CENTER OF GRAVITY AND MOMENTS OF INERTIA OF HUMAN HEADS

by

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I INTRODUCTION

Certainly, the head and the neck are among the most exposed elements to acceleration hazards. To apply the effects of experimentally produced impact accelerations utilizing human volunteers to the complete variety of the human being with respect to size, weight, attitude etc. as well as to extrapolate the results up to and even beyond human tolerance by mathematical and physical models, physical data of these elements have to be acquired on a broad scale. About the center of gravity of human heads relative to the long axis reported HARLESS (1), DEMPSTER (2), and CLAUSER et al. (3). WALKER et al. (4) determined the mid-sagittal coordinates of the center of gravity of 17 embalmed cadavers. Their results are directly comparable to the data of this paper, since we adopted their plane of dissection and refer to the same coordinate reference system. Some inertial properties are known from the works of DEMPSTER (2) and LIU et al.(5). There is, however, still a lack of three-dimensional data on the mass distribution of human heads, and the values known from measurements on preserved cadaveric specimens ask for validation under utmost 'living' conditions; i. e. fresh cadaveric material, since whole body measurements on living human beings can not provide these data. Therefore measurements were performed on fresh human cadavers in order to determine

- the three-dimensional location of the center of mass of the head related to an anatomically based coordinate reference system,
- the moments of inertia of the head about any axis in this anatomically based coordinate reference system.

II MATERIAL

Fresh, unpreserved human heads of 19 male and 2 female cadavers have been investigated. These specimens were selected from the autopsies, done at the Institut für Rechtsmedizin der Universität München during the period of 1975 to 1977. Attention was paid that the selected cadavers did not show any evidence of

TAB. 1: CAUSE OF DEATH AND PHYSICAL DATA OF THE CADAVERS

Ser. No.	Age at death (years)	Body length (cm)	Body weight (Kg)	Cause of death	Measure ment p.m.
1	21	173	59	Undetermined	1d
2	41	187	88	Coronary trombos.	44h
3	48	175	66	Traum.rupt. heart	86h
4	54	160	53	Coronary trombos.	43h
5	51	156	69	Traum.rupt. aorta	3d
6	40	175	61	Undetermined	2d
7 ♀	43	165	82	Drug overdose	5d
8	59	179	81	Carbonmonoxide	3d
9	--	179	66	Drowning	--
10 ♀	51	160	68	Drug overdose	3d
11	43	169	85	Myocardial infarc.	2d
12	50	178	99	Carbonmonoxide	--
13	52	180	79	Myocardial infarc.	3d
14	19	181	70	Drug overdose	4d
15	64	172	72	Carbonmonoxide	38h
16	36	177	95	Drug overdose	5d
17	39	185	73	Drowning	12h
18	35	172	65	Drowning	2d
19	28	177	85	Drowning	2d
20	28	176	77	Drowning	3d
21	41	172	76	Drug overdose	2d

extensive blood loss, head injuries, bodily abnormalities, wasting desease or significant alterations due to immersion in water where it applies.

Age at death, body length and weight, cause of death and time elapsed between death and measurements are recorded for all specimens in Tab. 1. The ages at death range from 19 to 64 years with a mean value of 42.4 years and a median of 42 years. The body lengthes range from 156 to 185 cm with a mean value of 173 cm and a median of 175 cm. The body weights range from 53 to 95 Kg with a mean value of 74 Kg and a median of 73 Kg.

III METHODS AND DEFINITIONS

Preparation of the specimens and measurements were done at room temperature of 20 to 22 ^{O}C. Until these procedures could be performed the cadavers were stored at 4 to 6 ^{O}C. Maximum time elapsed between death and measurement was 5 days. Prior investigation has shown that there is no significant change in brain weight of fresh cadavers kept at 4 to 6 ^{O}C within at least the first one hundred hours after death (6).

