine the angular momentum value, thereby limiting the quantitative use of this simulation.

Although most simulations are based on Newtonian mechanics, Boysen, Francis, and Thomas (1977) used a Lagrangian approach to simulate two-dimensional airborne motions. The 5 segment model used input data similar to Miller (1970) to simulate forward layout and forward 1.5 dives in the pike position. The error for these activities were 1.36 +/- 1.94 deg and 7.75 +/- 5.23 deg respectively. The simulation package was also made interactive for easier modifications and visual feedback. The interactive component for this package was an ideal step towards bridging the gap between existing mathematical models and usable research/teaching tools, however, the use of a 5 segment model and the lack of a component which can perform analysis on the simulated data (kinematics, power, etc.) limited the use and analysis capability of the model.

Dapena (1981) created a three-dimensional (3-D) computer simulation which he used to simulate a high jump and various trampoline stunts. The input for the 15 segment simulation model (hands and feet were assumed to be rigidly attached to their proximal segments) was similar to Miller's input (1970). The error for somersaulting was as large as 20 degrees. Although this simulation model can be used on most airborne movements the time commitment, data collection factors, analysis, and interpretation involved with 3-D simulation can counteract the added information provided by this procedure. As well, 3-D data collection is very difficult in competitive, uncontrolled situations (where two dimensional simulations can be more easily applied).

A more general simulation model was developed by Yeadon (1986). This study dealt with twisting somersaults and the contribution of different twisting techniques to the performance. The model itself consisted of 11 segments and 17 degrees of freedom (which were to represent the free fall phase of the prospective movement). The input data necessary for the simulation was obtained from 3-D kinematics and anthropometrics. After comparing various twisting techniques Yeadon supported the conclusion of other researchers (Frohlich, 1979; van Gheluwe, 1981) that the twist produced during the contact phase was relatively small in comparison to the use of asymmetric twisting techniques while airborne. This model also has the problems previously outlined for 3-D simulation.

In summary, there have been several attempts to simulate the flight phases of various human motions. The use of the conservation of angular momentum in these simulations was justified under the controlled conditions under which the simulation were applied (only conservative forces were applied to the system). The available models; however, either use an estimated angular momentum term, are limited by the anthropometric model used, have not been validated, or are too complicated for general use.

In view of these limitations, it was desirable to validate a mathematical model that could be used to simulate airborne human motions. Once the simulation has been constructed and validated it can be used in a variety of cases: the examination of the fundamental capabilities and techniques required to perform an activity (Miller, 1970; van Gheluwe, 1981; Yeadon, 1984); development of new skills (Nissinen, et al., 1985); coaching and athlete education (Walton and Kane, 1978; Dapena, 1981; Nissinen, et al., 1985); and teaching students the effects of parameter changes (angular momentum, limb position, etc.) on motion. In a training situation a computer simulation model would be very effective since the coach would be able obtain the input information during practice and experiment with style changes to the athlete's performance on a computer before the next session. This would help to make athlete contact time more efficient since many possible style changes could been tried out in advance. Also the chances of injury will be reduced since less trial and error experimentation with technique will be needed and the athlete will not have to be placed, unknowingly, in potentially dangerous situations.

Purpose

The purpose of this study was to validate a computer model for simulating planar airborne human motions. This model assumed no effects due to air resistance, that the segments acted as rigid bodies, and that the feet and hands did not have a significant independent effect of the total body motion.

METHODS

Simulation Model

The computer model consisted of 10 link segments and their corresponding joints (table 1). The use of 10 segments allowed for the observance of variations in bilateral asymmetry and recognized the contribution of the head-neck segment to the resultant motion.

Table 1: DEFINITION OF SEGMENTS FOR MODEL

SEGMENT	Proximal End	Distal End
Head-Neck	Mid-point between proximal ends of humerii	Mid-point between centres of ears
Upper Arm	Transverse centre of arm 5 cm below superior border of acromion	Mid-point between medial and lateral epicondyles of humerus
Forearm-Hand	Mid-point between medial and lateral epicondyles of humerus	Mid-point between styloid processes of radius and ulna
Trunk	Mid-point between proximal end of femurs	Mid-point between proximal ends of humerii
Thigh	Transverse centre of thigh at the greater trochanter	Mid-point between medial and lateral condyles of femur
Shank-Foot	Mid-point between medial and lateral condyles of femur	Mid-point between medial and lateral malleoli

The simulation required the following input data:

1. Total body weight.
2. Segment lengths (obtained by cinematographical analysis of the activity or direct measurement).
3. Initial orientation of the subject (used to determine the initial centre of gravity and the initial segment angles).
4. Resultant take-off velocity and angle.
5. Total body angular momentum at take-off.
6. Changes in joint angles during flight.
7. Time interval between the successive joint angles.

Segmental masses, radii of gyration, and centres of gravity were calculated from the proportions described by Dempster (1955) and Winter (1979). All other information necessary to calculate the body's absolute orientation in space were determined via the computer simulation model.

The absolute angular momentum of the trunk was computed based on the following equation and knowing the total body angular momentum, each segments moment of momentum (relative to the trunk), and each segments angular momentum (relative to the trunk).

$$H_o = I_o \omega_o = \text{constant}$$

$$= H_{tr} + \sum_{i=1}^{n} I_i \omega_i + \sum_{i=1}^{n} |r_i \times m_i . v_i|$$

where,

H_o	=	total body angular momentum
I_o	=	total body moment of inertia about an axis through the total body centre of gravity
ω_o	=	total body angular velocity
H_{tr}	=	trunk angular momentum
I_i	=	segmental moment of inertia about an axis through the segment centre of gravity
ω_i	=	segmental angular velocity
r_i	=	position vector from the segment

		centre of gravity to the total body centre of gravity
m_i	=	segment mass
v_i	=	first derivative of the position plus the vector r_i multiplied by the trunk's angular velocity

Subsequently, the total body rotation angle was determined by integration of the angular velocity term (determined from the trunk's angular momentum) over the designated time interval. The segments were then rotated by this angle about the total body centre of gravity.

$$\theta_{tr} = \theta_{tr-1} + \omega_i(\Delta t)$$

where,	θ_{tr}	=	absolute trunk angle
	θ_{tr-1}	=	previous absolute trunk angle
	Δt	=	change in time

The linear position of the body was determined by translating the total body centre of gravity (along with all body segments) a distance determined by Newton's equations for projectile motion.

Input Data Acquisition

The input data were obtained from film taken of elite, Canadian divers, a Canadian champion long jumper, and provincial caliber gymnast. The following movements were simulated: layout dive (D101A), front 3.5 tuck dive (D107B), reverse 2.5 pike dive (D205C), long jump, standing broad jump, front somersault, and dive front roll.

A 16 mm high speed camera (LOCAM), set at 100 frames per second, was used to collect the film data. The body mass was determined by direct measurement. The film was digitized (Hewlett-Packard 9874A - 0.3 cm measured accuracy) and then transferred to a mainframe computer for processing with the BIOMECH (Kinesiology

Department, U. of Waterloo) analysis package. Through direct use of this software package the initial orientation, take-off velocity, and total body angular momentum were determined. A subroutine was added to this package to calculate the changes in the relative angles over time and to prepare this information for input into the simulation.

Validation

Absolute motion of the subjects was known, in this case, from direct analysis of the source film. This absolute motion was used as the criterion for validation. The criteria were examined for validity on the basis of the variability of the angular momentum values (represented as the standard deviation and range of angular momentum scores) and the linear acceleration of the total body centre of gravity (represented as the difference between a vertical acceleration of -9.81 m/s^2 and the calculated vertical acceleration). Since the angular momentum of the total body should be constant over the airborne phase there should be little or no deviation from the mean value. The linear acceleration of -9.81 m/s^2 should also be constant over the airborne phase since it is assumed that gravity is the only external force being applied to the body.

To further quantify the validity of a simulation a root mean square error and a Pearson product moment correlation were computed to examine the degree of similarity between the simulation and the criterion. The correlations were used to examine the phase relationship between the dependent values while the root mean square error was used to estimate the error over the entire motion. These statistics used the trunk angle (rotation) and total body centre of gravity position (translation) as the determining factors. The error was also presented as a percentage of the full range of movement (with an acceptable error being within 10% of the maximum range).

RESULTS

Upon examination of the validity of the criterion (original) data it was found that the total body angular momentum value was not constant over the flight phase. The total body angular momentum had a standard deviation ranging from 4.55 to 9.89 $kg.m^2/s$ and a maximum range of 42.1 $kg.m^2/s$ over the various trials. The linear acceleration of the centre of gravity overestimated the true value of -9.81 m/s^2 with an average value of -10.1 m/s^2 over the trials.

Table 2: CRITERION VALIDATION

	Angular Momentum			Vertical Acceleration of Centre of Gravity		
Skill	Range[1]	Mean[2]	S.D.[3]	Range	Mean	S.D.
D101A	29.27	-25.98	5.59	28.09	-10.89	4.55
D107B	38.55	-50.04	7.59	21.03	- 9.39	5.10
D205C	51.56	57.80	9.26	13.99	- 9.49	4.20
Front - Somersault	42.12	-59.23	9.89	32.27	- 9.53	5.18
Dive Roll	32.02	-42.98	7.50	19.00	-10.91	3.73
Broad Jump	41.72	41.72	4.55	16.05	-11.08	3.40
Long Jump	36.54	-11.03	9.21	35.93	- 9.32	6.26

[1] Range of the criterion values ($kg.m^2/s$ for angular momentum and m/s^2 for centre of gravity).
[2] Mean of angular momentum values and centre of gravity values. Sign indicates direction of spin (negative = clockwise).
[3] Standard deviations.

The results from the angular validation procedure are displayed in table 3 and in figures 1 to 3. The values in the table represent the range of trunk rotation (absolute amount of rotation) for the simulation, time in air (time over which the simulation was applied), root mean square error (RMSE) between the simulation and the criterion trunk angles, Pearson correlation coefficient (between the criterion and the simulation), and percentage error between the simulation and the criterion trunk angles. From table 3, the maximum RMSE was found in the D107B dive while the maximum percentage error was found in the long jump. All the correlation coefficients were above 0.9.

Table 3: COMPARISON OF CRITERION AND SIMULATED TRUNK ANGLES

Skill	Range[1]	t[2]	RMSE[3]	r[4]	error[5]
D101A	143.81	1.42	2.09	0.999	1.45
D107B	1165.40	1.30	7.74	0.999	0.66
D205C	739.69	1.17	3.65	0.999	0.49
Front Somersault	362.11	0.60	1.29	0.999	0.36
Dive Roll	158.14	0.42	1.26	0.999	0.80
Broad Jump	41.25	0.49	1.56	0.999	3.78
Long Jump	24.06	0.71	2.64	0.919	11.00

1 Range of angular rotation of the simulated trunk (deg)
2 Time in air (s).
3 Root mean square error between the simulated and criterion trunk angles (deg).
4 Pearson correlation coefficient between the simulated and criterion trunk angles.
5 Percent error between the simulated and criterion trunk angles.

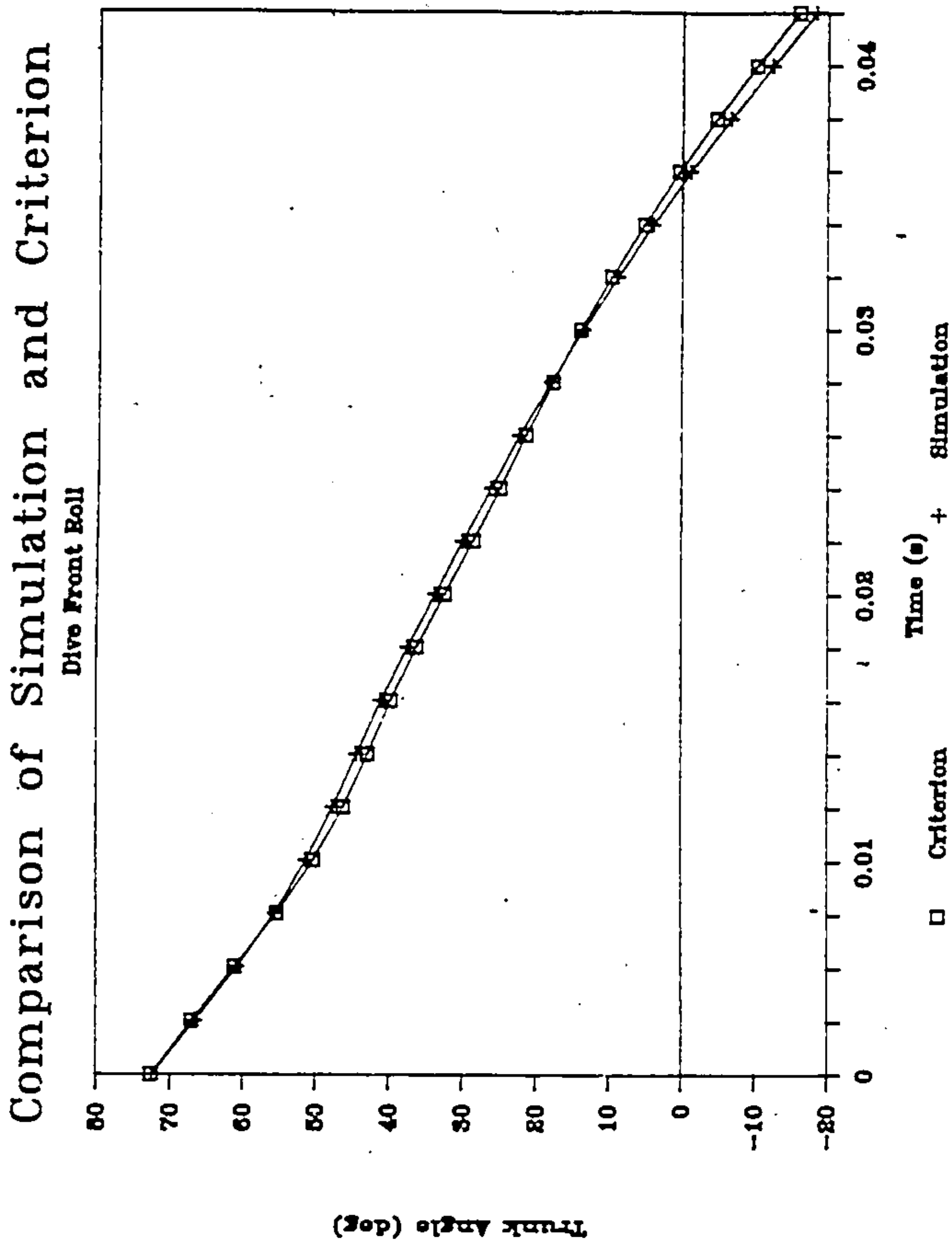


Figure 1: SIMULATION AND CRITERION TRUNK ANGLE VERSES TIME - DIVE ROLL

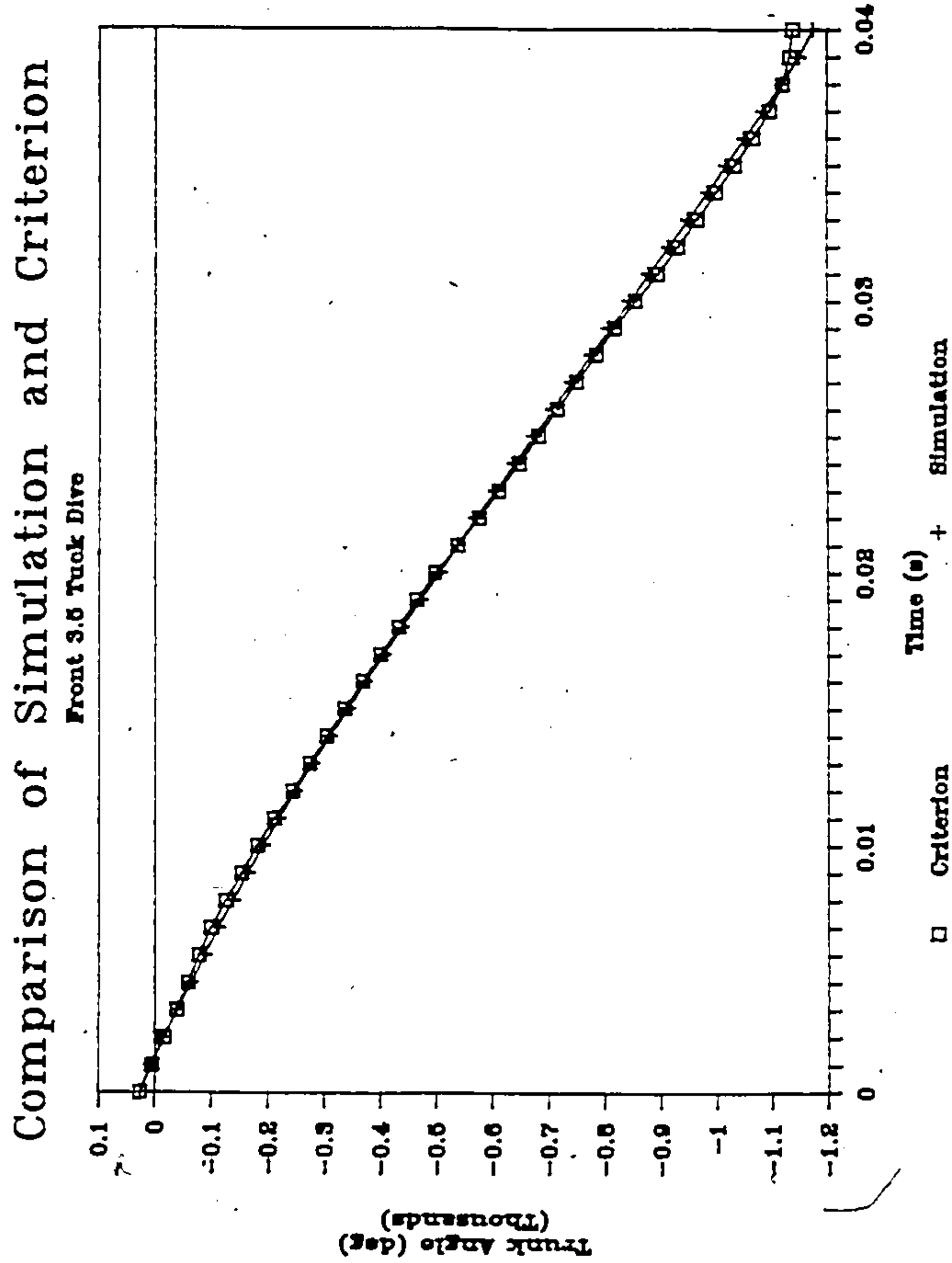


Figure 2: SIMULATION AND CRITERION TRUNK ANGLE VERSES TIME - 3.5 TUCK DIVE

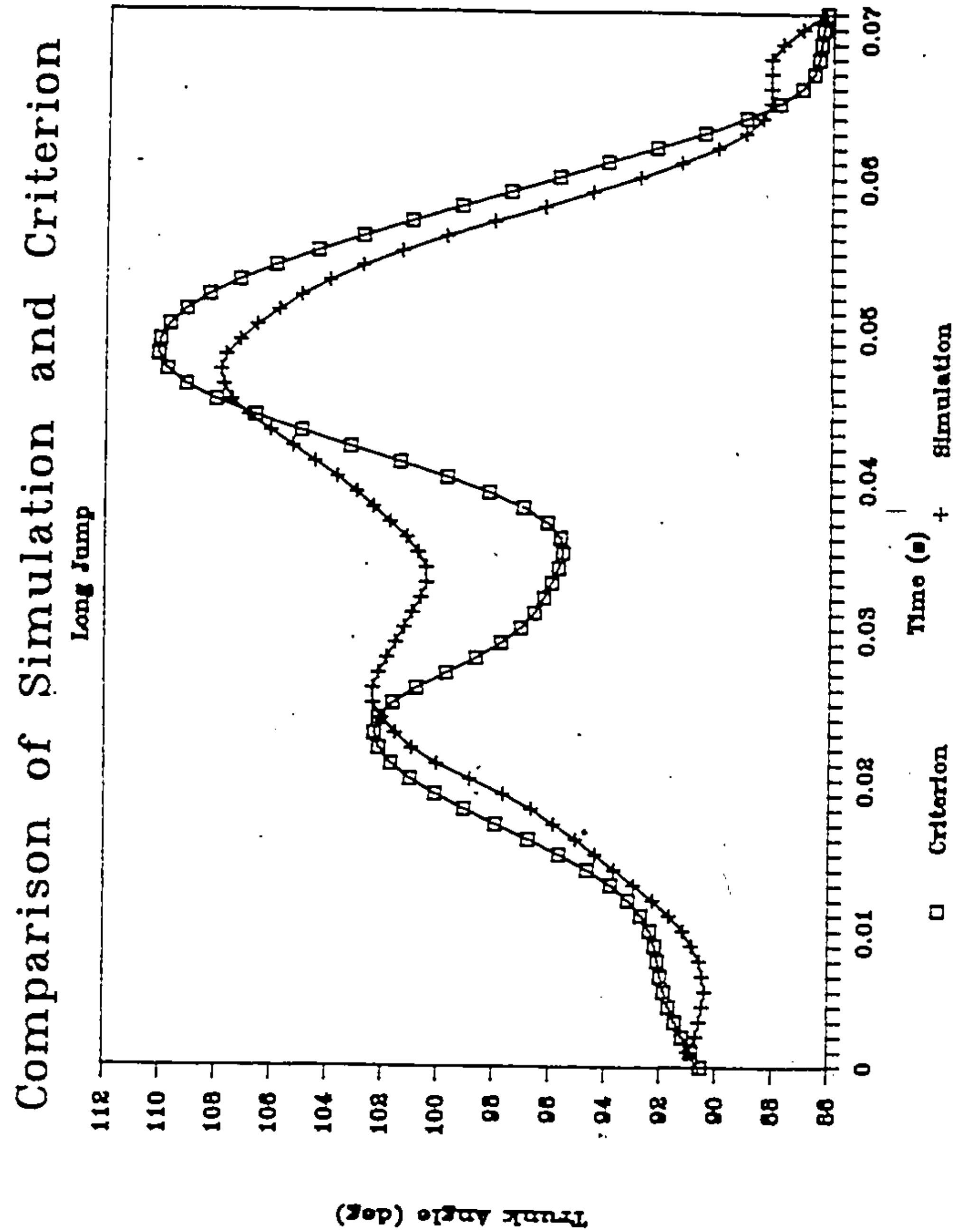


Figure 3: SIMULATION AND CRITERION TRUNK ANGLE VERSES TIME - LONG JUMP

The validation results for translation are presented in table 4 and figure 5. In this case, the RMSE, Pearson correlation coefficient, and percentage error were between the simulation and criterion centre of gravity coordinates. It is apparent from these results that the RMSEs were reasonably low (less than 6 centimetres) except for the dives. It should be noted that the total body centre of gravity trajectories for the actual dives do not follow a parabolic path. In all cases, though, the Pearson correlation coefficient exceeded 0.85.

Examples of the graphic output (marker position for the total body) for the simulation and the criterion are displayed in figures 5 and 6.

Table 4: COMPARISON OF TRAJECTORIES OF CRITERION AND SIMULATED CENTRE OF GRAVITY

	Horizontal Direction			Vertical Direction		
SKILL	RMSE[1]	r^2	%[3]	RMSE	r	%
D101A	6.0	0.99	7.3	17.0	0.99	3.7
D107B	7.0	0.99	4.7	26.5	0.97	8.1
D205C	12.8	0.98	7.4	24.5	0.85	10.9
Front - Somersault	2.0	0.99	1.2	3.0	0.99	5.7
Dive Roll	5.0	1.00	2.7	2.0	0.99	4.5
Broad Jump	6.0	0.99	4.1	4.0	0.98	8.1
Long Jump	4.0	1.00	0.7	2.0	0.99	2.7

1 Root mean square error between simulation and criterion coordinates (cm).
2 Pearson correlation coefficient.
3 Percent error between simulation and criterion coordinates.

