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16. Abstract

A study has been conducted as an initial step in determining the differences observed between the motions of a living human impact sled test subject and a dummy test subject. The mechanism which is proposed for accomplishing this is the HSRI Two-Dimensional Mathematical Crash Victim Simulator. A series of measurements were taken on human test subjects including classical and non-classical anthropometric measurements, range of motion measurements for the joints, and maximum foot force measurements. A series of mathematical expressions have been used to predict body segment weight, centers of gravity, and moments of inertia using the results of the various body measurements. It was then possible to prepare a data set for use with the mathematical model. In addition to the body measurements described above, it was necessary to determine the deceleration profile for the Daisy sled and to determine the geometry as well as the force-deformation characteristics for the seat and restraint environment. This being accomplished, a computer simulation of an impact sled test involving a human volunteer was made. The results are presented to conclude the report.

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1. INTRODUCTION

A study has been conducted as an initial step in determining the differences observed between the motions of a living human impact sled test subject and a dummy test subject. The mechanism which is proposed for accomplishing this is the HSRI Two-Dimensional Mathematical Crash Victim Simulator. A series of measurements were taken on human test subjects including classical and non-classical anthropometric measurements, range of motion measurements for the joints, and maximum foot force measurements. A series of mathematical expressions have been used to predict body segment weight, centers of gravity, and moments of inertia using the results of the various body measurements. It was then possible to prepare a data set for use with the mathematical model. In addition to the body measurements described above, it was necessary to determine the deceleration profile for the Daisy sled and to determine the geometry as well as the force-deformation characteristics for the seat and restraint environment. This being accomplished, a computer simulation of an impact sled test involving a human volunteer was made. The results are presented to conclude the report.

2. ANTHROPOMETRIC MEASUREMENTS

The six human volunteer impact sled test subjects involved in the airbag evaluation program participated in a series of classical and non-classical anthropometric measurements which were designed to provide input data for use with mathematical simulations of crash victim motions. These were supplemented by maximum voluntary foot force and range of motion measurements.

2.1 CLASSICAL AND NON-CLASSICAL ANTHROPOMETRIC MEASUREMENTS

A series of 108 anthropometric measurements on each of the six Holloman Sled Test subjects was accomplished. Equipment utilized included the Siber Hebner Anthropometer, hinged and sliding calipers, wallboards, a foot board, a 2000 mm steel tape and physician's scale. The measurements selected represented a combination of standard anthropometry, to allow comparison relative to other populations such as the "Air Force" population, and non-classical anthropometry aimed at defining the external shape of the body. Since the major objective of these measurements was for the latter purpose, and ultimately to define inputs for a mathematical model, many of the measurements listed have not previously been taken.

Included is a description of each measurement together with a precise definition of its location. It should be noted that classical anthropometry is based upon body landmarks or points which have a bony basis and allow therefore a certain degree of accuracy. However, many of the non-standard body measurements necessary to define the body shape could not be based on precise bony landmarks, therefore will show less precision and greater variation. An attempt was made to measure these as accurately as possible and it is believed that these data are valid for the purpose designed, providing a much more useful "map" of the contours of the body.

The measurement number and description is given in the following list. Those numbers designated with an asterisk are non-standard measurements. The subjects were unclothed except for an athletic supporter. The majority of measurement Nos. 1-62 were taken with the subject standing and the remainder with the subject seated.

1. Weight

   Nude weight taken to nearest tenth of a pound on standard military medical scale. Also ask if weight taken while test subject and if so, record this.

2. Stature

Vertical distance from floor to top of the head using anthropometer and subject standing erect with head oriented in Frankfort Plane.

3. Menton Height*

Vertical distance from floor to chin, using anthropometer and subject standing erect with head oriented in Frankfort Plane.

4. Cervicale Height

Vertical distance from floor to posterior base of neck at the 7th cervical vertebrae with the subject standing erect (Mark cervicale).

5. Acromial Height

Vertical height from the floor to the shoulder at the right acromion of the erect subject.

6. Axilla Height

Vertical distance from the floor to the armpit, with the subject standing erect and extending both arms horizontally, then lowering.

7. Suprasternale Height

Vertical distance from the floor to the upper edge of the sternum, (mark).

8. Substernale Height

Vertical distance from the floor to the lower margin of the sternum, (mark).

9. T-12 Height*

Vertical distance from the floor to the spinous process of the 12th thoracic vertebra, taken from rear, (mark).

10. Rib Height*

Vertical distance from the floor to the lowest point on the right front of the rib cage, (mark).

11. Waist Height

Vertical distance from the floor to the superior margin of the right iliac crest, taken from rear, (mark).

12. Trochanteric Height*

Vertical distance from floor to lateral projection of right major trochanter (mark).

13. Maximum Hip Breadth

From rear, at maximum diameter of hips (No. 12) previously marked. Anthropometer. Subject Standing.

14. Maximum Hip Height*

Vertical distance from floor to point coinciding with maximum hip breadth (measurement No. 13). Taken from rear.

15. Maximum Buttock Depth

Subject standing. From right side. Anthropometer. Depth of body at the level of maximum protrusion of the buttocks.

16. Buttock Height No. 1*

Vertical distance from floor to point on buttocks coinciding with maximum bottock depth (measurement No. 15). Taken from rear.

17. Maximum Buttock Circumference

Subject standing, in horizontal plane circumference at level of greatest rearward protrusion of buttocks. From right side.

18. Buttock Height No. 2*

Vertical distance from floor to point on buttocks coinciding with maximum buttocks circumference (measurement No. 17). Taken from rear.

19. Crotch Height

Vertical distance from floor to midpoint of crotch.

20. Maximum Calf Breadth

Taken from rear, right leg. Anthropometer. Maximum diameter of calf.

21. Maximum Calf Height*

Vertical distance from floorto point coinciding with maximum calf breadth (measurement No. 20). Right leg.

22. Lower Patellar Height*

Vertical distance from floor to inferior boxes of knee cap (knee pivot point). Right leg.

23. Biacromial Diameter (anthropometer section)

Width between acromion-acromion of shoulder. From rear, subject seated.

24. Bideltoid Diameter (shoulder breadth)

Maximum shoulder breadth across lateral aspect of deltoid muscles. From rear, subject seated. Anthropometer.

25. Cervicale-Axilla Distance*

Distance measured from cervicale to armpit with subject raising arm and lowering after instrument in place. Point is marked for level of chest depth and breadth measurements. From rear, subject standing. Anthropometer.

26. Chest Breadth

Subject holds arms raised and lowers after instrument is in place, breadth measured during normal breathing. From rear, subject standing. Anthropometer.

27. Chest Depth

Subject raises arms and lowers after instrument in place. Measured on right side at nipple level during normal breathing. From right side, subject standing. Anthropometer.

(NOTE: measurements 23, 24, 25 should be taken at same level, but
this level may differ from level at which 24 or 25 taken.
If so, measurements at each level for each point will be
taken and noted).

28. Chest Breadth at Xiphoid

Chest depth measured at level of bottom of sternum. Subject standing, from right side. Anthropometer.

30. T-12 Chest Breadth*

From rear, using T-12 reference point marked, subject standing. Anthropometer.

31. T-12 Chest Depth* (NOTE: Backbone indents at this point-instead measure maximum).

From right side, depth measured at T-12 reference level, subject standing. Anthropometer.

32. Chest Breadth, inferior margin rib cage*

From front, subject standing. Chest Diameter at level of lowest point on rib cage, previously marked.

33. Chest Depth, inferior margin rib cage*

From right side, subject standing, chest depth at level of lowest point on rib cage.

34. Waist Breadth

From front, subject standing. Waist diameter to level of top of lateral border iliac crests, previously marked. Anthropometer.

35. Waist Depth

From right side, subject standing. Waist depth at level of top of lateral border iliac crests, previously marked. Anthropometer.

36. Hip Depth

From right side, depth of hips at level of trochanter point previously marked (12). Anthropometer. Subject standing.

(NOTE: Hip breadth and hip depth may vary from standard when taken at this level, and if so both measures for each may be taken. Note that hip pivot point cannot be measured accurately externally.)

37. Hip Breadth

Subject standing. Anthropometer. At level of trochanter (12).

38. Height at Maximum Hip Breadth

Subject standing. Anthropometer. At level of trochanter (12).

39. Crotch Breadth

Taken from front. Anthropometer. Body diameter at level of crotch.

40. Crotch Depth

Taken from right side. Anthropometer. Depth at level of crotch.

41. Neck Circumference

Subject standing erect. Right side circumference in plane perpendicular to axis of neck and just below "Adams Apple."

42. Shoulder Circumference

Maximum Circumference around shoulders at maximum lateral protrusion of deltoid muscles.

43. Upper Chest Circumference*

Subject standing. Right side. Taken at level of Measurement Nos. 24-25.

44. Chest Circumference

Arms raised then lowered. Maximum circumference is measured at level of nipples, during normal breathing. In front.

45. Xiphoid Chest Circumference*

Subject standing. Front. Circumference at level of inferior border of Xiphoid at base of sternum.

46. T-12 Chest Circumference*

Subject standing. From rear. Circumference taken at T-12 level.

47. Lower Rib Cage Circumference*

Subject standing. From front. Circumference taken at level of lowest point on rib cage, previously marked.

48. Waist Circumference

Subject standing, from front. Taken at level of superior iliac crest previously marked.

(NOTE: This circumference may vary from standard)

49. Hip Circumference

Subject standing. From right side. Taken at point of maximum hip diameter previously marked.

50. Left Thigh Circumference at Crotch

Subject stands erect, legs slightly apart.

51. Right Thigh Circumference at Crotch

52. Lower Thigh Circumference

Subject stands erect. Horizontal circumference just above right kneecap.

53. Knee Circumference*

Subject stands erect. Circumference at midpoint of patella.
(NOTE: This is not in same plane as pivot point)

54. Lower Knee Circumference*

Subject stands erect. Circumference taken at inferior border of patella. (Still may be above pivot point but provides an additional reference measure.)

55. Calf Circumference

Subject stands erect. Right leg. Maximum circumference of calf of lower leg.

56. Lower Leg Circumference

Subject stands erect. Right leg. Circumference at point of minimum lower leg diameter, previously marked.

57. Ankle Circumference (minimum)

Subject stands erect. Right ankle circumference taken above lateral malleolus projection.

58. Upper Arm Circumference (axillary)

Subject standing. Right arm. Circumference taken at armpit with subject raising, then lowering arm.

59. Elbow Circumference*

Subject standing. Right elbow circumference measured in unflexed position.

60. Lower Arm Circumference

Subject standing. Right arm. Maximum circumference of the forearm below the elbow.

61. Wrist Circumference

Subject standing. Right arm. Circumference is measured just proximal of the styloid process of ulna.

62. Fist Circumference

Subject makes tight fist with right hand with thumb lying across the end of the fist. Tape passes over thumb and knuckles.

63. Head Circumference

Maximum circumference of head above brow ridges.

64. Head Ellipse Circumference (Bennett measurement)

Head circumference from menton (chin) to point on back of head at maximum distance.

65. Head Breadth (spreading caliper)

Maximum breadth of the head in a plane perpendicular to the mid-sagittal plane. From rear, subject seated.

66. Head Length (spreading caliper)

Maximum length of head from glabella to occipital area.

67. Anterior Neck Length (tape)

Subject standing, erect, with head in Frankfort plane. Surface distance from supersternale to the juncture of the chin and neck.

68. Upper Neck Circumference

Subject standing, erect, with head in Frankfort plane. Horizontal circumference from juncture of chin and neck to lowest point of occipital region (at or below inion).

69. Posterior Neck Length

Subject standing, erect, with head in Frankfort plane. Surface distance is measured from cervicale to the lowest point of occipital region (at or below inion).

70. Lower Neck Circumference

Horizontal circumference from suprasternale to cervicale.

71. Erect Sitting Height (anthropometer)

Subject erect, head in Frankfort plane, with feet resting on a surface so that knees are bent at right angle. Distance measured from sitting surface to top of head.

72. Erect Sitting Height

Internal canthus height, sitting position. Subject seated erect in Frankfort plane, horizontal with knees at right angles to floor. Vertical distance from the sitting surface to the inner corner of the eye. Right eye.

73. Slumped Sitting Height

Subject allowed to assume normal slumped sitting position. Distance measured from sitting surface to top of head.

74. Slumped Sitting Eye Height

Subject allowed to assume normal slumped sitting position. Distance measured from sitting surface to the inner corner of right eye.

75. Vertical Arm Reach, Sitting

Subject seated in erect Frankfort horizontal,extends right arm, maintaining shoulders pressed against seat back. Distance measured from surface of seat back to tip of longest finger using anthropometer held horizontally.

76. Elbow-to-Elbow Breadth

Subject seated erect with upper arms hanging at sides and forearms extended horizontally, with elbows resting lightly against side of body. The maximum horizontal distance is measured with the anthropometer across the lateral surfaces of the elbows.

