ANATOMICAL COORDINATE SYSTEMS FOR HUMAN BODY SEGMENTS

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INTRODUCTION

The Ad Hoc Committee on Guidelines for the Comparison of Human and Human Analogue Biomechanical Data has recommended the use of anatomically based coordinate systems for human body segments to ensure precise comparisons of mechanical data from diverse studies of impact events on human subjects and human analogues. In its second annual report, it has adopted five guidelines for such coordinate systems, and has proposed specific systems for the head, the first thoracic vertebra, and the pelvis.

This paper proposes anatomical coordinate systems for all major body segments and demonstrates the application of such systems for the location of centers of gravity and of transducers attached to these segments. The following principles were used for the establishment of each coordinate system:

(i) Description of essential geometry should use three-dimensional coordinate systems.

(ii) All coordinate systems should be orthogonal and should be constructed by specifying an origin, a first (X-) axis and a second (Y-) axis taken in order, and a third (Z-) axis constructed by the right-hand rule.

(iii) For convienence, a fixed order of rotation should be followed. For example, yaw, pitch, and roll; yaw being a rotation about the Z-axis, pitch about the intermediate Y-axis, and roll about the final X-axis.

(iv) The landmarks chosen for the establishment of coordinate axes should be palpable on cadavers as well as volunteers. They should also be readily identifiable reontgenographically.

PROPOSED ANATOMICAL COORDINATE SYSTEMS

Each segment is assumed to be in its anatomical position. An attempt is made to choose Z-axis as closely as possible to the inferior-superior direction. The X-axis is chosen in a general anterior direction and should lie in the mid-sagittal plane, or any sagittal plane. The Y-axis is directed laterally. Recommended landmarks for the establishment of anatomical coordinate systems of the head and neck, the upper, central and lower torso, the upper and lower arm, and the upper and lower leg are presented.

(i) Head - A head anatomical coordinate system has been proposed by Ewing and Thomas (1). It is based on the Frankfort plane which passes through the superior edge of each auditory meatus and inferior border of both infraorbital notches. The origin is located at the midpoint of a line connecting the superior edges of the right and left auditory meati. The positive X-axis is constructed by drawing a line connecting the origin with the mid-point of a line joining the inferior border of the infraorbital notches. The positive Z-axis is from the origin in the superior direction, perpendicular to the Frankfort plane. The coordinate system is shown in Figures 1 and 2.

(ii) Neck - Ewing and Thomas (1) have also proposed a neck coordinate system. The origin is located in the mid-sagittal plane, at the anterior-superior border of the first thoracic vertebra (T1). The positive X-axis is a directed line segment connecting the mid-point of the superior and inferior corner of the posterior spinous process of T1 to the origin. The positive Z-axis extends superiorly and is normal to the X-axis in the mid-sagitttal plane which contains the above three points. Figure 3 shows a lateral view of T1 and the proposed coordinate system.

(iii) Torso Segments - The procedure recommended for the establishment of the neck anatomical coordinate system can be extended to any or all of the thoracic and lumbar vertebrae to establish coordinate systems for various parts of the torso above the pelvis. In many gross motion simulators, the torso is assumed to be made up of three main segments: namely, the thoracic or upper torso, the lumbar or central torso, and the lower torso or the pelvic girdle.

For the upper torso, it is proposed that the origin of its anatomical coordinate system be located at the anterior-superior border of T1 in the mid-sagittal plane, coincident with that of the neck coordinate system. This coordinate system is shown in Figures 4 and 5.

The central torso is centered around L1, the anterior-superior corner of which can be used as the location of the origin. The directions of the coordinate axes are defined in a similar manner as those of the neck and upper torso.

The coordinate system of the lower torso is defined with reference to the pelvic girdle which is composed of the two hip bones and the sacrum. A plane can be defined by the right and left anterior-superior iliac spine and the mid-point of the upper edge of the pubic symphysis. The origin is located in this plane at the mid-point of the line joining the right and left anterior-superior iliac spine. The first axis (+X) is normal to the plane of the triangle which is closest to the anterior direction. The second axis (+Y) is to the left along the line connecting the anterior-superior iliac spines. The third axis (+Z) is at right angles to the other two which is closest to the inferior-superior direction. This coordinate system was proposed by the Ad Hoc Committee. It is shown in Figures 6, 7, and 8 in three views.