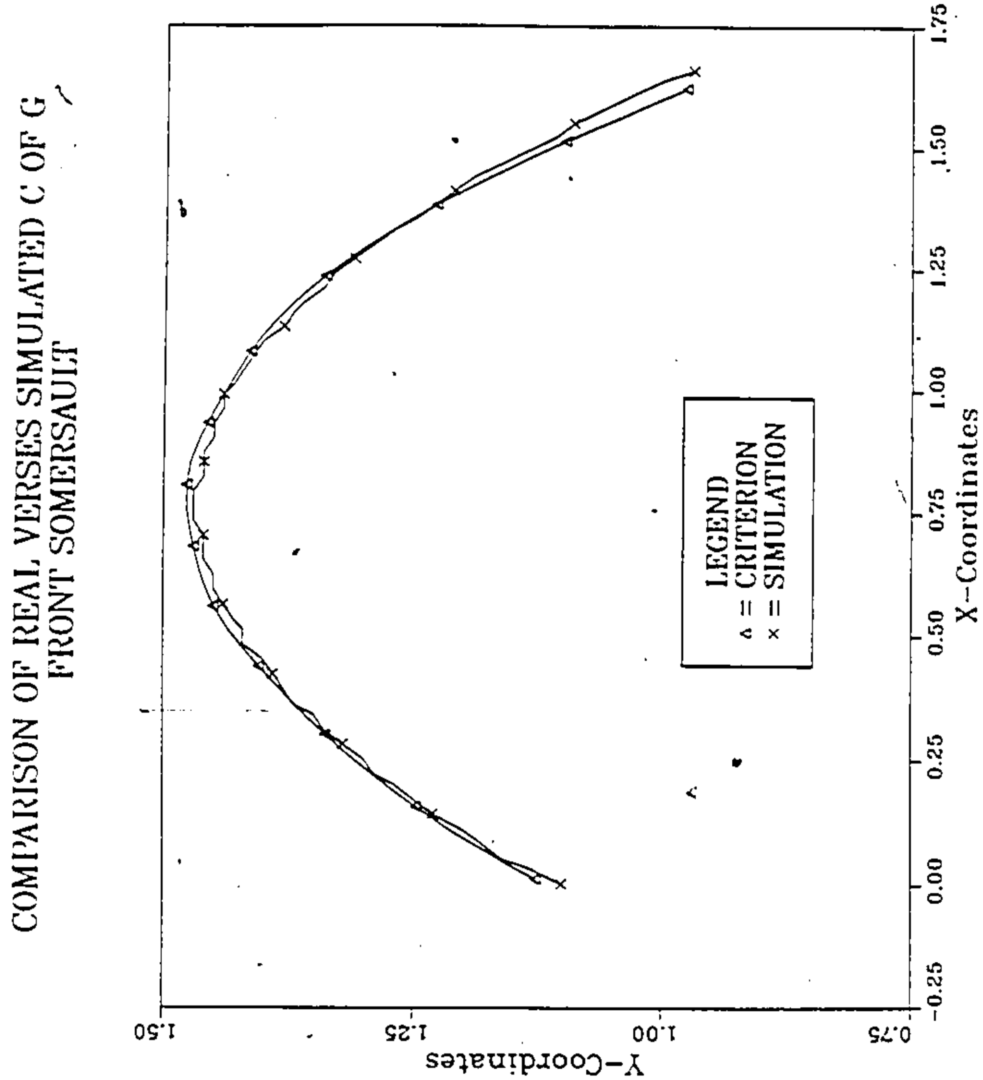
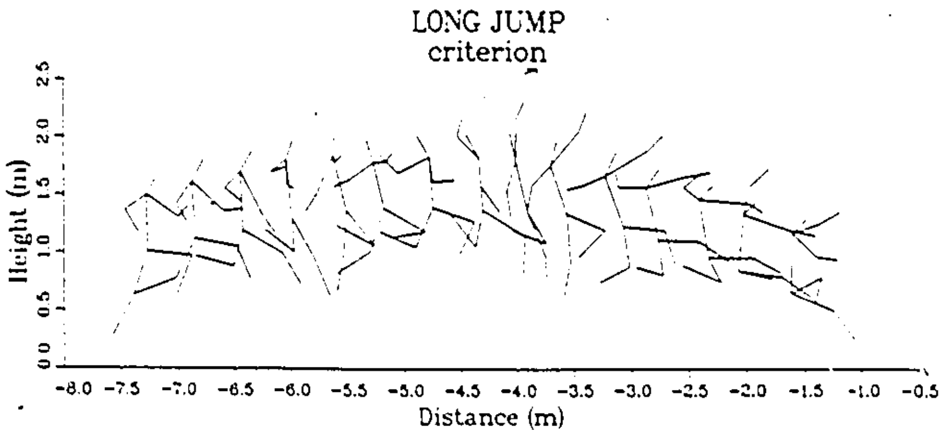


Figure 4: SIMULATION AND CRITERION CENTER OF GRAVITY TRAJECTORY



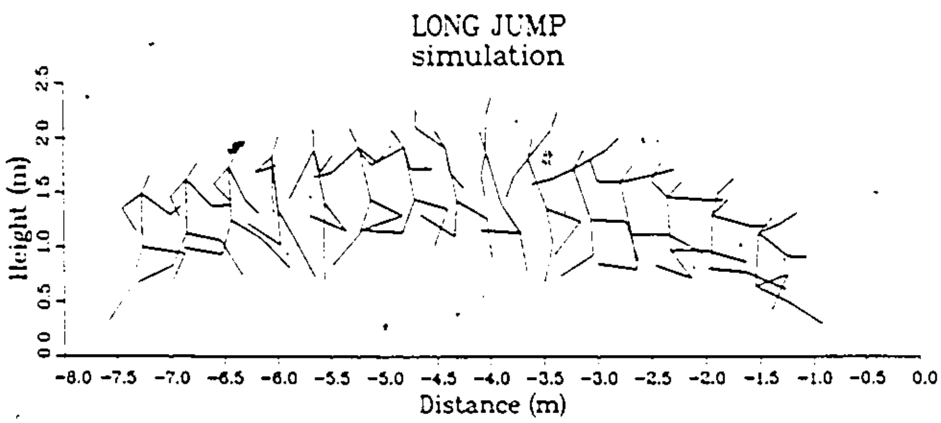


Figure 5 TOTAL BODY PLOTS OF SIMULATION AND CRITERION - LONG JUMP

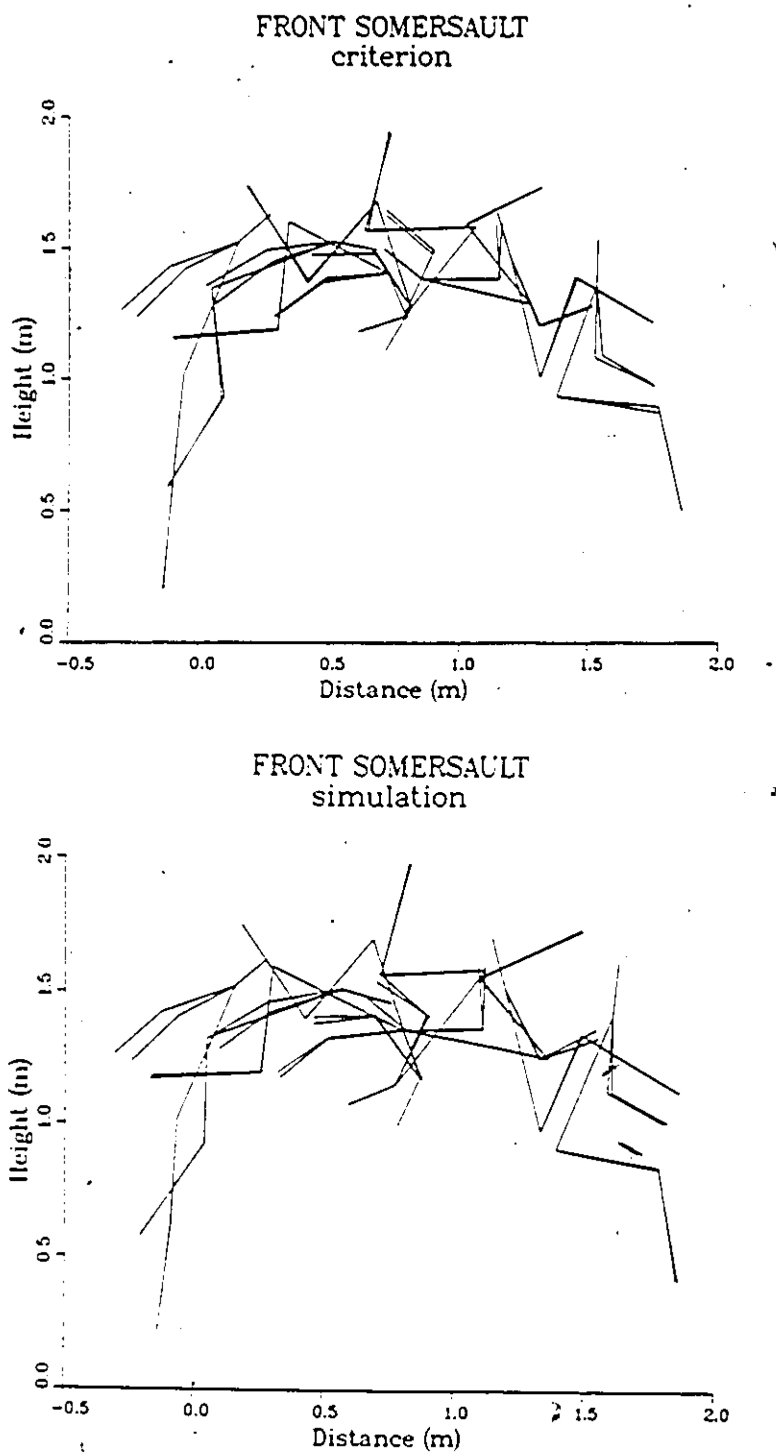


Figure 6: TOTAL BODY PLOTS OF SIMULATION AND CRITERION - SOMERSAULT

DISCUSSION

In all but one case the root mean square error (RMSE) and percentage error for the trunk angle comparisons were within acceptable limits (10%). These low errors reflect the similarity between the criterion and simulation trunk angles (all the valid trials were under 11.0% error and all but two trials were under 1.5% error). The Pearson correlations were also very high (all above 0.910 with all but one trial above 0.990) signifying a nearly perfect phasic relationship between the simulation and criterion angles.

Similarity was also found for the translation of the body. This is not surprising since the total body centre of gravity should follow a parabolic path while in flight. It is surprising, though, that the error was approximately 5% for most of the trials and over 8% for two of the dive trials. For both rotation and translation, various factors account for the errors that do occur.

The criterion itself displayed various discrepancies which influence the simulation validation. First, the angular momentum calculated from the film was extremely variable over the airborne phase. This variability is consistent with the results of other researchers (Miller, 1970; Dapena, 1981) and is attributable to errors in data collection and processing and to errors in the estimation of body segment parameters. To estimate the true total body angular momentum, which was required for the simulation, the mean angular momentum was calculated as an initial estimate of the actual value. An iterative approach was then used to adjust this estimate so that it fit with the original data.

The second discrepancy occurred with the translation of the total body centre of gravity. Although the mean values for the vertical acceleration of the centre of gravity were very close to the criterion (2.7% error) the standard deviations were larger than expected. It was assumed that the reason for these differences were the same as for the total body angular momentum calculation. The problems with the criterion were most observable in the dives and the standing broad jump. The path of the total body centre of gravity for these activities did not follow a smooth parabola; therefore, the translational validation for these trials does not reflect the true accuracy of the simulation model.

For cases where there was limited back flexion and essentially planar motion (limbs move in the sagittal plane, e.g., broad jump, dive roll, layout dive) the RMSEs and percentage errors were very small. When the spine is flexed or extended an error will result in the calculated trunk moment of inertia and trunk angular momentum values. This will greatly effect the determination of the total body rotation since the trunk's mass is a relatively high proportion of the total body mass.

The larger percentage error on the standing broad jump can be attributed to the smaller range of angular motion, to the large amount of spinal motion in the final phase before landing, and to the estimation of the body segment parameters. Possible reasons for the increase in mean error for the somersaulting dives are an increase in spinal motion while in a pike or tuck position, errors due to estimating the segment lengths from film, and errors in the body segment parameters. Although the RMSE was higher for these dives, the percentage error shows that, over the whole dive, the simulation was valid (under 1% error) for these skills.

Not surprisingly, the long jump showed the highest percentage error of all the skills. The long jump had a reversing trunk angle (the trunk rotated in a both a clockwise and counterclockwise direction while airborne), limb motion out of the sagittal plane, axial rotation of some segments, bilaterally asymmetric limb movements, flexion and extension of the spine, and estimated segment lengths (i.e., obtained from the film). The reversing trunk angle (the trunk initially rotated counterclockwise and then clockwise) was a common difference between the long jump and the other trials but it is was not possible to determine whether this was the main cause of the larger amount of error. Although the long jump simulation did not meet the validation requirement the proximity to the validation limit (the validation limit was exceeded by only 1%), justifies the use of the long jump simulation in various, non-research, situations. A simulation of the long jump could be used for educational purposes (to teach about the influences of parameter changes on resulting motion), to aid in body imagery for the athlete, or to test style changes. It is possible that direct measurement of the limb lengths would produce a better simulation of the long jump.

Translationally, the validation of the simulation was within acceptable limits for all but the diving trials. As discussed, the apparent errors in the diving trials were a result of the errors in the criteria. The simulation could be used to help correct for these errors by supplying a comparison for the criterion which best represents the parabolic path of the total body centre of gravity while airborne.

When compared to the results of previous validations of airborne simulation models, this model appears to be exceptional in its replication of the original motion. Spaepen, et al. (1983) reported a mean difference below 7 degrees for a back handspring; Dapena (1981) a 12 to 28 degree somersault error for various somersault and twisting motions; Boysen, et al. (1977) a 1.36 +/- 1.94 degree and 7.75 +/- 5.23 degree error for a forward pike dive and a forward 1.5 dive, respectively; and Miller (1970) a maximum error of 15 degrees for layout and 1.5 pike dives. The simulation model used in this study was shown to be, comparatively, better than these previous models on the basis of mean error.

Upon examination of the time of flight and the error estimates it is seen that there is no relationship between these two variables. It can, therefore, be suggested that the time in air is not a large influence on the simulation of an activity. The larger influence must be the movement of the limbs and the error that is present as a result of the movements.

The error may be reduced, in some cases, by introducing a two or three segment back into the model to help deal with flexion and extension of the spine. Although the curvature of the spine is minimal for the long jump, the bending that does occur over the centre portion of the airborne phase (corresponding to the largest error) may be better explained through a two or three segment back model. It is also recommended that precise measurement of the segment lengths and determination of the appropriate segment parameters (for the body type and sex) be used in place of estimation of the lengths from film and the use of standard segment parameters.

The simulation of airborne motion has many uses in the area of human performance; for example, teaching about the factors influencing airborne motion, letting an athlete see how changing his/her position affects the overall motion, allowing a coach experiment with style changes before introducing them to an athlete, and creating new motions. The simulated movement pattern can also be kinematically and kinetically analyzed to determine the joint moments and power necessary to produced the desired motion. The simulation model from this study may be valid for non-twisting dives in the layout, tuck, and pike positions; gymnastic dive front rolls and front somersaults; and the standing broad jump. It could also be assumed that trampoline stunts, which are similar to the motions experienced for dives, are also valid for this simulation model. The long jump, while being just out of the validation limits, could be useful for non-scientific simulation applications.

To make this simulation accessible it has been integrated into the BIOMECH (Kinesiology Department, U. of Waterloo) analysis package for ease of input data manipulation, graphic output, and the capability of performing kinematic and kinetic analyses for the simulated motion. This simulation model for planar airborne motion is expected to be very useful in the analysis and understanding of airborne human performances.

CONCLUSION

The computer simulation model of airborne motion in the sagittal plane developed for this study has been shown to be valid for a variety of planar movements (including long jumps, non-twisting springboard dives, various tumbling moves). Furthermore, the results obtained support the use of the link-segment model as a valid means of mathematically representing the human body. It is expected that this simulation will be of use in teaching, coaching, and research.

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Appendix A

FIGURES OF SIMULATION AND CRITERION TRUNK ANGLES VERSUS TIME

1. Layout dive
2. Front 3.5 tuck dive
3. Reverse 2.5 pike dive
4. Front somersault
5. Dive front roll
6. Standing long jump
7. Long jump