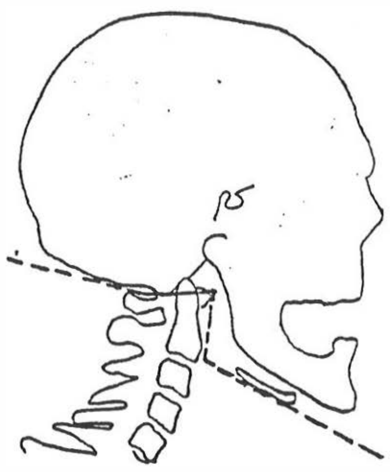

Fig. 1: Plane of division

The plane of division of the head from the neck as indicated in Fig.1 was that developed by WALKER et al. (4): The head is removed from the neck by a cut originating at a point about 2 cm below the external occipital protuberance and proceeding anteriorly and inferiorly to the atlanto-occipital joint. The cut proceeds to a point anterior to the prevertebral muscle mass. At this point, it intersects with a cut which begins at a point immediately inferior to the hyoid bone and extends cranially and posteriorly toward the cut described above.

The head was removed from the cadaver using a special procedure to maintain a standard distribution of fluids in the specimen, i.e. that of a cadaver laying supine upon a table. Following the dissection the large vessels are tied up, the small ones cauterized. The foramen magnum is plugged with a small piece of tissue paper, and the whole surface sealed with hot paraffin. This technique guaranteed that the weight losses during the course of the measurements are kept within 1 % of the total head weight. The additional mass due to the paraffin, tissue and suture material is less than 25 g.

The measurements proceeded in the following order: (1) Head weight, (2) Radiography, (3) Center of Gravity, (4) Moment of Inertia, (5) Final Head Weight, (6) Reference Measurements.

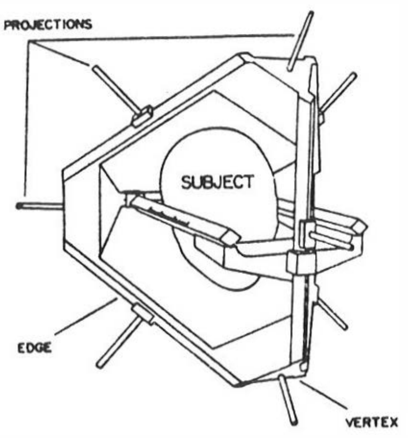

Fig. 2: Stereotaxic jig.

The procedures for measuring the center of gravity and the moments of inertia are that developed by BECKER (7). In these procedures, the head is placed in a stereotaxic jig as shown in Fig. 2. This stereotaxic jig is designed to facilitate the center of gravity and moment of inertia measurements.

In addition to these measurements, the settings of the stereotaxic unit are recorded in order to locate the head anatomical coordinates relative to the jig hardware.

For center of gravity measurements the jig is positioned to rest on three of its edge-midpoint projections and the load on each projection is measured using a load cell. Since the jig can be supported on each of four different sets of these projections, a total of twelve measurements is obtained. The use of the load cell yields measurements accurately to within ±.005 LBS (±2.3 g) and is recommended in Ref.(7) over the balance employed there.

For the determination of the inertial properties the jig is suspended from three wires in the manner of a trifilar pendulum. (The suspension of the jig from the wires differs slightly from the technique described in Ref.(7), since a cup and cone device was provided which permits much closer control of pendulum geometry.) There are ten different orientations in which the jig may be suspended, four involving suspension by three of the vertexes and six more involving two vertexes and one edge-midpoint projection.
A light beam reflects from a mirror positioned on the jig in such a manner that slight rotational oscillations of the pendulum sweep the beam edge back and forth across a light sensitive device. This light sensitive device is coupled to an electric counter which measures the time for one hundred oscillations with an accuracy of one millisecond. The measurement is made twice for each of the ten orientations, and three times, if the difference between the first two readings exceeds one hundred milliseconds.