In a normal pelvis, the Z-axis will coincide with a line joining the origin to the mid-point of the upper edge of the pubic symphysis. The advantage of this coordinate system is twofold. Firstly, the proposed landmarks are easy to locate either by palpation or by x-ray. Secondly, this coordinate system can be defined for either the seated or standing position. The ability to determine the landmarks by a palpation and the availability of equipment to locate them in three-dimensional space (see Nyquist (2) 1975) are important aspects that should be considered, mainly because the use of x-ray anthropometry in the pelvic area may not be feasible, when human volunteers are involved.

There are many other pelvic landmarks that can be used, such as the right and left posterior-superior iliac spines. These are easily identified in a lateral x-ray but may not be palpable in an obese subject.

(iv) Upper Limbs - For the upper arm, the origin of its coordinate system can be located at the eminence of the lateral epicondyle which is quite prominent when viewed anteriorly and identifiable laterally. The superior border of the greater tubercle should also be identifiable from both the lateral and A-P view. Thus, the positive Z-axis is a directed line segment connecting the lateral epicondyle to the superior-most point of the greater tubercle. The positive X-axis is directed anteriorly, normal to the Z-axis in the sagittal plane (lateral x-ray). The positive Y-axis can be constructed by using the right-hand rule. It is directed laterally towards the left. The proposed coordinate system is shown in Figures 9 and 10.

An obvious candidate landmark for the origin of the forearm coordinate system is the vertex of the lateral edge of the head of the radius which is identifiable on both the lateral and A-P x-rays. The positive Z-axis is a directed line segment connecting the tip of the styloid process of the

radius to the origin. The positive X-axis is directed anteriorly from the origin normal to the Z-axis in the sagittal plane and the positive Y-axis is directed laterally towards the left. This coordinate system is shown in Figures 11 and 12.

(v) Lower Limbs - The recommended origin of the anatomical coordinate system of the thigh is the summit of the anterior border of the greater trochanter. The positive Z-axis is established by joining the tip of the lateral epicondyle to the origin. The positive X-axis is directed anteriorly normal to the Z-axis in the sagittal plane and the positive Y-axis is again directed laterally towards the left. The coordinate system is shown in Figures 13 and 14.

For the lower leg, the medial edge of the medial condyle of the tibia is recommended as the origin for its coordinate system. The same procedure for establishing the Z-axis is proposed. The medial tip of the medial malleolus is identified and the positive Z-axis is a directed line segments connecting this point to the origin. The positive X-axis is directed anteriorly normal to the Z-axis in the sagittal plane. The coordinate system is shown in Figures 15 and 16.

(vi) Remarks - The landmarks proposed for the major body segments appear to be those that can be identified directly on x-ray and are palpable. Geometrical construction has also been minimized. Consideration has not been given to anatomical abnormalities which are encountered occasionally.

It is important to point out that x-ray anthropometry is subject to serious parallax errors. An off-center beam can cause errors in the location of the origin. This was demonstrated by King et al (3).

APPLICATION

The proposed anatomical coordinate systems have been identified on

four cadaveric subjects which were used in a pedestrian-vehicle impact study by Krieger et al (4). The following body segments were studied:

(i) Head-neck
(ii) Upper torso
(iii) Central torso
(iv) Lower torso
(v) Upper leg
(vi) Lower leg
(vii) Upper arm
(viii) Lower arm

The center of gravity (c.g.) of each segment was determined using a radiological method described by Krieger (5). In the study, it was also necessary to define a coordinate system located at the c.g. of each segment. For this system, both the X- and Z-axis are in the sagittal plane. The positive X-axis is directed anteriorly while the positive Z-axis is directed vertically upward. The positive Y-axis is directed laterally to the left and is perpendicular to the sagittal plane. Since the center of gravity can vary from one subject to another, this coordinate system is not a well-defined common data base. However, it can be related to the anatomical coordinate system by a system of direction cosines (or Euler angles) and a position vector.