77. Elbow Clearance Out (horizontal)

The horizontal distance from the tip of the elbow to the midline of the back, with the elbow held out laterally.

78. Elbow Clearance Out (vertical)

The erect seated subject extends the right upper arm laterally as in 77. Distance is measured vertically from surface of seat to tip of the elbow.

79. Elbow Clearance Back (horizontal)

The subject sits erect with right elbow flexed at 90°. The upper arm is then circumducted posteriorally as far as possible and the horizontal distance between the tip of the elbow and the plane of the back is measured.

80. Elbow Clearance Back (vertical)

With position same as in 79, the vertical distance is measured from the tip of the elbow to the seat surface.

81. Hip Breadth, Sitting

The maximum diameter of the seated subject's hips.

82. Thigh Clearance

With the subject seated, the vertical distance between the anterior aspect of the thigh, just distal to the inguinal line, and the seat surface.

83. Maximum knee spread (sitting)

The distance between the most lateral points on each knee, with the erect seated subject spreading knees as far as possible.

84. Seat Back-Abdomen

With the seated subject in erect posture the distance is measured from the surface of the seat back to the anterior surface of the abdomen.

85. Seated Functional Arm Reach (left) Horizontal

The seated subject extends the left arm laterally, touching the thumb to the middle finger.

86. Seated Functional Arm Reach (right) Horizontal

Same as 85, to right side.

87. Seated Maximum Arm Reach (left) Horizontal

88. Seated Maximum Arm Reach (right) Horizontal

89. Seated Shoulder Height

With subject in erect posture, vertical distance from seat surface to right acromion.

90. Seated Cervicale Height

With subject in erect posture, vertical distance from seat surface to cervicale.

91. Waist Height, Sitting

With subject in erect posture, knees bent 90°, distance from seat surface to right iliac crest (marked).

92. Buttock-Knee Length

Seated erect subject, anthropometer, horizontal distance from rear-most point of right buttock to front of the kneecap.

93. Knee Height, Sitting

Seated subject with feet flat and knees bent 90°, distance from footrest surface to top of right knee (not to kneecap).

94. Popliteal Height, Sitting

Seated subject, feet flat and knees bent 90°, distance from footrest surface to underside of right knee.

95. Minimum Lower Leg Diameter

Taken from rear. Right leg. Anthropometer. Minimum diameter of lower leg.

96. Lower Tibial Height*

Vertical distance from floor to point coinciding with minimum lower leg diameter (measurement No. 95). Right leg. Use foot board.

97. Lateral Malleolus Height*

Vertical distance from floor to inferior border fibula lateral malleolus. Use foot board.

98. Foot Length

Subject stands, right foot on foot measuring board, weight equally distributed. Heel to furthest toe distance.

99. Foot Breadth

Subject stands, right foot on foot measuring board, weight equally distributed. Distance at widest part of foot.

101. Hand Length (sliding caliper)

Hand extended, palm up. Distance from proximal edge of the navicular bone at wrist to the tip of the middle finger.

101. Hand Breadth at Thumb (sliding caliper)

Hand extended, palm up, with thumb lying along side and in plane of the palm. Breadth measured across thumb knuckle.

102. Hand Breadth at Metacarpale (sliding caliper)

Hand extended, palm up, maximum distance across metacarpale III.

103. Hand thickness at metacarpale III (sliding caliper)

Hand and fingers extended, thickness of knuckle of middle finger.

104. Arm Span

Subject erect, back to wall, with arms extended laterally to maximum middle finger of one hand just touching side wall (or block). Distance is measured on scale placed on wall from finger tip to finger tip.

105. Vertical Reach (standing)

Subject erect, back to wall, with right arm extended overhead and heels touching floor. Use wall board and block to read maximum distance from floor to tip of longest finger.

106. Arm Reach from Wall

Subject erect in corner of room, shoulders pressed against wall, with left arm and hand extended horizontally along side wall. Use wall scale to measure distance from wall to longest finger tip.

107. Maximum Reach from Wall

Subject erect in corner of room, with back pressed against the rear wall and his left shoulder thrust as far forward as possible; his left arm and hand extended horizontally along the side wall. Measure distance from wall to tip of longest finger on wall scale.

108. Functional Reach

Subject erect in corner of room, with both shoulders pressed against the rear wall, and left arm and hand extended horizontally along the side wall, except that the tips of his thumb and forefinger are pressed together. Measure distance from rear wall to the tip of the thumb using wall scale.

TABLE 1. INDIVIDUAL MEASUREMENTS, DAISY TEST SUBJECTS (page 1)

Measurement No.	Subject No. 1	Subject No. 2	Subject No. 3	Subject No. 4	Subject No. 5	Subject No. 6	Range
1	136 lbs*	199 lbs	157.5 lbs	155 lbs	178 lbs	176.5 lbs	136 - 199 lbs
2	180.0	176.2	169.2	170.8	177.2	180.5	196.2 - 180.5
3	157.7	152.2	146.5	147.2	154.0	158.4	146.5 - 158.4
4	156.0	149.6	144.8	144.5	152.9	156.0	144.5 - 156.0
5	150.8	145.3	136.5	137.4	149.1	151.0	136.5 - 151.0
6	139.3	134.5	131.1	133.0	141.7	138.0	131.1 - 141.7
7	146.6	139.8	135.1	146.2	145.7	147.8	135.1 - 147.8
8	128.3	120.7	119.2	117.4	123.2	131.7	117.4 - 131.7
9	119.2	113.5	104.8	114.3	116.2	123.5	104.8 - 123.5
10	115.4	106.0	103.6	105.2	113.2	112.8	103.6 - 115.4
11	111.1	97.6	98.5	100.6	109.2	111.0	97.6 - 111.1
12	94.5	90.5	86.0	88.2	94.6	93.5	86.0 - 95.6
13	30.3	35.7	33.0	31.8	35.8	37.2 trochanter	30.3 - 37.2
14	94.7	90.5	85.9	91.6		93.3	85.9 - 94.7
15	21.1	24.7	21.8	23.0	23.1	23.7	21.1 - 24.7
16	92.1	90.5	84.8	84.1	92.7	93.7	84.1 - 93.7
17	87.5	104.5	96.5	95.5	101.8	102.5	87.5 - 104.5
18	92.8	87.5	85.5	83.5	93.2	94.6	83.5 - 94.6
19	84.5	77.6	74.5	77.6	83.3	82.9	77.6 - 84.5
20	11.0	12.8	11.4	12.2	11.3	11.5	11.0 - 12.8
21	32.6	30.5	31.3	34.2	34.7	33.7	30.5 - 34.7
22	46.0	42.0	43.0	44.4	45.8	46.6	42.0 - 46.6

*NOTE: The units of Measurement No. 1 is pounds and of all other measurements are centimeters.

TABLE 1. INDIVIDUAL MEASUREMENTS, DAISY TEST SUBJECTS (page 2)

Measurement No.	Subject No. 1	Subject No 2	Subject No. 3	Subject No. 4	Subject No. 5	Subject No. 6	Range
23	36.7	42.3	40.0	41.0	39.2	40.7	36.7 - 42.3
24	42.4	45.6	48.8 44.6	45.8 max 44.0	47.5 max 43.1	45.8 max 42.5	42.4 - 47.5
25	21.6?	28.2?	22.3?	23.6?	24.2?	24.5?	21.6? - 28.2?
26	29.0?	41.1 axilla	32.8?	30.4 axilla	32.5?	32.9 axilla	29.0? - 43.1
27	20.6	28.6	22.8 Nipples dep	21.4	25.6	24.0	20.6 - 31.3
28	27.5	36.2	30.2	30.6	33.7	31.8	27.5 - 36.2
29	18.8	28.2	22.5	20.4	24.5	24.2	18.8 - 28.2
30	26.0	34.7	29.5	29.4	31.7	30.1	26.0 - 34.7
31	18.0?	26.2	23.0	20.0	24.2	23.5	18.0 - 26.2
32	26.2	34.0	29.3	29.2	33.3	31.2	25.0 - 34.0
33	18.6	25.6	23.2	20.6	22.8	21.9	18.0 - 25.6
34	26.3	35.0	29.9	30.5 Bulges	34.5	32.6	26.3 - 35.0
35	19.0	23.8	23.5	21.3	22.8	22.6	17.8 - 23.8
36	20.3	24.6	22.6	21.4	22.8 trochanter	23.4 trochanter	17.6 - 24.6
37	30.2	35.2	33.5	31.4	35.8	37.2	30.2 - 37.2
38	93.4	89.1	85.7	94.8	96.6	93.0	85.7 - 96.6
39	30.4	36.4	33.3	33.4	37.9	36.7 gluteal furrow	30.4 - 36.7
40	17.1	18.8	20.5	19.5 gluteal furrow	20.6 gluteal furrow	19.7 gluteal furrow	17.1 - 20.6

TABLE 1. INDIVIDUAL MEASUREMENTS, DAISY TEST SUBJECTS (page 3)

Measurement No.	Subject No. 1	Subject No. 2	Subject No. 3	Subject No. 4	Subject No. 5	Subject No. 6	Range
41	34.0	42.0	39.5	36.8	39.0	37.7	34.0 - 42.0
42	103.5	121.5 bideltoid	109.5	107.7	104.1	104.4	103.5 - 121.5
43	89.5	113.0 axilla	95.0 axilla	91.5 axilla	99.5 axilla	98.0 axilla	89.5 - 113.0
44	87.0	111.5	94.0 nipple	88.2 nipple	99.5 nipple	98.0 nipple	87.7 - 111.5
45	77.3	100.8	84.0	82.5	93.7	93.4 Xiphoid almost at nipple level	73.4 - 100.8
46	74.3	95.6	84.5	82.0	91.5	86.4	74.3 - 95.6
47	71.0	96.0	87.0	78.2	92.0	86.1	71.0 - 92.0
48	72.0	93.5	85.5	83.5	94.3	87.7	72.0 - 94.3
49	88.6	102.8	84.0	83.0	102.7	102.7	88.6 - 102.8
50	51.0	63.6	57.0	58.5	63.5 gluteal furrow	60.2 gluteal furrow	51.0 - 63.6
51	50.0	63.0	57.0	58.0	62.5 gluteal furrow	60.2	50.0 - 63.0
52	35.0	41.0	38.5	40.2	42.5	43.2	35.0 - 43.2
53	35.0	39.5	36.5	39.0	39.5	41.9	35.0 - 41.9
54	32.5	36.5	32.5	34.0	36.8	37.3	32.5 - 37.3
55	36.2	41.0	36.0	38.6	38.2	35.7	35.7 - 41.0
56	21.7	23.6	22.5	23.1	22.9	21.0	21.0 - 23.6
57	22.5	24.9	23.0	25.1	24.2	26.0	22.5 - 26.0
58	26.7	36.5	35.2	34.8	36.0	37.7	26.7 - 37.7
59	24.5	30.0	26.8	25.2	26.7	28.7	24.5 - 30.0

TABLE 1. INDIVIDUAL MEASUREMENTS, DAISY TEST SUBJECTS (page 4)

Measurement No.	Subject No. 1	Subject No. 2	Subject No. 3	Subject No. 4	Subject No. 5	Subject No. 6	Range
60	26.2	31.3	27.8	27.0	27.5	27.6	26.2 - 31.3
61	16.5	18.0	17.5	18.2	16.5	18.0	16.5 - 18.0
62	28.5 seated	29.0	29.2	29.8	29.1	29.1	28.5 - 29.8
63	54.5	58.5	61.0	55.0	56.6	56.5	54.5 - 61.0
64	62.6	67.5	70.1	64.5	66.8	65.5	62.6 - 70.1
65	15.2	16.6	15.8	15.4	15.3	14.4	15.2 - 16.6
66	18.4	19.0	21.1	18.2	18.9	19.3	18.4 - 21.1
67	9.2	11.0 to 13.8 menton	8.5 to 11.5 menton	11.0 clean	8.5	9.0	8.5 - 11.0
68	34.0	42.0	40.0	36.8	39.3	39.7	34.0 - 42.0
69	7.7	8.3	7.5	9.7	10.0	9.0	7.7 - 10.0
70	36.0	42.2	40.0	39.0	41.5	39.5	36.0 - 42.0
71	87.6	91.2	90.5 (change)	92.4	88.9	92.7	87.6 - 92.7
72	76.6	78.7	78.6	80.7	76.0	81.4	76.0 - 81.4
73	85.4	89.2	85.4	89.9	87.3	88.8	85.4 - 89.9
74	70.8	76.0	73.7	76.1	73.8	75.9	70.8 - 76.1
75	89.5	86.2 unable to get shoulder back	132.0	139.5	141.1	143.8	86.2 - 143.8
76	37.8 40.4 elbow at side	55.2	39.9	45.6	52.0?	45.9?	37.8 - 55.2
77.	46.5	45.5	44.8	46.6	48.7	46.9	44.8 - 48.7
78	?						
79	9.5	15.6	19.0?	27.5?	18.0?	27.5?	9.5 - 27.5