After completion of these measurements the head is removed from the jig, the holding devices are reset to their initial positions, and all measurements repeated on the empty jig for reference. The calculations are made as described by BECKER (7).

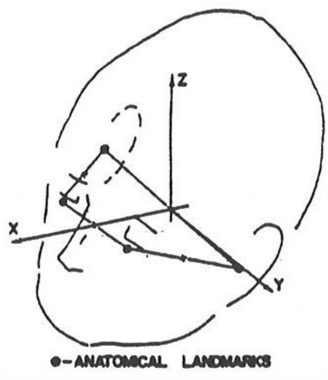

Fig. 3: Coordinate reference system (Ref. 8)

The coordinate reference system to which all locations and directions of the physical head data refer is that described by THOMAS (8) and shown in Fig. 3. It is based on four anatomical landmarks located on the skin over the left and right infraorbital notches and at the superior edge of the left and right external auditory meati. These four points are assumed conplanar (Frankfort Plane). The origin is at the midpoint of the left and right infraorbital notches. The X-Z plane is considered the mid-sagittal plane.

IV RESULTS

IV-1 HEAD WEIGHTS

The head weights are recorded along with body length and weight for each of the subjects in Tab. 2. The head weights listed are

TAB. 2: HEAD WEIGHT AND CENTER OF GRAVITY

Ser. No.	Body Length (cm)	Body Weight (Kg)	Head Weight (g)	Head (Loss) (g)	Center of Gravity X (cm)	Y (cm)	Z (cm)
1	173	59	4207	(115)	0.72	-0.17	3.25
2	187	88	4120	(31)	1.37	-0.05	2.18
3	175	66	3949	(18)	1.05	-0.11	3.31
4	160	53	4028	(5)	0.85	-0.12	3.35
5	156	69	4025	(15)	0.88	-0.05	2.85
6	175	61	4190	(32)	1.02	-0.14	3.11
7	165	82	4544	(5)	0.28	0.05	2.96
8	179	81	4652	(21)	0.69	-0.19	4.24
9	179	66	4319	(37)	0.68	0.00	4.20
10	160	68	3705	(18)	0.66	-0.17	2.87
11	169	85	4350	(19)	0.63	0.34	2.70
12	178	99	4335	(7)	0.40	-0.15	2.67
13	180	79	4749	(13)	1.10	0.00	4.13
14	181	70	4627	(46)	0.90	0.03	3.31
15	172	72	4251	(15)	0.72	0.07	2.98
16	177	95	5257	(10)	1.13	-0.15	2.94
17	185	73	4269	(5)	0.62	-0.09	3.17
18	172	65	3676	(9)	0.97	-0.26	2.67
19	177	85	3938	(28)	1.14	-0.10	2.53
20	176	77	4142	(25)	0.79	-0.04	2.67
21	172	76	5069	(5)	0.82	0.15	3.72

those taken before the measurements. The loss shown is the difference between these weights and those taken after completion of the measurements. With the exception of specimen No. 1 the weight losses encountered are all less than 1 % of the total head weight.
The head weights range from 3676 to 5257 g. The mean value is 4305 g, the standard deviation is 402 g. Applying the T-test, no significant difference is found to the sample of 17 preserved specimens investigated by WALKER et al. (4), whose data yield a mean head weight of 4376 g and a standard deviation of 591.

IV-2 CENTER OF GRAVITY

The center of gravity in the anatomically based coordinate reference system is recorded in Tab. 2.
The distributions of the X, Y and Z coordinates are shown in the histograms of Fig. 4 to Fig. 6. The values range

for the X-coordinate from 0.2 to 1.3 cm,
for the Y-coordinate up to ± 0.3 cm,
for the Z-coordinate from 2.2 to 4.3 cm.

The data show that the center of gravity is located almost exactly in the X-Z-plane of the anatomical coordinates which is the mid-sagittal plane of the head. The maximum deviation from this plane is less than 3 millimeters.