Miniature acceleromenters were attached to all of these segments. The origin of the instrumentation coordinate system of the acceleromenter mounts were referenced to the c.g. coordinate system which in turn could be re-referenced to the anatomical coordinate system. Data are presented in Tables I through VI for seven of the eight segments. The origin of anatomical coordinate system is located with respect to the c.g. coordinate system. A simple inversion of the direction cosine matrix yields the location of the c.g. coordinate system. The instrumentation coordinate system is also located with respect to the c.g. coordinate system. An additional transformation is required to locate it with respect to the anatomical coordinate

system.

CONCLUSIONS

1. A set of landmarks has been proposed for the torso and the extremities to define anatomically based coordinate systems.

2. The coordinate systems proposed by the Ad Hoc Committee on Guidelines for the Comparison of Human and Human Analogue Biomechanical Data were also described. They were for the head, neck, and pelvis.

3. The systems were located on four cadaveric subjects and were related to anatomical coordinate systems located at the center of gravity of each segment. A transformation of the data can be effected to locate the c.g. with respect to the anatomical coordinate system.

4. Transducer location can be described in the same manner.

REFERENCES

1. Ewing, C.L. and Thomas, D.J., "Human Head and Neck Response to Impact Acceleration," NAMRA Monograph 21, 1972

2. Nyquist, G.W. and Murton, C.J., "Static Bending of the Human Lower Torso," Proceedings of the 19th Stapp Car Crash Conference, Society of Automotive Engineering, Inc., San Diego, California, November, 1975

3. King, A.I., Padgaonkar, A.J. and Krieger, K.W.: Work done under contract entitled, "Contact Loads," Contract No. DOT-HS-146-3-711, at Biomechanics Research Center, Wayne State University, Detroit, Michigan, Sponsored by NHTSA

4. Krieger, K.W., Padgaonkar, A.J. and King, A.I., "Full-Scale Experimental Simulation of Pedestrian-Vehicle Impacts," Proceedings of the 20th Stapp Car Crash Conference, Society of Automotive Engineering, Inc., Dearborn, Michigan, October, 1976

5. Krieger, K.W., "Full-Scale Experimental Simulation of Pedestrian-Vehicle Impacts," Ph.D. Dissertation, Wayne State Univeristy, 1976

TABLE I
HEAD AND NECK

LOCATION (IN) AND ORIENTATION (DEG) OF ANATOMICAL COORDINATE SYSTEM WITH RESPECT TO CENTER OF GRAVITY

CADAVER	X	Y	Z	YAW	PITCH	ROLL
3350	0	0	0	0	5.0	0
3352	0	0	0.2	0	-1.5	0
3375	0	0	0	0	5.0	0
3392	0	0	0	0	-7.0	0

LOCATION (IN) AND ORIENTATION (DEG) OF ACCELEROMETER MOUNT-FIXED COORDINATE SYSTEM WITH RESPECT TO CENTER OF GRAVITY

CADAVER	X	Y	Z	YAW	PITCH	ROLL
3350	-1.6	-0.5	4.5	0	0	5.0
3352	-0.9	-0.9	5.4	0	6.5	9.0
3375	-1.9	-0.4	4.5	0	0	5.0
3392	-2.4	-0.5	4.4	0	-8.0	0

TABLE II
UPPER TORSO

LOCATION (IN) AND ORIENTATION (DEG) OF ANATOMICAL COORDINATE SYSTEM WITH RESPECT TO CENTER OF GRAVITY

CADAVER	SEGMENT	X	Y	Z	YAW	PITCH	ROLL
3350	U.T.	0.9	0	3.9	0	50	0
3352	U.T.	1.7	0	5.2	0	42	0
3375	U.T.	1.6	0	4.3	0	36	1.0
3392	U.T.	0.8	0	5.3	0	40	0

LOCATION (IN) AND ORIENTATION (DEG) OF ANTERIOR ACCELEROMETER MOUNT-FIXED COORDINATE SYSTEM WITH RESPECT TO CENTER OF GRAVITY

CADAVER	SEGMENT	X	Y	Z	YAW	PITCH	ROLL
3350	U.T.	4.1	-0.5	1.4	0	0	-3.0
3352	U.T.	3.9	0	-0.9	0	-6.0	0
3375	U.T.	3.3	0.2	0.3	0	-15.0	0
3392	U.T.	3.9	0.2	-0.6	0	0	2.0