TABLE 1. INDIVIDUAL MEASUREMENTS, DAISY TEST SUBJECTS (page 5)

Measure-ment No.	Subject No. 1	Subject No. 2	Subject No. 3	Subject No. 4	Subject No. 5	Subject No. 6	Range
80	?						
81	31.2	36.8	35.3	33.1	38.5	38.5	31.2 - 38.5
82	16.7	17.5	14.9	15.4	16.5	15.7	14.9 - 17.5
83	97.6	89.5	86.5	91.6	90.0	99.9 former dancer	89.5 - 99.9
84	22.5	26.3	25.6	21.0	26.7	24.1	21.0 - 26.7
85	86.6 vertebral	85.0 83.5	80.3 longer	80.5	87.5	88.0	80.3 - 88.0
86	85.3	86.0	81.9	81.8	86.0	88.5	81.9 - 88.5
87	91.0	90.5		86.8	93.8	93.5 left handed	90.5 - 93.8
88	92.0	91.0	87.6	88.4	92.7	94.4	88.4 - 94.4
89	61.4	60.7	56.9	59.2	59.1	62.6 63.0 left measured twice	59.1 - 62.6
90	64.1	65.2	59.6?	66.2	63.1	66.8	59.6 - 66.8
91	23.8	16.2	20.0	23.5	20.6	22.8	16.2 - 23.8
92	61.0	60.0	56.4	57.2	63.1	62.3	56.4 - 63.1
93	56.6	53.6	50.0	52.3	33.7 55.4 55.9	55.9	50.0 - 56.6
94	46.7	44.2	42.7	43.2	45.8	45.8	42.7 - 46.7
95	5.4	6.0	5.9	6.4	5.2	6.0	5.2 - 6.4
96	6.0	10.0	9.0	8.0	9.3	10.5	6.0 - 10.5
97	7.0	8.0	7.0 at center	7.0	7.2	8.0	7.0 - 8.0

TABLE 1. INDIVIDUAL MEASUREMENTS, DAISY TEST SUBJECTS (page 6)

Measurement No.	Subject No. 1	Subject No. 2	Subject No. 3	Subject No. 4	Subject No. 5	Subject No. 6	Range
98	26.5	26.2	25.7	26.9	25.5	25.8 long toe nail	25.5 - 26.9
99	9.5	9.0	9.0	10.4	9.6	10.0	9.0 - 10.4
100	19.4	18.8	17.9	18.8	19.3	19.1	17.9 - 19.4
101	10.6	10.5	9.9	11.1	10.7	10.4	9.9 - 11.1
102	8.4	8.7	8.4	9.1	8.9	9.0	8.4 - 9.1
103	2.8	2.8	3.4	2.8	3.0	2.8	2.8 - 3.4
104	181.5 standing	177.0	169.8	175.1	185.7	184.4	175.1 - 185.7
105	228.1	220.0	211.2	119.2	229.1	231.3	119.2 - 231.3
106	83.4	(1) 85.9 (2) 83.7 (3) 81.7	80.3 left	80.9	88.7	84.0 left	80.3 - 88.7
107	99.7	99.5	88.8	91.9	100.0	100.5	91.9 - 100.5
108	80.5	79.4	74.2	79.0	84.9	78.8 left	74.2 - 84.9

TABLE 2. A COMPARISON OF HOLLOMAN SLED TEST SUBJECTS WITH 1950 AIR FORCE STUDY

Measurement	Percentile Range for Holloman Subjects
1 - weight	8 to 95 percentile
2 - stature	15 to 80 percentile
4 - cervicale height	18 to 85 percentile
5 - acromiale height	12 to 90 percentile
7 - suprasternale	9 to 81 percentile
8 - substernale	11 to 93 percentile
11 - waist height	2 to 85 percentile
19 - crotch height	9 to 60 percentile
23 - biacromial diameter	4 to 89 percentile
24 - bideltoid breadth	10 to 81 percentile
41 - neck circumference	1 to 98 percentile
42 - shoulder circumference	2 to 86 percentile
44 - chest circumference	3 to 97 percentile
48 - waist circumference	10 to 94 percentile
49 - hip circumference	9 to 85 percentile
50 - thigh circumference (L)	10 to 91 percentile
51 - thigh circumference (R)	6 to 91 percentile
52 - lower thigh circumference	1 to 40 percentile
55 - calf circumference	35 to 97 percentile
57 - ankle circumference	45 to 96 percentile
58 - upper arm circumference	2 to 98 percentile
60 - lower arm circumference	4 to 86 percentile
61 - wrist circumference	18 to 71 percentile
62 - fist circumference	25 to 63 percentile
63 - head circumference	5 to 98 percentile
65 - head breadth	40 to 99 percentile
66 - head length	3 to 99 percentile
67 - anterior neck length	46 to 94 percentile
68 - upper neck circumference	1 to 98 percentile
69 - posterior neck length	16 to 70 percentile
70 - lower neck circumference	14 to 98 percentile
71 - erect sitting height	14 to 66 percentile

TABLE 2. A COMPARISON OF HOLLOMAN SLED TEST SUBJECTS WITH 1950 AIR FORCE STUDY (page 2)

Measurement	Percentile Range for Holloman Subjects
72 - erect sitting eye height	10 to 66 percentile
81 - hip breadth (sitting)	2 to 90 percentile
89 - shoulder height (sitting)	49 to 89 percentile
92 - buttock-knee length	9 to 89 percentile
93 - knee height (sitting)	2 to 73 percentile
94 - popliteal height	41 to 97 percentile
97 - lateral malleolus height	55 to 96 percentile
98 - foot length	15 to 60 percentile
99 - foot breadth	7 to 94 percentile
100 - hand length	10 to 70 percentile
101 - hand breadth at thumb	55 to 96 percentile
102 - hand breadth at metacarpale	14 to 74 percentile
103 - hand thickness at metacarpale III	16 to 99 percentile
104 - arm span	26 to 77 percentile
106 - arm reach from wall	4 to 56 percentile
107 - maximum reach from wall	9 to 70 percentile
108 - functional reach	2 to 75 percentile

2.2. RANGE OF MOTION MEASUREMENTS

In addition to defining the shape of the body, it was necessary to develop a set of range of motion measurements capable of being used as input to mathematical models in order to define the locations of stops limiting rotations between adjacent body segments. A series of fifteen measurements was taken involving standing, sitting, prone, and kneeling subjects. In each case, the subject was asked to assume the position required for a measurement and a photograph was taken to document the position. Each measurement was repeated three times. The angular stop locations were determined directly from the photographs and an average of the three measurements computed. The individual measurements are described in the following list.

1. Elbow Flexion

   The subject stands with his right side facing the camera. The right elbow is flexed so that the plane described by the upper and lower arm is perpendicular to the direction in which the camera is pointing. The acute angle between the upper and lower arm is measured to define the location of the elbow flexion stop.

2. Elbow Extension

   The subject stands with his right side facing the camera. The right elbow is extended so that the plane described by the upper and lower arm is perpendicular to the direction in which the camera is pointing. The obtuse angle between the upper and lower arm is measured to define the location of the elbow extension stop.

3. Back (hip) Dorsal Extension

   The subject stands with his right side facing the camera. He is instructed to lean backwards as far as possible keeping the knees locked. The arms may be extended to the front for the subject to keep his balance. The purpose is to flex at the waist. The acute angle between a line constructed along the upper leg and a line constructed parallel to the back defines the location of the back dorsal extension stop.
   This measurement was difficult to make and could be improved by targeting body landmarks or by x-ray techniques.

4. Hip Lateral Bend (right)

   The subject stands facing the camera. He is instructed to lean to right side as far as possible keeping the knees locked and not twisting the hips. The arc described by the body during the rotation should be in a plane perpendicular to the direction in which the camera is pointing. The acute angle between lines constructed parallel to the lower extremities and parallel to the midline of the torso defines the location of the stop limiting hip lateral bending motion. This measurement was difficult to make because of the uncertainty of the location of the torso midline but could be improved by targeting body landmarks or by x-ray techniques.

5. Hip Lateral Bend (left)

This measurement is similar to the previous one.

6. Hip Twist (rotation)

The subject stands facing the camera. He is instructed to twist his upper torso to the right as far as possible keeping the knees locked and the lower extremities facing front. The objective was to determine the voluntary twist motion possible in the torso. Only a rough estimate of this quantity was possible without body landmark targets, and an additional camera to take the three-dimensional nature of the measurement into consideration.

7. Shoulder Flexion (right shoulder maximum overhead)

The subject stands with his right side facing the camera. He is instructed to flex his right arm to its maximum extent overhead. The right arm was to be kept straight and the arc through which the arm was swung described a plane perpendicular to the direction in which the camera was pointed. The obtuse angle between a line drawn along the upper arm and a line drawn parallel to the back of the subject defines the location of the shoulder flexion stop.

8. Shoulder Extension (right shoulder maximum dorsal)

The subject stands with his right side facing the camera. He is instructed to extend his right arm to its maximum extent rearward. The right arm was to be kept straight and the arc through which it was swung described a plane perpendicular to the direction in which the camera was pointed. The acute angle between a line drawn along the upper arm and a line drawn parallel to the back defines the location to the shoulder extension stop.

9. Neck Ventral (forward) Flexion

The subject sat with his right side facing the camera. He was instructed to bend his head forward to its maximum extent while keeping his back against the seat. The acute angle between a line drawn parallel to the back and a line drawn parallel to the back of the head-neck combination was used to define the location of the neck ventral flexion stop. This was a difficult measurement to make because of the lack of body landmark targets and because of the curvature in the upper thoracic and cervical spines. It should be noted that much of the ventral flexion takes place in the upper thoracic spine, a fact which should be noted in designing future dummies and mathematical crash victim simulators. X-ray studies of this motion should be made in order to chose both joint locations and motion limiting stops with a greater degree of accuracy.

10. Neck Dorsal (rear) Extension

The subject sat with his right side facing the camera. He was instructed to bend his head to the rear its maximum extent while keeping his back against the seat. The acute angle between a line drawn parallel to the back and a line drawn parallel to the back of the head was used to define the location of the neck dorsal extension stop. This was a difficult measurement to make because of the difficulty of locating the line defining the location of the head and because of the curvature of the spine. A comparison of the results of this measurement should be made with neck ventral flexion. In that case much of the rotation took place in the upper thoracic spine whereas in dorsal extension most of the motion was in the upper cervical spine. Thus it is possible that one neck joint location should be used for forward crash simulations and another for rearward crash simulations. This should be confirmed in X-ray studies of neck motion.

11. Torso Maximum Flexion

The subject sat with his right side facing the camera. He was instructed to bend forward the maximum extent possible keeping his knees together. The acute angle between a line drawn parallel to the upper leg and a line connecting the estimated center of gravity of the upper torso with the estimated hip point defines the location of the torso flexion stop. This measurement was difficult to perform because of spinal curvature, the uncertainty of the upper torso center of gravity and the uncertainty of the hip point. X-ray studies will be necessary in order to define this quantity with accuracy.

12. Knee Flexion (voluntary)

The subject was face down on a table with his right side facing the camera. He was instructed to flex his right knee the maximum possible extent. The acute angle between a line drawn parallel to the lower leg and a line drawn parallel to the upper leg defines the knee flexion stop.

13. Neck Roll

The subject sat facing the camera. He was instructed to roll his head to the side keeping his eyes forward and without moving his upper torso. The acute angle between a line drawn parallel to the midline of the torso and a line drawn parallel to the midline of the head defines the neck roll stop.

14. Neck Lateral Rotation (yaw)

The subject was prone on the table with his head in the direction of the camera. He was instructed to twist his head to the right side the maximum amount possible relative to the torso. The acute angle between a line drawn parallel to the top of the table and a line running fore-aft along the midline of the head defines the neck lateral rotation stop.

15. Knee Flexion (forced)

The subject kneeled on the table top with his right side facing the camera. He was instructed to put the maximum weight possible over his hip in order to flex his knee the maximum amount. The acute angle between a line drawn along the lower leg and a line drawn along the upper leg defines the forced knee flexion stop. It should be noted that there is approximately 20° difference between the locations of the forced and voluntary knee flexion stops. Certainly a greater difference exists between the voluntary stop and the flexion required to cause injury than exists between the voluntary and forced stops indicating that the stop locations determined by these measurements represent a conservative motion limit beyond which the potential exists for injury.