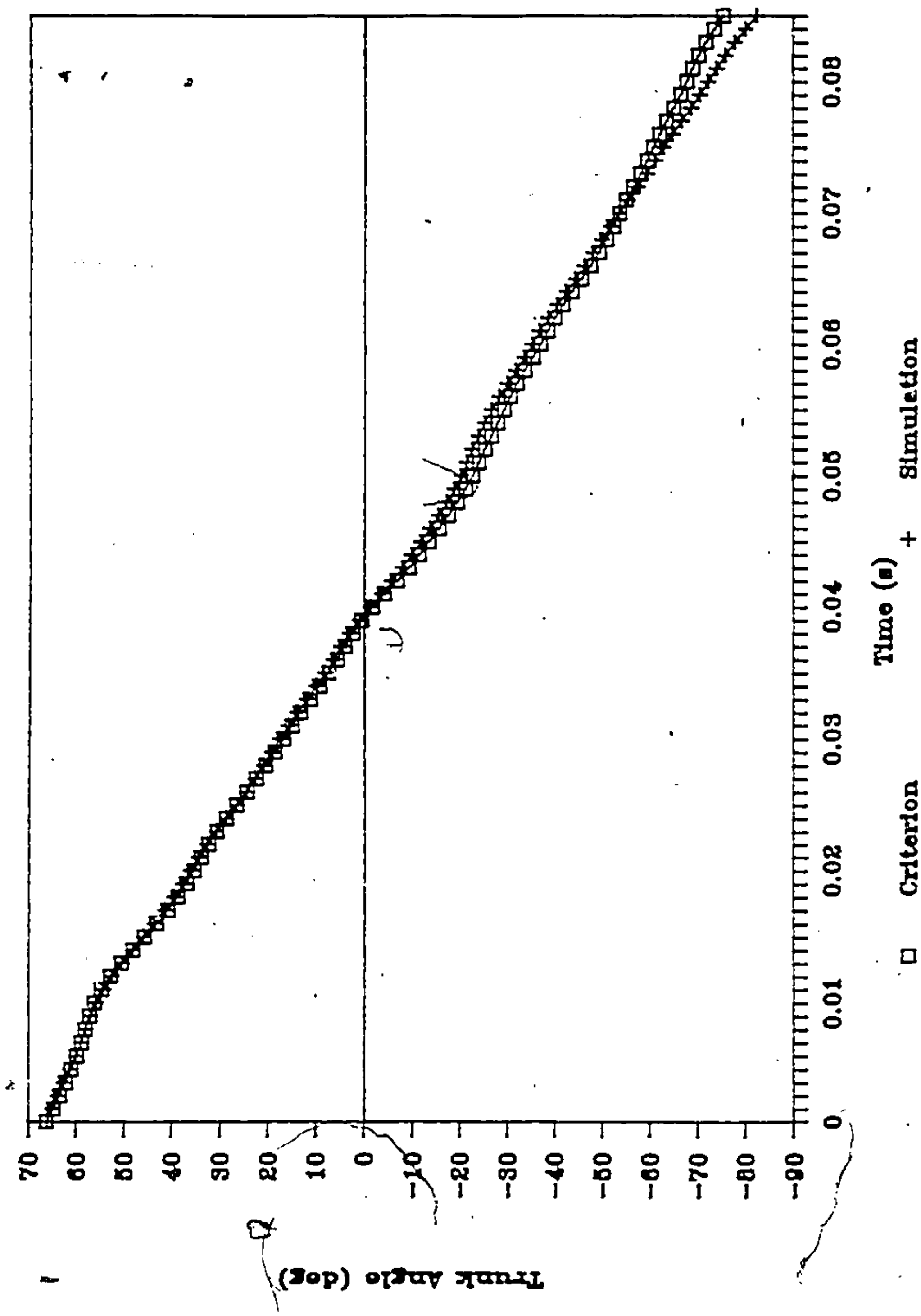

Figure 7: SIMULATION AND CRITERION TRUNK ANGLES VERSES TIME - LAYOUT DIVE

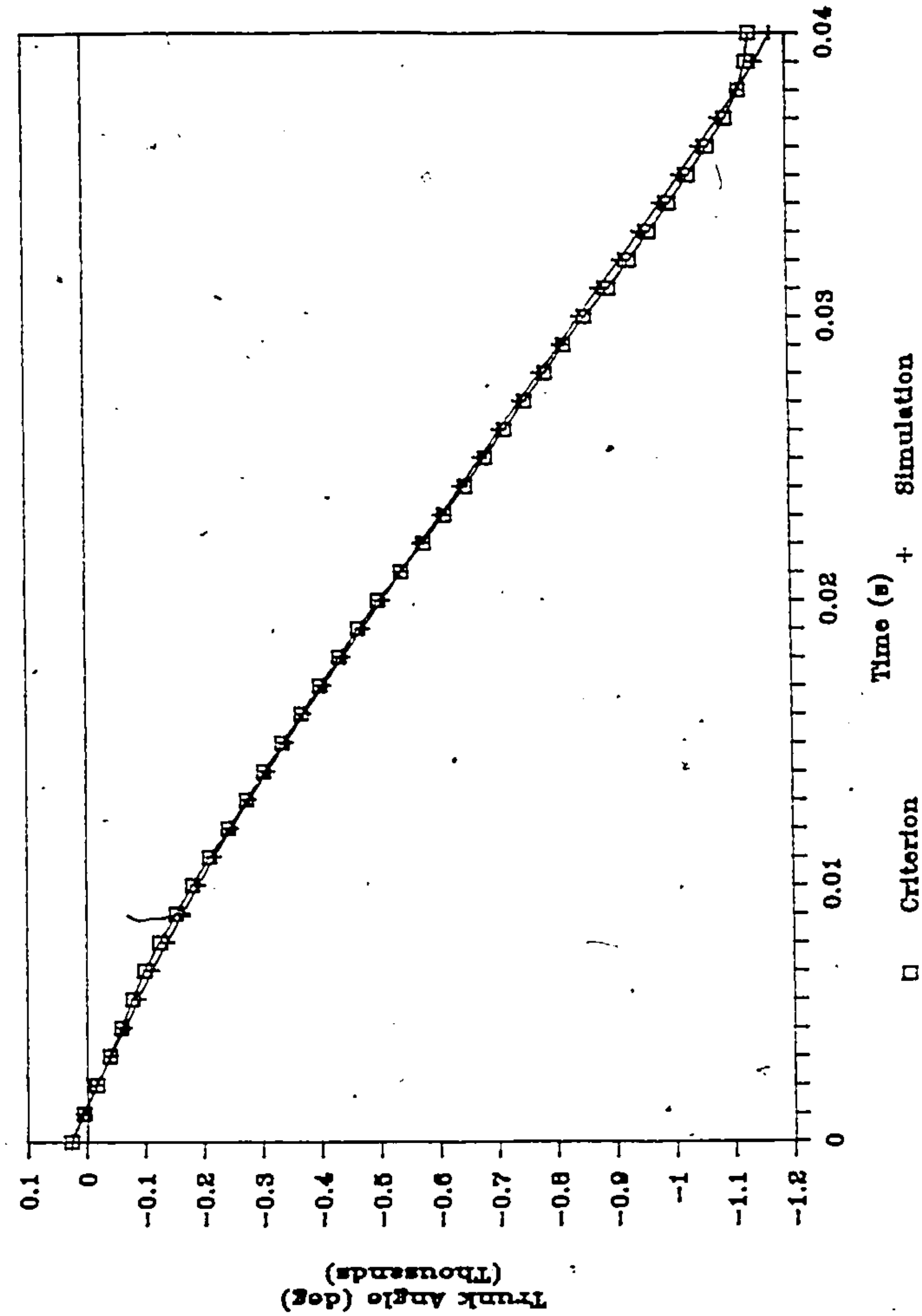

Figure 8: SIMULATION AND CRITERION TRUNK ANGLES VERSES TIME - 3.5 TUCK DIVE

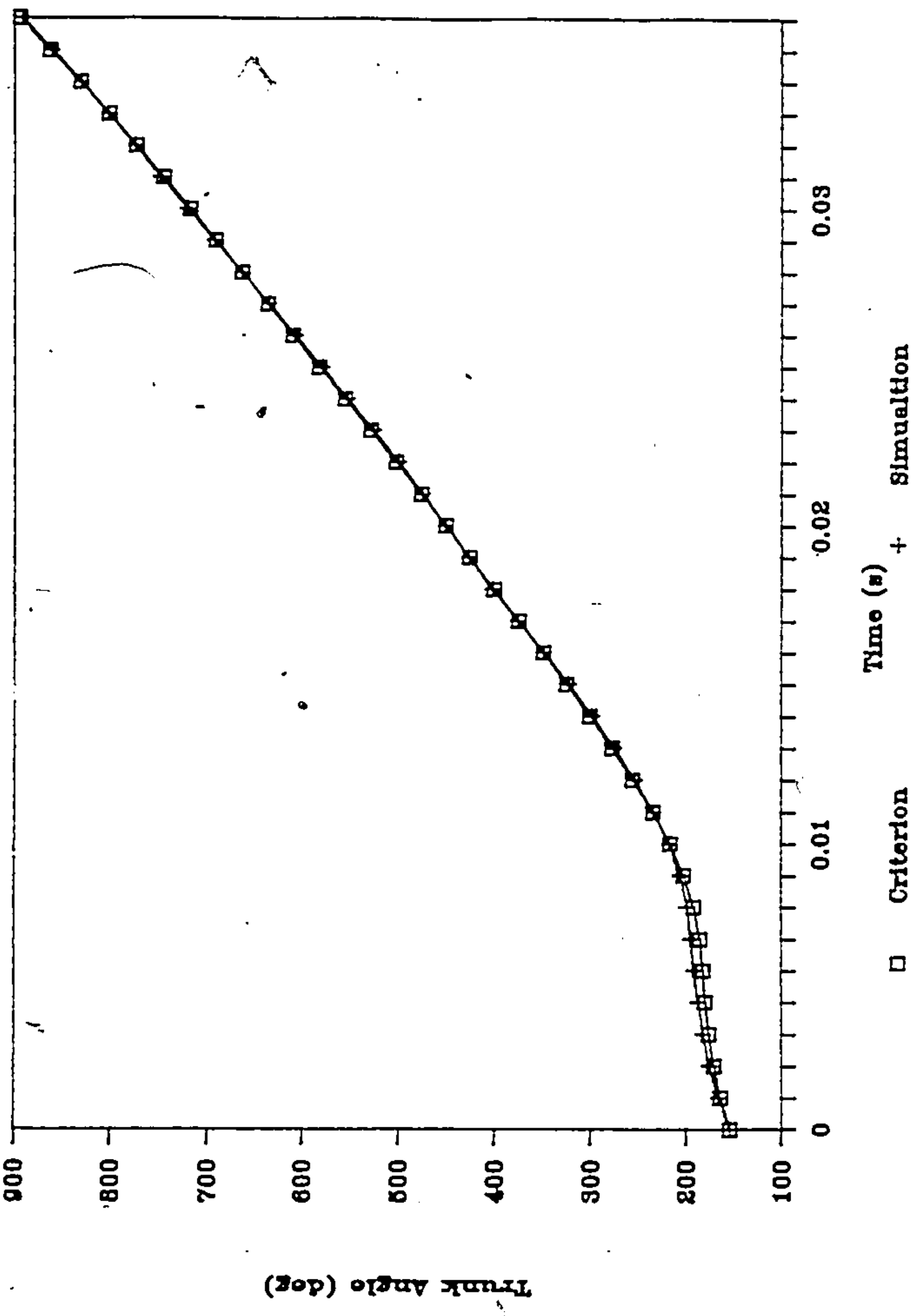

Figure 9: SIMULATION AND CRITERION TRUNK ANGLES VERSES TIME - 2.5 PIKE DIVE

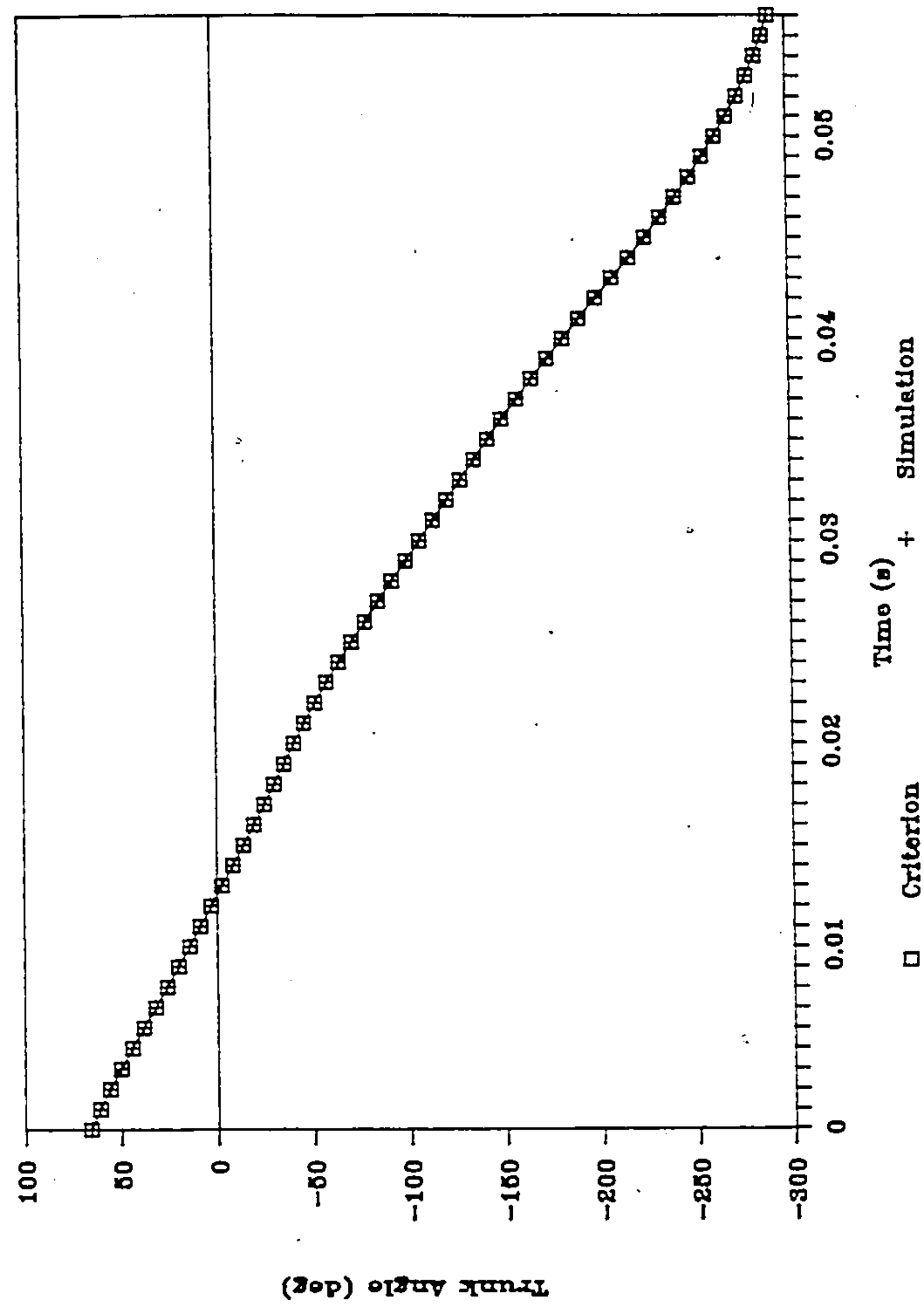

Figure 10: SIMULATION AND CRITERION TRUNK ANGLES VERSES TIME - SOMERSAULT

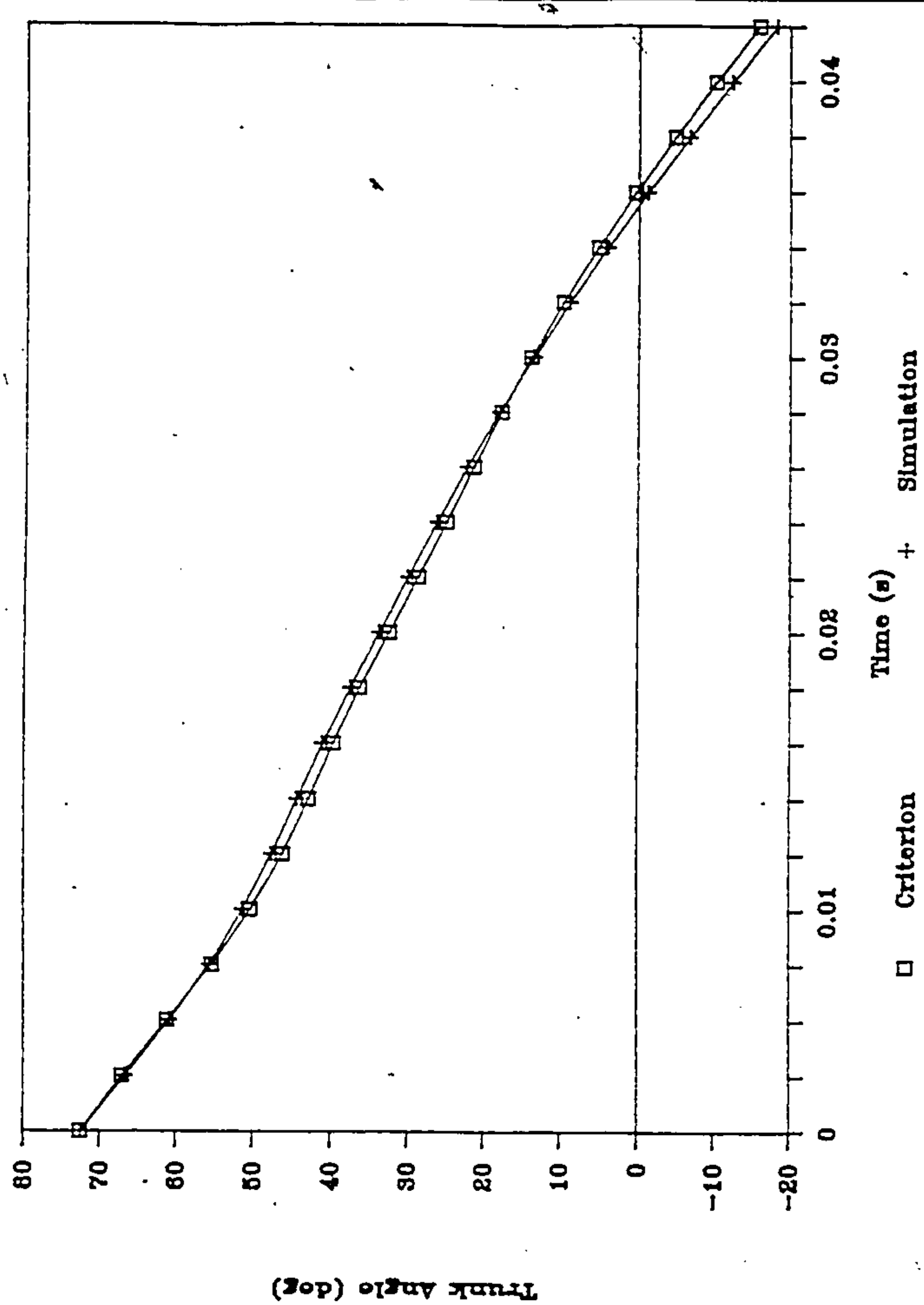

Figure 11: SIMULATION AND CRITERION TRUNK ANGLES VERSES TIME - DIVE ROLL

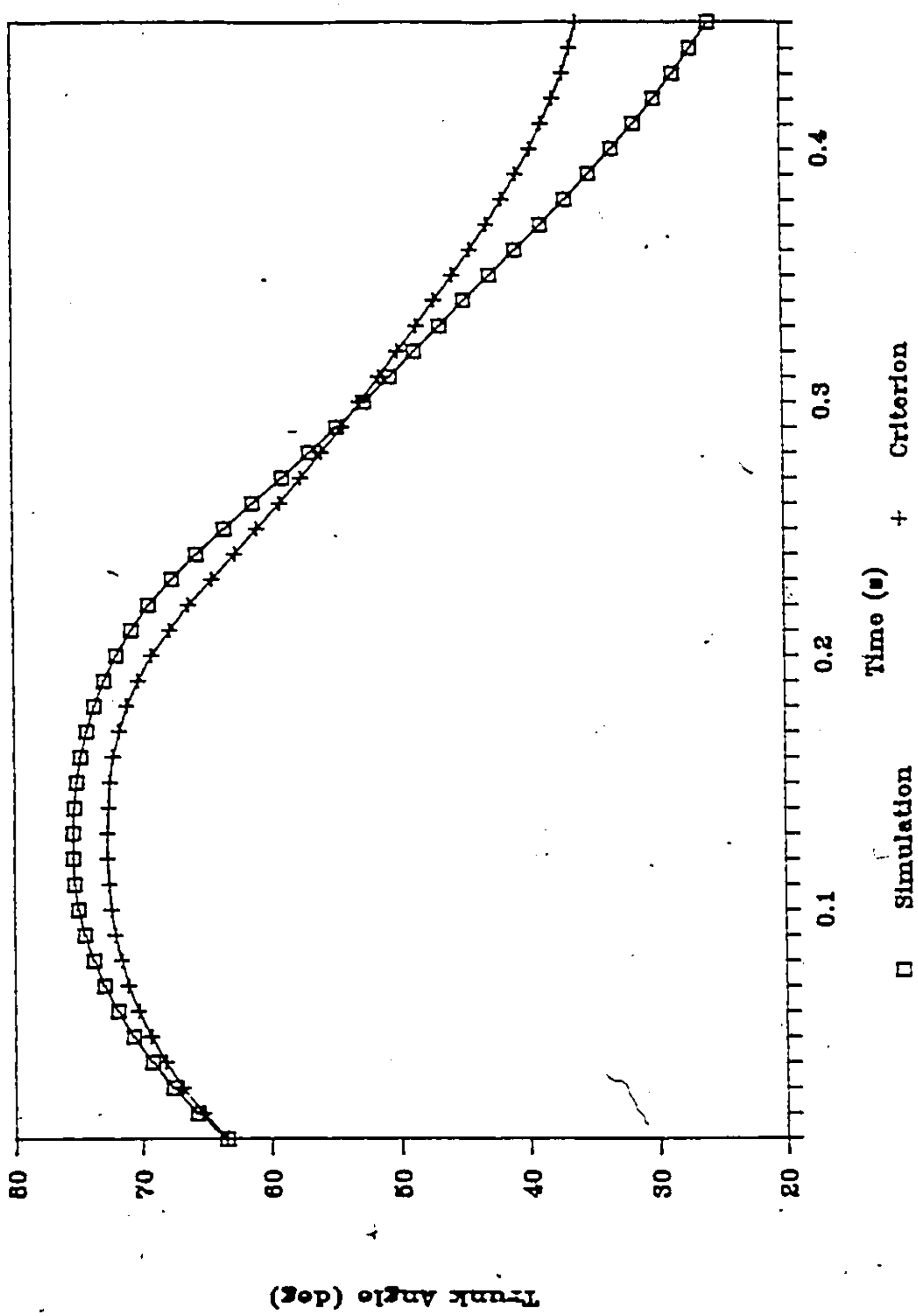

Figure 12: SIMULATION AND CRITERION TRUNK ANGLES VERSES TIME - STANDING JUMP

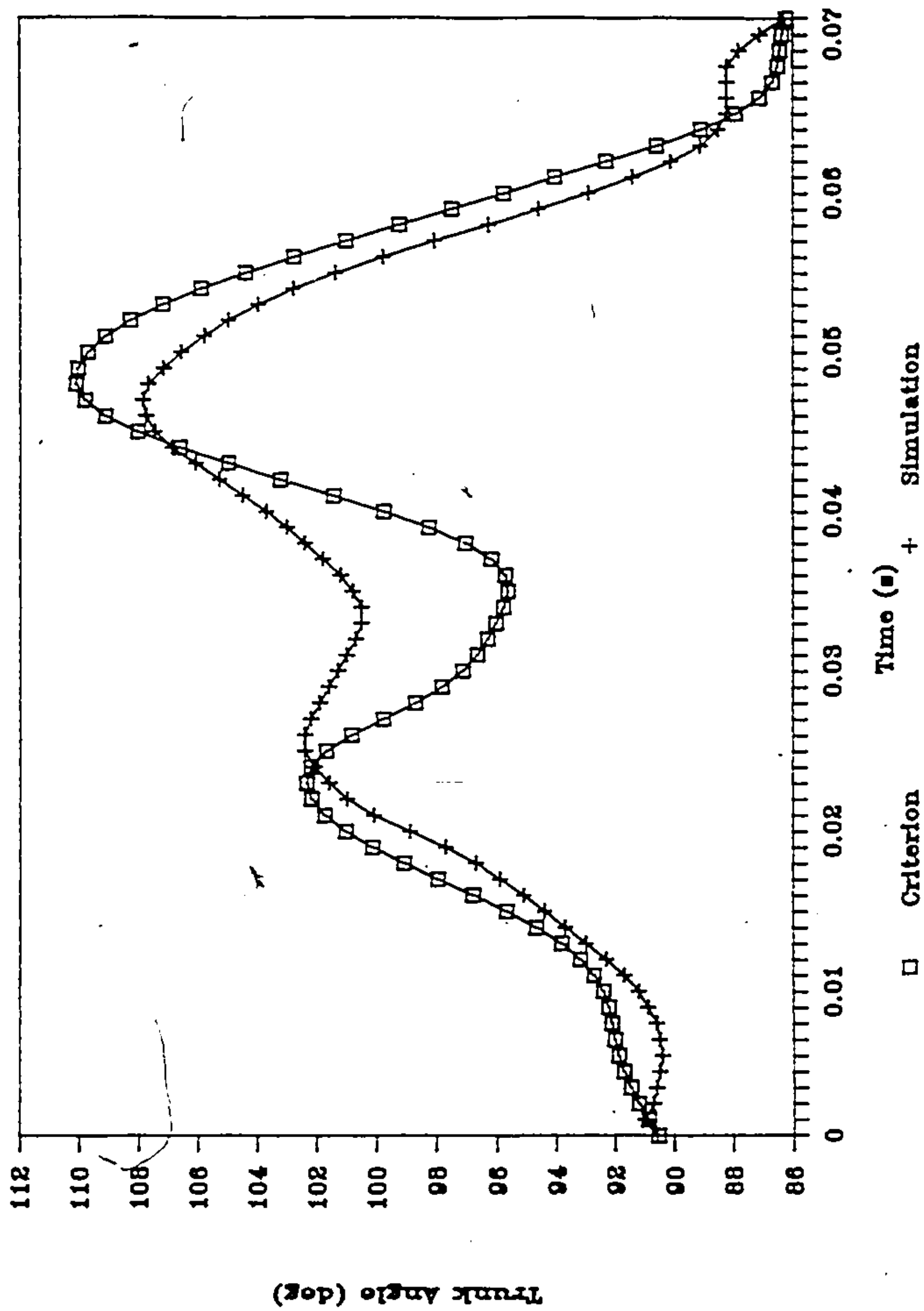

Figure 13: SIMULATION AND CRITERION TRUNK ANGLES VERSES TIME - LONG JUMP

Appendix B

FIGURES OF SIMULATION AND CRITERION CENTRE OF GRAVITY TRAJECTORIES

1. Layout dive
2. Front 3.5 tuck dive
3. Reverse 2.5 pike dive
4. Front somersault
5. Dive front roll
6. Standing long jump
7. Long jump