LOCATION (IN) AND ORIENTATION (DEG) OF POSTERIOR ACCELEROMETER MOUNT-FIXED COORDINATE SYSTEM WITH RESPECT TO CENTER OF GRAVITY

CADAVER	SEGMENT	X	Y	Z	YAW	PITCH	ROLL
3350	U.T.	-2.4	0	8.5	0	32.0	0
3352	U.T.	-2.4	0	5.5	0	42.0	0
3375	U.T.	-1.6	0	5.0	0	36.0	0
3392	U.T.	-2.4	0.5	4.9	0	40.0	0

TABLE III
LCWER TORSO

LOCATION (IN) AND ORIENTATION (DEG) OF ANATOMICAL COORDINATE SYSTEM WITH RESPECT TO CENTER OF GRAVITY

CADAVER	SEGMENT	X	Y	Z	YAW	PITCH	ROLL
3352	L.T.	3.9	0	0.9	0	-7.0	0
3375	L.T.	3.0	-0.3	1.9	0	-12.0	1.0
3392	L.T.	3.6	0.5	0.6	0	-3.0	0

LOCATION (IN) AND ORIENTATION (DEG) OF ACCELROMETER MOUNT-FIXED COORDINATE SYSTEM WITH RESPECT TO CENTER OF GRAVITY

CADAVER	SEGMENT	X	Y	Z	YAW	PITCH	ROLL
3352	L.T.	-3.8	0.8	3.0	0	0	-2.5
3375	L.T.	-4.4	1.5	1.9	0	12.0	-3.0
3392	L.T.	-4.3	1.1	1.8	0	11.0	-2.0

TABLE IV
UPPER LEG

LOCATION (IN) AND ORIENTATION (DEG) OF ANATOMICAL COORDINATE SYSTEM WITH RESPECT TO CENTER OF GRAVITY

CADAVER	SEGMENT	X	Y	Z	YAW	PITCH	ROLL
3350	RUL	-0.1	0.6	7.0	0	0	-8.0
3352	RUL	0.7	-0.5	9.5	0	6.5	0
3375	LUL	-1.1	0.3	7.6	0	-6.0	5.0

LOCATION (IN) AND ORIENTATION (DEG) OF ACCELEROMETER MOUNT-FIXED COORDINATE SYSTEM WITH RESPECT TO CENTER OF GRAVITY

CADAVER	SEGMENT	X	Y	Z	YAW	PITCH	ROLL
3350	RUL	0	0.9	-1.9	0	0	2.5
3352	RUL	1.3	0.9	-0.4	0	8.0	-5.0
3375	LUL	0	-1.4	0.1	0	-7.0	3.5

TABLE V
LOWER LEG

LOCATION (IN) AND ORIENTATION (DEG) OF ANATOMICAL COORDINATE SYSTEM WITH RESPECT TO CENTER OF GRAVITY

CADAVER	SEGMENT	X	Y	Z	YAW	PITCH	ROLL
3352	RLL	0	2.0	11.4	0	0	-2.0
3375	LLL	0.3	-1.8	9.1	0	2.0	2.0
3392	LLL	-1.0	-1.4	10.9	0	-5.0	4.0

LOCATION (IN) AND ORIENTATION (DEG) OF ACCELEROMETER MOUNT-FIXED COORDINATE SYSTEM WITH RESPECT TO CENTER OF GRAVITY

CADAVER	SEGMENT	X	Y	Z	YAW	PITCH	ROLL
3352	RLL	-0.1	1.1	4.9	0	2.5	-3.5
3375	LLL	-0.2	-1.1	3.5	0	8.0	2.0
3392	LLL	-0.6	-1.1	4.3	0	-1.0	-3.0

TABLE VI
UPPER EXTREMITIES

LOCATION (IN) AND ORIENTATION (DEG) OF ANATOMICAL COORDINATE SYSTEM WITH RESPECT TO CENTER OF GRAVITY

CADAVER	SEGMENT	X	Y	Z	YAW	PITCH	ROLL
3375	RUA	-0.3	-1.2	-5.8	0	6.0	2.5
3375	LUA	-0.5	0.8	-6.4	0	7.5	0
3352	LLA	-1.0	-0.9	6.4	0	-3.0	5.5
3375	LLA	0.4	0	7.0	0	1.0	-2.5