TABLE 3. RANGE OF MOTION MEASUREMENTS

Measurement	Subject No. 1	Subject No. 2	Subject No. 3	Subject No. 4	Subject No. 5	Subject No. 6
Elbow Flexion	28.8	38.6	39.7	35.2	34.2	36.1
Elbow Extension	180.	180.	180.	180.	180	180.
Back Dorsal Extension	50.4	46.2	51.	57.3	31.9	50.5
Hip Lateral Bend (right)	34.9	46.8	36.2	39.0	39.6	47.9
Hip Lateral Bend (left)	44.8	45.1	32.1	48.7	35.4	50.2
Hip Twist	60-90	60-90	60-90	60-90	60-90	60-90
Shoulder Flexion	155.4	168.5	141.8	159.7	166.	169.3
Shoulder Extension	83.1	65.6	79.8	57.1	35.5	75.8
Neck Ventral Flexion	71.8	77.7	44.5	69.5	66.7	72.6
Neck Dorsal Extension	83.8	53.5	84.7	62.8	70.9	87.8
Torso Maximum Flexion	41.7	39.9	41.8	53.9	37.0	37.1
Knee Voluntary Flexion	37.6	50.2	47.0	45.9	46.5	42.0
Neck Roll	43.9	45.9	40.2	39.0	51.6	51.1
Neck Lateral Rotation	0.	9.8	12.8	14.9	15.6	21.1
Knee Forced Flexion	18.1	27.8	26.5	28.1	18.4	19.6

2.3 FOOT FORCE MEASUREMENTS

During the past few years it has been found that human volunteer impact sled test subjects are able to influence their motions in an impact environment by tensing their muscles. As an attempt to determine the level of force which can be voluntarily applied through the legs to resist motion, a series of foot force measurements were made on the Daisy sled. Each subject sat in usual test configuration on the sled,restrained with a lap belt, and was required to push as hard as possible with his feet. The Daisysled and a test subject are shown in Figure 1. Instrumentation consisted of force transducers measuring foot downward push into the transducer, force to the left or right on the transducer, and force on the transducer in the heel-to-toe direction. These are supplemented by the loads applied to the seat pan, the loads applied to the back of the seat, and the lap belt loads. The subjects were asked to repeat the push three times to provide an estimation of reproducibility. It should be noted that some subjects did not seem to be putting forth a maximum effort, and there may be not only variation here, but also a wide variation between the voluntary effort and the actual force exerted during an actual dynamic test. The force values measured in this test can be used to measure the torque potential at the knee point, an input variable of the mathematical model which can have a marked influence on body motions. The results of the tests are given in Table 4.

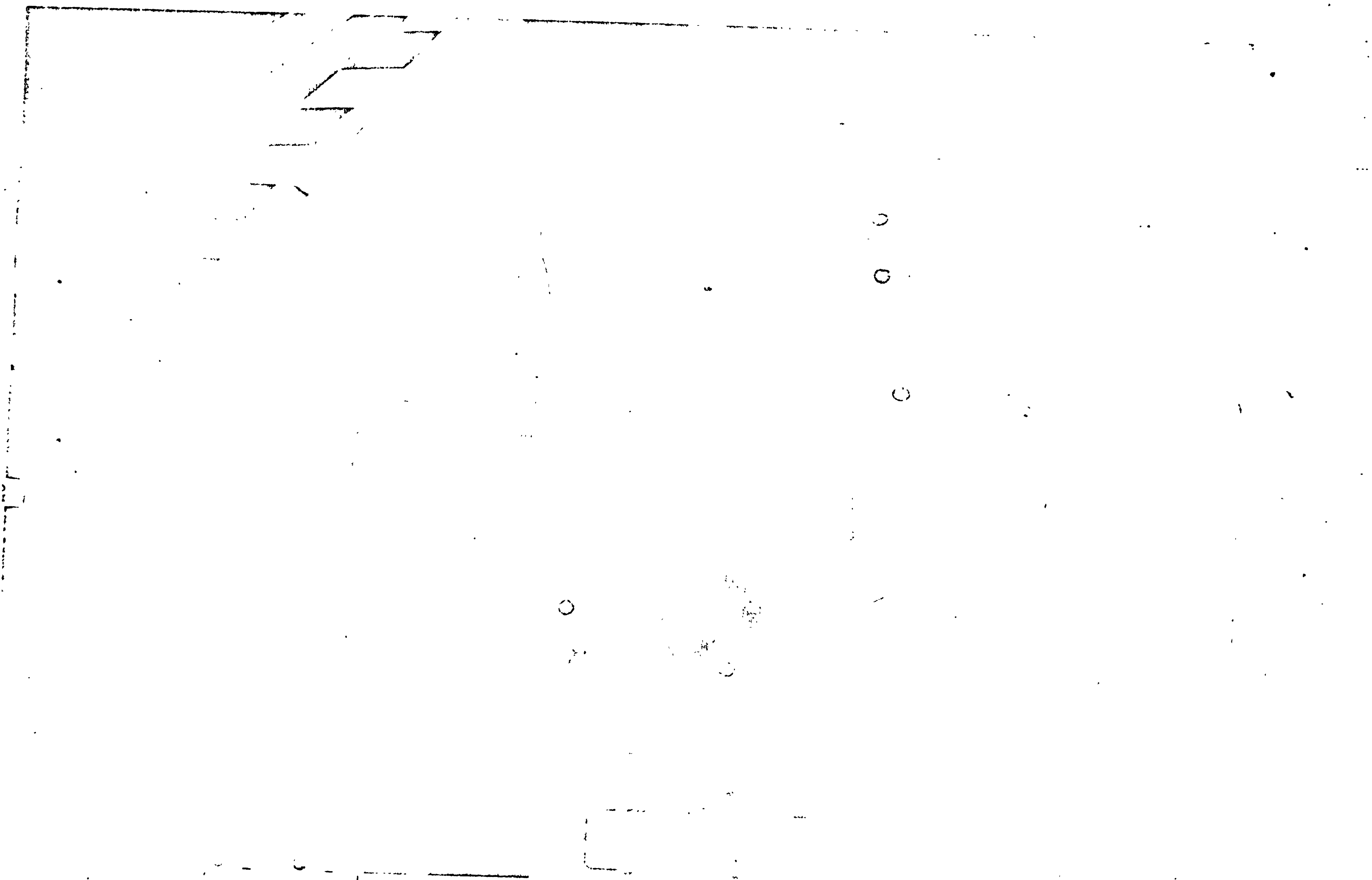

FIGURE 1. OVERALL TEST SETUP

TABLE 4. FOOT PUSH MEASUREMENTS

Subject	Left foot down, lbs.	Right foot down, lbs.	Left foot toe-heel force, lbs.	Right foot toe-heel force, lbs.	Left foot side force, lbs.	Right Foot side force, lbs.	Seat pan down-ward, force, lbs.	Seat pan down-ward, force lbs.	Seat back fore-ward, force, lbs.	Seat back vertical force, lbs.	Left lap belt lbs.	Right lap belt lbs.
No. 1	580	560	195	190	45	7	0	0	600	0	130	140
No. 2	970	1170	325	365	75	109	0	0	1170	55	200	210
No. 3	470	530	155	150	50	63	0	0	530	0	75	95
No. 4	640	530	175	170	55	48	0	0	560	0	90	110
No. 5	380	480	135	145	50	62	0	0	450	0	45	50
No. 6	620	550	140	85	45	30	0	0	650	0	175	245

3. COMPUTATION OF BODY MASSES, CENTERS OF GRAVITY, AND MOMENTS OF INERTIA

3.1 BODY SEGMENT WEIGHT

The weight of the body segments have been computed using the regression equations proposed by Barter.[2] These are restated here as

$$W \text{ (head and neck)} = .079\ \overline{W}$$
$$W \text{ (trunk)} = .391\ \overline{W} + 12.$$
$$W \text{ (upper arms)} = .08\ \overline{W} - 2.9$$
$$W \text{ (forearms and hands)} = .06\ \overline{W} - 1.4$$
$$W \text{ (upper legs)} = .18\ \overline{W} + 3.2$$
$$W \text{ (lower legs and feet)} = .13\ \overline{W} + 0.5$$

where $\overline{W}$ is the total body weight of the subject. The weights of the various body segments for each subject are given in Table 5.

3.2 A MODEL FOR BODY SHAPE AND MOMENTS OF INERTIA

A model of body shape has been developed to provide input for the HSRI Two-Dimensional Crash Victim Simulator.[3] The body has been divided into eight mass elements (head, upper torso, middle torso, lower torso, upper legs, lower legs, upper arms and lower arms) with seven joints (neck, shoulder, middle spine, lower spine, hip, knee, and elbow). A side view schematic of the body model is shown in Figure 2. The head-neck structure is modeled by the combination of an ellipsoid and a circular cylinder. The torso is split into three segments and includes the volume of the body between cervical vertebra No. 7 and the buttocks including the hip joint. The first element includes the volume included between cervical vertebra No. 7 and thoracic vertebra No. 12; the second element includes the volume between thoracic vertebra No. 12 and the waist; and the third element includes the pelvic structure, buttocks and hip joint. The upper legs are modeled by a truncated cone starting at the front of the abdomen (seated subject) and extending to the knee joint while the lower legs are modeled by the combination of two circular cylinders with perpendicular axis representing the lower leg and foot structures. Both the upper and lower arms are represented by circular cylinders. The formulas for computing the moments of inertia, and where difficult, the centers of gravity are given in the following 2-6. The dimensions of the various geometrical elements are given in Figures text and the various anthropometric quantities in Table 1. The moments of inertia are summarized in Table 6.

TABLE 5. BODY SEGMENT WEIGHTS (lbs.)

Body Segment	Subject No. 1	Subject No. 2	Subject No. 3	Subject No. 4	Subject No.5	Subject No. 6
head and neck	10.7	15.7	12.4	12.2	14.0	13.9
trunk	65.3	89.8	73.6	72.7	81.7	81.1
upper arms	8.0	13.0	9.7	9.5	11.3	11.2
forearms and hands	6.8	10.5	8.1	7.9	9.3	9.2
upper legs	27.7	39.0	31.6	31.1	35.2	35.0
lower legs and feet	18.2	26.4	21.0	20.7	23.6	23.4