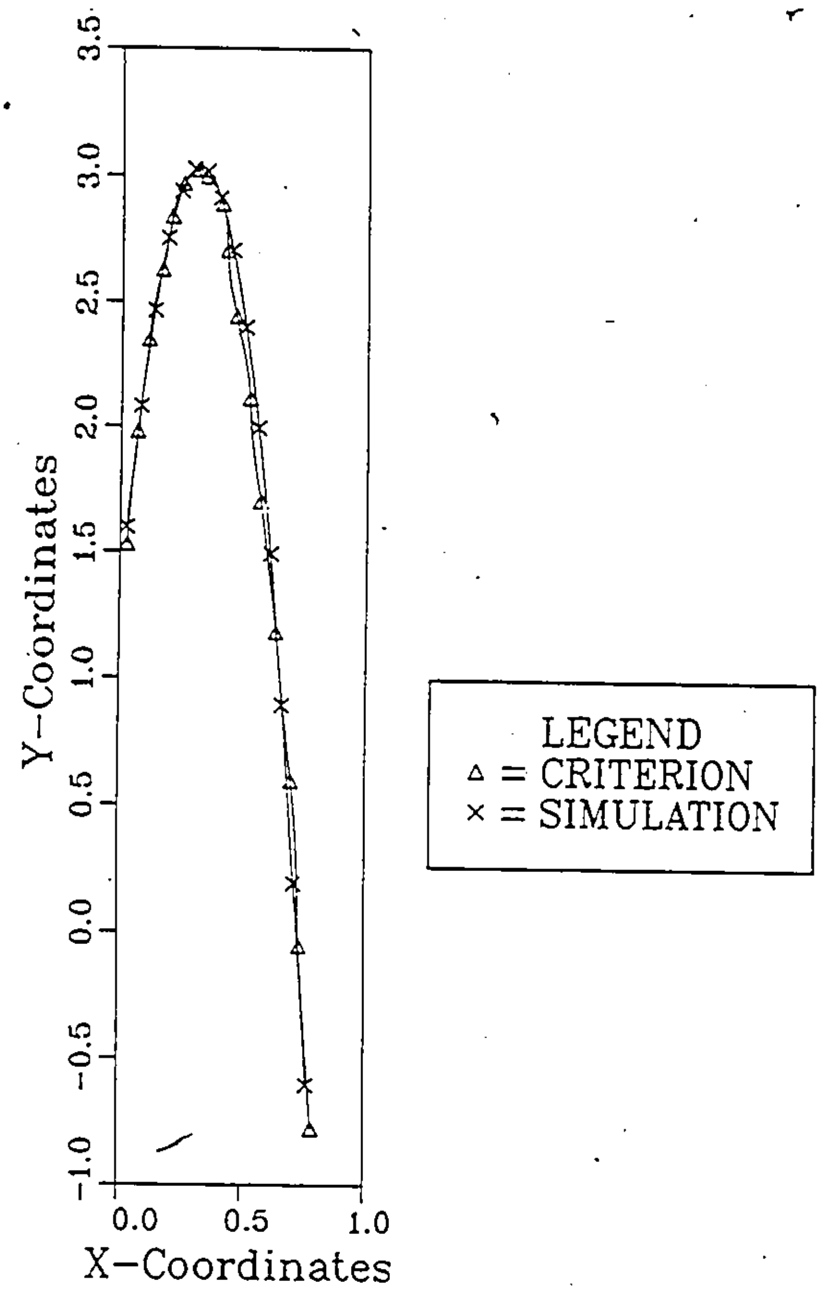

Figure 14: SIMULATION AND CRITERION CENTRES OF GRAVITY - LAYOUT DIVE

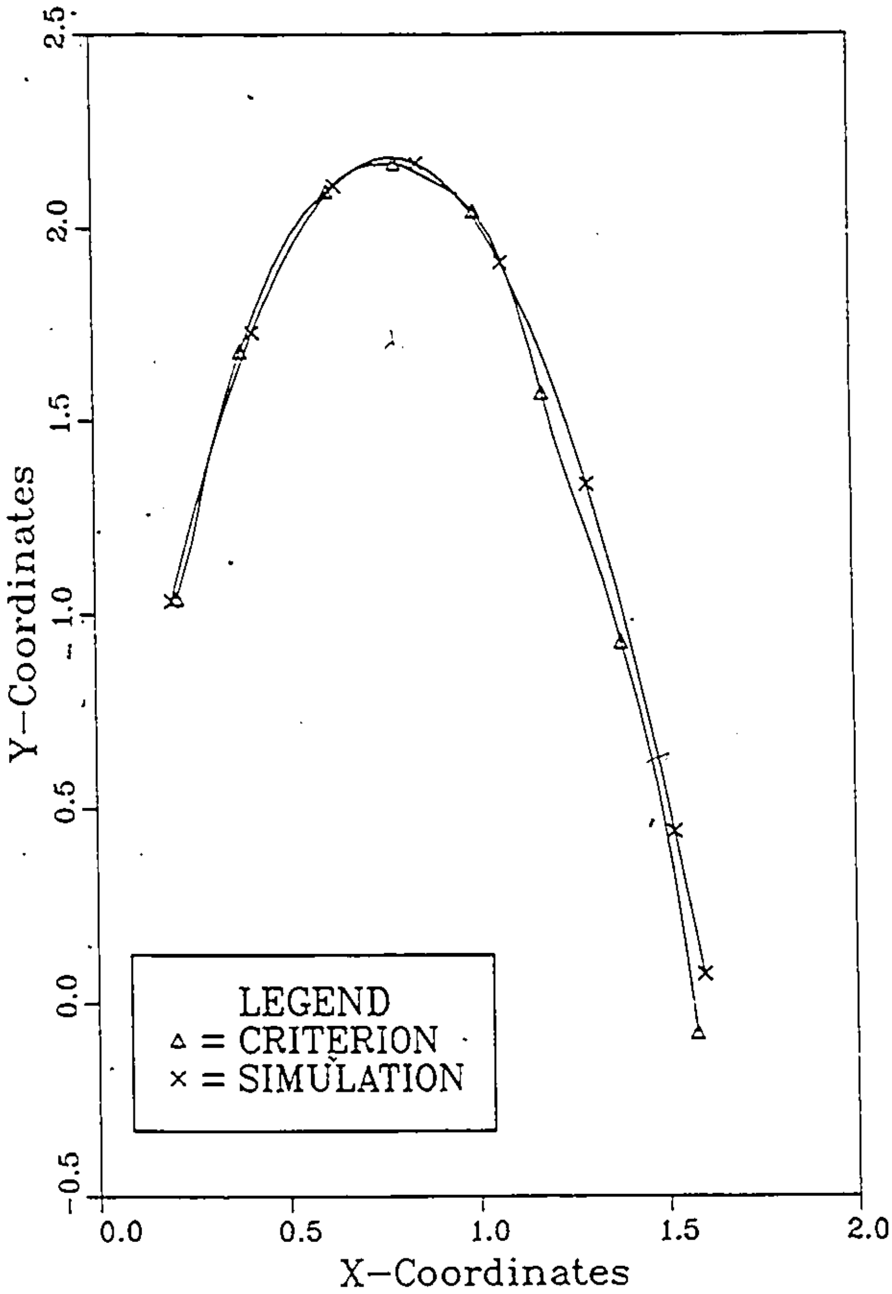

Figure 15: SIMULATION AND CRITERION CENTRES OF GRAVITY - 3.5 TUCK DIVE

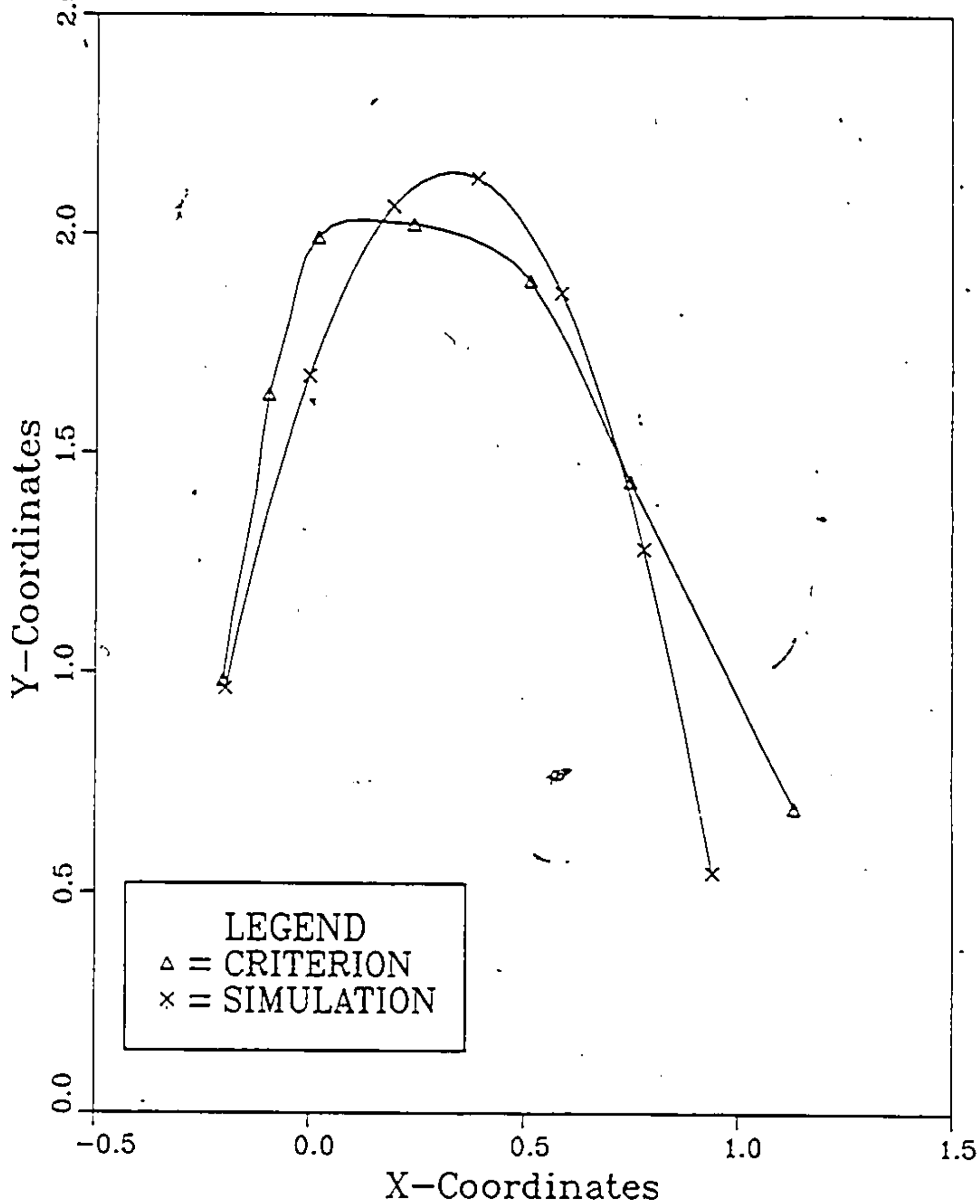

Figure 16: SIMULATION AND CRITERION CENTRES OF GRAVITY - 2.5 PIKE DIVE

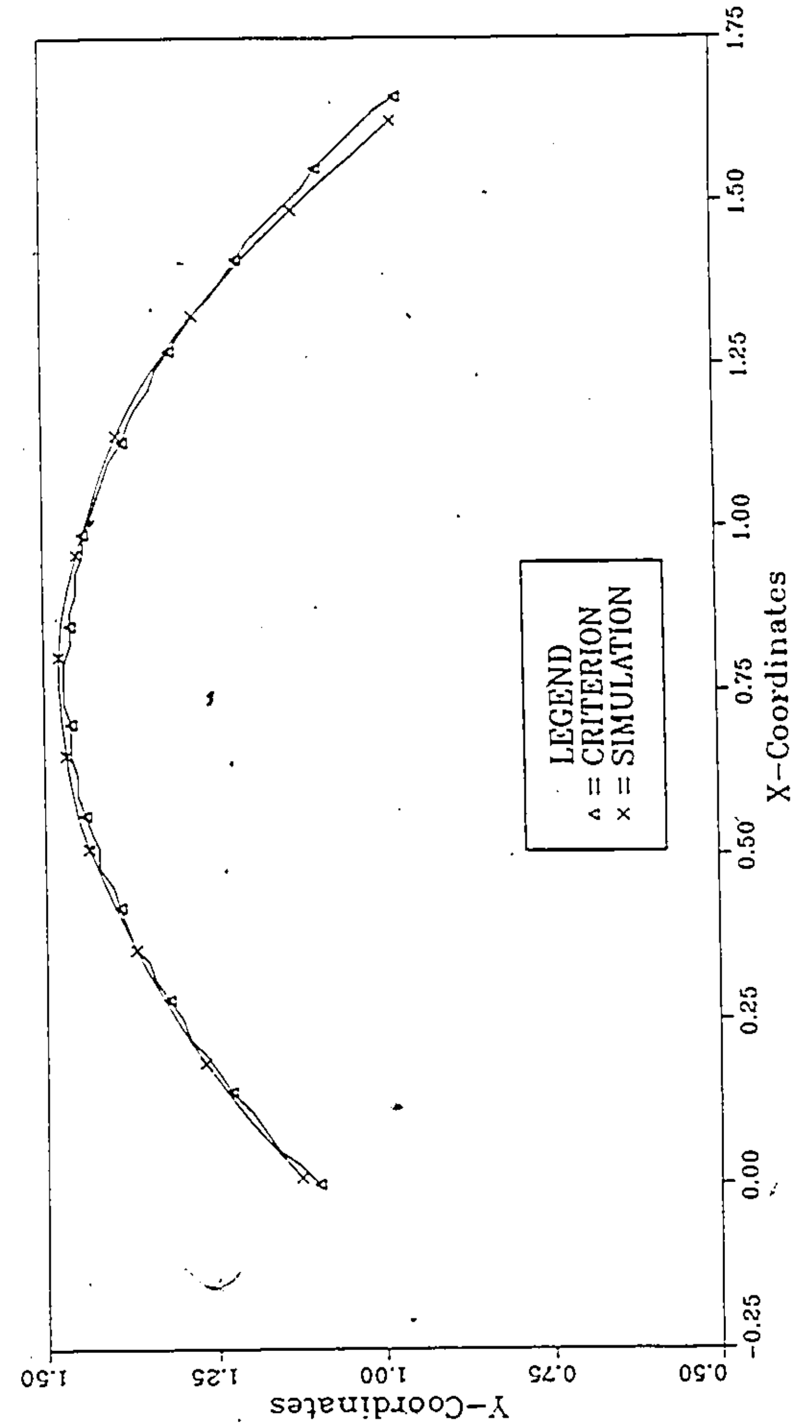

Figure 17: SIMULATION AND CRITERION CENTRES OF GRAVITY - SOMERSAULT

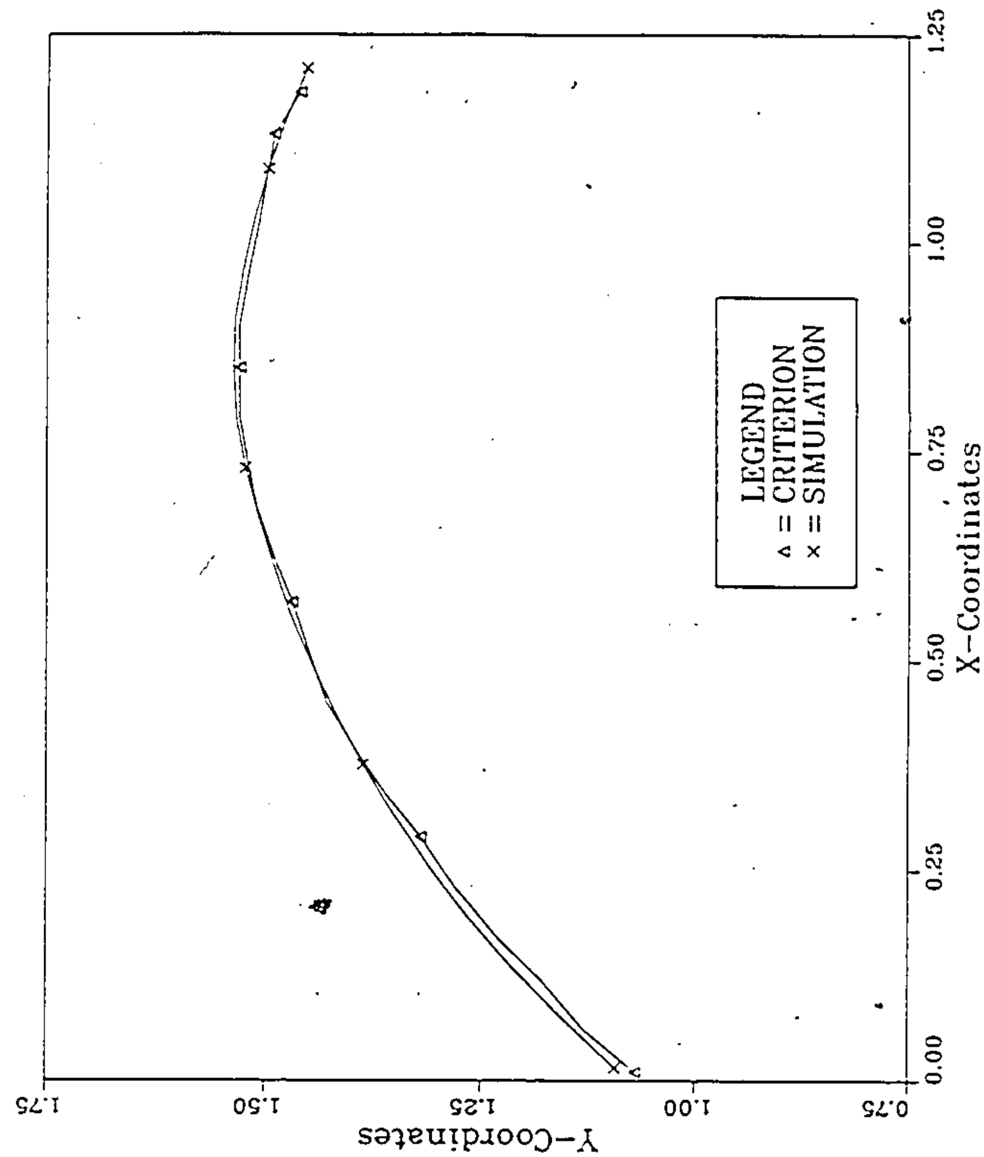

Figure 18: SIMULATION AND CRITERION CENTRES OF GRAVITY - DIVE ROLL

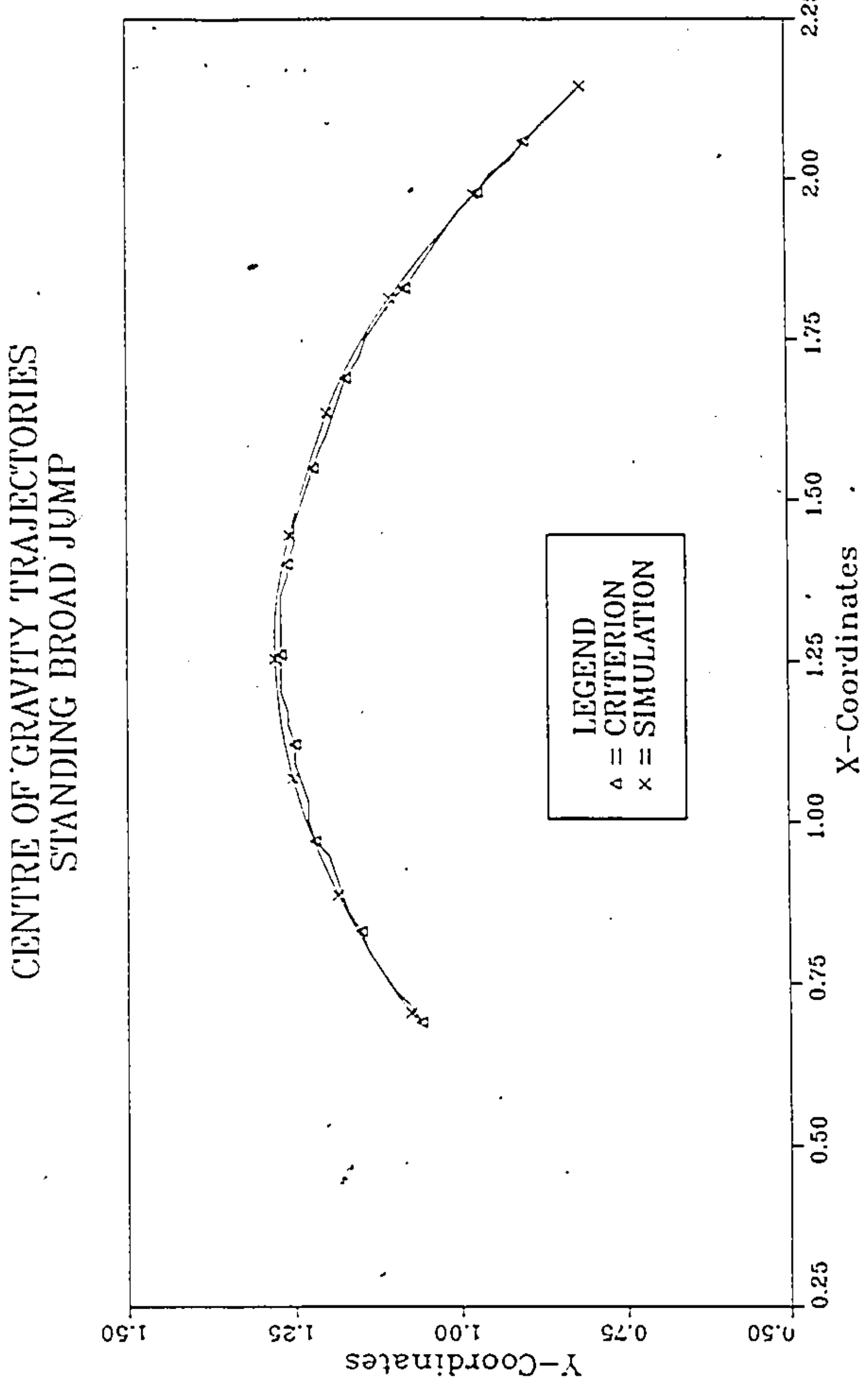

Figure 15: SIMULATION AND CRITERION CENTRES OF GRAVITY - STANDING JUMP

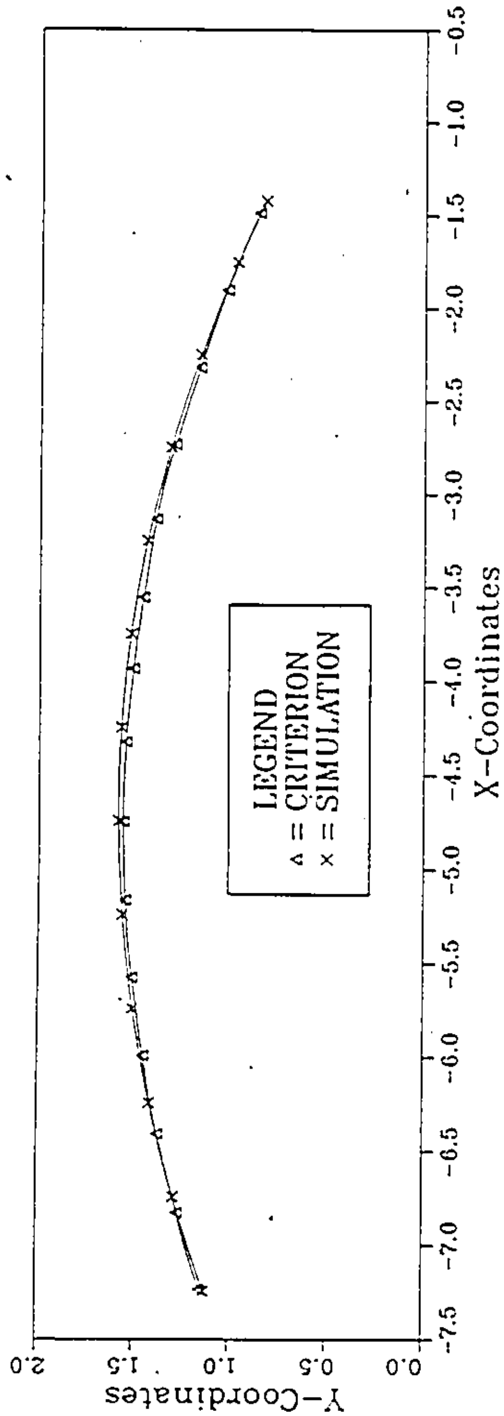

Figure 20: SIMULATION AND CRITERION CENTRES OF GRAVITY - LONG JUMP

Appendix C

FIGURES OF SIMULATION AND CRITERION TOTAL BODY MOTION

1. Layout dive - criterion
2. Layout dive - simulation
3. Front 3.5 tuck dive - criterion
4. Front 3.5 tuck dive - simulation
5. Reverse 2.5 pike dive - criterion
6. Reverse 2.5 pike dive - simulation
7. Front somersault - criterion
8. Front somersault - simulation
9. Dive front roll - criterion
10. Dive front roll - simulation
11. Standing long jump - criterion
12. Standing long jump - simulation
13. Long jump - criterion
14. Long jump - simulation