LOCATION (IN) AND ORIENTATION (DEG) OF ACCELEROMETER MOUNT-FIXED COORDINATE SYSTEM WITH RESPECT TO CENTER OF GRAVITY

CADAVER	SEGMENT	X	Y	Z	YAW	PITCH	ROLL
3375	RUA	-0.3	-0.6	-1.0	-35.0	5.0	-5.0
3375	LUA	-0.7	0.2	-0.1	69.0	-6.0	6.0
3352	LLA	-0.1	-0.1	0.6	0	-3.0	-3.5
3375	LLA	-0.9	-0.9	2.0	0	7.5	-2.0

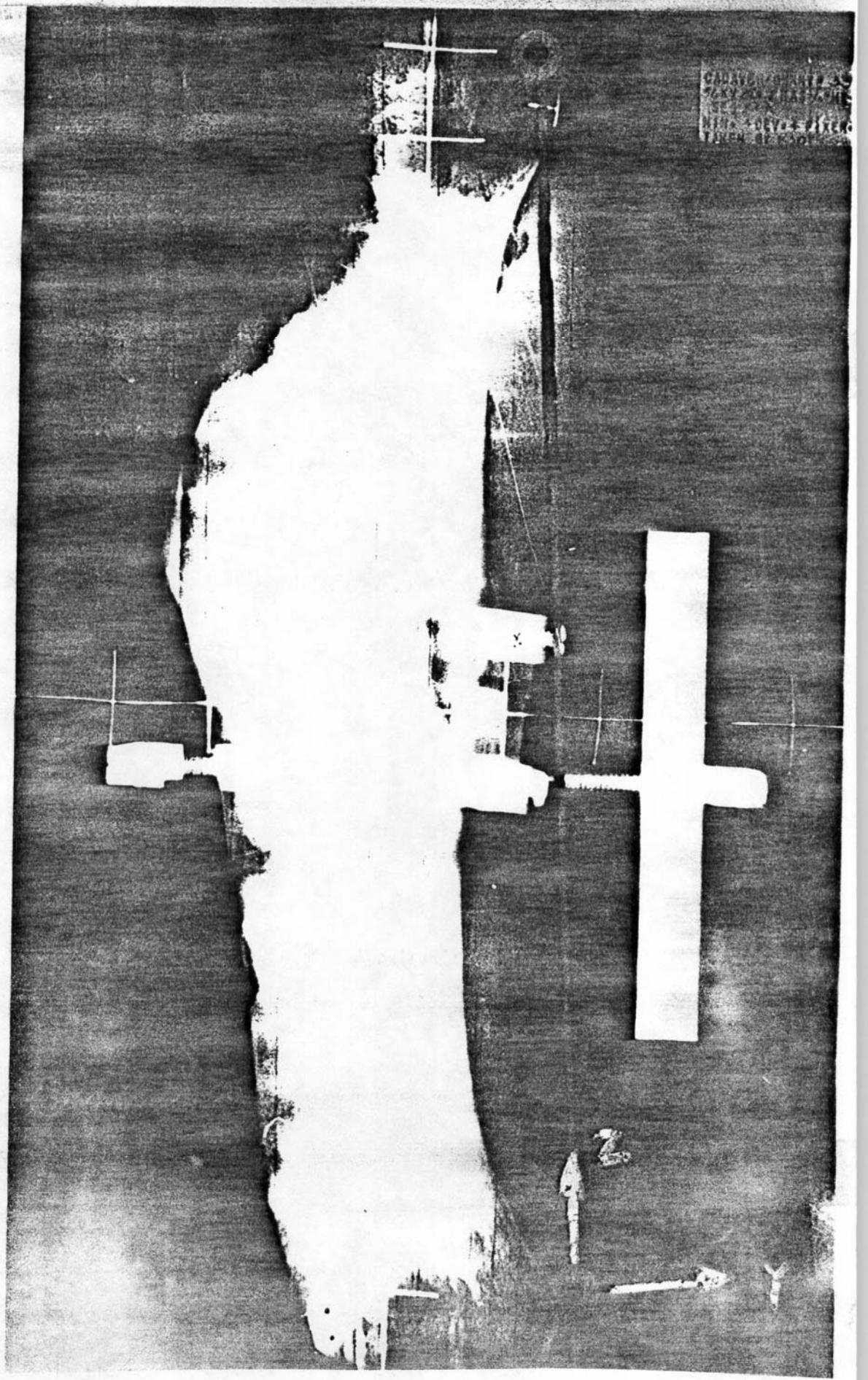
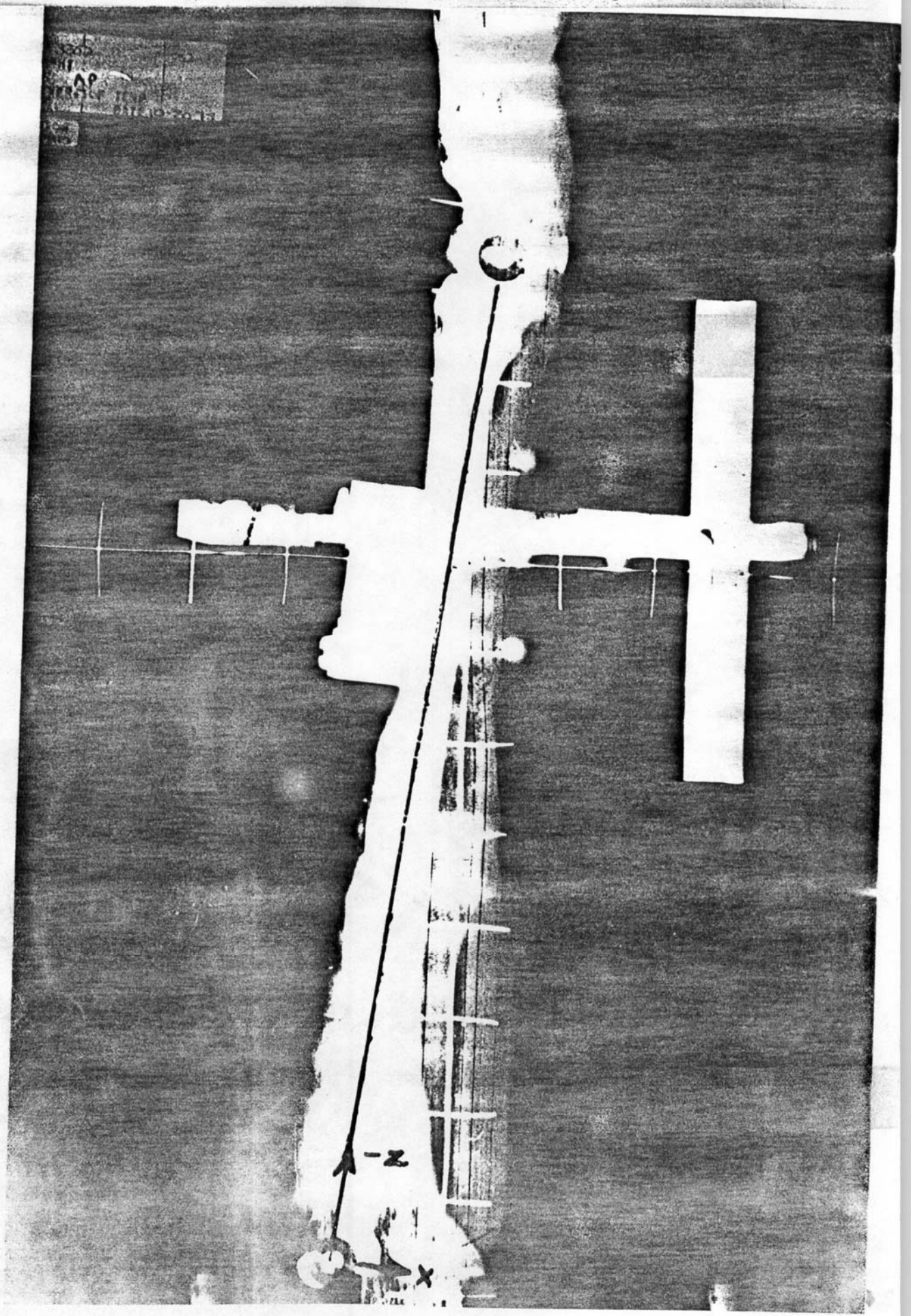