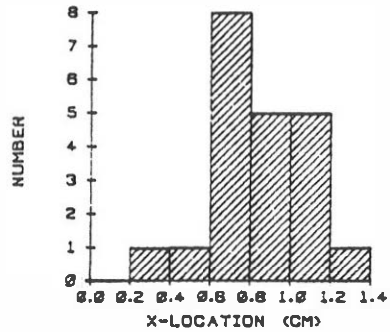

Fig. 4: Distribution of the X-coordinates of the center gravity.

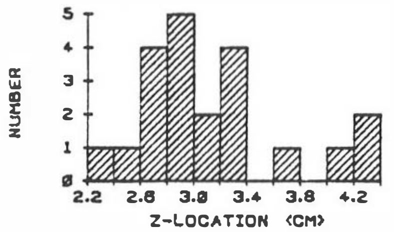

Fig. 5: Distribution of the Z-coordinates of the center of gravity.

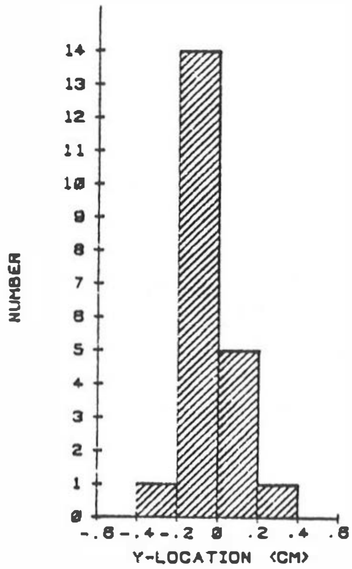

Fig. 6: Distribution of the Y-coordinates of the center of gravity.

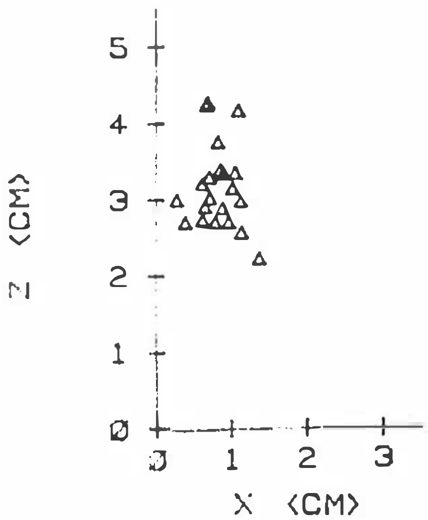

Fig. 7: Location of the center of gravity within the X-Z-plane.

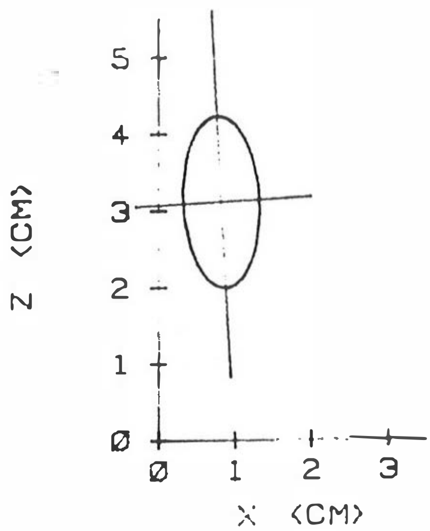

Fig. 8: Location of the mean center of gravity within the X-Z-plane and the 2s-ellipse of standard deviation.

TAB. 3: ANALYSIS OF THE CENTER OF GRAVITY DATA

	BEIER ET AL.					WALKER ET AL. (4)	
	Mean	Std.Dev.	Eigenvektors			Mean	Std.Dev.
X	.83	.25	.990	-.136	.054	1.42	.76
Y	-.05	.13	.137	.990	-.004	--	--
Z	3.12	.56	-.053	.012	.999	2.41	1.03
Number of Specimens:			21			17	

The locations of the centers of gravity within the X-Z plane are shown in Fig. 7. The means and standard deviations are given in Tab. 3. As a mean, the center of gravity of the head is located within the mid-sagittal plane, 0.8 cm in front of the auditory meatuses and 3.1 cm above the Frankfort Plane (Fig. 8).