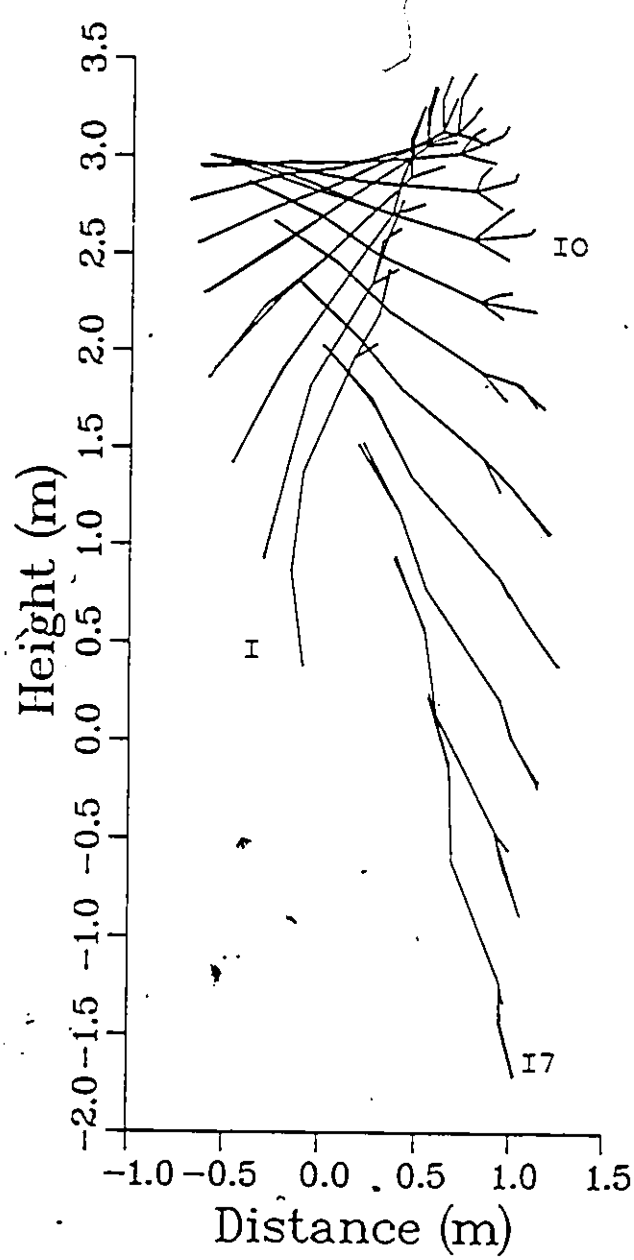

Figure 21: LAYOUT DIVE - CRITERION

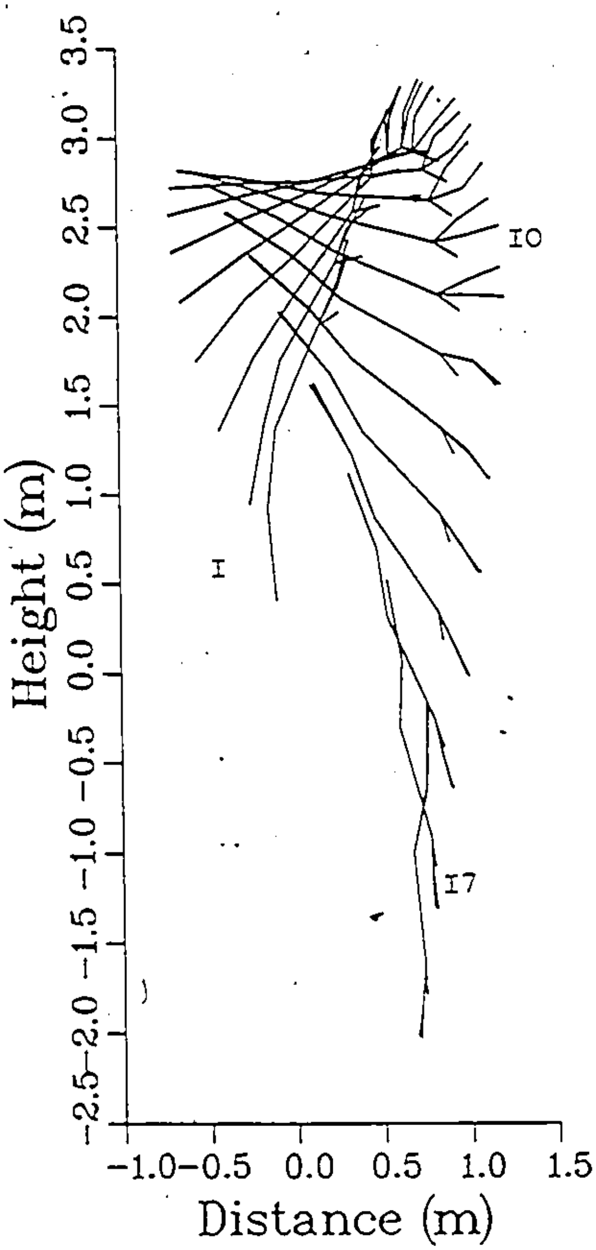

Figure 22: LAYOUT DIVE - SIMULATION

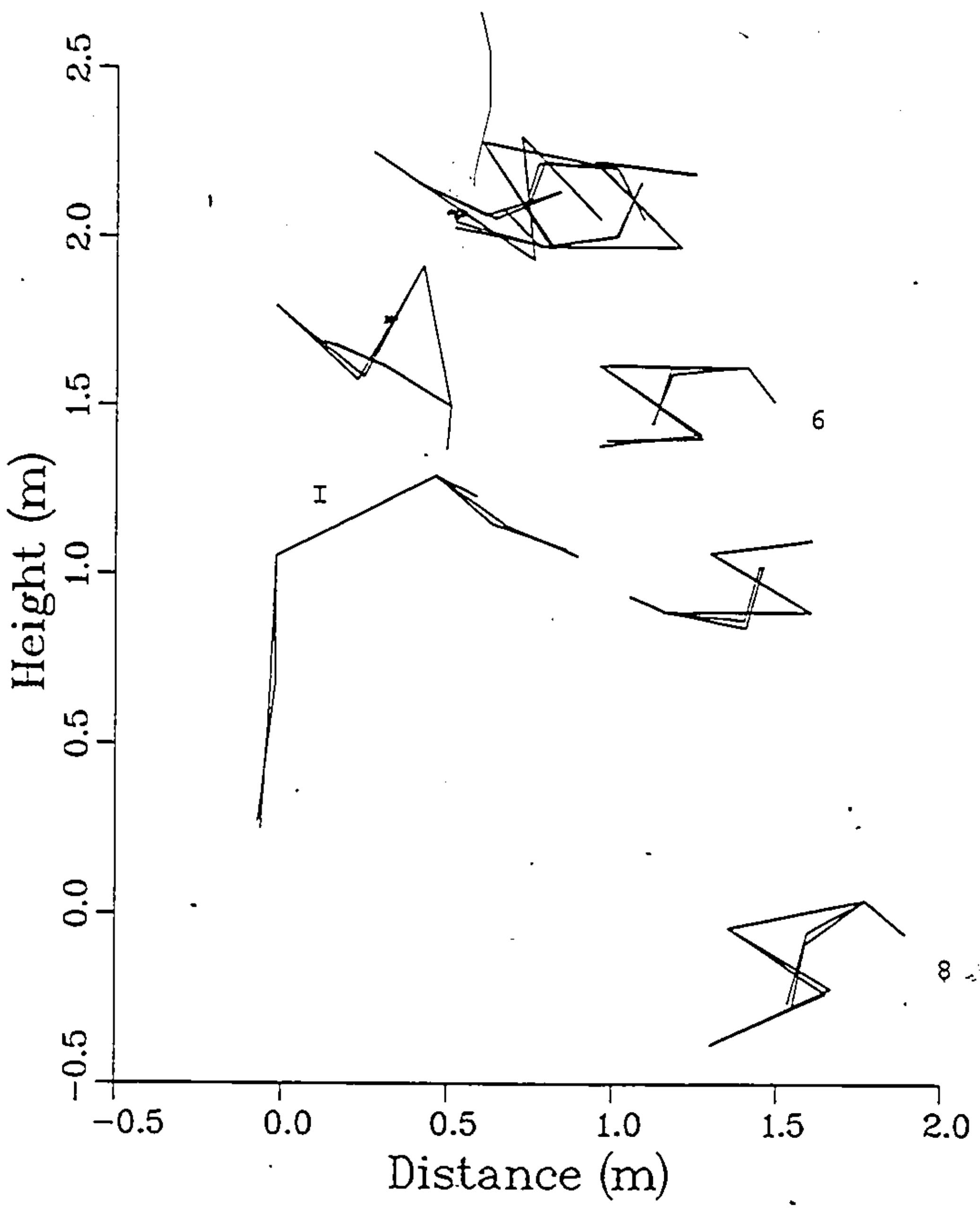

Figure 23: FRONT 3.5 TUCK DIVE - CRITERION

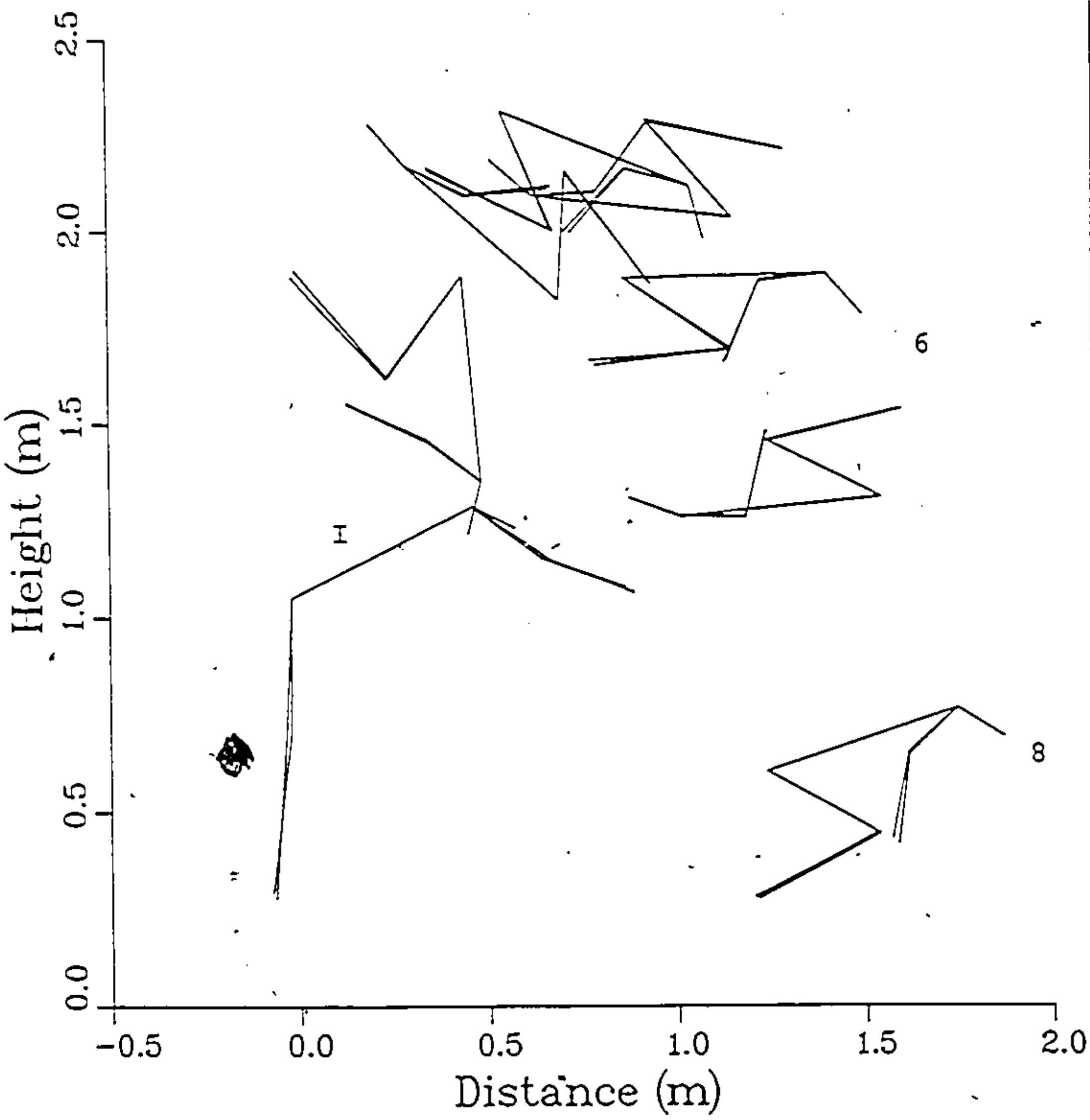

Figure 24: FRONT 3.5 TUCK DIVE - SIMULATION

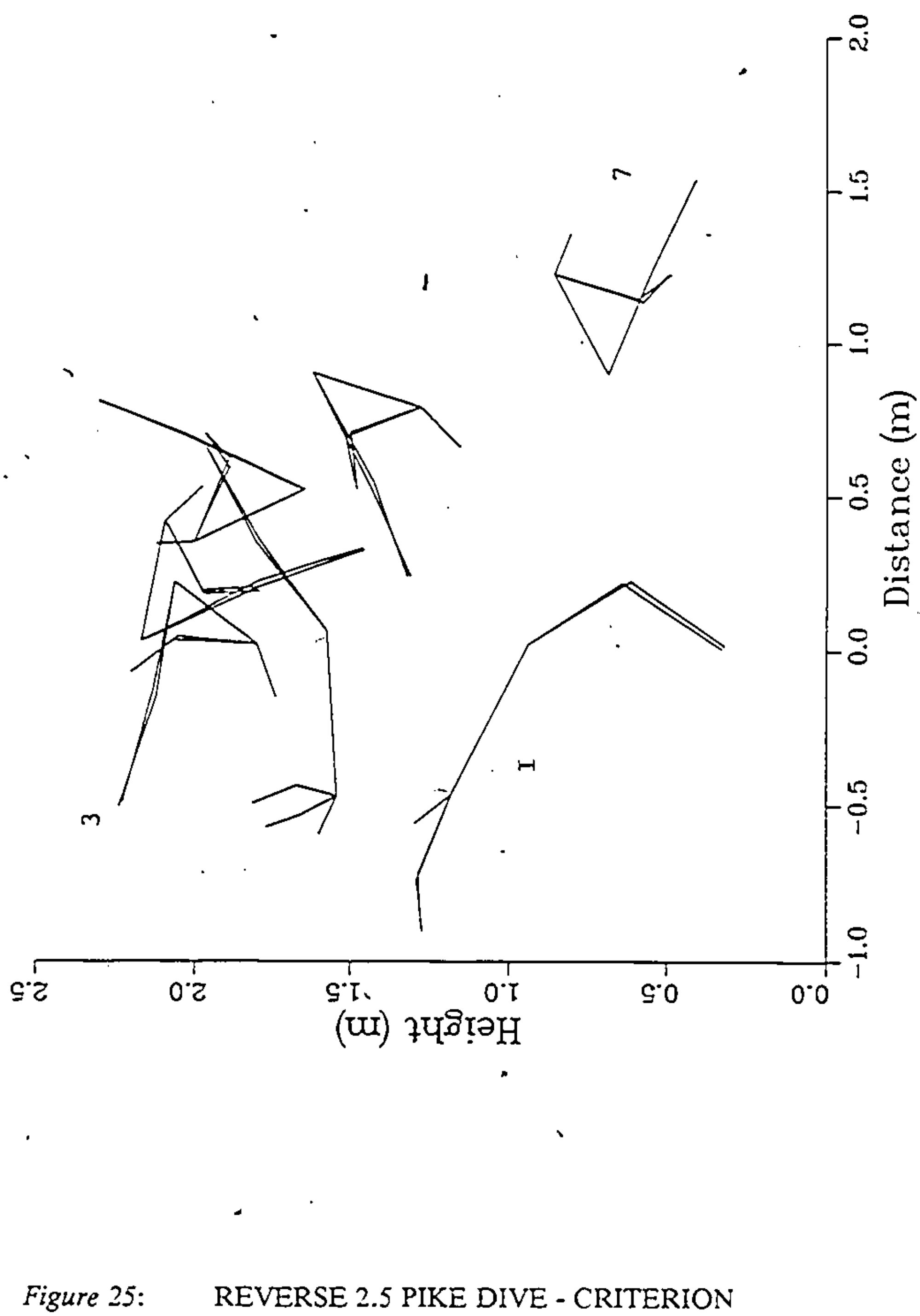

Figure 25: REVERSE 2.5 PIKE DIVE - CRITERION

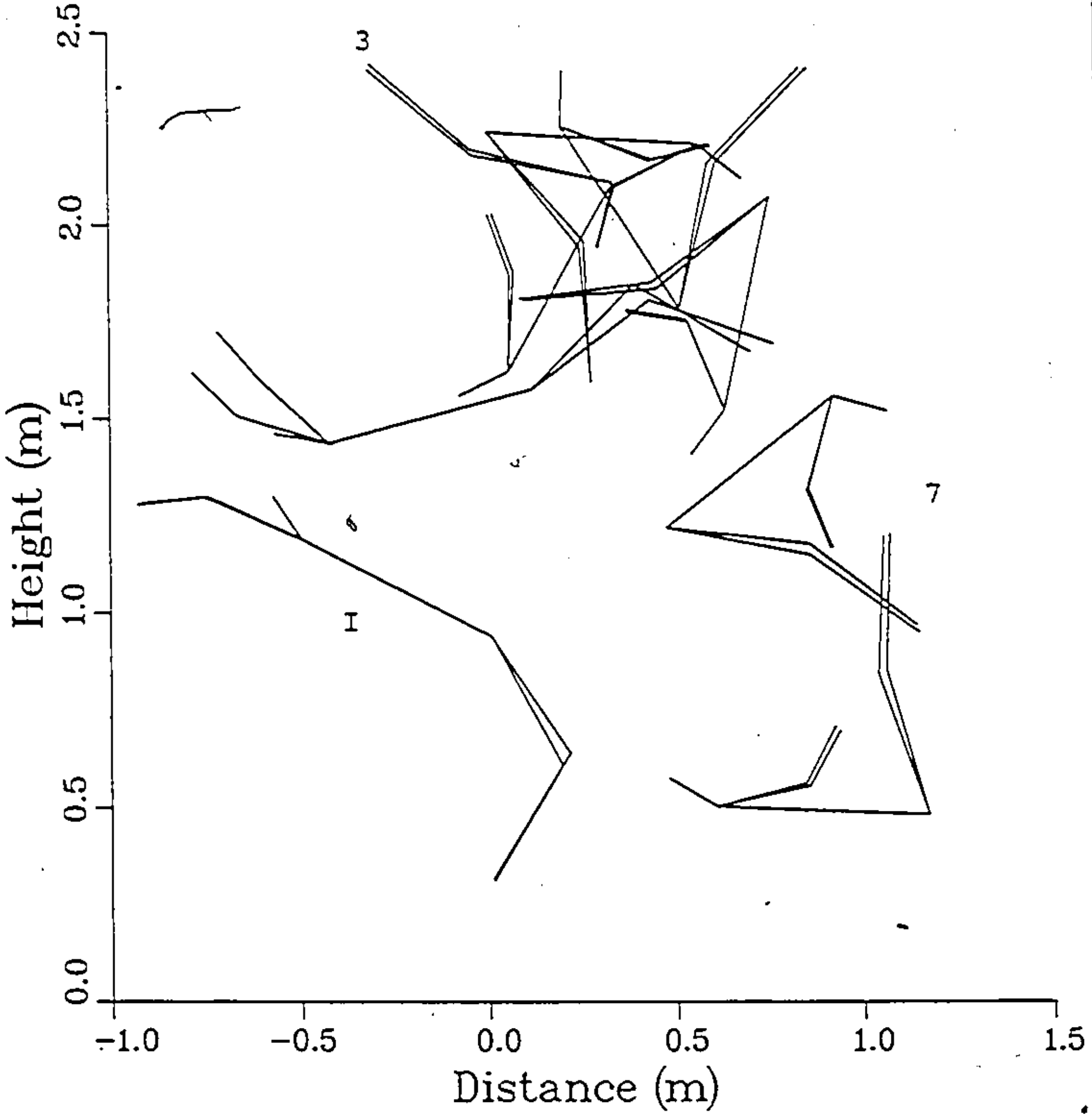

Figure 26: REVERSE 2.5 PIKE DIVE - SIMULATION

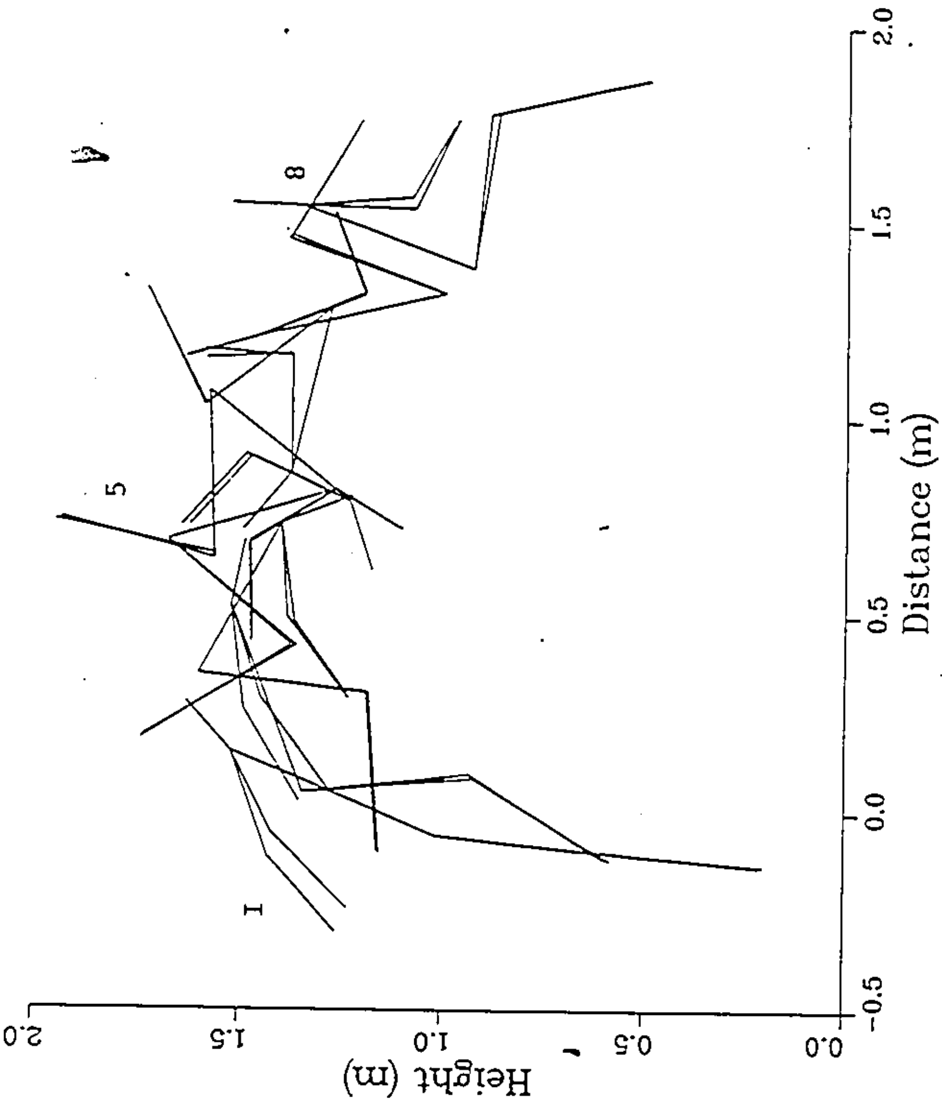

Figure 27: FRONT SOMERSAULT - CRITERION

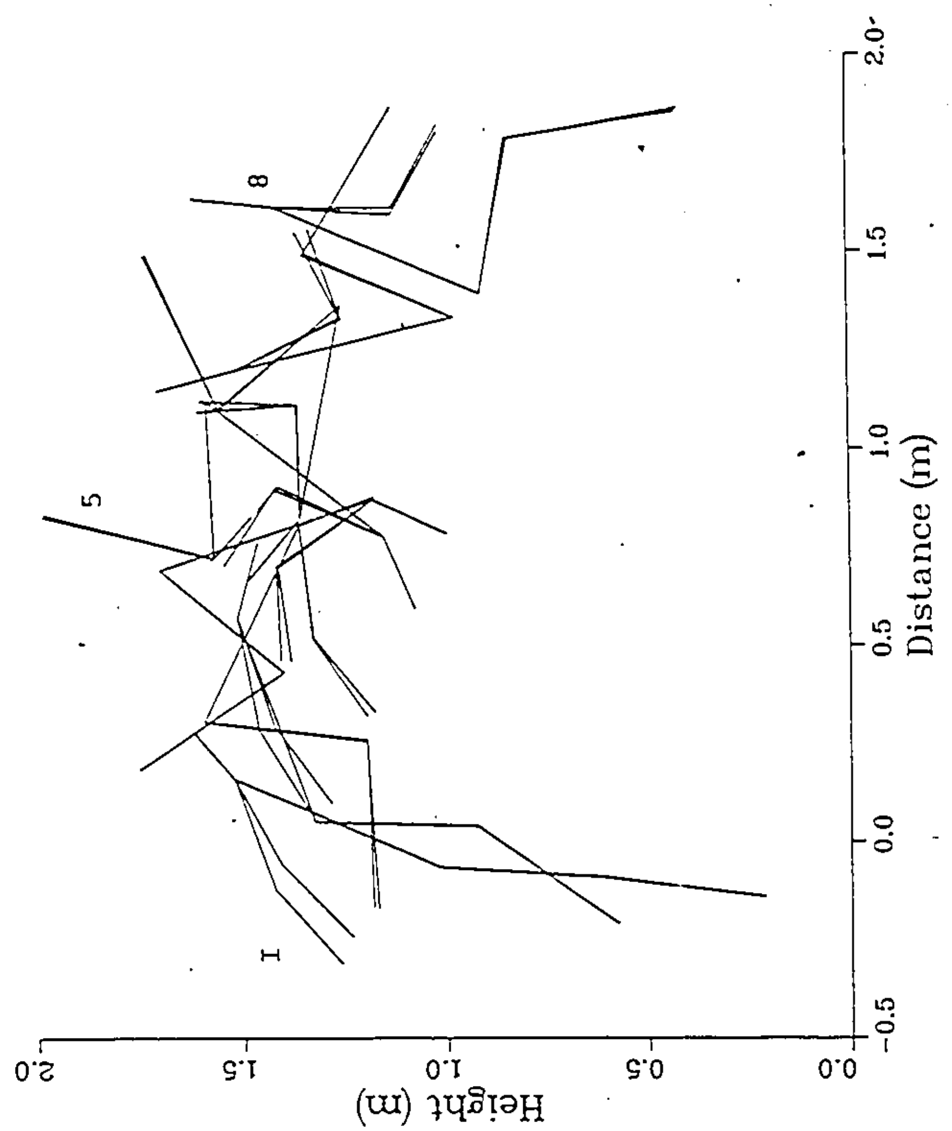

Figure 28: FRONT SOMERSAULT - SIMULATION

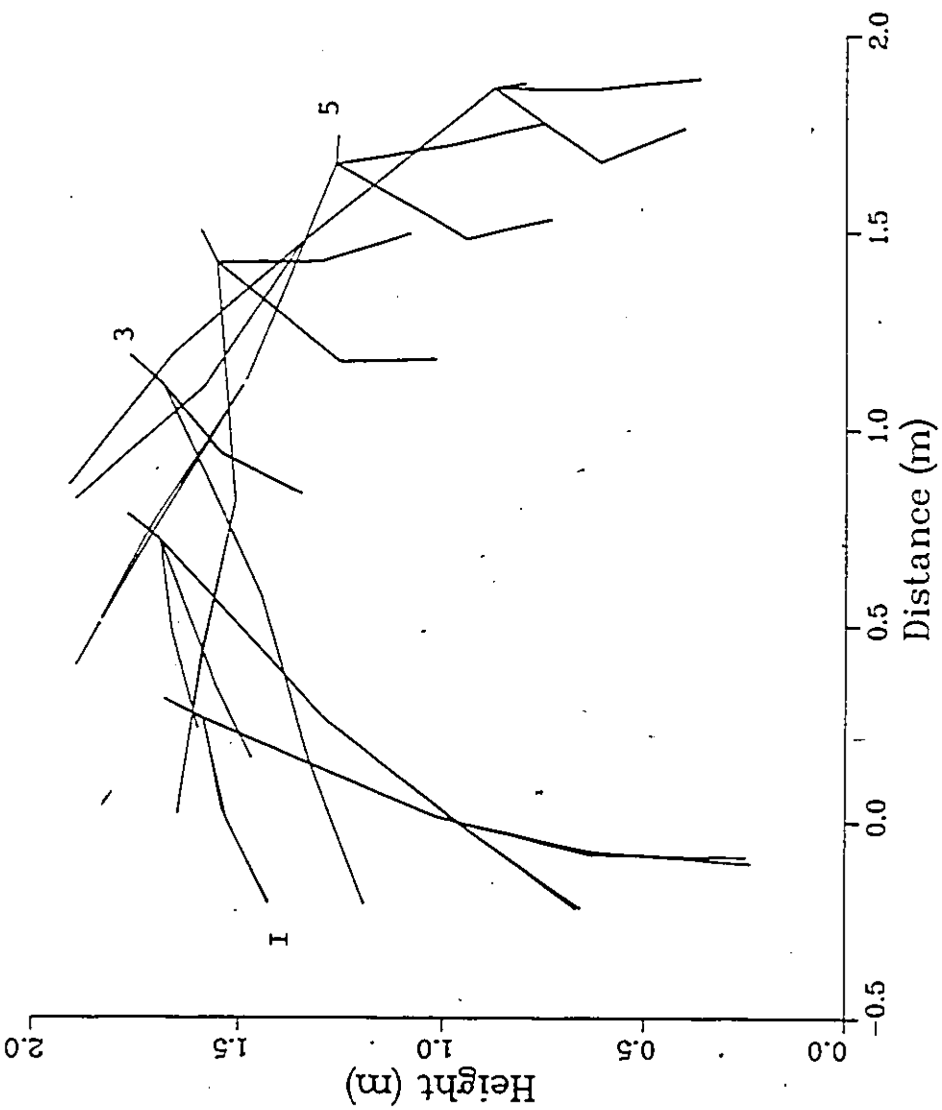

Figure 29: DIVE FRONT ROLL - CRITERION

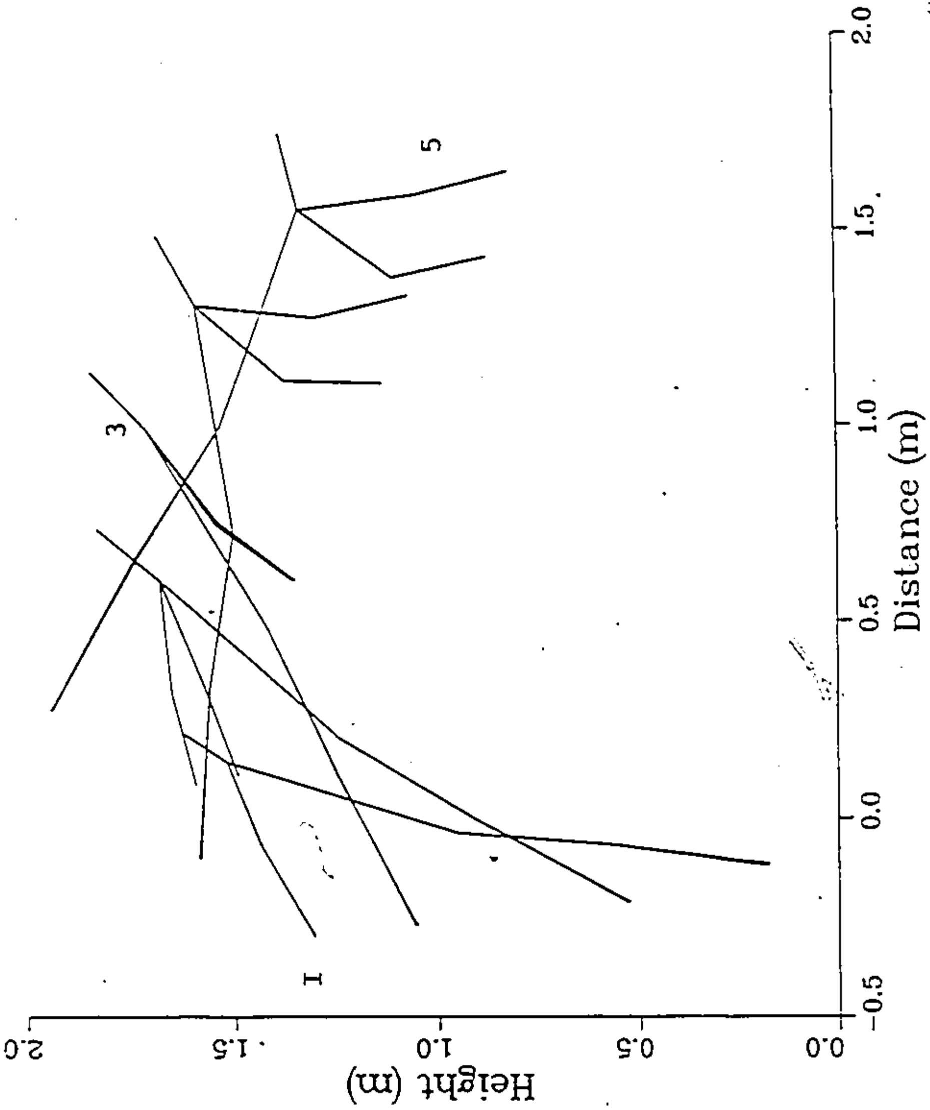

Figure 30: DIVE FRONT ROLL - SIMULATION

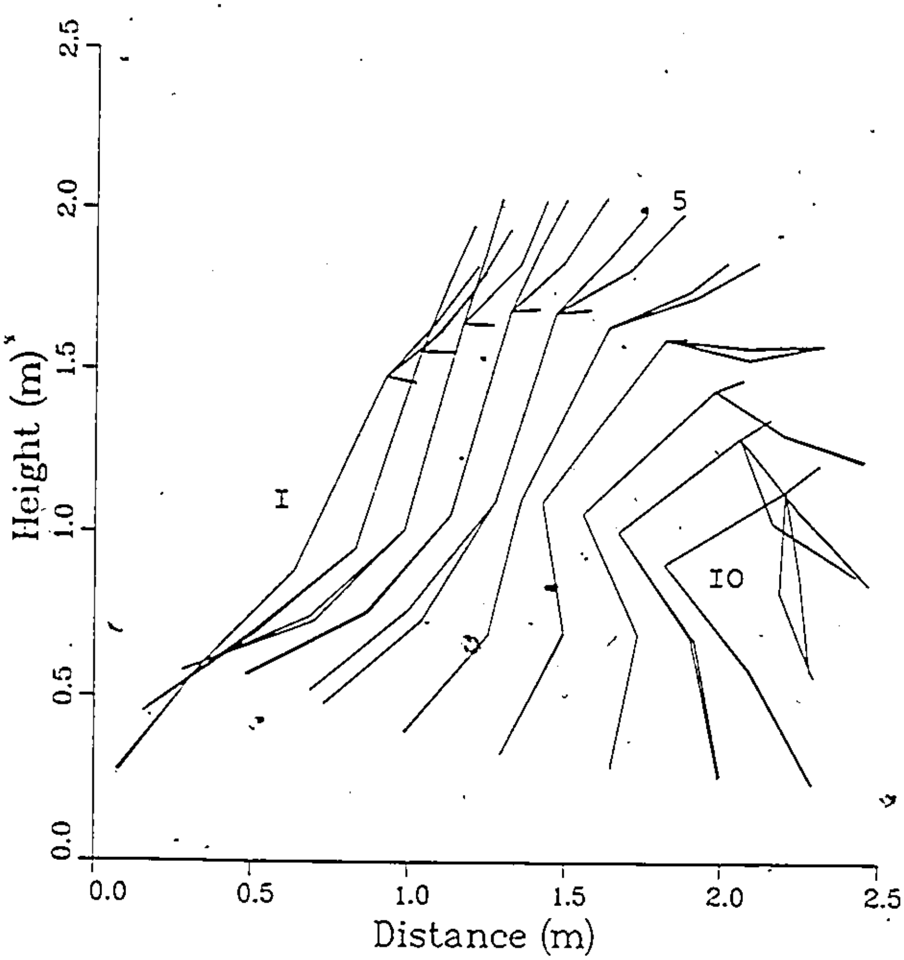

Figure 31: STANDING BROAD JUMP - CRITERION

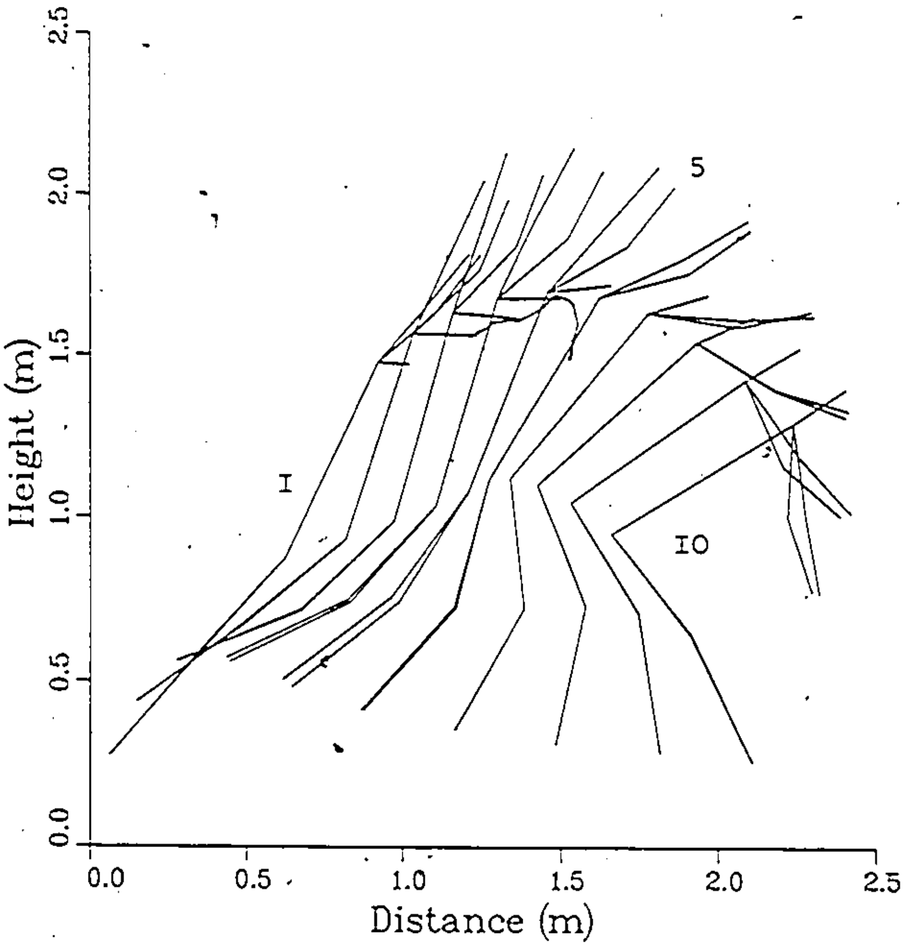

Figure 32: STANDING BROAD JUMP - SIMULATION

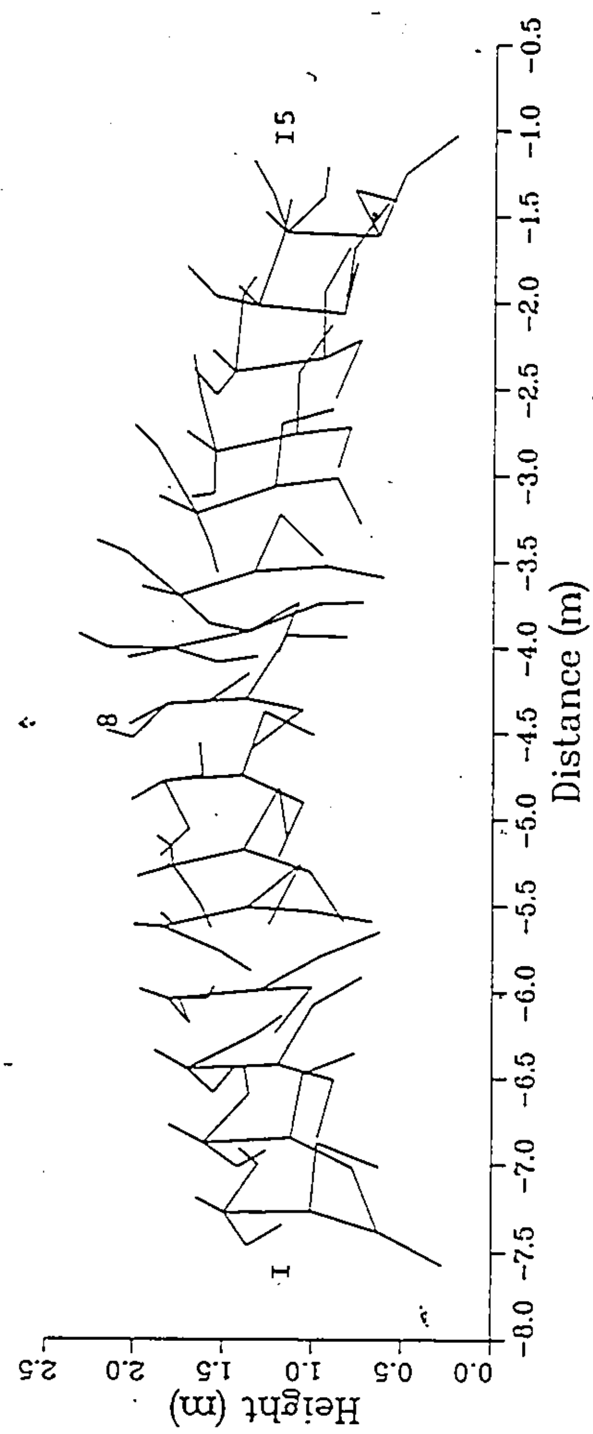

Figure 33: LONG JUMP - CRITERION

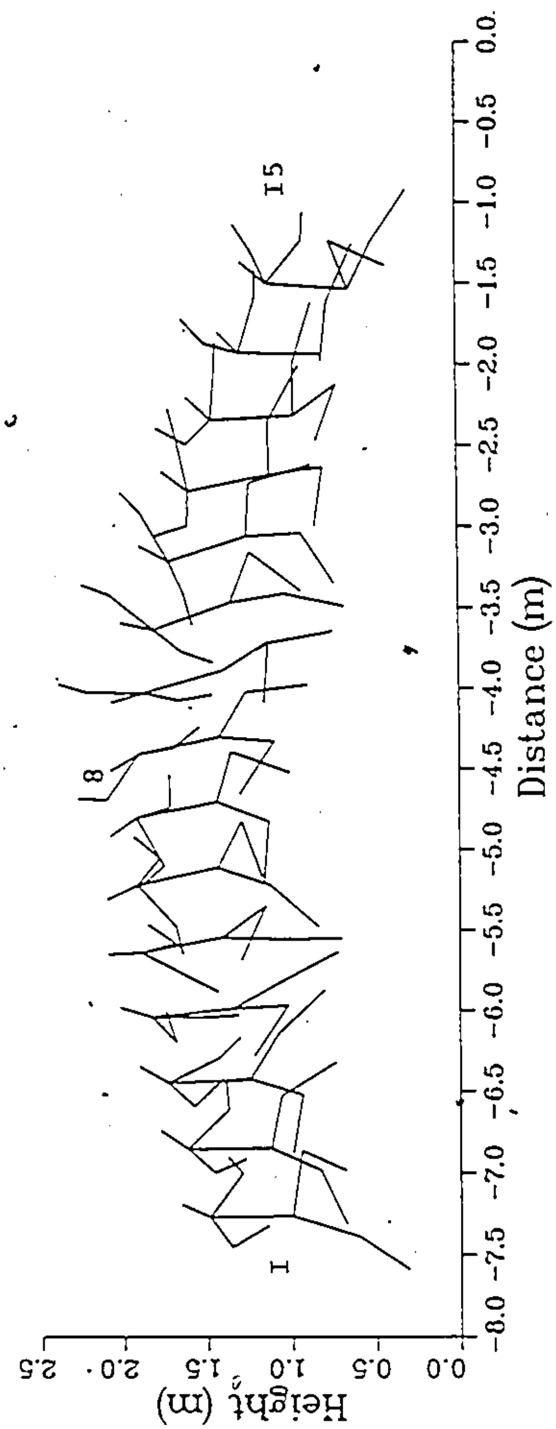

Figure 34: LONG JUMP - SIMULATION

Appendix D

SIMULATION EQUATIONS

Moments of Momentum

$\underline{M}_i = m_i (\underline{D}_i \times (\underline{V}_i + (\underline{D}_i \times \underline{\omega}_1))$ where,