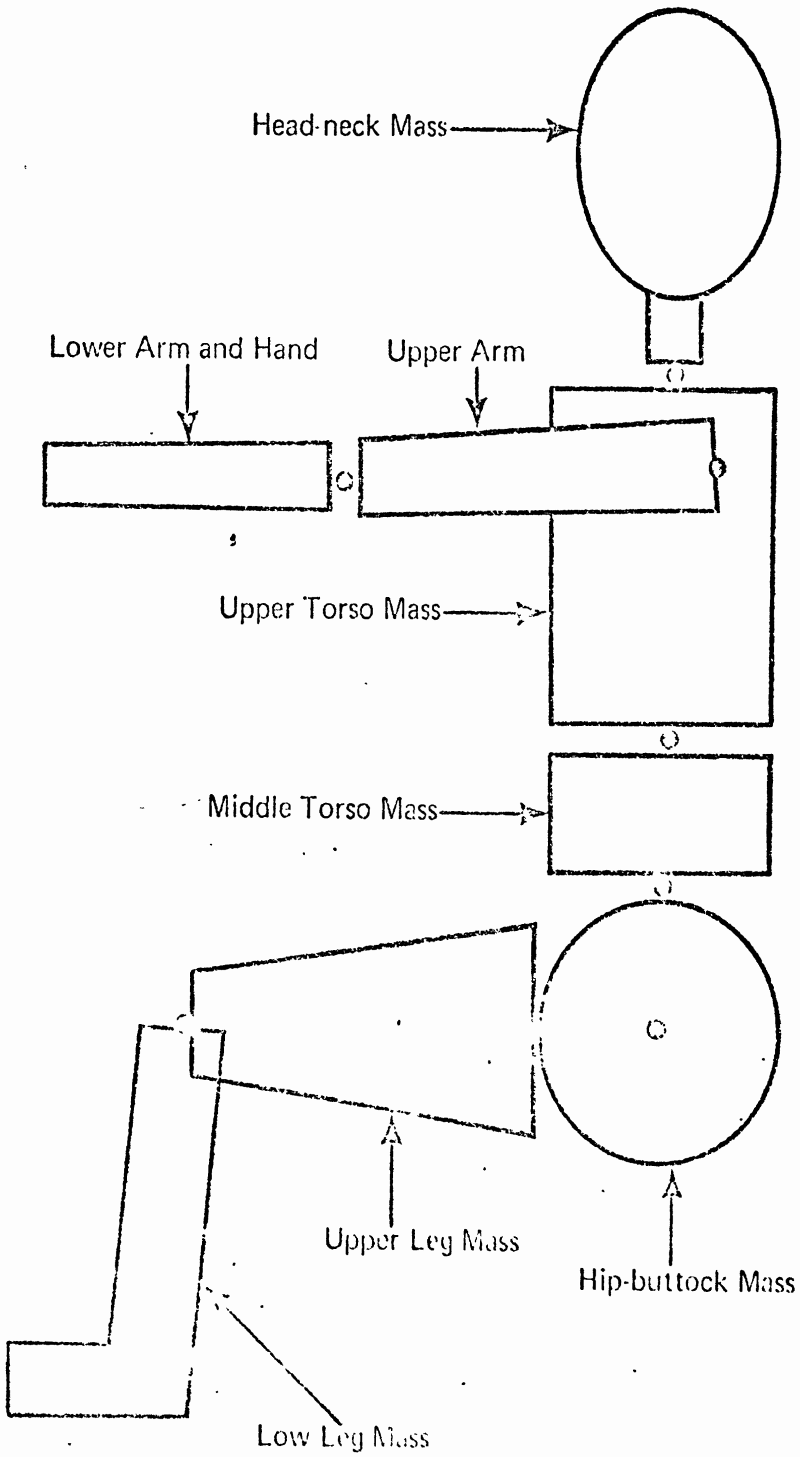

FIGURE 2. · SIDE VIEW SCHEMATIC OF BODY MODEL

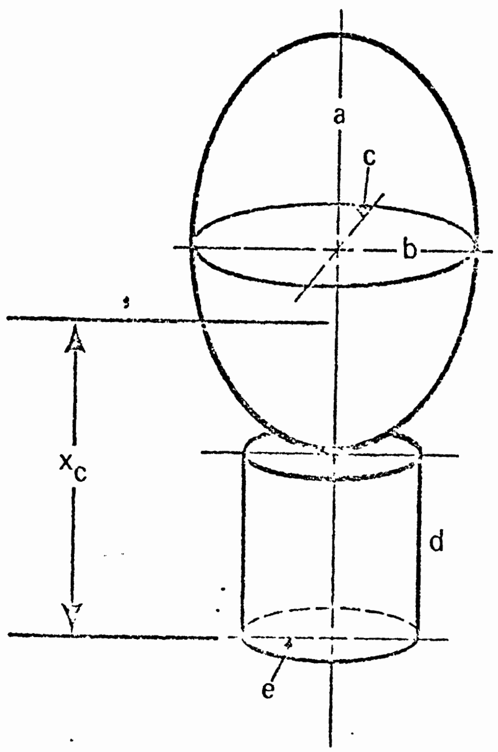

FIGURE 3. HEAD-NECK MODEL

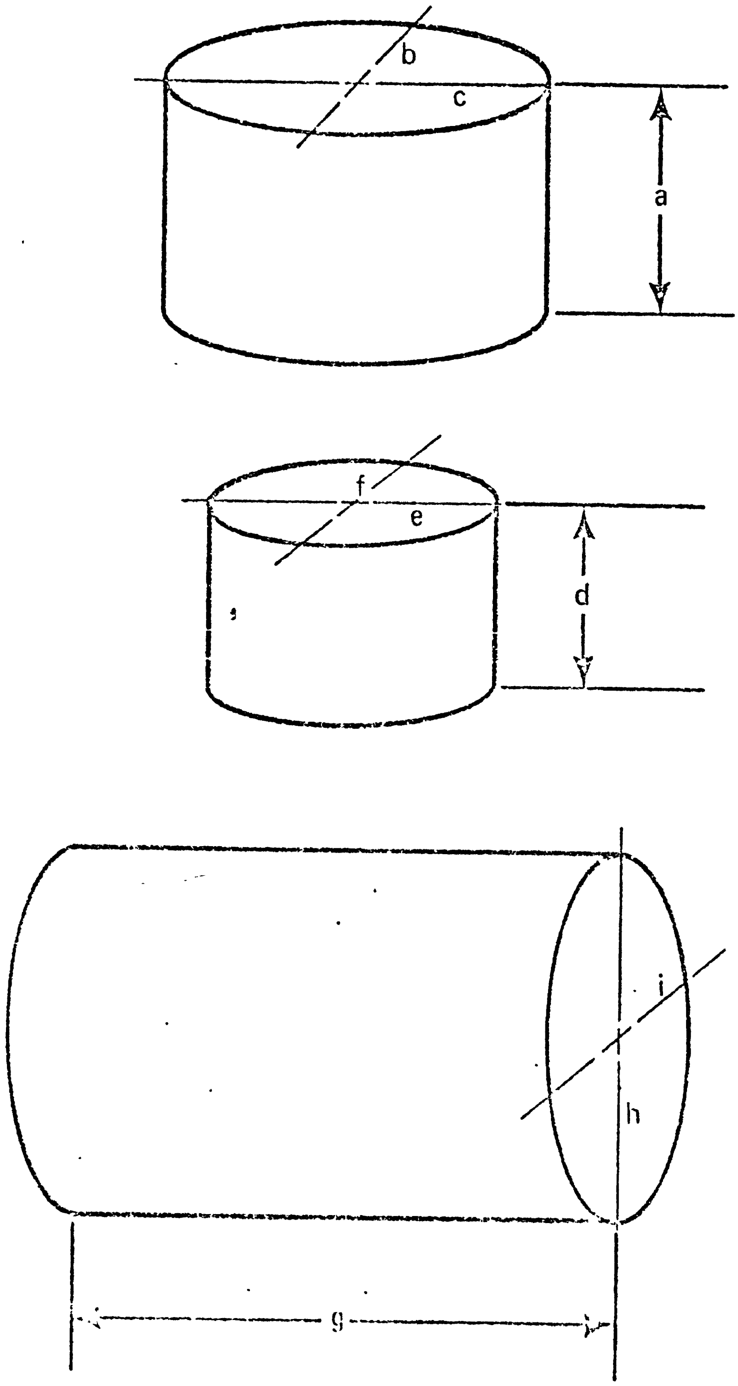

FIGURE 4. TORSO MODEL

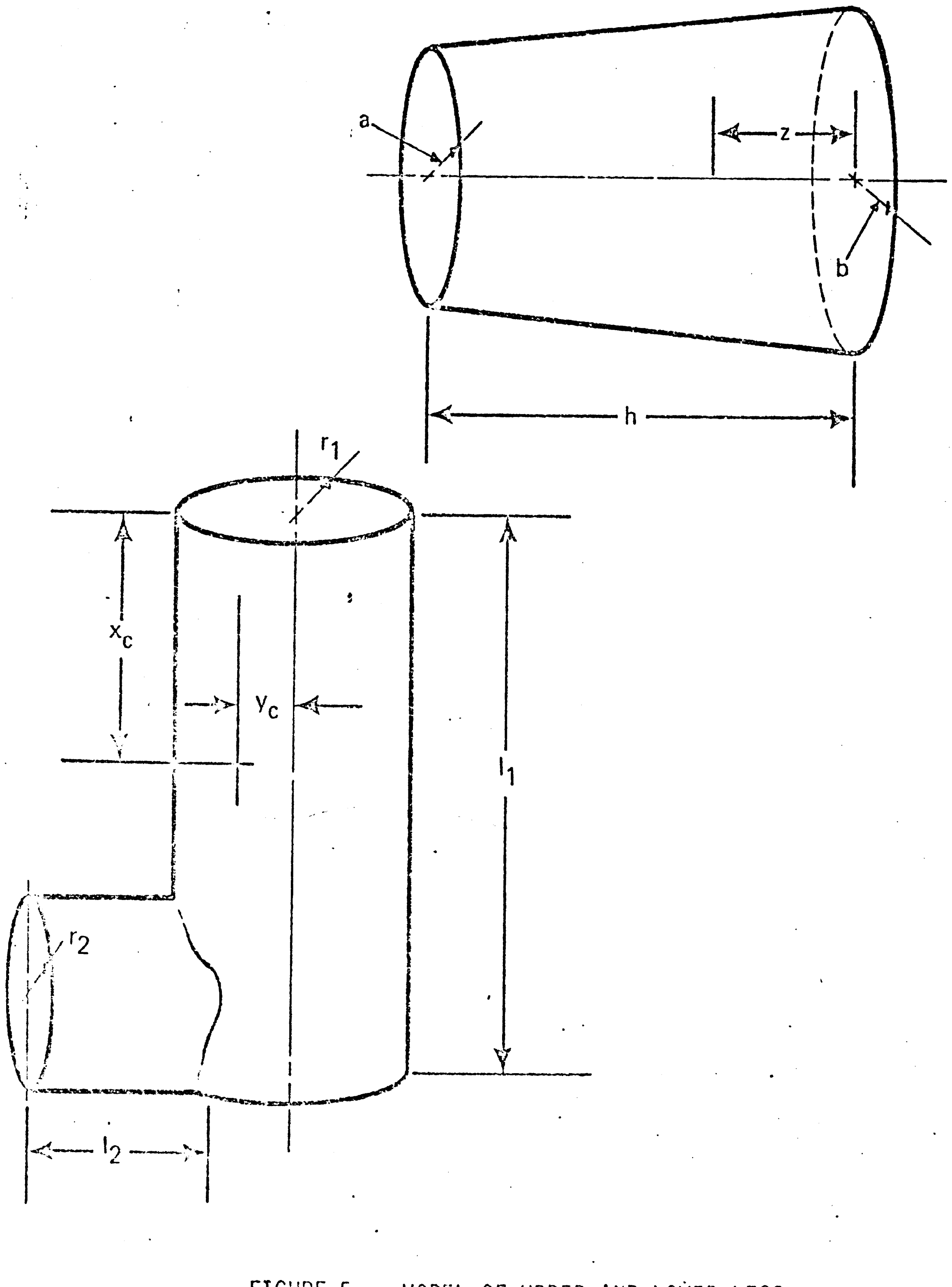

FIGURE 5. MODEL OF UPPER AND LOWER LEGS

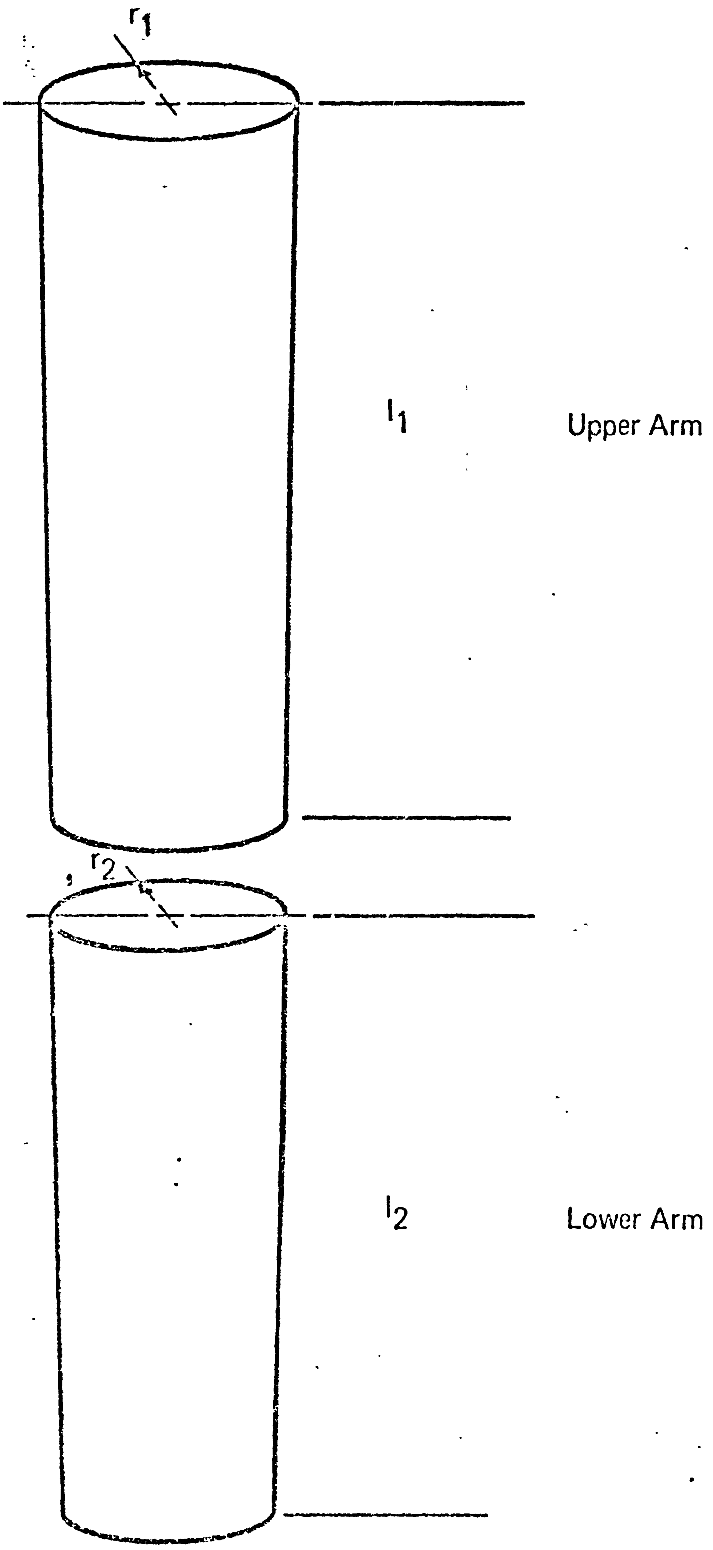

FIGURE 6. MODEL OF UPPER AND LOWER ARMS

The head is composed of two masses, an ellipsoid representing the head and a circular cylinder representing the neck as shown in Figure 3. The weight of these two segments is divided between them on a volume basis where

$$V_e = \frac{4}{3}\pi abc, \; V_e = \frac{\pi}{4} e^2 d$$

and

$$W_e = \frac{V_e}{V_e + V_c} W_t, \quad W_c = \frac{V_c}{V_e + V_c} W_t$$

where
V_e = volume of ellipsoid
V_c = volume of cylinder
W_e = weight of ellipsoid
W_c = weight of cylinder, and
W_t = weight of head-neck combination from Table V.