FIG. 10. An [illegible] Coordinate System for the Human Upper Arm, Y-Z (A-P) View, (Left [illegible]



An Anatomical Coordinate System for the Human Lower Arm, X-Z (Lateral) View. (Left Arm)

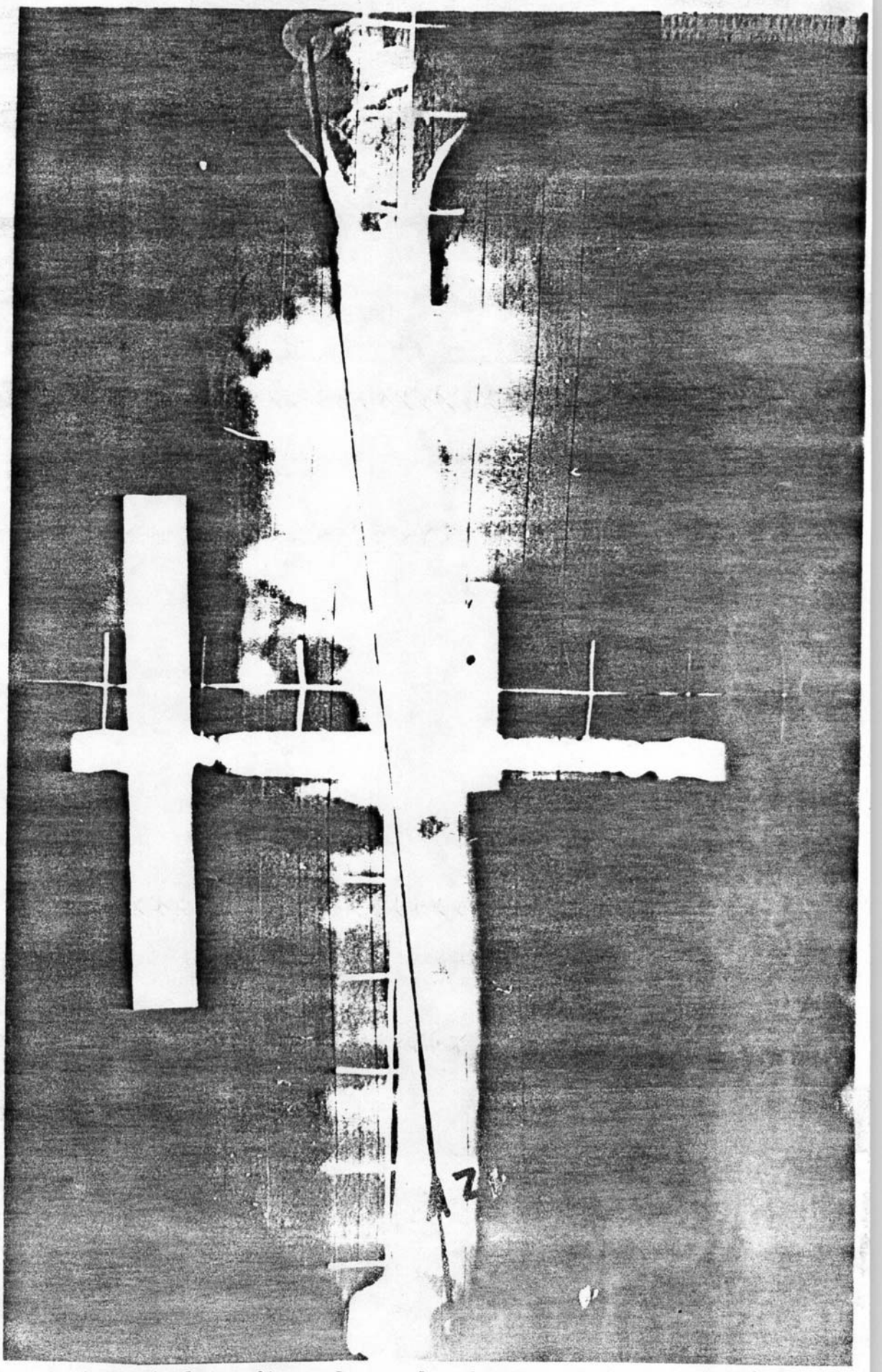


FIG. 9. An Anatomical Coordinate System for the Human Upper Arm, X-Z (Lateral) View (Left Arm)