$\underline{M}_i$ = segment moment of momentum
m_i = segment mass
$\underline{D}_i$ = vector joining the centre of gravity of the segment and the centre of gravity of the total body
$\underline{V}_i$ = first derivative of Di (linear velocity of the segment centre of gravity)
$\underline{\omega}_1$ = the angular velocity of the trunk

Segment Angular Momentum

$H_i = I_i (\omega_1 + \omega_{i/1})$ where,

H_i = segment angular momentum about an axis through the segment's centre of gravity
I_i = segment moment of inertia about an axis through the segment's centre of gravity
$\omega_{i/1}$ = segment angular velocity relative to the trunk
ω_1 = trunk angular velocity

Total Body Angular Momentum

$$H_t = \sum_{i=1}^{11} |\underline{M}_i| + \sum_{i=1}^{11} H_i \quad \text{where,}$$

H_t = total body angular momentum about an axis through the total body centre of gravity
$\underline{M}_i$ = segment moment of momentum
H_i = segment angular momentum about an axis through the segment's centre of gravity

Angular Momentum for the Trunk

$$H_1 = H_t - \sum_{i=1}^{11} |\underline{M}_i| - \sum_{i=2}^{11} H_i \quad \text{where;}$$

H_1 = angular momentum for the trunk about an axis
through the trunk's centre of gravity
H_t = total body angular momentum about an axis through the total body centre of gravity
$\underline{M}_i$ = segment moment of momentum
H_i = segment angular momentum (excluding trunk) about an axis through the segment's centre of gravity

Angular Velocity of Trunk

$\omega_1 = H_1/I_t$ where,

ω_1 = trunk angular velocity about the total body centre of gravity
H_1 = trunk angular momentum about an axis through the trunk's centre of gravity
I_t = total body moment of inertia about an axis through the total body centre of gravity

Trunk Angle

$\theta_j = \omega_{1_j} t + \theta_{j-1}$ where,

θ_j = absolute angle for trunk at jth time interval
ω_{1_j} = angular velocity for trunk about the total body centre of gravity between j and j-1
t = time interval
θ_{j-1} = angle for trunk at previous time interval

Appendix E

PROGRAMME LISTING

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      SIMUL - AIRBORNE SIMULATION PROGRAM                C
C      COPYRIGHT 1987 ED LEMAIRE, D.G.E ROBERTSON         C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C   This program will simulate the airborne motion of a 10
C   segment human body.  You must have a DR, CF and SIMIN
C   file to run this program.
C
C
      BLOCK DATA
C     This block data subroutine initializes the proportions that
C     are used to compute the segmental parameters. These values
C     have been taken from Patterns of Human Movment by S. Plagenhoef.
C     'POFSL' Gives the location of the segment centre of gravity as a
C        fraction of the segment length from the proximal end point.
C     'POFBW' Gives the segment's weight relative to the total body
C        weight.
C     'ROFGYR' Gives the radius of gyration as a fraction of the
C        segment's length.
C     'IPROX' Defines the ith segment's proximal end point's index
C        for the arrays x and y.
C        'IDIST' defines the ith segment's distal end point's index
C        for the arrays x and y.
C
C
        IMPLICIT REAL*8(A-H,O-Z)
      COMMON /PROPR/ POFSL(10),POFBW(10),ROFGYR(10),IPROX(10),IDIST(10)
C
C
      DATA POFSL/.495D0,0.0D0,.436D0,.682D0,.436D0,.682D0,
     +       .433D0,.606D0,.433D0,.606D0/
C
       DATA POFBW/.496D0,.079D0,.027D0,.022D0,.027D0,.022D0,
     +       .102D0,.0615D0,.102D0,.0615D0/
C
       DATA ROFGYR/.640D0,1.116D0,.542D0,.827D0,.542D0,.827D0
     +      ,.540D0,.735D0,.540D0,.735D0/
C
       DATA IPROX/1,2,2,4,2,6,1,8,1,10/
       DATA IDIST/2,3,4,5,6,7,8,9,10,11/
```

```
C
      END
C
C
C     'BETA' is the angle of the takeoff from the right horizontal
C        in degrees
C     'BW' is the body weight of the subject in newtons.
C     'COFGX' and 'COFGY' are the total body COFG coordinates (cm).
C     'DANGLE' are the changes in the relative angles of the segments.
C        They are in radians and must be less than pi.
C     'DCX' and 'DCY' define the amount of translation in meters per
C        time interval that the centre of gravity must travel.
C     'DEG' is pi/180. It is used to change radians to degrees.
C     'DT' is  the interval of time (sec.) between each body position.
C     'DX' and ''DY' define the position vectors from the total body
C        centre of gravity to the segment's centre of gravity.
C     'FACTOR' is the number of meters per input unit of x and y.
C     'G' is the gravitational acceleration constant (m/s*s)
C     'GL' is the ground level that the person takes off from. Note,
C        that when any point falls below this level the simulation
C        will stop.
C     'HT' is the height of the centre of gravity in meters at takeoff.
C       'IPLOT' tells the program the rate at which the figures will
C        be plotted. 1 means all, 2 means every second , etc.
C     'N' is the counter for the number of calculated COFG'S.
C     'OMEGA' are the angular velocities of the segments.
C     'SGANG' are the absolute angles of the segments in radians.
C     'SGI' are the segment's moments of inertia in N-m.m.
C     'SGLEN' are the lengths of the segments in meters.
C     'SGMASS' are the segments masses in newtons.
C     'TBH' is the total body angular momentum which will be conserved
C        during the flight.
C     'TBI' is the total body moment of inertia.
C     'TBMASS' is the total body mass in N.
C     'THETA' is the rotation (radians) that the body undergoes.
C     'TIME' tells the time in seconds from the starting time 0.
C     'TITLE' is a descriptive title of the motion that is being
C        simulated. It will appear as the title of the plotted
C        figures (maximum of 52 characters).
C     'TMAX' is the maximum time that the body can be airborne for the
C        given conditions after this time the COFG is at ground
C        level.
C     'VR' is the resultant takeoff velocity in m/s.
C     'VCX' is the horizontal takeoff velocity in m/s.
C     'VCY' is the vertical takeoff velocity.
C     'X' and 'Y' define the segment end point coordinates
C        which are in arbitrary units.
C
C
C
C
C
C
C
```

```
C
C-----------------------------------------------------------------------
C
C     This is the start of the main program
C
C-----------------------------------------------------------------------
C
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 DX0(10),DY0(10), DX1(10),DY1(10),DX2(10),DY2(10),TEMPD
      REAL*8 DANGLE(9), OMEGA(10),SA1(9),SA2(9),X1(11),Y1(11)
      REAL*4 XS,YX,XH,XL,YH,YL,PCGX(150),PCGY(150),GL,YESNO
      INTEGER SIMIN
      CHARACTER TITLE*52,CHAR
      COMMON/ORIENT/COFGX(150),COFGY(150),GX(10),GY(10),X(11),Y(11),N
      COMMON/PARMS/SGLEN(10),SGMASS(10),SGANG(10),SGI(10),BW,TBMASS
      COMMON/PROPR/POFSL(10),POFBW(10),ROFGYR(10),IPROX(10),IDIST(10)
      DATA G/9.81D0/,DEG/57.2958D0/,PI/3.1415926D0/,PI2/6.2831852D0/
      IN=4
      SIMIN=5
C     -----'In' gives the unit number of the input file.
      REWIND 5
      REWIND 4
      REWIND 2
C  -----  Unit 4 will store the body coordinates that will be plotted.
C         Read in the required parameters for the simulation.
C
C
      READ(SIMIN,*) TITLE,VR,BETA,DT,BW,FACTOR,GL,IPLOT,TBH,YESNO
      TBMASS =BW/G
      TIME =0.
C  -----  Read in body orientation at takeoff
      READ(SIMIN,*) X
      READ(SIMIN,*) Y
C  -----  Convert all input units to meters before starting.
      DO 10 I=1,11
      X(I)=X(I)*FACTOR
      Y(I)=Y(I)*FACTOR
   10 CONTINUE
      GL=GL*FACTOR
C  -----  Read in segment lengths.
      READ(SIMIN,*) SGLEN
C  -----  Determine the vertical and horizontal components of the
C         takeoff velocity.
      VCX = VR*DCOS(BETA/DEG)
      VCY = VR* DSIN (BETA/DEG)
      PRINT 102,VR, BETA, VCX, VCY, DT, BW, TBH
      PRINT 103, TITLE
      N=1
C  -----  Calculate centre of gravity of the initial body position.
C
      CALL COFG (DX0,DY0)
C
C  -----  Determine the segmental parameters.
C
```

```
      CALL SGPARM
C
C  -----  Store the initial trunk angle.
      TANGLE = SGANG(1)
C  -----  Calculate the total body moment of inertia.
      TBI = 0.
      DO 20 I=1,10
   20 TBI=TBI+SGI(I)+SGMASS(I)*(DX0(I)**2+DY0(I)**2)
C
      CHAR = '*'
      DTHETA = 0D0
      PRINT 104,N,COFGX(N),COFGY(N),TBI,TIME,DTHETA,SGANG(1)*DEG
C  -----  Store the initial position of the centre of gravity.
      CGX = COFGX(1)
      DCGX = VCX*DT
      HT = COFGY(1)
C  -----  Find the maximum time that the body can be airborne.
      TMAX = (VCY/G)+ DSQRT((2*(((VCY*VCY)/(2*G))-GL))/G)
      MAXN=TMAX/DT+0.5
      MAXN=MIN0(150,MAXN)
C
C  -----  Save the initial segment angles which will be needed later.
      WRITE (2) SGANG
C  -----  Convert coordinates to centimetres.
      DO 43 J=1,11
      X(J)=X(J)*100.
      Y(J)=Y(J)*100.
   43 CONTINUE
C  -----  Write initial orientation to -.CN file.
      WRITE (7,143) (X(I),Y(I),I=1,11),N
C  -----  Convert coordinates to metres.
      DO 44 J=1,11
      X(J)=X(J)*0.01
      Y(J)=Y(J)*0.01
   44 CONTINUE
C
C=========================================================================
C
      DO 200 IPHASE=1,MAXN
C
C  -----  Read in the changes in relative angles.
      READ(IN,101,END=201) DANGLE
C
C  -----  If necessary, copy the segments to the contralateral side.
C     IF(YESNO.NE.1) GO TO 163
C
C     DANGLE(9)=DANGLE(5)
C     DANGLE(8)=DANGLE(4)
C     DANGLE(7)=DANGLE(5)
C     DANGLE(6)=DANGLE(4)
C     DANGLE(5)=DANGLE(3)
C     DANGLE(4)=DANGLE(2)
C
C
```

```
C  -----  Modify the relative body position to correspond with the
C         given relative angular displacements.
C
C  -----  Change the position of the head-neck segment
  163 SA=SGANG(2)+DANGLE(1)
      X(3) = X(2)+SGLEN(2)*DCOS(SA)
      Y(3) = Y(2)+SGLEN(2)*DSIN(SA)
C
C
C  -----  Change the position of the right upper limb.
      CALL MVLIMB (1.D0,3,2,4,DANGLE)
C  -----  Change the position of the left upper limb.
      CALL MVLIMB (1.D0,5,2,6,DANGLE)
C  -----  Change the position of the right lower limb
      CALL MVLIMB (1.D0,7,1,8,DANGLE)
C  -----  Change the position of the left lower limb.
      CALL MVLIMB (1.D0,9,1,10,DANGLE)
C  -----  Find the position vectors of the modified body.
C
C

      N=N+1
C
C  -----  Calculate the new centre of gravity location.
C
      CALL COFG (DX1,DY1)
C
C  -----  Calculate the new absolute segment angles.
      DO 190 I=2,10
       IP=IPROX(I)
       ID=IDIST(I)
       IF (((Y(ID)-Y(IP)).EQ.0.).AND.((X(ID)-X(IP)).EQ.0.)) THEN
         SGANG(I)= 0.0
         PRINT*,'THE POINT MASS, SGANG=0, PORTION HAS BEEN ENTERED'
        ELSE
         SGANG(I) = DATAN2(Y(ID)-Y(IP),X(ID)-X(IP))
       ENDIF
  190 CONTINUE
C
C  -----  Write COFG, marker position, and absolute angles to a
C         file for re-reading.
      WRITE (2) N,DX1,DY1,X,Y,(SGANG(I),I=2,10)
  200 CONTINUE
C
C
C     This section will reread the contents of unit 2 in order
C     to calculate the angular velocities of the segments and the
C     moment arms of each segment's COFG.
C
  201 ENDFILE 2
C
C-----------------------------------------------------------------------
C
      REWIND 2
      READ(2) SGANG
```

```
      READ(2) N,DX1,DY1,X,Y,SA1
      DT2 = DT+DT
      MAXN = MIN0(MAXN,IPHASE-2)
C
      DO 500 IPHASE=1,MAXN
      READ(2) N1,DX2, DY2, X1,Y1,SA2
      N = N1-1
      CHAR = ' '
C  -----  Sum up each segment's moment of momentum term.
      SUMOFM = 0.
      TBI = 0.
       DO 220 I=1,10
        VX = (DX2(I)-DX0(I))/DT2
        VY = (DY2(I)-DY0(I))/DT2
        SUMOFM = SUMOFM+SGMASS(I)*(DX1(I)*VY-DY1(I)*VX)
C  -----  Calculate the total body moment of inertia.
        TBI=TBI+SGI(I)+SGMASS(I)*(DX1(I)**2+DY1(I)**2)
        DX0(I) =DX1(I)
        DX1(I) =DX2(I)
        DY0(I) =DY1(I)
        DY1(I) =DY2(I)
 220   CONTINUE
C  -----  Compute sum of segmental angular momenta and velocity.
       SUMOFH =0D0
       DO 230 I=2,10
        IM1=I-1
C  -----  DA is the change in angle of each segment with respect to
C         the trunk angle.
        DA=SA2(IM1)-SGANG(I)
        IF(DA.GT.PI) GO TO 224
        IF(DA.LT.-PI) GO TO 223
        GO TO 225
  223   DA=DA+PI2
        GO TO 225
  224   DA=DA-PI2
C  -----  Calculate the segment's angular velocity (OMEGA(I)).
  225   OMEGA(I) = DA/DT2
C  -----  Sum up each segment's angular momentum (except the trunk's).
        SUMOFH = SUMOFH+OMEGA(I)*SGI(I)
        SGANG(I) = SA1(IM1)
        SA1(IM1) = SA2(IM1)
  230  CONTINUE
C  -----  Determine the trunk's angular velocity (OMEGA(1)).
      IF(SGI(1).EQ.0.) GO TO 233
C     OMEGA(1) = ((TBH-SUMOFH-SUMOFM)/SGI(1))
      OMEGA(1) = ((TBH-SUMOFH-SUMOFM)/TBI)
C
C  -----  Calculate the change in trunk angle (DTHETA)
  233 DTHETA = OMEGA(1)*DT
C  -----  Calculate the new trunk angle (SGANG(1)).
      SGANG(1) = SGANG(1)+DTHETA
      DTHETA = DTHETA*DEG
C  ----- Calculate THETA (the angle that the stored coordinates
C        will be rotated through (in radians)).
```

```
      THETA = SGANG(1) - TANGLE
C
C
C  -----  Translate the body to its next centre of
C         gravity location.
C
C
      TIME - TIME + DT
      DCX = COFGX(N)
      DCY = COFGY(N)
C  -----  Calculate and store the COFG coordinates in ' COFGX' and
C          'COFGY'.
C
      CGX = CGX + DCGX
      COFGX(N) = CGX
      COFGY(N) = HT + TIME*(VCY-TIME*(G/2.))
C
      DCX = COFGX(N)-DCX
      DCY = COFGY(N)-DCY
C  -----  Translate the coordinates a distance 'DCX,DCY'.
      DO 250 I=1, 11
      X(I) = X(I) + DCX
      Y(I) = Y(I) + DCY
 250    CONTINUE
C  -----  Calculate the total body moment of inertia.
      TBI=0.
      DO 310 I=1,10
      TBI = TBI+SGI(I)+SGMASS(I)*(DX1(I)**2+DY1(I)**2)
 310  CONTINUE
C
C  -----  Rotate the body through 'THETA' radians.
C
      CALL ROTATE(THETA)
C
C  -----  Convert coordinates to centimeters
      DO 73 J=1,11
      X(J)=X(J)*100
      Y(J)=Y(J)*100
  73  CONTINUE
C  -----  Write final orientation to CN file
      WRITE (7,143) (X(I),Y(I),I=1,11),N
 143  FORMAT (12F6.1/10F6.1,T78,I3)
C  -----  Convert coordinates to meters
      DO 74 J=1,11
      X(J)=X(J)*.01
      Y(J)=Y(J)*.01
  74  CONTINUE
C  -----  Test for a landing.
      DO 410 I=1,11
 410  IF (Y(I).LT.GL) GO TO 509
      CHAR = '#'
C  -----  Write final results to output file.
      PRINT 104,N,COFGX(N),COFGY(N),TBI,TIME,DTHETA,SGANG(1)*DEG
      DO 495 I=1,11
```

```
      X(I)=X1(I)
  495 Y(I)=Y1(I)
C
  500 CONTINUE
C
      PRINT*,'THE TIME IN AIR IS',TMAX,'AND THE # DIVISIONS IS',MAXN
      PRINT*,'NO LANDING HAS OCCURRED. MAXIMUM OF 150 TIME INTERVALS.'
      GO TO 510
  509 PRINT*,' >>>>>>> LANDING <<<<<<<'
      CHAR = '
      PRINT 104,N,COFGX(N),COFGY(N),TBI,TIME,DTHETA,SGANG(1)*DEG
      PRINT*,'THE TIME IN AIR IS',TMAX,'AND THE # DIVISIONS IS',MAXN
C
  510 IF(YESNO.EQ.99999999)THEN
      GOTO 999
      ENDIF
  199 FORMAT ('1'/10(' >>>>  END OF SIMULATION  <<<<'//))
  999 STOP
  990   PRINT*,'     ERROR WHILE IN S/R  STICK2, ATTEMPT ANOTHER RUN'
      GO TO 999
C
C     FORMAT STATEMENTS
C
C
  101 FORMAT ( 9F8.5)
  102 FORMAT('1','  THE TAKEOFF VELOCITY IS',F8.4,' m/s',
     1 F7.2,' deg.'/'  THE HORIZONTAL AND VERTICAL VELOCITIES ARE'
     2 ,2F8.4,' m/s.'/    '  THE TIME INCREMENT IS ', F8.5,' s.
     3 '/ '  THE SUBJECT WEIGHS  ', F6.2,' kg',
     4 '  AND HAS AN ANGULAR MOMENTUM OF ',F7.2,' kg.m.m/s.'//)
  103 FORMAT (10X,A52//T5,'N',T13,'COFGX',T23,'COFGY',T34,'TBI',
     1  T43,'TIME', T53,'THETA',T61,'TRUNK ANGLE'/  T15,'m',T25,
     2  'm',T32,'kg.m.m',T44,'s',  T54,'deg',  T65, 'deg'//)
  104 FORMAT (' ',I4,2X,  2(3X,F7.3),4X,F6.3,T41,F8.5,3X,F7.2,
     1  T63,F7.1)
  105 FORMAT (/5F8.5)
  120 FORMAT (I3,3X,11(F6.3,1X,F6.3,3X))
        END

       SUBROUTINE COFG (DX,DY)

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      This subroutine calculates the total body and                  C
C      segmental centres of gravity. These are then stored in a       C
C      common block. After the total body centre of gravity is        C
C      calculated the position vectors joining the segmental and      C
C      total body centres of gravity are computed. The values are     C
C      then passed back as "DX" and "DY". The input units are         C
C      assumed to be meters                                           C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      IMPLICIT REAL*8(A-H,O-Z)
C
      COMMON/ORIENT/COFGX(150),COFGY(150),GX(10),GY(10),X(11),Y(11),N
```

```
      COMMON/PARMS/SGLEN(10),SGMASS(10),SGANG(10),SGI(10),BW,TBMASS
      COMMON/PROPR/POFSL(10),POFBW(10),ROFGYR(10),IPROX(10),IDIST(10)
      REAL*8 DX(10),DY(10)
      SUMX = 0D0
      SUMY = 0D0
C
      DO 20 I=1,10
C ------ Calculate the segmental centres of gravity.
      IP = IPROX (I)
      ID = IDIST (I)
      GX(I) = (X(ID)-X(IP))* POFSL(I) + X(IP)
      GY(I) = (Y(ID)-Y(IP))* POFSL(I) + Y(IP)
C ------ Take moments and sum to find the total body COFG.
      SUMX = SUMX + GX(I) * POFBW(I)
      SUMY = SUMY + GY(I) * POFBW(I)
   20 CONTINUE
C
C ------ Compute the position vectors of each segment.
      DO 30 I=1,10
      DX(I) = (GX(I)-SUMX)
      DY(I) = (GY(I)-SUMY)
   30 CONTINUE
C
C ------ Assign the COFG to arrays "COGX" and "COFGY".
      COFGX(N) = SUMX
      COFGY(N) = SUMY
C
      RETURN
      END
      SUBROUTINE SGPARM
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     This subroutine must be called after the segment centres of     C
C     gravity are computed. It will then find the segment masses,     C
C     lengths, and moments of inertia. The total body weight in N     C
C     be stored in "BW" so that the total body mass can be            C
C     determined. All calculated values are stored in the appropriate C
C     common block for use by other program segments.                 C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
      INTEGER FB
C ------ Common blocks
      COMMON/ORIENT/COFGX(150),COFGY(150),GX(10),GY(10),X(11),Y(11),N
      COMMON/PROPR/POFSL(10),POFBW(10),ROFGYR(10),IPROX(10),IDIST(10)
      COMMON/PARMS/SGLEN(10),SGMASS(10),SGANG(10),SGI(10),BW,TBMASS
C
      FB=0
C
      DO 20 I=1,10
C
C ------ Compute segment mass from proportions and total body mass.
      SGMASS(I) = POFBW(I)*TBMASS
      IP = IPROX(I)
```

```
      ID = IDIST(I)
      RUN  = X(ID) - X(IP)
      RISE = Y(ID) - Y(IP)
C
C  -----  Compute segment length from input configuration.
C     SGLEN(I) = DSQRT(RISE**2 + RUN**2)
C
      IF ((RUN.EQ.0).AND.(RISE.EQ.0)) THEN
        FB=1
        SGANG(I) = 0.0
       ELSE
        SGANG(I) = DATAN2(RISE,RUN)
      ENDIF
C  ------  Compute I about segment centre using parallel axis theorem.
      RSQRD = (SGLEN(I)*POFSL(I))**2
      SGI(I)= SGMASS(I) * ((ROFGYR(I) * SGLEN(I))** 2 - RSQRD)
   20 CONTINUE
C
      IF (FB.EQ.1) THEN
        PRINT*,'POINT MASS WAS USED, SGANG SET TO 0.'
      ENDIF
C
      RETURN
      END
              SUBROUTINE ROTATE (THETA)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     This subroutine rotates the body coordinates through an         C
C     angle of 'THETA' radians about the total body centre of         C
C     gravity.                                                        C
C     Note that the centre of gravity must be in its true location.  C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON/ORIENT/COFGX(150),COFGY(150),GX(10),GY(10),X(11),Y(11),N
C
      IF (THETA.EQ.0D0) GO TO 50
C  ------  Begin calculations to enable a rotation of the body about
C          its total centre of gravity.
C
      CX=COFGX(N)
      CY=COFGY(N)
      DO 40 I=1,11
      XPT=X(I)-CX
      YPT=Y(I)-CY
      SLEN= DSQRT(XPT*XPT+YPT*YPT)
C
      IF((YPT.EQ.0).AND.(XPT.EQ.0))THEN
      SANG=THETA
      ELSE
      SANG=DATAN2(YPT,XPT)+THETA
      ENDIF
C
      ISANG=SANG*57.2958D0
      IF(ISANG/180) 20,24,22
```