The matrix of the Eigenvectors (Tab. 3) - which gives the orientation of the ellipsoid of variance - may be considered as a unit matrix and the distribution of the variance on each of the three axes assumed to be independent. Thus the principal values give the standard deviation of each of the three axes. In Fig. 8 the distribution within the X-Z-plane is revealed by the 2s-ellipse about the mean center of gravity.

For comparison, the mean and standard deviation calculated from the data published by WALKER et al. (4) are added to Tab. 3. Applying the T-test a significant difference (p = 0.01 and 0.05 resp.) exists between the means of WALKER's sample and that of this study. Compared to the embalmed specimens the mean center of gravity of fresh human heads is located about 1 cm retrocranial, i. e. towards the center of the brain. Besides possible systematical differences due to different experimental procedures the reason may be a weight-loss of the soft tissue during fixation or fluid loss during the measurements of the embalmed specimens.

IV-3 MOMENTS OF INERTIA

For each specimen the tensor of the principal axes (X', Y', Z') of the moments of inertia were calculated. These tensors yield orientations relative to the planes of the anatomical based coordinate reference system.

The following orientations are listed in Tab. 4 and shown in the diagrams of Figs. 9 to 12:

The deviation of X' from the X-Z (mid-sagittal) plane
= the projection of X' onto the Frankfort plane (Fig. 9).

The deviation of Y' from the X-Z (mid-sagittal) plane
= the projection of Y' onto the Frankfort plane (Fig. 10).

The deviation of Z' from the Y-Z (latero-lateral) plane
= the projection of Z' onto the mid-sagittal plane (Fig. 11).

The deviation of Z' from the X-Z (mid-sagittal) plane
= the projection of Z' onto the latero-lateral plane (Fig. 12).

TAB. 4: ORIENTATIONS OF THE PRINCIPAL MOMENTS

Deviation of the principal axes (X', Y', Z') of the moments of inertia (degrees)

Ser. No.	X' from X-Z plane	Y' from X-Z plane	Z' from Y-Z-plane	Z' from X-Z-plane
1	-19.5	73.7	-21.0	- 1.8
2	-35.9	63.8	-35.6	2.1
3	27.6	-71.7	-37.6	- 0.1
4	6.3	-80.5	-34.8	-10.9
5	19.6	-79.1	-40.5	1.8
6	18.0	-78.0	-37.6	0.8
7	- 2.2	87.3	-31.9	2.3
8	-19.8	72.5	-24.2	2.5
9	-46.9	53.6	-41.0	20.6
10	21.3	-75.1	-36.4	- 1.6
11	-54.2	45.2	-31.8	4.8
12	11.2	-84.3	-36.2	3.6
13	- 7.1	83.2	-24.1	2.0
14	- 9.3	84.3	-32.7	- 2.3
15	44.7	-63.1	-44.7	- 1.2
16	-24.4	71.9	-35.3	3.2
17	- 6.4	-85.3	-44.5	16.0
18	-39.6	59.2	-32.1	0.1
19	2.1	-87.4	-23.9	- 1.8
20	3.4	88.8	-41.9	6.2
21	-18.5	77.3	-28.7	- 5.3

The distributions of the X' and Y' deviations from the mid-sagittal plane as shown in the diagrams of Figs. 9 and 10 reveal, that these principal moment orientations are almost indistinct with respect to the mid-sagittal plane. In the mean, therefore, the X'-Y'-cross-section of the principal inertia ellipsoid de- generates to a circle rendering calculation of the orientations meaningless.

The deviation of Z' from the Y-Z (latero-lateral) plane (Fig.11) varies from -21 to -45 degrees with a mean of 34 degree. The lateral variation of Z' (Fig. 12) may exceptionally amount to $\pm$20 degree, but is in 85 % of the specimens smaller than $\pm$10 degree. No side seems to be favored.