The center of gravity is given by

$$X_c = \frac{\frac{W_c d}{2} + W_e\,(a+d)}{W_t}$$

The moment of inertia of the head-neck combination is

$$I_{hn} = \frac{1}{12} M_c \left(\frac{3e^2}{4} + 4d^2\right) + M_c \left(X_c - \frac{d}{2}\right)^2$$

$$+ \frac{1}{5} M_e\,(a^2+c^2) + M_e\,(a+d-X_c)^2$$

where the dimensions are given by

$$a = (M_2 - M_3)/2$$

$$b = M_{65}/2$$

$$c = M_{66}/2$$

$$d = M_{71} - M_{90} - a$$

$$e = (M_{41} + M_{68} + M_{70})/3$$

and the subscript of M defines the anthropometric measurement in Table 1.

The torso weight is broken up into three parts: an upper torso (ut) represented by an elliptical cylinder, and a lower torso (lt) represented by an elliptical cylinder with its axis perpendicular to the axis of the other two. The dimensions of these geometrical figures as defined in Figure 4 and Table 1 are

$$a = M_4 - M_9$$

$$b = (M_{27}+M_{29}+M_{31})/6$$

$$c = (M_{26}+M_{28}+M_{30})/6$$

$$d = M_9 - M_{11}$$

$$e = (M_{32}+M_{34})/4$$

$$f = (M_{33}+M_{35}+M_{84})/6$$

$$g = (M_{37}+M_{81})/2$$

$$h = M_{91}/2$$

$$i = M_{36}/2$$

The mass of the torso as given in Table 5 is divided among the three body elements on a volume basis.

$$V_{ut} = \pi abc, \; V_{mt} = \pi def, \; V_{el} = \pi ghi$$

$$V = V_{ut} + V_{mt} + V_{el}$$

The weight of each segment is computed as

$$W_{ut} = W_t \, V_{ut}/V; \; W_{mt} = W_t \, V_{mt}/V; \; W_{el} = W_t \, V_{el}/V$$

The moments of inertia are then given by

$$I_{ut} = \frac{W_{ut}}{12g} (3b^2+4a^2)$$

$$I_{mt} = \frac{W_{mt}}{12g} (3f^2+4d^2)$$

$$I_{lt} = \frac{W_{mt}}{4g} (i^2+h^2)$$

The upper legs are represented as truncated circular cones as illustrated in Figure 5. The geometry is based on anthropometric measurements as follows

$$a = M_{52}/2\pi$$

$$b = (M_{50}+M_{51})/4\pi$$

$$h = M_{92} - M_{36}$$

The formulas for center of gravity, density, and moment of inertia are derived from Patten[4] and are stated as follows

$$\rho = 3\,W_{el}/[\pi g h(a^2+ab+b^2)]$$

$$\bar{Z} = \frac{h(3a^2+2ab+b^2)}{4(a^2+ab+b^2)}$$

$$I_{ul} = \pi h\rho\left[\frac{h^2(6a^2+3ab+b^2)}{30} + \frac{(a^4+a^3b+a^2b^2+ab^3+b^4)}{20}\right] - \frac{W_{ul}}{g}\bar{Z}^2$$

The lower legs are given by a combination of two circular cylinders as shown in Figure 5. The geometry is based on anthropometric measurements as follows

$$r_1 = (M_{55}+M_{56})/4\pi$$
$$l_1 = M_{22}$$
$$r_2 = M_{99}/2$$
$$l_2 = M_{98} - 2r_1$$

The weight of the lower leg and foot is distributed between the two cylinders on a volume basis the subscript "f" indicates the foot and "ll" indicates the lower leg

$$V_{ll} = \pi r_1^2 l_1, \quad V_2 = \pi r_2^2 l_2$$

$$W_f = \frac{V_f\,W_t}{V_f + V_{ll}}; \quad W_{ll} = \frac{V_{ll}\,W_t}{V_f + V_{ll}}$$

The center of gravity of the composite is defined by

$$X_c = \frac{\frac{W_{11} l_1}{2} + W_f(l_1 - r_2)}{W_{11} + W_f}$$

$$Y_c = \frac{W_f \left(r_1 + \frac{l_2}{2}\right)}{W_{11} + W_f}$$

The moments of inertia of the individual segments are

$$I_{11} = \frac{W_{11}}{12g}\left(3r_1^2 + 4l_1^2\right)$$

$$I_f = \frac{W_f}{12g}\left(3r_2^2 + 4l_2^2\right)$$

and the moment of inertia of the composite is

$$I = I_{11} + I_f + \frac{W_{11}}{g}\left[\left(X_c - \frac{l_1}{2}\right)^2 + Y_c^2\right]$$

$$+ \frac{W_f}{g}\left[(l_1 - r_2 - X_c)^2 + \left(r_1 + \frac{l_2}{2} - Y_c\right)^2\right]$$

The upper and lower arms are both modeled by circular cylinders as illustrated in Figure 6. The geometry is based on anthropometric measurements as follows

$$r_1 = \frac{1}{4\pi}\left(M_{53} + M_{59}\right)$$

$$l_1 = M_{77} - 1/2\, M_{23}$$

$$r_2 = \frac{1}{4\pi}\left(M_{60} + M_{61}\right)$$

$$l_2 = \frac{1}{2} M_{105} - M_{77}$$

The moments of inertia are

$$I_{ua} = \frac{W_{ua}}{12g}\left(3r_1^2 + 4l_1^2\right)$$

$$I_{la} = \frac{W_{la}}{12g}\left(3r_2^2 + 4l_2^2\right)$$

TABLE 6. COMPUTED CENTERS OF GRAVITY AND MOMENTS OF INERTIA

Quantity	Subject No. 1	Subject No. 2	Subject No. 3	Subject No. 4	Subject No. 5	Subject No. 6
I (head-neck)	1.150*	1.830	1.985	1.476	1.618	1.554
Distance from neck joint to head c.g.	7.4	7.6	8.8	7.9	7.7	7.5
I (upper torso)	5.54	10.26	9.78	4.46	9.13	5.28
Distance from neck joint to upper torso c.g.	7.25	7.1	7.85	5.95	7.2	6.4
I (middle torso)	0.638	1.016	0.136	0.551	0.193	0.521
Distance from T-12 to middle torso c.g.	1.6	3.15	1.25	2.7	1.4	2.45
I (pelvis-buttock mass)	0.546	0.441	0.549	0.517	0.669	0.691
Distance from hip point to pelvis-buttock mass c.g.	0.	0.	0.	0.	0.	0.
I (upper legs)	1.64	1.92	1.40	1.65	1.75	2.02
Distance from hip point to c.g. of upper legs	11.13	10.92	10.29	10.77	10.76	11.53
I (lower legs and feet)	4.47	5.67	4.68	4.99	5.91	5.90
Distance from knee to c.g. of lower legs and feet (X_c)	11.1	9.2	10.1	10.7	10.8	11.3
Distance from axis of lower leg to c.g. (Y_c)	1.4	1.2	1.3	1.6	1.3	1.5
I (upper arms)	1.183	1.317	1.079	1.170	1.664	1.388
Distance from shoulder to c.g. of upper arms	5.55	4.8	4.9	5.15	5.75	5.25
I (lower arms and hands)	2.158	2.458	2.060	2.100	2.818	2.925
Distance from elbow to c.g. of lower arms and hands	8.7	8.45	7.9	8.05	8.7	8.9

*NOTE: The units for moment of inertia are in lb sec^2 and for distance as inches.

3.3 COMPUTATION OF MOMENTS OF INERTIA FOR HUMAN SUBJECTS USING ANTHROPOMETRIC MEASUREMENTS

The anthropometric measurements described in Part 2.1 of this report have been selected to provide a map of the outer boundaries of the human body. Extracted from this list were 44 measurements which have been used to compute the moments of inertia as outlined in Part 3.2. These are given in Table 7. The fact that all measurements have not been used in computing the moments of inertia is based on two reasons. First, some classical measurements which were made allow comparison of the test subjects with the results of previous anthropometric studies in order to determine his relative size but do not offer meaningful input to mathematical models. The second reason is that the list of measurements represents a conservative initial attempt to include all potential measurements which might be useable in providing inputs to mathematical models.

The model chosen for the head is based on the fact that in ventral flexion the pivot point for the head-neck mass appears to be lower on the neck than in dorsal extension. The head dimensions are chosen as follows: 1. head height (2a) from stature and chin height; 2. head breadth (2b) directly; 3. head length (2c) directly; 4. neck length (d) from cervicale height and sitting height; and 5. neck diameter from circumferences measured at three locations.

The torso has been divided into three masses, again based on observations of body flexibility. The joints are chosen at T-12 height, at the waist, and at the hips. The upper and middle masses are chosen to be elliptical cylinders while the hip mass is a circular cylinder with its center of gravity located at the hip point. The torso dimensions are chosen as follows: 1. upper torso height (a) from cervicale and T-12 heights; 2. upper torso breadth (2c) from breadth measurements at three locations along the height; 3. upper torso depth (b) from depth measurements at three locations along the height; 4. middle torso height (d) from waist and T-12 heights; 5. middle torso breadth (2e) from breadth measurements at two locations along the height; 6. middle torso depth (2f) from depth measurements at two locations along the height; 7. hip breadth (g) from measurements at the trochanter and of seated hip breadth; 8. hip mass height (2h) from sitting waist height; and 9. hip mass depth (2i) from hip depth.

TABLE 7. ANTHROPOMETRIC MEASUREMENTS USED IN MOMENT OF INERTIA COMPUTATIONS

M_1 - body weight
M_2 - stature
M_3 - menton height
M_4 - cervicale height
M_9 - T-12 height
M_{11} - waist height
M_{22} - lower patellar height
M_{23} - biacromial diameter
M_{26} - chest breadth
M_{27} - chest diameter
M_{28} - chest breadth at xiphoid
M_{29} - chest depth at xiphoid
M_{30} - T-12 chest breadth
M_{31} - T-12 chest depth
M_{32} - chest breadth at inferior margin of rib cage
M_{33} - chest depth at inferior margin of rib cage
M_{34} - waist breadth
M_{35} - waist diameter
M_{36} - hip depth
M_{37} - hip breadth at trochanter
M_{41} - neck circumference
M_{50} - left thigh circumference at crotch
M_{51} - right thigh circumference at crotch
M_{52} - lower thigh circumference
M_{55} - calf circumference
M_{56} - lower leg circumference
M_{58} - upper arm circumference
M_{59} - elbow circumference
M_{60} - lower arm circumference
M_{61} - wrist circumference
M_{65} - head breadth
M_{66} - head length
M_{63} - upper neck circumference

TABLE 7. ANTHROPOMETRIC MEASUREMENTS USED IN MOMENT OF INERTIA COMPUTATIONS

M_{70} - lower neck circumference

M_{71} - erect sitting height

M_{77} - elbow clearance out (horizontal)

M_{81} - sitting hip breadth

M_{84} - seat back to abdomen

M_{90} - seated cervicale height

M_{91} - sitting waist height

M_{92} - buttock - knee length

M_{98} - foot length

M_{99} - foot breadth

M_{104} - arm span

The legs are split into two masses. The upper leg includes that portion of the upper leg in front of the hip mass which extends to the knee joint. It is modeled by a truncated circular cone. The lower leg is modeled to include the foot mass and includes two circular cylinders - one extending from the knee to the heel and the other representing the forefoot. The leg dimensions are chosen as follows: 1. upper leg mass length (h) from buttock-knee length and hip depth; 2. upper leg mass maximum radius (b) from thigh circumference at crotch; 3. upper leg mass minimum radius (a) from lower thigh circumference; 4. lower leg length (l_1) directly; 5. lower leg radius (r_1) as an average from lower leg and calf circumferences; 6. forefoot length (l_2) using foot length; and, 7. forefoot radius (r_2) from foot breadth.

The arms are also split into two masses, both of which are modeled by circular cylinders. The lower arm is assumed to have the fingers extended. The arm dimensions are chosen as follows: 1. upper arm length from elbow clearance out and biacromial diameter; 2. upper arm radius from upper arm circumference and elbow circumference; 3. lower arm length from arm span and elbow clearance out; and, 4. lower arm radius from lower arm and wrist circumferences.