```
   20 SANG=SANG+6.283185D0
      GO TO 24
   22 SANG=SANG-6.283185D0
   24 CONTINUE
C  ------  Calculate the new coordinates after the rotation.
      X(I)=CX+SLEN*DCOS(SANG)
      Y(I)=CY+SLEN*DSIN(SANG)
   40 CONTINUE
   50 RETURN
      END
        SUBROUTINE MVLIMB (SIGN,IS,IP,ID,DANGLE)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     This subroutine is used to calculate the new position that       C
C     each segment will be in relation to the trunk. Only one system   C
C     of (i.e., right arm and forearm or left thigh and shank) limbs   C
C     can be moved per call to this routine                            C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      IMPLICIT REAL*8(A-H,O-Z)
C
C
      COMMON/ORIENT/COFGX(150),COFGY(150),GX(10),GY(10),X(11),Y(11),N
      COMMON/PARMS/SGLEN(10),SGMASS(10),SGANG(10),SGI(10),BW,TBMASS
        REAL*8 DANGLE(9)
C
C  ------  Move distal limb.
      IS1 = IS + 1
      ID1 = ID + 1
      SA1=SGANG(IS1)-(SIGN*DANGLE(IS))
      X(ID1) = X(ID) + SGLEN(IS1)*DCOS(SA1)
      Y(ID1) = Y(ID) + SGLEN(IS1)*DSIN(SA1)
C  ------  Move proximal limb.
      SA2 = SGANG(IS)+(SIGN*DANGLE(IS-1))
      X(ID) = X(IP) + SGLEN(IS)*DCOS(SA2)
      Y(ID) = Y(IP) + SGLEN(IS)*DSIN(SA2)
      RUN =  X(ID1) - X(IP)
      RISE = Y(ID1) - Y(IP)
      SLEN = DSQRT(RISE**2 + RUN**2)
C
C  ------  Move distal limb in relation to movement of proximal limb.
      IF((RISE.EQ.0).AND.(RUN.EQ.0)) THEN
      SA3 = SIGN*DANGLE(IS-1)
      PRINT*,'MVLIMB SUB. POINT MASS IF STATEMENT WAS REACHED'
      ELSE
      SA3 = DATAN2(RISE,RUN) + (SIGN*DANGLE(IS-1))
      ENDIF
      X(ID1) = X(IP) + SLEN * DCOS(SA3)
      Y(ID1) = Y(IP) + SLEN * DSIN(SA3)
      RETURN
      END
```

Appendix F

REVIEW OF LITERATURE

Angular Momentum

Angular momentum is a key factor in the successful simulation of human movement and in performing the movement itself (Ramey, 1973; Frohlich, 1980; Miller, 1970). Once a body has reached an airborne state the angular momentum possessed by the body will be conserved, assuming that the forces applied to the body are central forces, thereby limiting the ability to produce rotational motion (Stroup & Bushnell, 1969; Miller, 1970; Ramey, 1973; Frohlich, 1980; Sanders & Wilson, 1987; Sprigings, et.al, 1987).

Frohlich (1980) examined the concept of conservation of angular momentum in relation to somersaulting and twisting. It was stated that the magnitude and direction of angular momentum could be changed by a diver during the board contact phase but, once airborne, the angular momentum vector would not change. This conservation, though, was determined to be useful when examined in relation to moment of inertia and angular velocity. By changing the total body moment of inertia (i.e., tucking, putting the arms out, etc.) the angular velocity of the body would change inversely, thereby allowing for the variation of somersault speed in the air. The importance of angular momentum for divers, gymnasts and astronauts was also outlined.

Because of this importance it was necessary to examine techniques used in the determination of the body's angular momentum.

Hay and Wilson (1976) compared three techniques for the determination of angular momentum in the human body. The three methods examined were Miller (1970), Ramey (1973) and Hay and Wilson (1975). These three methods were distinguished by the following:

1. MILLER
   a. quasi-rigid body position
   b. no external forces exerted on the body
   c. total body moment of inertia was calculated from film data through the use of a segmental model
   d. the total body angular momentum was calculated using the equation, H=Iw, where w is the total body angular velocity (calculated from film)
2. RAMEY
   a. film and force records (force obtained from a force plate) were combined to produce moment-time curves of the activity
   b. the angular momentum upon departure from the ground was calculated by integrating the moment-time curve.
3. HAY & WILSON
   a. a 14 segment model was used in conjunction with cinematographical results to solve for the angular momentum using a segmental-transfer method.

In order to examine these three approaches Wilson and Hay put eight male college gymnasts through each of the three protocols (a standing front somersault was the analyzed motion). The forces produced during the somersault were recorded through the use of a force plate but only the horizontal force component was utilized (possibly inducing error into Ramey's method). Cinematographic data was collected using a Locam camera (set at 100 frames/s) with synchronization between the camera and the force plate coordinated through a timing light (set at 10 Hz). Since the film rate was at 100 Hz (10 times the force record frequency) a cubic spline function was used to approximate the force data for each 0.02 second interval. The use of curve fitting instead of direct measurement of the forces may also have induced unnecessary error into Ramey's method. The centres of gravity and segment masses were determined from Dempsters normative data (Dempster, 1955; Clauser et al., 1969) and the segment moment of inertias were obtained from Miller and Nelson (1973).

The researchers found that the results from the Miller and Hay-Wilson methods differed the least (the largest difference of the eight subjects was 11.17 N-m-s) and the method of Ramey differed greatly from the other two methods.

Wilson and Hay mentioned various inherent errors in the three approaches which may account for the differences that do exist. The Miller technique required a quasi-rigid state to be properly applied. The quasi-rigid position was defined to be a position in which "the joint angles change by less than 5 degrees over 20 frames". The importance of a correct trunk moment of inertia was also stated as the trunk accounted for approximately 30 percent of the total body moment of inertia when in a tuck position. The Hay-Wilson technique was suggested to be the least sensitive to changes in anthropometrics. Of the three methods used the Miller technique was the least complex in administration and calculation but the Hay-Wilson technique was the most versatile. It was suggested that the Miller method be used in each case as a quick check for the angular momentum value calculated from the other methods.

In 1977 Hay, Wilson, and Dapena further tested the Wilson-Hay calculation technique for angular momentum. A computer program was constructed to perform the following ten steps:

1. The body segment parameters were entered using the norms of Dempster (1955) for segment masses; Clauser, et al. (1969) for centre of gravity and Whitsett (1963) for moments of inertia. The x,y coordinates for each segment end point were used to obtain these values.
2. A cubic spline was used to smooth the x,y coordinate data.
3. The x,y coordinates for the segment and total body centre's of gravity were calculated.
4. The distance was calculated from each segments centre of gravity to the principle axis (normal to the body's plane of motion).
5. The gradient of each segment and the gradient of the line from the total body centre of gravity to the principle axis were calculated and converted to angles. The angular displacement between frames was subsequently calculated.
6. The segment lengths from the film were compared to the actual lengths and corrections were made computationally.
7. The moments of inertia were adjusted to the new segment lengths.
8. The angular momentum about the principle axis was calculated.
9. The transfer term (for the parallel axis theorem) was calculated.
10. The local and transfer terms were summed to give the total body angular momentum value.

Four activities were used to test this procedure: a forward somersault, a long horse vault, a high jump and a pole vault. The criterion for a valid measure of angular momentum was a low standard deviation for the trial. The use of a standard deviation for the validation, though, does not supply information on the absolute accuracy (determining the correct angular momentum value) of this method. It was found that the standard deviations for all the trials were within 3.75 kg*m^2/s (and within 2.80 kg*m^2/s in all but one case).

Hay, Wilson, and Dapena also outlined certain potential sources of error in this technique. These include:

1. Errors from longitudinal rotation of the segments
2. Data processing error (digitization, etc.)
3. Inappropriate anthropometric data

Overall the researchers termed their procedure robust and versatile since it was able to analyse movements in non-experimental (laboratory) conditions and analyse movements that did not involve a quasi-rigid phase.

Two methods for the calculation of angular momentum were utilized and compared by Sanders and Wilson (1987) in their study of the angular momentum requirements for diving. The first technique utilized "inverse dynamics" to determine the reaction forces from the diving board (by differentiation of centre of gravity displacement data) and from these forces calculate the related moments of force. These torques were subsequently integrated over the take-off time to yield the angular momentum at takeoff. This technique was stated to be "highly variable" as the researchers found a maximum variation of +/- 15 $kg*m^2/s$ over three digitizations of the same trial. This variation was attributed to the effects of double differentiation (increasing the errors that are present in the initial digitization), the accuracy with which the centre of gravity and the line of action of the reaction forces can be determined, and the small size of the subject on the film itself (due to the necessity of filming the entire dive).

The second method used by Sanders and Wilson was similar to the method described by Miller (1970). The technique was used to determine the angular momentum during both the hurdle phase (initial) and just before the entry (final) as the body was in a quasi-rigid state for both these positions. The results from the initial angular momentum calculation resembled related results as all values were very low (-1 to 4 kg*m^2/s). This is not surprising due to the lack of rotation in the hurdle phase of a dive. The low angular momentum values, therefore, do not support the calculation of angular momentum in the hurdle phase of a springboard dive simulation.

Various studies have included values for total body angular momentum for many airborne activities. Table 5 displays the results for these skills.

Although a wide range of values are shown, Table 1 does supply some guidelines with which to compare angular momentum results in future studies.

Of all the techniques examined, it appears that the method of Wilson and Hay (1976) was the best for determination of angular momentum since, within expected limits of variability, this method did not impose as many limitations on its use (measurement of force, quasi-rigid position) in situations involving airborne motion.

Table 5: ANGULAR MOMENTUM VALUES

Angular momentum values from a variety of studies and conditions. All values are for the total body in a two dimesional plane.

EVENT	ANG. MOM. ($kg*m^2/s$)	SOURCE
Dive (103B) Dive (5132D)	-58, -45, -42 -61, -48, -50	Saunders & Wilson (1987)
Dive (107A)	-39.32	Miller (1981)
Dive (105B)	-44, -25, -27	Miller (1981)
Dive (205C)	57.2, 54.0	Miller (1985)
Dive (107C)	-70.2	Miller (1985)
Dive (101A)	-18.2, -15.0	Miller (1985)
Dive (105C) Dive (204C)	-72.44 39.46	Hamill, Ricard, Golden (1986)
Standing Front-Somersault	Miller Method (-32.93:-73.50) Ramey Method (-9.41: -83.10) Hay-Wilson (-28.13: -63.50)	Wilson & Hay (1976) (N*m*s)
Long Jump Long Jump (H.Kick)	-5.4 20.31	Ramey (1974)
Front Somersault Long Horse Vault High Jump	-58.98:-73.26 -27.99:-34.50 - 1.00: 8.96	Hay, Wilson, Dapena & Woodward (1977)
High Jump Pole Vault	5.05 15.34: 26.18	(cited Hay, et al., 1974)
Pole Vault Forward Dive (pike) Forward Dive (layout)	21.16 -26.49 -28.74	(cited Miller 1970)

Centre of Gravity and Trajectory of the Human Body

In the study of the airborne human it is essential to define the trajectory of the body's centre of gravity through space. Before this subject can be addressed, though, the best means for the determination of the body's centre of gravity must be examined.

Initially, determination of the centre of gravity was restricted to the whole body approach. Using a balance board or balance board-scale setup (Haycraft and Sheen, 1900; du Bois-Reymond, 1900 - cited from Hay, 1973) the bodies centre of gravity location along the board was estimated as a function of the position of the body on the balance board and the scale reading. This principle sparked the development of more sophisticated techniques to determine the total body centre of gravity location in the various planes and in various body positions.

In order to deal with the constraints of the whole body approach (static positions, error due to movement, difficulty in determining centre of gravity for multiple dimensions) researchers concentrated on the segmental approach. These researchers determined the segmental masses and centres of gravity through the dissection of cadavers and developed regression equations to relate these values to the general population (Braune & Fischer, 1889; Dempster, 1955; Clauser, 1969). While the segmental method is much superior to the whole body method, due to the ability to analyse dynamic situations (from film), errors are inherent in these methods due to cadaver factors (fluid shifts, loss of muscle mass, decrease in bone density, effects of freezing, tissue loss due to cutting, effects of disease, etc.), statistical factors (the sample sizes were very low, N<10), subject factors (cadavers were male and, in most cases, over 50 years of age), and experimental factors.

Sprigings, Burko, Watson, and Laverty (1987) examined three methods for the determination of the total body centre of gravity: Hatze (1980), Clauser (1969), and Dempster (1955). These researchers emphasized the importance of an accurate estimate of the body's centre of gravity since, for the study of airborne motion, this measure is a fundamental constraint on the governing equations for body orientation (since the centre of gravity is the reference point about which the bodies angular momentum is calculated). It was also noted that the segmental approach for determining the centre of gravity was superior to the "entire body" approach.

To compare these three techniques the acceleration of the bodies centre of gravity during free fall was calculated using each of the three methods. Since it was assumed that there were no external forces during the airborne phase the acceleration of the total body centre of gravity must be -9.81 m/s^2. As a result of this conclusion -9.81 was selected as the criterion value upon which the calculated centre of gravity accelerations would be compared (the closer the calculated value to the criterion, the better the method)

Ten male subjects (20-31 yrs, 68.5-102.5 kg) were filmed performing a tuck-extension motion in air. A steel shot was also propelled through the same field of view as the subjects and filmed in the same manner. To satisfy the Hatze model 242 anthropometric measures were taken from each subject (as in the protocol defined by Hatze (1979)). The film for the trials was digitized and the segmental and total body centres of gravity were calculated using Dempster's proportions (1955), Clauser et al.'s proportions (1969), and Hatze's mathematical modelling technique (1980). Displacement curves were produced for all trials and used in comparison to the criterion by parabolic curve fitting with a linear least squares method. The other means of comparison involved comparing the second derivative of the smoothed displacement time data to the criterion.

The metal shot results were used to correct for the measured frame rate (by adjusting the frame rate to 99.60 fps the shot acceleration was -9.81 m/s^2). After this correction was introduced it was concluded that Hatze's technique was the best (x=-9.95, MSE=0.0247), Dempster's technique was second (x=-9.63, MSE=0.0451), and Clauser's technique was the least accurate (x=-9.40, MSE=0.193).

Although Hatze's method was the best, it took 80 min per subject to obtain the required anthropometic measures. Because of the problems associated with this process it would be recommended to utilize the method of Dempster, which was not substantially worse than Hatze's method, as it gives a close (under) estimate of the total body centre of gravity in a reasonable length of time.

The path of the total body centre of gravity during flight has been the subject of investigation as early as 1940 (Lanoue, 1940). In this study Lanoue experimentally supported the view that after a diver leaves the diving board the movement of the diver's centre of gravity follows a regular parabolic path. This consideration allowed Lanoue to examine the relationship between the height of the dive, velocity, and time through the use of Newton's equations of motion.

Groves (1950) also performed an analysis of the mechanics of diving but in this case the total body centres of gravity were determined from the board-scale technique. The subjects were placed on the board in a position that resembled the flight position during a dive. The dive in question was filmed and the centre of gravity positions (obtained from the scale-board setup) were placed onto the images. The resultant centre of gravity displacements were found to travel along a parabolic curve.

The works of Lanoue (1940) and Groves (1950) were examined by Stroup and Bushnell (1969). The researchers supported the claims of Lanoue and Groves, addressing the problem that, since the centre of gravity follows a parabolic path, a diver must sacrifice some height in order to miss the diving board on the way down.

It becomes apparent that an accurate means of determining the total body centre of gravity is essential for the successful simulation of the airborne human as both the angular rotation and translational path are dependant on the centre of gravity as a reference point.

Human Body Models and Inertial Parameters

To model the human body it is essential to have valid and reliable measures of its inertial parameters. While the centre of gravity and mass of the segments have been discussed the moment of inertia or (radius of gyration) is an essential component of this group. The relatively few studies into this area can be divided into two sections: compound pendulum and mathematical modeling.

The compound pendulum method consisted of setting the body in motion as a pendulum (the body was fixed at one point) and then determining the period of its oscillation. The moment of inertia was then determined by relating these values to the body weight and the distance from the centre of gravity to the suspension point. The equation $Io = mk^2$ was used to calculate the radius of gyration (k) and the equation $Io = Icg + mh^2$ was used to calculate the moment of inertia about the centre of gravity (Icg).

The two main studies using the compound pendulum technique were by Fischer (cited from Hay, 1974) and by Dempster (1955). Using cadavers, the body segments were dissected and subjected to the pendulum test for moment of inertia determination. The radius of gyration and the moment of inertia about the centre of mass were determined from the experimental moment of inertia value.

Pendulum studies were also carried out on live humans by Santschi, DuBois and Omoto (cited from Hay, 1974). The 66 male subjects involved in the study were strapped in a pendulum device and set in motion. By measuring the period of oscillation of three pendulums in the three planes of motion the moment of inertia relative to the three principle axes were calculated. A variety of body positions were used.

Drillis and Contini (cited from Hay, 1974) performed a similar study as the previous researchers but in this case a plaster casting of the limb was oscillated. Once the period of oscillation was determined a modification of that period was computed on the basis of the relative weights of the segment and the casting.

All the moment of inertia studies utilizing the compound pendulum resulted in the determination of regression equations (so the experimental results could be used in future experimental situations).

The mathematical modeling method involved the representation of the human body by a series of geometric solids (from which the moments of inertia were already known). The range of these studies falls from Amar (with the trunk as a cylinder and the limbs as frustra's of cones) to Whitsett or Hanavan (utilizing ellipsoids, cylinders, frustrum's of cones, spheres, and rectangular parallelpiped's) (Hay, 1974). The dimensions and properties of the geometric segments were determined, in most part, from the previous research on body segment parameters: Dempster, 1955; Barter, 1957; Hertzberg, et.al, 1954)

The modeling of the human body has been attempted in a variety of ways. In fact, with the emergence of the computer, a satisfactory body model has become an even larger concern. Much of the research into these models was initially aimed at the design of anthropometric dummies or creating normative data on the human body for military use (Miller, 1979) but later models attempted to represent the total body or sections of the body in mathematical terms.

Hanavan (1964) created a 15 segment model that has been used extensively in biomechanical research. His model consisted of geometric shapes that resembled their corresponding segments. By matching the model to the subject (through anthropometric measures) the researcher was able to calculate centres of gravity and moments of inertia of the segments in question.

A dynamic mathematical model of the human body similar to Hanavan's was constructed by Huston and Passerello (1971). The body model consisted of cylinders, frustrums of elliptical cones, and ellipsoids joined with either hinge or ball and socket joints. Equations of motion were developed so that the displacement and rotation of the body could be calculated (once the external forces and relative angular positions of the limbs were known). The model was tested by using it to solve the kinematic or kinetic unknowns for: a person lifting a 50 lb load on the earth and the moon, underwater scissor kick, and kicking by a suspended man. Although values were calculated for all these activities there were many assumptions made and no comparison of the calculated results to standard values (i.e., no validation).

Aleshinsky and Zatsiorsky (1978) designed a multi-link model, which was similar in application and design to Dainis (1974), to study the joint moments in three dimensional motion. The researchers made the following assumptions in designing the human body model:

1. All links, except the upper and lower trunk, are rigid
2. The segments inertial parameters corresponded to the true segment values
3. Segments are connected by frictionless spherical joints
4. Longitudinal twisting of the arms are defined by the corresponding rotation of the cross sections of the real segments
5. The line of action of the joint forces passes through the joint centre of the segment
6. The joint moments are the net reaction moments required to maintain the desired motion

Input into the model consisted of:

1. Absolute coordinates of the joint markers
2. Body segment mass distributions

3. The ground reaction forces (obtained from force plates)

The model was used to determine the moments required to perform a normal walk, sport walk, and sprint run. After the moments were calculated the information was displayed digitally, graphically (as a function of time), and as a series of stick figures. This study did not include a validation or a sufficient portrayal of the results, subsequently, the accuracy and usefulness of this human body model cannot be investigated.

Modelling of Airborne Motion

A variety of models have been constructed to examine and simulate the airborne phase of physical activity. This wide range of models have emerged due to the abundance of situations where the human body experiences free fall and the increases in technology over the past two decades.

One of the early attempts to simulate the airborne phase of diving, through the use of computers, was the model developed by Miller (1970). The model consisted of four segments representing the trunk-head-neck, each arm, and each leg. The body segment parameters for these sections were obtained from a modification of Hanavan's model for adult males. Although three dimensional cinematography was employed to determine certain input parameters (velocity of the body centre of mass at take-off, the absolute angle of the trunk at takeoff, the angular momentum of the system, and the relative angular displacements between the limbs) the simulation was designed to deal with planar, non twisting dives in the layout or pike positions. Utilizing the principle or law of conservation of angular momentum Miller developed an equation for the angular momentum of the system as compared to its centre of mass.

Miller was then able to derive the three components of the head-trunk segment angular velocity. By integration of this value over equal 0.01 second time intervals the absolute angular displacement of head-trunk segment was determined. With the head-trunk orientation being known the orientation of the limbs were designated through their relationship to the head-trunk segment (via the relative angle histories of the limbs).

The translation of the diver was subsequently obtained through direct application of Newton's laws of motion for the motion of a projectile. Miller stated that the head-trunk segment did not follow the parabolic path so a transformation was performed on the head-trunk location vector (relative to the centre of mass) to the translational displacements on the inertial reference frame.

The computer model required certain input data to perform the required steps outlined by the equations of motion.

1. Anthropometric measurements for each limb.
2. Angular velocity functions of the arms and legs.
3. Take-off velocity and trunk angle.
4. Angular momentum components.
5. Dive identification.

The output from the computer model consisted of:

1. Inertial properties of the four segments.
2. Absolute position of the system centres of mass and the total body centre of mass.
3. Angular velocity of the main body.
4. Angular displacement of the main body.

To validate this tool, Miller analyzed dives from six male divers (18-22 years). The anthropometric data on these divers were obtained as outlined by Hanavan (1964) and the two dives that each diver performed were filmed in three dimensions.

After testing the program for errors in calculation and accuracy, data from a null case (arm angles=0, trunk-leg angle=180, all angular velocities=0) were used as input since, in this case, the angular velocity calculated for the trunk should equal the angular velocity which was supplied as input in the total angular momentum value. Also, the trunk angular velocity should remain constant as there was no change in the related parameters. The results were displayed graphically on a CALCOMP plotter. Of the 20 dives filmed 11 were used in the validation (due to difficulties in filming and due to the lack of a quasi-rigid state in some dives). The validity of the model was based on the interpretation of the simulator and experimental graphs of the trunk angles.

Miller found difficulty in determining the total angular momentum from the film. It was estimated that an error of +/- 1.5 foot-pound-seconds could occur in the process. Errors that occurred in the estimation of the trunk angle (1.18 - 13.60 degrees) were attributed to bending of the limbs when they were modeled as straight rigid bodies and inaccuracies in data smoothing and filtering. In cases where the arms were straight, a "good correspondence" was found in the forward 2.5 somersault. The dives in the pike position tended to be overestimated in terms of trunk angle and the dives in the layout position tended to be underestimated. It was also concluded that the body segment parameters were not a serious problem for the simulation model since most of the deviations from the graphs could be traced to the input variables. Standard deviations between the angular displacement graphs showed a standard deviation range of 2.67 to 10.98 and an absolute mean difference range of 22.94 to

1.08. These differences were assumed to be within acceptable limits. It was also recommended that an interactive graphics display be constructed to replace the noncontinuous nature of the plotter. Overall, the researcher described the simulation as adequate when used for simulating airborne, non-twisting dives but was unsure as to the applications outside the adult male group.

The simulation model by Miller was an essential step in the evolution of computer simulation of human motion but there were some drawbacks in the technique. The use of a four-segment model greatly limited the number of possible applications for the simulation (basically to layout and, in some cases, pike movements). The model also failed to recognize a contribution from the head (the head alone accounts for 7.9% of the bodies weight as compared to 4.9% for an arm) or motion at the knee or elbow. There was also the problem of using inferior filtering routines on the incoming data, a problem that can be remedied with modern methods.

Another airborne simulation was constructed by Ramey (1973) but in this case the running long jump was the target activity. Ramey's model consisted of a system of 9 rigid, hinge connected bodies which represented each upper arm, each lower arm, each thigh, each shank, and the head-neck-trunk complex. The "physical properties of the body segments" were obtained from the normative data of Scher and Kane on the 50th percentile U.S.A. airforce man. It was assumed that the effect from air resistance was negligible and that angular momentum was conserved throughout the flight phase. Newtons equations of ballistic motion were used to locate the centre of mass relative to the take off point.