The principal moments are listed along with head weights in Tab. 5. Their distribution is shown in the histograms of Figs. 13 to 15. The principal moments vary

from 136 to 274 $Kg \cdot cm^2$ about the X' axis
from 167 to 298 $Kg \cdot cm^2$ about the Y' axis
from 110 to 198 $Kg \cdot cm^2$ about the Z' axis.

X' pm kgm^2 = -113 + 75 × HW (kg)
= -131 + 82 × HW
Y'
Z' = -91 + 55 × HW

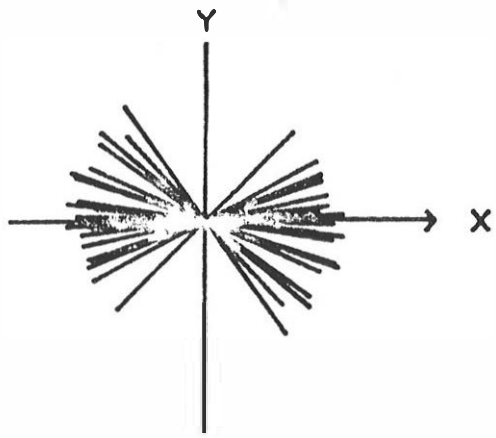

Fig. 9: Projection of the principal axis X' onto the Frankfort plane.

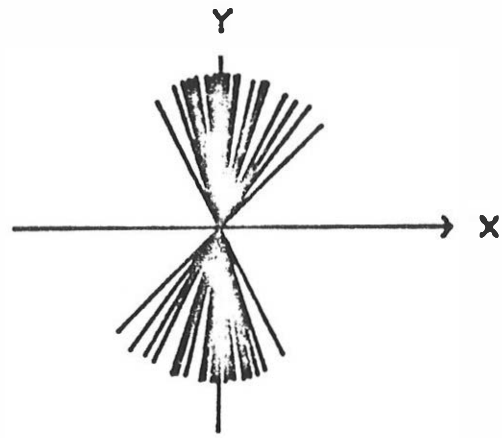

Fig. 10: Projection of the principal axis Y' onto Frankfort plane.

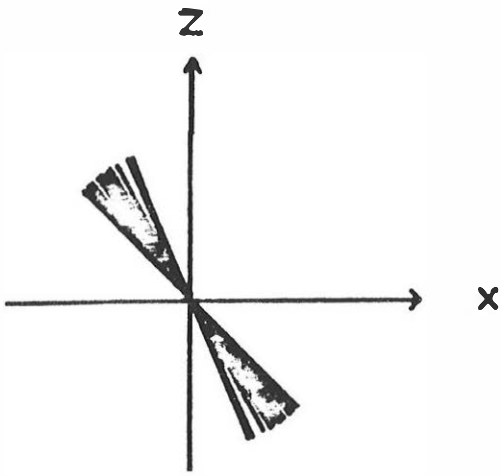

Fig. 11: Projection of the principal axis Z' onto the mid-sagittal plane.

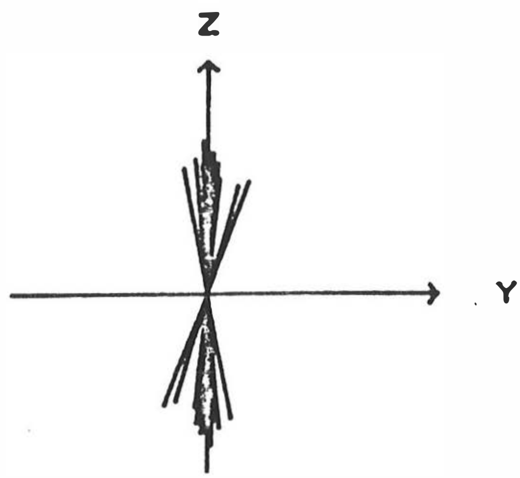

Fig. 12: Projection of the principal axis Z' onto the latero-lateral plane.