3.4 DISCUSSION

Part 4 of this report has outlined procedures for computing body masses, centers of gravity, and moments of inertia based on a series of classical and non-classical anthropometric measurements. Several other investigators have developed either analytical or experimental procedures for determining these quantities. Much of this work is summarized in Reference 4 and the results show a great deal of divergence. In some instances the values of moment of inertia obtained in the present study are considerably larger than those obtained in other studies.

Two recommendations can be made which should aid in reconciling the differences predicted by the various investigators. The first is to determine the sensitivity of moments of inertia to the values of the various anthropometric quantities. This could lead to refinements and/or simplifications in the formulas proposed in this report. The second is to use the moments of inertia, as predicted by the various investigators, in running the HSRI Two-Dimensional Crash Victim Simulator to determine the sensitivity of predicted motions to variations in moment of inertia input data. In case wide variations in moments of inertia do not significantly affect the motions, then the simplest estimates of these quantities should be adequate for most simulation tasks.

4. PREPARATION OF DATA SET FOR USE WITH HSRI TWO-DIMENSIONAL MATHEMATICAL CRASH VICTIM SIMULATOR

The next several paragraphs describe the preparation of an input data set for use with the HSRI Two-Dimensional Crash Victim Simulator which is intended to describe Holloman Daisy Sled Test No. 5228. Three major parameter groups must be determined for any input data set - occupant description, deceleration pulse shape, and seat-restraint system environment.

4.1 OCCUPANT

4.1.1. Mass, Geometric Properties, and Initial Position. The weight of the eight body segments have been determined in Part 3.1 of this report. The masses for these segments are: 1. lower torso (0.072 lb sec^2/in); 2. middle torso (0.0238 lb sec^2/in.); 3. upper torso (0.121 lb sec^2/in.); 4. head (0.0363 lb sec^2/in.); 5. upper arms (0.0292 lb sec^2/in.); 6. lower arms (0.0241 lb sec^2/ in.); 7. upper leg (0.0912 lb sec^2/in.); and, 8. lower legs (0.0611 lb sec^2/in.).

Table 6 gives the locations for the various centers of gravity and the values of the moments of inertia associated with each mass element. The lengths of the body elements have been chosen so that the radius of contact sensing circles attached to the extremities (head, hand, buttock, and foot) must be added to give total body length. The lengths of the various elements are: 1. lower torso (4.1 in.); 2. middle torso (2.8 in.); 3. upper torso (14.4 in.); 4. head (7.7 in.); 5. upper arm (11.5 in.); 6. lower arm (15.4 in.); 7. upper arm (18.8 in.); and, 8. lower arm (16.1 in.). The distance from the upper spine joint (T-12) to the shoulder joint is 12.8 in.

For the prediction of force interactions between the subject and the Daisy sled a series of contact-sensing circles are attached to the body. The hip contact radius is chosen to be 4.3 inches which represents a compromise on the distance between the hip point and seat cushion and the distance between the hip point and seat back. The chest contact radius, which will be used to predict the force applied to the chest by the airbag, is chosen to be 4.9 in. which represents the length of the semi-minor axis of the elliptical cylinder used to compute the moment of inertia of the upper torso. The radius of the head contact circle is chosen to be 3.7 in., which is the semi-minor axis of the head ellipsoid in the direction of head depth. The elbow radius is 1.7 in. based on elbow circumference; the hand radius is 2.0 in. based on fist circumferences; the knee radius is 2.48 in. based on knee circumference; and the foot radius is 1.9 in. based on foot width.

The initial position of the body is based on the position of the occupant as measured at the beginning of the test. This is similar to Figure 1 and the values are given in Figure 7.

4.1.2. Description of Joint Structures. The properties of the joint structures are described in the model in terms of four quantities: range of motion, friction torque, force-deformation characteristics of joint stops, and spring characteristics of the joint in its range of free motion. The range of motion data given in Table 3 provided directly all joint stop locations with the exception of the upper and lower spine stops and hip stop. These were determined from the torso maximum flexion photographs to be 41.0° for the lower spine (waist), 25.5° for the upper spine (T-12) and 71.3° for hip flexion.

No data is available on joint friction torques, joint elasticity, and joint stop elasticity. Joint stop elasticity models the behavior of the joint under stress when it is forced to stretch beyond the ordinary range of motion. Because of the potential for injury in determining values for this quantity, no measurementes were made. The stops were chosen to be very stiff springs (minimum of 40,000 in lb/rad).

Joint elasticity is a quantity resisting motion between the stops. Because muscle tone is believed to exert a constant torque during the brief impact event, the values for this quantity have been chosen to be zero.

Friction torque is used to approximate a constant torque resisting angular motion at the joints. It is particularly applicable to the case of anthropometric dummies where the joints can be torqued to a prescribed setting. Three potential values for this quantity are available. The first is the standard 1 G setting often used with dummies. Based on the weight and center of gravity of the lower leg, the 1 G torque at the knee should be 249 in lb. It is impossible to condition a human volunteer to preset all his joints at a particular torque. Based on foot, seat pan, seat back, and belt transducer loads, the torque at the knee was approximately 360 in lb.

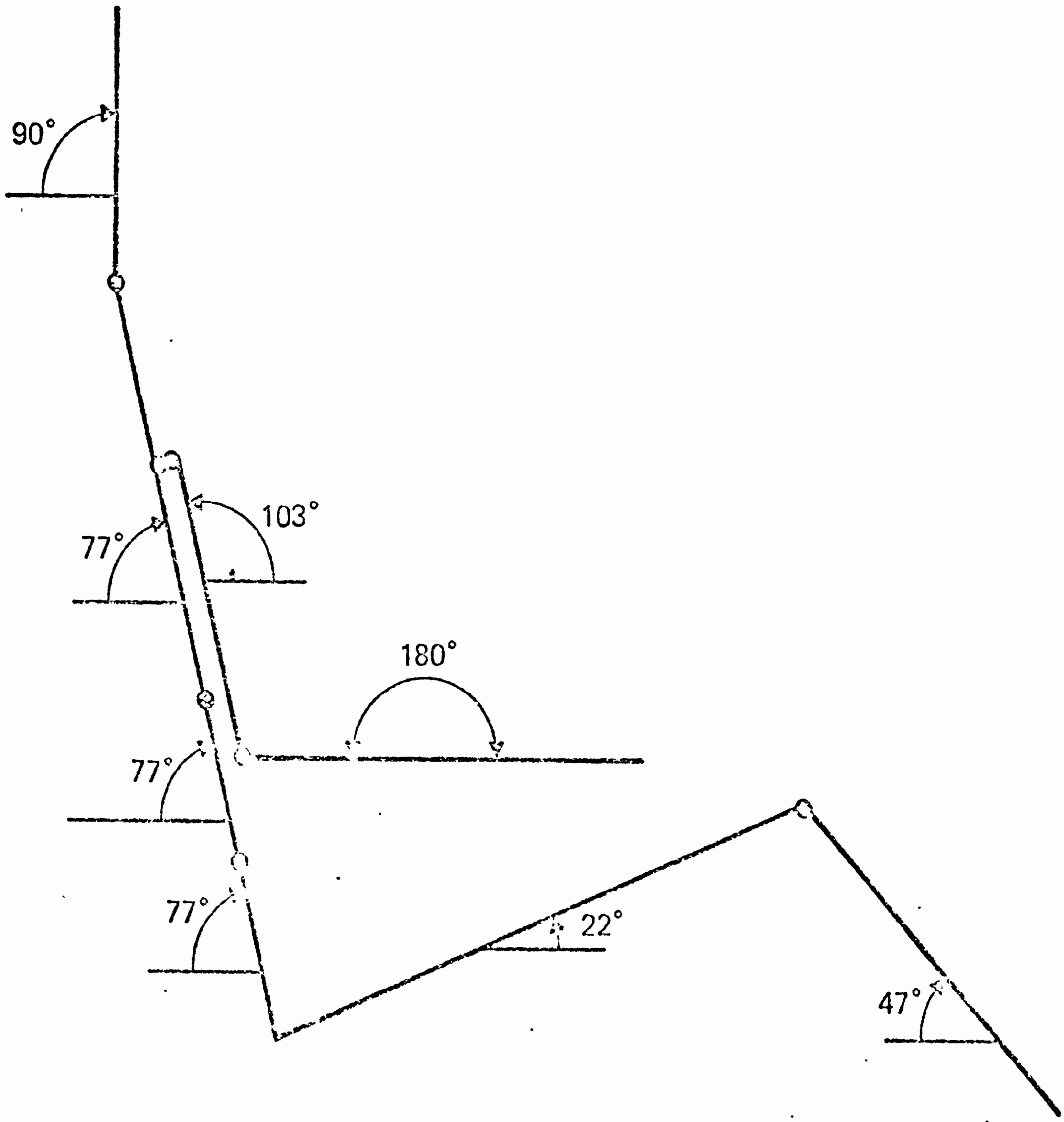

FIGURE 7. INITIAL BODY POSITION

as the sled entered the brake during the test. The volunteer was tensed beyond the 1 G level. Using data from the same load cells in the static foot push measurements described in Part 2.3 of this report., the voluntary maximum foot push yielded a knee torque of about 5040 in.lb. This corresponds to torquing the knees to 20 G's and indicates the potential which the subject has for influencing his motions. For the computer simulation a value of 360 in.lb.was chosen for the knee joint based on the measurement at the time of the test. The other joints were assumed to be loose (0 in.lb.torque) on the basis of a lack of data. Parameter studies should be carried out on this particular quantity using the mathematical model to determine the magnitude of the effect which the subject can exert on his motions.

4.2 INPUT DECELERATION FROM DAISY SLED

The input deceleration which drives the mathematical model was determined directly from the light beam oscillographic record made at the time of the test. Table 8 describes this pulse as a series of straight line segments suitable for use with the Crash Victim Simulator.

4.3 SEAT AND RESTRAINT ENVIRONMENT

The seat and restraint environment has been modeled by a lap belt, seat cushion, seat back, floor, toe board, chest airbag contact and head airbag contact. Each of these surfaces is located for the simulation as it was during the test to apply forces to the body of the subjects. Figure 1 shows the subject prior to the test. The belt, seat, and foot contacts retain the geometry shown. However, the airbag is located to represent its fully inflated position just before the occupant moves into contact with it. Both the chest and head airbag contacts are modeled by vertical surfaces located initially approximately 1/2 inch in front of the chest and head contact-sensing circles.

The seat cushion is represented by a horizontal surface. Because the actual seat consisted of an essentially rigid plate covered by a two inch foam pad(which nearly bottomed out under the weight of the subject), it was given the properties of a stiffening spring which produces 500 lb. during the first inch of deflection and 2325 lb. during the second inch and increases load substantially at larger deflections. It was observed during the test that the ratio of forward loading to downward loading on the seat pan was

TABLE 8. SLED DECELERATION PULSE

Time (sec)	Deceleration (in/sec^2)
0.	0.
0.025	- 1261.
0.050	- 3240.
0.058	- 3660.
0.067	- 3870.
0.075	- 3660.
0.100	- 2565.
0.125	- 1303.
0.142	- 463.
0.160	0.

0.73. A value of 0.73 was chosen for seat cushion friction on that basis. The seat back was modeled in a similar manner.

The seat belt was modeled as a linear spring. Slack was assumed to be zero. The force-deformation coefficient for the spring (566 lb/in) was determined on the basis of elongations observed in the high speed motion pictures plotted against forces recorded from the belt load transducers. The procedures were similar to those outlined in Reference 3.

The test subjects kept their feet in position on the foot force transducers during the tests. Therefore, the toe board was modeled as a stiff spring (1000 lb/in) to minimize motion. The surface was also provided with friction to minimize motion along the surface and with energy absorption to minimize rebound.

The airbag contact surfaces were both modeled as springs during initial impact. In each case, the load-limiting mechanism available on the mathematical model was used to prevent loads from exceeding a maximum value (1160 lb. for chest and 164 lb. for head) while deflection increased. This was used effectively to model energy absorption while the subject was riding down the airbag. The force deflection profiles were prepared using the techniques outlined in Reference 5.

5. COMPARISON BETWEEN DAISY TRACK TEST AND COMPUTER SIMULATION

The HSRI Two-Dimensional Crash Victim Simulator was exercised using the data set outlined in Part 4 of this report. The resulting computer printout was then compared with the data gathered during Daisy Test No. 5228 and presented in Figures 99, 101, and 102 of reference 6. A tabulation of the peak values observed in the test and predicted using the model are given in Table 9. All these quantities were easy to measure with the exception of head forward motion. In that case only an estimate was possible as the head was enveloped by the airbag.