The simulation required certain information in addition to the 50th percentile norms before it could proceed. These included the initial orientation angle between segments, the take off velocity and the angular momentum. All these measures are easily obtained from film except for the angular momentum. Ramey proposed a method for the determination of the angular momentum value, which was used to determine the configuration (rotation about the centre of mass) of the body at each 0.05 second time interval, by solving for the orientation of the trunk. This was done by isolating the trunk segment and solving the resulting equation. The value for the angular momentum was initially assumed and adjusted until a suitable landing was achieved. The angular momentum for the second part of the jump was adjusted so that it remained equal to the angular momentum about the inertial reference frame (in order to provide a rigid body rotation).

Three styles of long jumps were analyzed from film: the hitch kick, the hang, and the sail.

Ramey found that the sail technique required the least amount of angular momentum to complete a good jump (with a desirable landing) followed by the hang and then the hitch kick. The researcher noted that, without the correct angular momentum at takeoff, distance would be lost on the jump due to compensatory movements required to maintain balance.

It was concluded that the simulation was effective for cases where adjustments could be made to an athletes performance in order to complete a technically correct jump without confusing the athlete with many different style and technique changes. It was also noted that there will always be some inherent error due to the assumption that there is no air resistance and the assumption that all limb movements are planar.

Ramey's simulation had the benefit of nine segments, thereby increasing the number of possible applications for the model; however, the head trunk segment was combined as a single unit (thereby suffering from the same problems as Miller, 1970). Although the model was said to be a "very good approximation" there was no published validation of this simulation. This model also relied on an assumed value for the total body angular momentum (which does not allow for simulation using the actual "real world" angular momentum value). By using a calculated value for the angular momentum the simulation would be capable of a more realistic approximation of the actual motion. The researcher also failed to acknowledge the existence of an initial total body angular momentum. Although this is not a factor for standing long jumps the running long jump has a substantial angular momentum before takeoff. By neglecting this term the practical application of this simulation for running jumps is questionable. Ramey (1981) followed up on his planar simulation with a simulation in three dimensions but the same problems as with the two dimensional model were found.

Dainis (1981) simulated an airborne motion but, in this case, the motion was a gymnastic vault. The researcher examined a vault from the point where the gymnast left the take-off board to the point where the feet contacted the ground; however, this simulation not only involved the airborne component of the skill but the contact, force influenced, component. The model consisted of three segments, the arms, trunk, and legs. The total vault was divided into four sections for the simulation: preflight, compression, repulsion, and after-flight. The origin for the reference frame was located at the wrist joint during the phase when the subjects hands were in contact with the vaulting horse.

The pre-flight section corresponded to the phase from take-off to initial contact with the vaulting horse (i.e., airborne motion). At the point of contact the centre of gravity of the body was determined from the initial position and velocity of the body and the distance between the wrists and the centre of gravity. It was assumed that the distance from the wrist to the centre of gravity was constant since the hip and shoulder angles were approximately 180 degrees at contact for most vaults (this assumption is considered a limitation in the simulation since cases where "bad form" was used cannot be validly assessed). Newtons equations for particle motion, represented in polar coordinates, were used to calculate the x,y coordinates for the total body centre of gravity . The velocity and angle of the body at contact were determined using the particle equations, initial conditions, and the wrist-centre of gravity distance. The amount of rotation of the body during the pre-flight phase was determined through the average angular velocity over the pre-flight time period.

The radial velocity at the contact point was also used to calculate the momentum that must be absorbed by the gymnast in order to attain a state of pure rotation about the contact point.

The second phase of the vault was from the first contact with the horse to the time where the radial velocity became zero. At the end of the compression phase the subject was expected to rotate as a rigid body (i.e., angular velocity of the body about the centre of mass equals the angular velocity of the centre of mass about the contact point). The angular momentum, about the origin, was considered to be altered solely by the gravitational force. The moment of inertia of the body was assumed to be constant. Both these assumptions likely lead to errors as the wrist rotation point is not a frictionless ball and socket joint and interjoint motion will undoubtedly change the total body moment of inertia. The angular momentum relationship was used to calculate the angular velocity of the subject.

The repulsion phase was from the end of compression to the point where the hands left the horse. The equations of motion were used to calculate the radial and tangential forces exerted on the horse. The same problems surfaced in this stage as with compression phase but, in this case, the calculated values were used to determine the angular velocity when leaving the horse.

The landing phase involved the same calculations as the pre-flight stage in terms of the path of the centre of gravity, although the input data for the landing was obtained from the last point of the repulsion phase.

Since the tangential and radial forces on the horse were responsible for the rotation and trajectory of the gymnast the two stages, repulsion and landing, were solved together using a pre-set, optimal landing angle as the independent variable. Although the selection of such a landing angle will give insight into the forces required to attain such a result it also limits the application of the model to real-life situations.

This model was validated through the analysis of four handspring vaults (four gymnasts - 12 to 15 years - were used in the study). Each vault was filmed with a high speed camera at 100 Hz and digitized to supply the coordinates for the ankle, hip, shoulder, and wrist. The initial velocities were obtained by calculating linear regression slopes of the displacement - time data. This method was used in place of digital filtering as the lack of sufficient data points at the beginning was assumed to cause error in the data smoothing.

This model contained the same limitations that were outlined for Miller (1970) and Ramey (1973) in that there are not enough segments included to portray a large variety of movements as well as disregarding the contribution of key segments (i.e head) but it does outline an interesting approach to determining the angular displacement characteristics from mathematically deduced forces.

van Gheluwe (1981) examined the airborne phase of human motion through a three dimensional, 7 segment model. The computer simulation was used on both twisting and somersaulting motions in order to examine two proposed methods of twisting (using the backward twisting somersault as the target skill). The simulation utilized the conservation of angular momentum and a modified Hanavan (1964) model to predict the absolute body position (input into the simulation model included: segment weight, segment centre of gravity, segment moment of inertia, etc.). Computer graphics representing the simulated results were produced for each time period. A comparison between the simulated and individual results on the basis of trunk somersault rotation, twist rotation, and inclination of the body relative to the plane of somersault rotation was performed to validate the simulation model. Although no numerical comparison was made, the simulation was termed to be a good representation of the criterion skill and the two methods for producing twist were supported. The simulation by van Gheluwe also suffered from the limitations of a 7 segment model as the contribution from knee joint movement was not recognized. It was not possible to examine the simulation procedure itself due to the lack of depth in this area.

1981 was also the year in which Dapena introduced a three dimensional method of simulating airborne motion. Dapena made common assumptions as related to previous airborne simulations: the rigid body model experienced no external forces or moments apart from gravity, the angular momentum about the total body centre of gravity was constant, the initial absolute position of the segments was known in both the inertial and fixed reference frames, internal forces are used to modify the bodies position in flight, and the modifications of the segments position in the fixed frame occurred such that the same changes relative to the inertial frame result in a constant angular momentum.

The simulation involved two stages, analysis of the original motion and generation of the simulated motion. A flow chart of these two phases are exhibited in figure 7 and 8.

The researcher chose the Fosbury-Flop high jump and various trampoline stunts as the input for the simulation. Using two cameras, the skills were filmed and analyzed to obtain three dimensional information. A 15 segment anthropometric model (involving the upper arms, forearms, hands, thighs, shanks, feet, head, upper trunk, and lower trunk) was used in the simulation with the segment masses and centre or gravity locations obtained from Dempster (1955). Moment of inertia values were

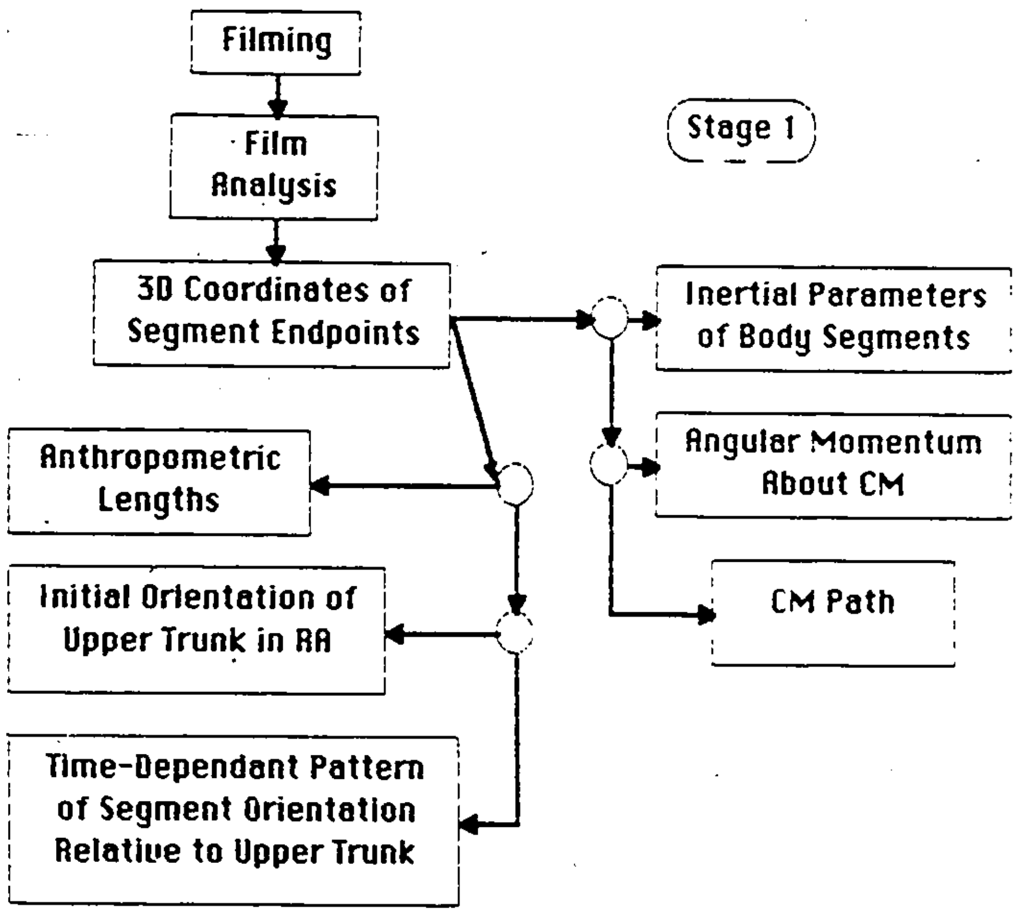

Figure 35: FLOWCHART FOR DAPENA'S MODEL, SECTION 1

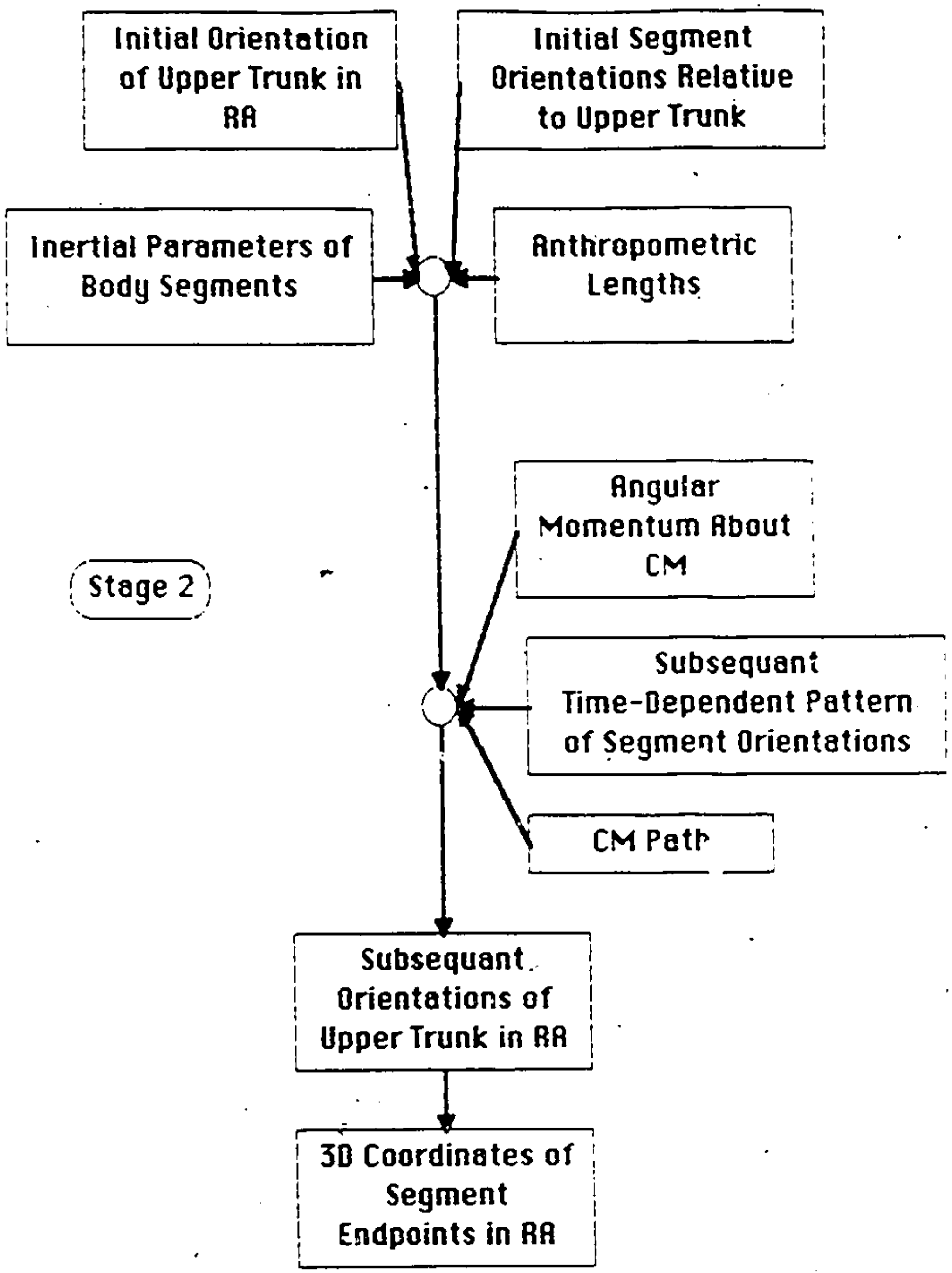

Figure 36: FLOWCHART FOR DAPENA'S MODEL, SECTION 2

obtained from Whitsett (1963). The contribution of the hands and feet to the airborne motion of the whole body was insignificant enough to be considered as fixed segments (i.e., consider the hands and feet as part of the arms and legs). The following data was required as input for the simulation:

1. Inertial parameters of the segment and anthropometric lengths
2. Initial orientation of the upper trunk in the inertial frame
3. Orientation of all the segments in the relative frame as a function of time
4. Angular momentum of the body in the inertial frame
5. Location of the centre of mass of the body

The input data was then used in the following steps of the simulation:

1. Locate segment endpoints
2. Compute the location of the segment centres of gravity in the relative reference frame
3. Calculate the angular velocities of the segments over each time interval
4. Compute the directional cosines of each segment
5. Calculate the inertial tensor values for each segment
6. Calculate the three components of the angular momentum value
7. Obtain the three angular velocity components of the trunk from the three angular momentum equations (in the inertial frame)
8. Calculate the angular displacement of the upper trunk
9. Compute the new orientation of the upper trunk in the inertial reference frame
10. Steps 4-8 were repeated in a loop (loop duration = time interval between successive orientations/time-step value of the integration process)
11. The directional cosines of the segments in the inertial frame were calculated

12. The new positions for the segment end points were obtained

13. All the steps were repeated for each new orientation of the body

The error in rotation of the body was determined through comparison of the original activity with the simulated activity in terms of the upper trunk angle. The validity of this method was designated as the time period over which the error in rotation of the body remained within acceptable limits. It was found that the somersault error remained under 12 degrees for the first 0.6-0.8 sec (under 28 degrees for twisting) and for the remainder of the simulation the error for the somersault component was under 20 degrees.

Certain problems were outlined in this simulation. The angular momentum values calculated over the airborne phase were not constant (as mechanically accepted). This occurrence was attributed to the errors present in estimating the anthropometric parameters. To deal with the range of angular momentum values Dapena averaged all the angular momentum results and used the end product in the simulation. This angular momentum difference was considered the cause of discrepancies between the simulated and actual rotation of the body. The data collection and smoothing techniques were also suspected to be a cause of error.

In terms of the validity of the simulation model, Dapena considered the simulation valid for the first 0.6-0.8 seconds of the skill. The latter portion of the activity could be analyzed as long as it was broken into 0.6-0.8 second sections. It was also suggested that more information on joint torques be amassed since, with this information, it would be possible to determine if a modified motion (using the simulator) is possible for a person to accomplish or if the motion is beyond human capacity.

Dapena's simulation model improved on many of the previous simulations as he involved the head segment, utilized a two segment back, and involved all the limbs (thereby allowing for a wide variety of possible motions). The method for calculation and manipulation of the angular momentum value seemed acceptable as they allow flexibility in application without being hampered by equipment requirements or extensive anthropometric measurements. The error reported for this simulation, though, was high enough to question the validity of this simulation. Also, the use of a three dimensional model would not be recommended for an interactive simulator designed for the coach or athlete. The complexity of three-dimensional cinematography coupled with the problems in visualizing a three dimensional system for most coaches and athletes indicates that a two-dimensional simulator would be more beneficial to these groups at the present time.

A 15 segment model was also used by Spaepen, Stijnen, Willems, and Van Leemputte (1983) to simulate the take-off and flight phases of human motion. The human model used was developed from the Hanavan model (1964) by fusing the hands to the forearms and dividing the trunk into two parts. The resultant model was evaluated by the results of a series of tests on 31 males.

The first test involved measuring the position of the "gravity line" from Kistler force plate output over 12 static positions. These positions were also recorded on 35mm film and subsequently used to calculate the gravity line from the digitized coordinates. The mean difference between these methods was 12 mm.

Using a pendulum-force plate setup the moment of inertia for the total body was determined for three static positions. These positions were also filmed and compared on the basis of the results. For straight positions the model performed very well but when an inclined position was assumed the error went as high as 1.7 $kg{*}m^2$. To help combat the errors in anthropometrics the optimal values for the mechanical parameters of the model were chosen. By using this technique the results for the position of the line of gravity improved by 5.4 mm and the moment of inertia value by 0.2 $kg*m^2$.

The simulation involving this model assumed the following as given:

1. The starting orientation of the subject
2. Position of segmental centres of gravity
3. Total body angular momentum
4. Total body momentum
5. Set of springs to use as a link between the model and the take-off
6. Joint angles as a function of time

From this information the trajectory and orientation of each segment was calculated for every time period of the activity. Since the angular momentum of the system was assumed to be constant the angular momentum equation was used as the basis for the simulation.

This equation was reduced to three first order ordinary differential equations and solved for the absolute position of the segments.

The take-off portion was similar to the flight portion except that second order differential equations were employed in order to get linear and angular accelerations (i.e., the force can be calculated using Newtons equations).

In order to test the simulation three gymnastics movements (back handspring, front roll, and back somersault) were filmed at 200 frames/s and synchronously measured in terms of force on take-off. The results of the original movement were then compared to the simulated results.

Spaepen et al. found that the mean difference between the trunk angles of the simulation differed from the trunk angles of the original motion by, at the most, 7 degrees. The error that did occur was attributed to errors in estimating the segmental moment of inertia and centre of gravity. Error was also suspected from film analysis techniques.

The researchers stated that the airborne phase of a movement can be successfully studied using a simulation model when one or more factors are varied. The force equations, though, require more work before they can be used effectively in the analysis of human movement.

This method was very similar to the model of Dapena (1981) except that Hanavan's model was used as the mathematical base, that the ground contact phase was included in the simulation, and that the simulation was in two dimensions. It is expected that with better data smoothing and anthropometric values this study can be improved upon.

A summary of the theories for two dimensional models of airborne motion was attempted by Preiss (1984) where he outlined equations to describe the said motion. It was stated that in order to simulate airborne motion three equations must be developed:

1. Vertical motion of the total body centre of gravity
2. Horizontal motion of the total body centre of gravity
3. Angular velocity of a selected segment

Where the first two equations are formulated through Newton's equations of motion and the third equations formulated through the conservation of angular momentum.

After assuming that there are no effects due to air resistance Preiss outlined various factors that must be known to simulate the motion:

1. Time history of all joint angles
2. Initial angular momentum value (about and axis at right angles to the centre of gravity)
3. Location vector for the centre of gravity in the reference frame
4. Velocity of the centre of gravity in the reference frame
5. Initial absolute position of an arbitrarily selected segment

It was suggested to approach the simulation task by first producing a set of equations for the position vectors of the segments (thereby giving the orientations of the segments). The total angular momentum of the body was then calculated from the local and transfer terms of the segments. Finally the orientation angle, as a function of time, was calculated from the conservation of angular momentum equation.

Preiss, rather than solving for individual parts, combined the centre of gravity translation, joint movement, and orientation changes into one equation.

This researcher was forced to make certain simplifications in order to produce the segment coordinate equation. The joint angles were defined so that when all the angles were zero (state of rest of the system) the segments were parallel to the x axis. A dummy angle, with a value of zero was also defined in order maintain consistency in the equations used to obtain the result.

Angular momentum was calculated from the "local term" (the rotation about the segment centre of gravity) and the "transfer term" (the rotation of the segment about the total body centre of gravity). The angular momentum equation was used to solve for the angular velocity, and subsequently the orientation angle, of the system. This value was substituted into the segment coordinate equation to determine the absolute orientation of the subject in airborne space.

Theoretically this simulation followed the standard format of previous simulation attempts for airborne motion but the addition of a dummy angle and the definitions of the angles to make the segments parallel to the x axis do not seem to be warranted in this case. Addition of a dummy angle is not necessary in most orientation equations and the extra calculations involved in non-parallel calculations would not be severe enough to warrant redefinition of the joint angles.

Yeadon (1986) used a three dimensional airborne simulation model to examine twisting somersaults. The simulation model consisted of 11 segments and 17 degrees of freedom. The input data were obtained from three dimensional cinematography and inertial parameter values as a function of the subjects anthropometric measures. Yeadon modified the film input into the model to examine the contribution of different techniques in relation to twisting. It was found that twist produced during the contact phase was relatively small in contribution when compared to the use of asymmetric twisting techniques.

This simulation appeared to be the most precise and intricate but the increase in complexity for this model could create problems in interpretation for coaches or athletes.

The airborne motions for high bar gymnastic movements were simulated in 1985 by Nissinen, Preiss, and Bruggemann. A six segment anthropometric model was used to represent the gymnast throughout the two-dimensional reference frame. The translation of the subjects centre of gravity was defined through Newton's laws of particle motion and the rotational component was defined by the conservation of angular momentum. Input for the simulation consisted of:

1. Total body angular momentum (about the centre of gravity)
2. Initial orientation angle of a selected segment
3. Initial location and velocity of the total body centre of gravity

4. Joint angles as a function of time

5. Inertial parameters of the segments (calculated from a modified Hanavan model)

Film data from the 1982 German Championships were obtained which showed various high bar dismounts. The film was digitized, filtered, and analyzed to give the necessary input information for the simulation. Computer graphics from the digitized data points were also constructed. The simulation results were compared to the original, on the basis of the trunk angular displacement, in order to validate the model. The researchers stated that the results of the validation were satisfactory. Once validated the researchers used the simulator to devise a triple back somersault dismount that is now being performed. It was also shown, using the simulator, that certain release movements would be essentially impossible to perform while certain other movements are realistic (eg. forward double somersault with recatch).

Although there was no quantitative assessment as to the validity of the simulation model and the limitation due to the existence of only six segments this study did demonstrate the practical use of a computer simulation in the field.

One study that did validate the use of a link segment simulation model was by Duck (1985). The researcher constructed a three segment steel bar model (with elastic bands to represent the muscular contribution) for the initial validation but the three, four, and five segment models were also validated using a human subject. Differential equations of motion for each of the segments were derived using Newtonian mechanics. As with the previous simulations relative joint angles, inertial properties of the segments, and initial orientation of the support segment were required as input. The validation involved comparing the angular positions of the support segment in the simulated ana measured conditions.

The mean difference between support segment angles was found to be very small in all cases (1.28 - 1.96). It was interesting to note that for all the human subject trials the mean difference increased as the number of segments increased. From these results it was suggested that increasing the number of body segments used in the symmetric, two dimensional simulation be increased to 6 or 7 so as to include non-symmetric activities. The simulation was expected to be of use in examining sequential versus synchronous joint coordination toward jump height and distance, internal joint moments as related to segment coordination, or segmental effects of total body angular momentum.

Once a simulation has been developed it falls to the researcher to make this tool accessible and easily interpretable. The use of computer graphics solves many problems in these areas. Boysen, Francis, and Thomas (1977) examined the use of interactive computer graphics in the study of planar free fall motions. The five segment model was derived using Lagrangian mechanics. The inertial parameters for this model were derived from a modified Hanavan model (the head, feet, and hands were fused to their proximal ends and only a unilateral view was taken).

The simulation was validated by comparing the trunk angle of the simulation to the trunk angles of the original motion over the individual time frames. Two springboard dives were used for this validation: a forward dive in the pike position and a forward one and one half somersault in the pike position. The mean and standard deviations of the difference between the two sets of angles were 1.36 degrees +/- 1.94 degrees for the first dive and 7.75 degrees +/- 5.23 degrees for the second dive. It was recommended to use a multi-segment back in order to reduce the error for the second dive (since curvature of the spine in the pike position was considered consequential).

This simulation, contrary to previous models, used an interactive approach for the input of the initial parameters for the simulation. This allowed a person to easily adjust the initial parameters and observe the results. Another option allowed for specific time intervals to be observed and modified, thereby directing the simulation to the part of the skill which was of interest. Input was monitored to assure that only anatomically feasible situations would be simulated (data for this operation was obtained from anatomical norms). The graphical display included a two-dimensional representation of the flight of the subject, parabolic parameters, and options information. Graphical representation of the torques used to produce the angular accelerations of the segments were also available (in order to examine the feasibility of performing the simulated motion). Output from the interactive package was available in a variable format in terms of units and time scale.

This interactive computer simulation package appeared to be an ideal step toward bridging the gap between existing mathematical models and usable research-teaching tools. The model itself was validated quantitatively, which lends credibility to the use of the simulation, although the unilateral, five segment model limits the possible applications. The model also fails to recognize a contribution from the head to the angular momentum equation. The interactive section could also make available easier means of manipulating the body, more analysis on the simulated motion (kinematics, power, etc.), and a means of comparing skills to optimal performances.

The interactive approach for computer simulation was also examined by Walton and Kane (1978) but in this case the interactive simulator was presented to actual coaches. The human body model was relatively simple, a three segment planar model with designated inertial parameters. The model was "prepared and tested" and then introduced to two Stanford University coaches (diving and gymnastics). The coaches were given an explanation of the system and the opportunity to examine a series of skills in each of their respective fields. The diving coach developed a lead-up skill for the 3m two and one half somersault that could be done from the 1m board. The gymnastic coach examined the timing in performing various dismounts. Although the researchers did not believe that the coaches benefitted greatly from their brief exposure to the system they believed that the coaches left in a "very positive frame of mind".

Walton and Kane did point out some factors to keep in mind when dealing with interactive simulations:

1. The limits of the model should be understood and taken into account
2. There was the need for an intermediary person to transfer needs such as a "tighter pike" or "tuck earlier" into mechanical input for the model
3. The input for each new trial should be kept to a minimum
4. Computer speed should be faster

This study was very qualitative; however, it does demonstrate an attempt to bring the available technology to an applicable state. With the invention of faster, more powerful computers the problems experienced with run time for the simulation and problems with input variables should be reduced considerably. It is also expected that the need for an intermediary person to run such an interactive simulator could be eliminated with a more accessible command structure.

From examination of previous computer simulations of airborne motion certain factors seem common and essential for the successful simulation of said motion:

1. The trajectory of the motion is modeled by Newtons equations for projectile motion (using the total body centre of gravity as the translation point)
2. The rotational motion is obtained through the equations associated with the conservation of angular momentum

3. A body model must contain enough segments to accommodate the motions to be analyzed
4. Validation should be carried out over the full range of the simulated skills
5. Interactive simulations should be easily modifiable and contain emplicit graphic output

It should also be noted that the lack of information on the limits of human performance and the optimal method of performing a skill will be a limiting factor for the predictive capabilities of simulated motion.

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