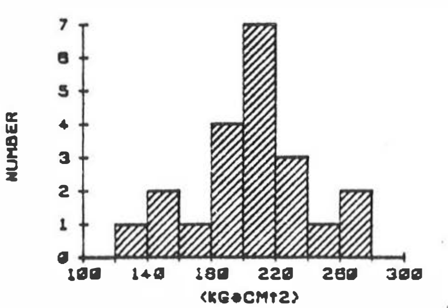

Fig. 13: Distribution of principal moments of inertia about the X' axis.

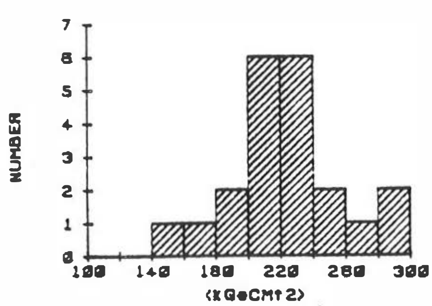

Fig. 14: Distribution of principal moments of inertia about the Y' axis.

TAB. 5: PRINCIPAL MOMENTS AND RADII OF GYRATION

Ser. No.	Head Weight (g)	Principal Moments X'	Y' (Kg·cm²)	Z'	Radii of Gyration X'	Y' (cm)	Z'
1	4207	200	238	143	6.89	7.52	5.83
2	4120	204	213	134	7.04	7.19	5.70
3	3949	191	207	119	6.95	7.24	5.49
4	4028	188	202	129	6.83	7.08	5.66
5	4025	193	197	138	6.92	6.99	5.86
6	4190	204	214	147	6.98	7.15	5.92
7	4544	227	238	156	7.06	7.23	5.85
8	4652	228	264	180	7.00	7.53	6.22
9	4319	197	232	148	6.75	7.33	5.85
10	3705	157	159	116	6.50	6.55	5.60
11	4350	215	225	153	7.03	7.19	5.93
12	4335	213	221	143	7.01	7.14	5.74
13	4749	247	243	169	7.21	7.15	5.97
14	4627	236	258	156	7.14	7.47	5.81
15	4251	215	208	142	7.11	6.99	5.78
16	5257	274	298	194	7.22	7.53	6.07
17	4269	136	223	198	5.64	7.22	6.81
18	3676	154	167	110	6.47	6.74	5.47
19	3938	175	192	121	6.66	6.98	5.54
20	4142	201	207	131	6.97	7.07	5.62
21	5069	268	286	189	7.27	7.51	6.11
Mean	4350	206	223	148	6.89	7.18	5.85
Std.Dev.	402	34.6	34.4	25.5	.36	.26	.30
Var. (%)	9.3	16.8	15.4	17,1	5.2	3.6	5.1

The radii of gyration included in Tab. 5 yield for the principal axes X', Y', and Z' the mean values 6.89, 7.18, and 5.85 cm, the standard deviations 0.36, 0.26, and 0.30 resp.. From the coefficients of variation follows, that the variation of head weight accounts for about 2/3 of the variations of the principal moments. A remaining correlation of the radii of gyration to the head weights is due to the correlation of head weight and size.

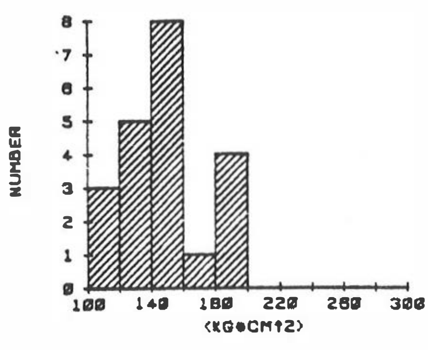

Fig. 15: Distribution of principal moments of inertia about the Z' axis.

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