TABLE 9. COMPARISON OF PREDICTED AND EXPERIMENTAL RESULTS

Quantity	Test	Simulation
head forward motion-in	6.7	5.9
head downward motion-in	3.2	3.3
head angle to rear-deg.	19.4	19.8
head resultant peak G-level	11.7	13.8
head angular acceleration - rad/sec^2	330	283

Figures 8, 9, and 10 of this report show linear and angular motions as well as accelerations experienced by the head. The horizontal and vertical motions are given in Figure 8. The magnitude of both vertical and horizontal motions is similar in the two cases. The G-loadings experienced by the head in the two cases are shown in Figure 9. The shape, phase, and magnitude of the curves are quite good. Figure 10 shows pitch angular motion quantities for the head. The magnitudes of rearward whiplash motion, the angular velocity, and angular acceleration were similar in both cases. The head does not appear to experience the same degree of rebound in the simulation as was the case in the test. It is possible that the amount of energy absorption assumed in the computer simulation was greater than that which actually occurred in the tests.

This preliminary computer simulation of human motions in an impact environment has yielded results which are sufficiently accurate to show the promise of analytical tools as a supplement to test programs. This tool may be used to

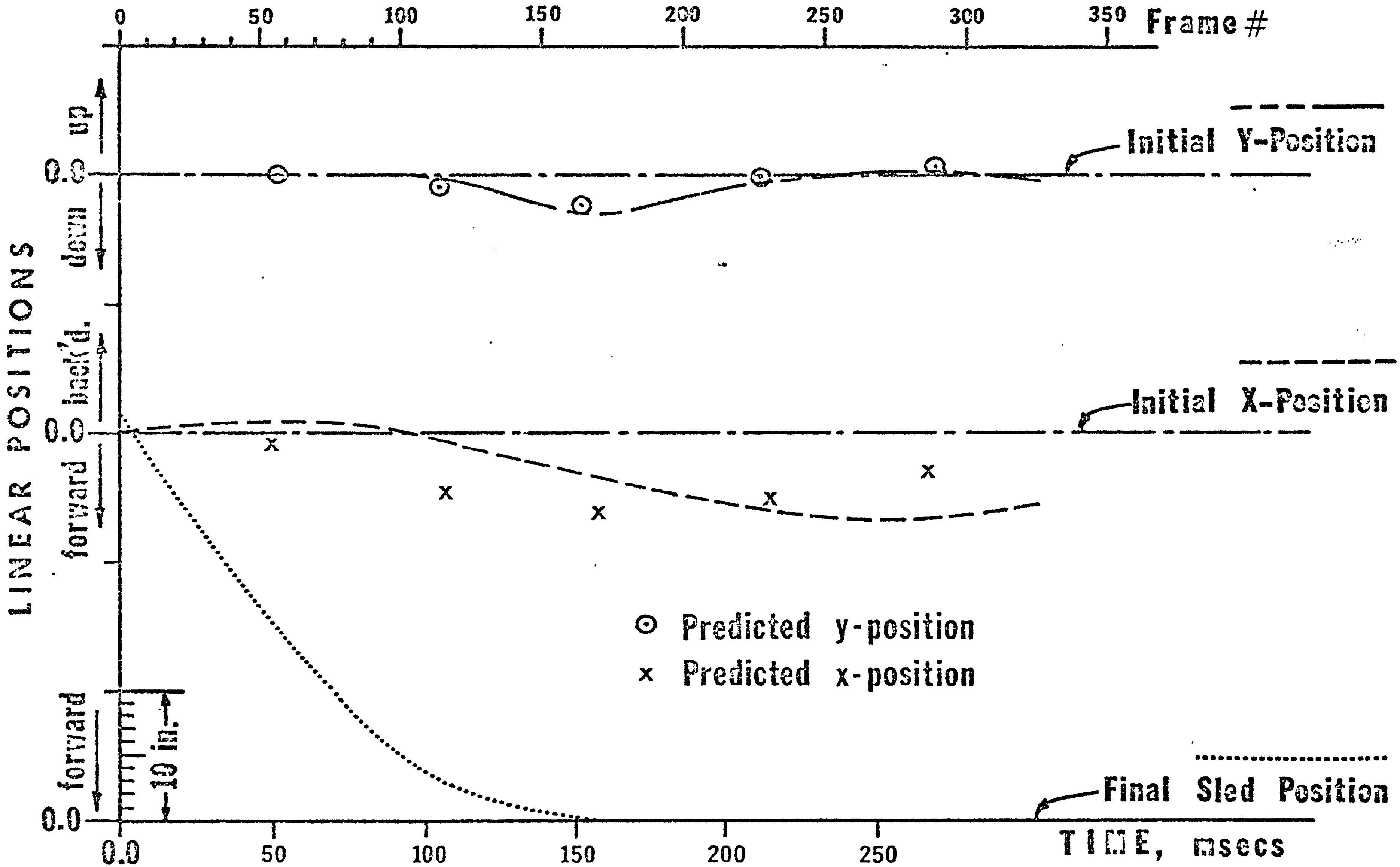

Fig. 8 HEAD MOTION Run Nr. 5228

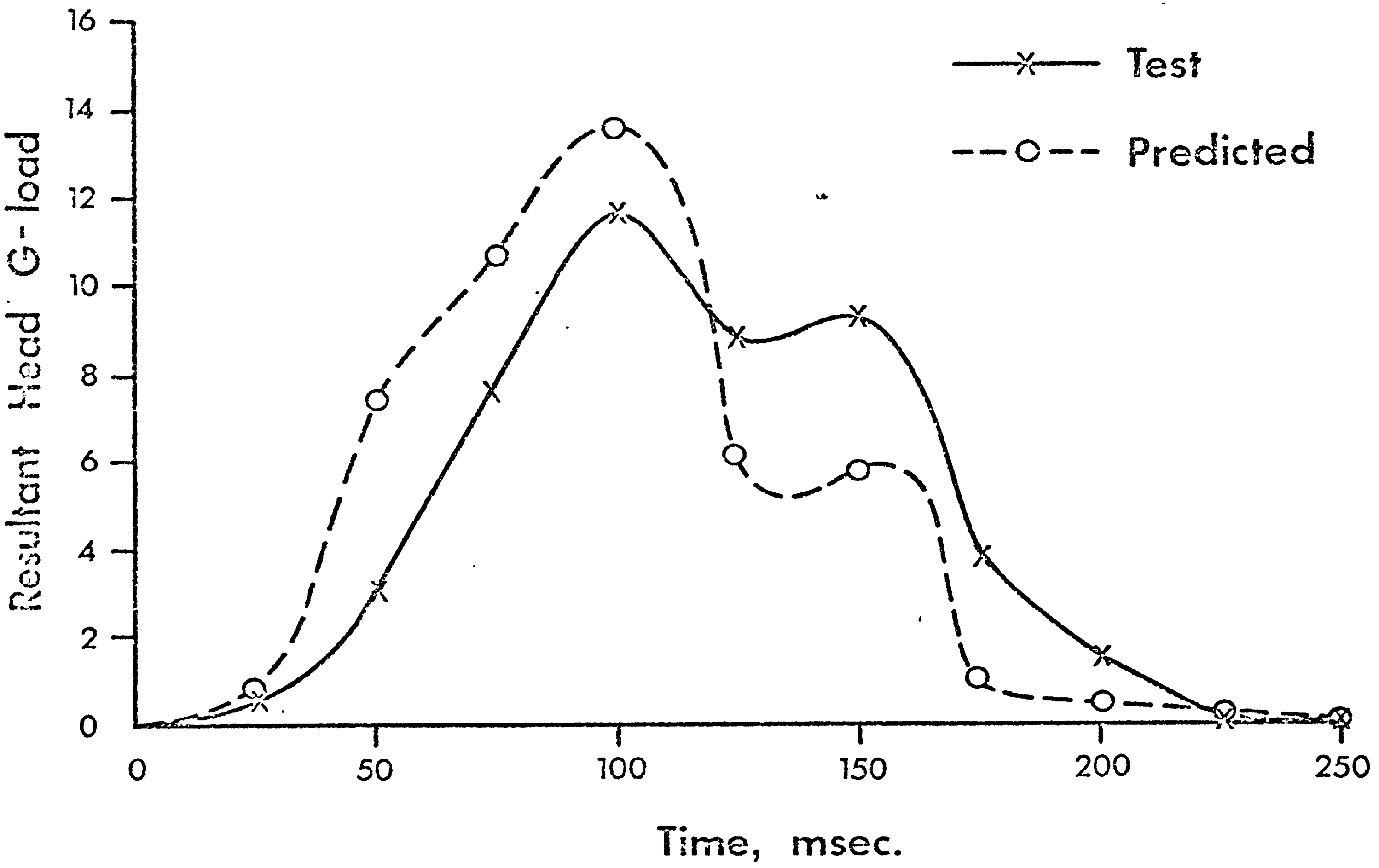

FIGURE 9. HEAD G-LOADING

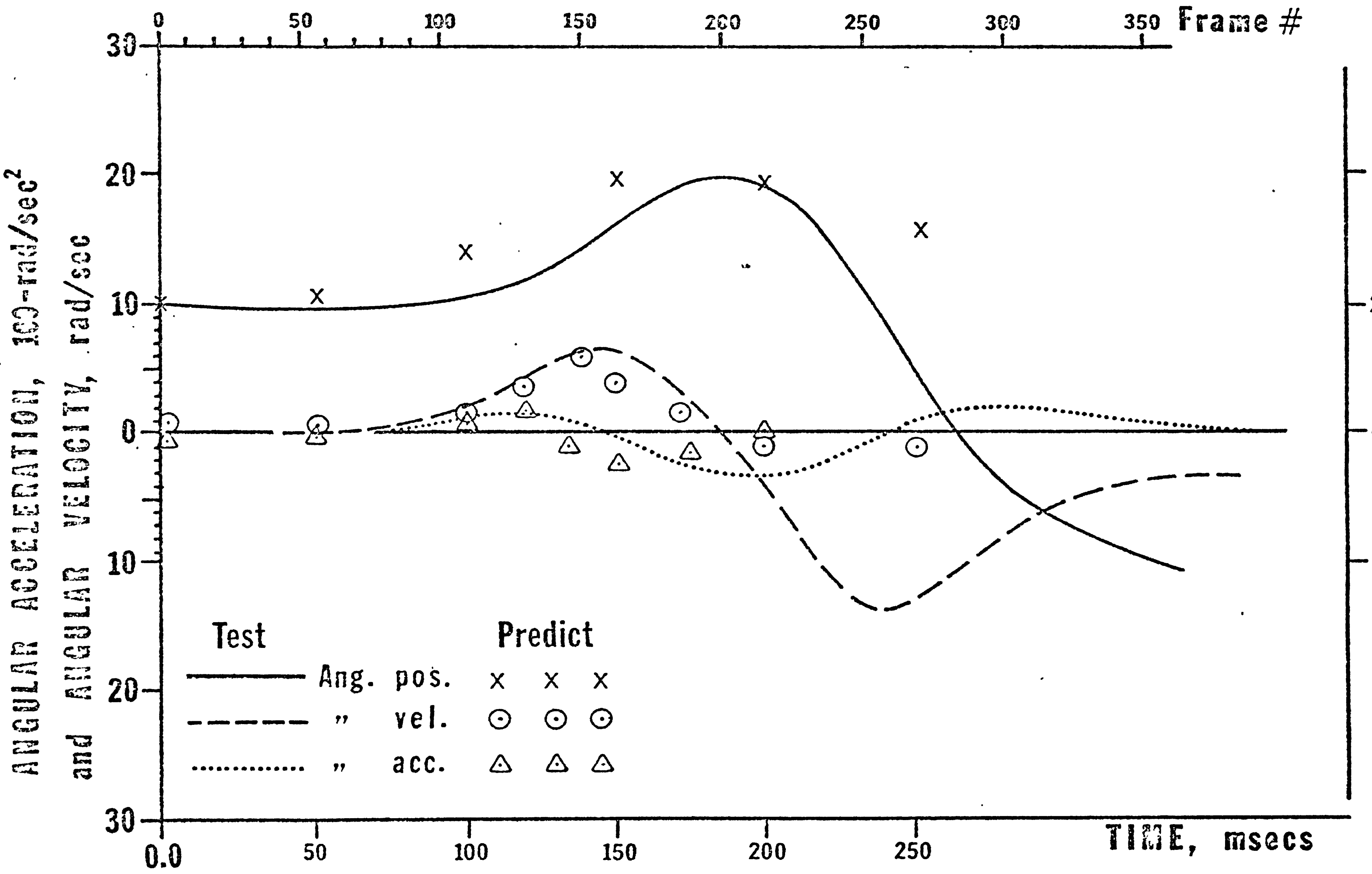

Fig. 10 HEAD MOTION Run Number 5228

compare the results of dummy tests with human tests. For example, the model can be used to duplicate both a human and a dummy test. Because the input data describing the joint properties such as muscle tone are well-defined in the model, the differences in these quantities necessary for correlation with test data in the two cases can be compared. The observed differences, particularly in the physical properties of the joint structures, could lead to suggestions for design improvements in dummies.

An additional application of the analytical tools can be made to human tolerance test programs. The models can be used as a rough guideline to estimate the added loadings which might be expected on the volunteers when impact velocity is increased during a test series. This could supplement the medical data available to the test program coordinators.

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