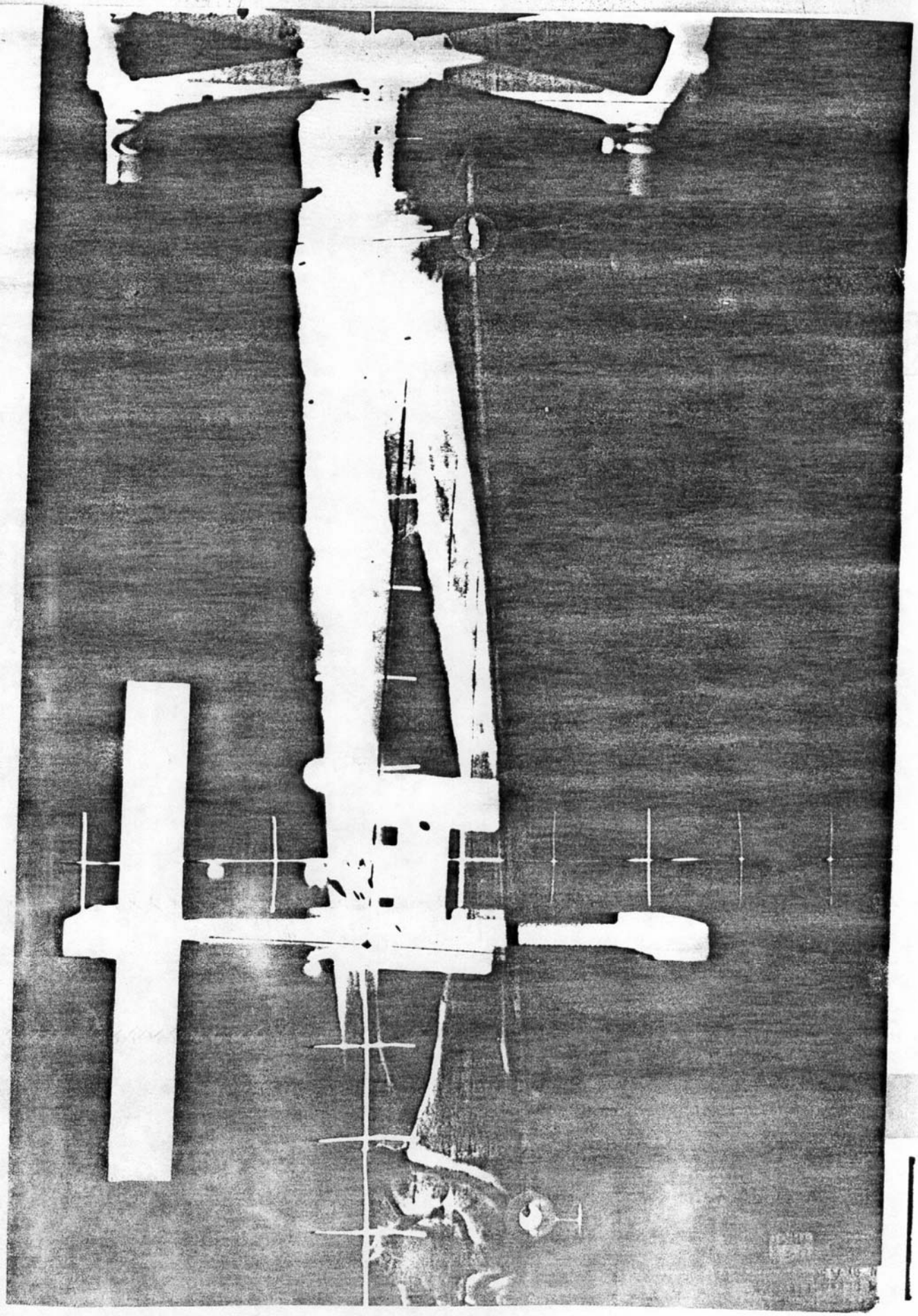


FIG. 12. An Anatomical Coordinate System for the Human Lower Arm, Y-Z (A-P) View, (Left Arm)

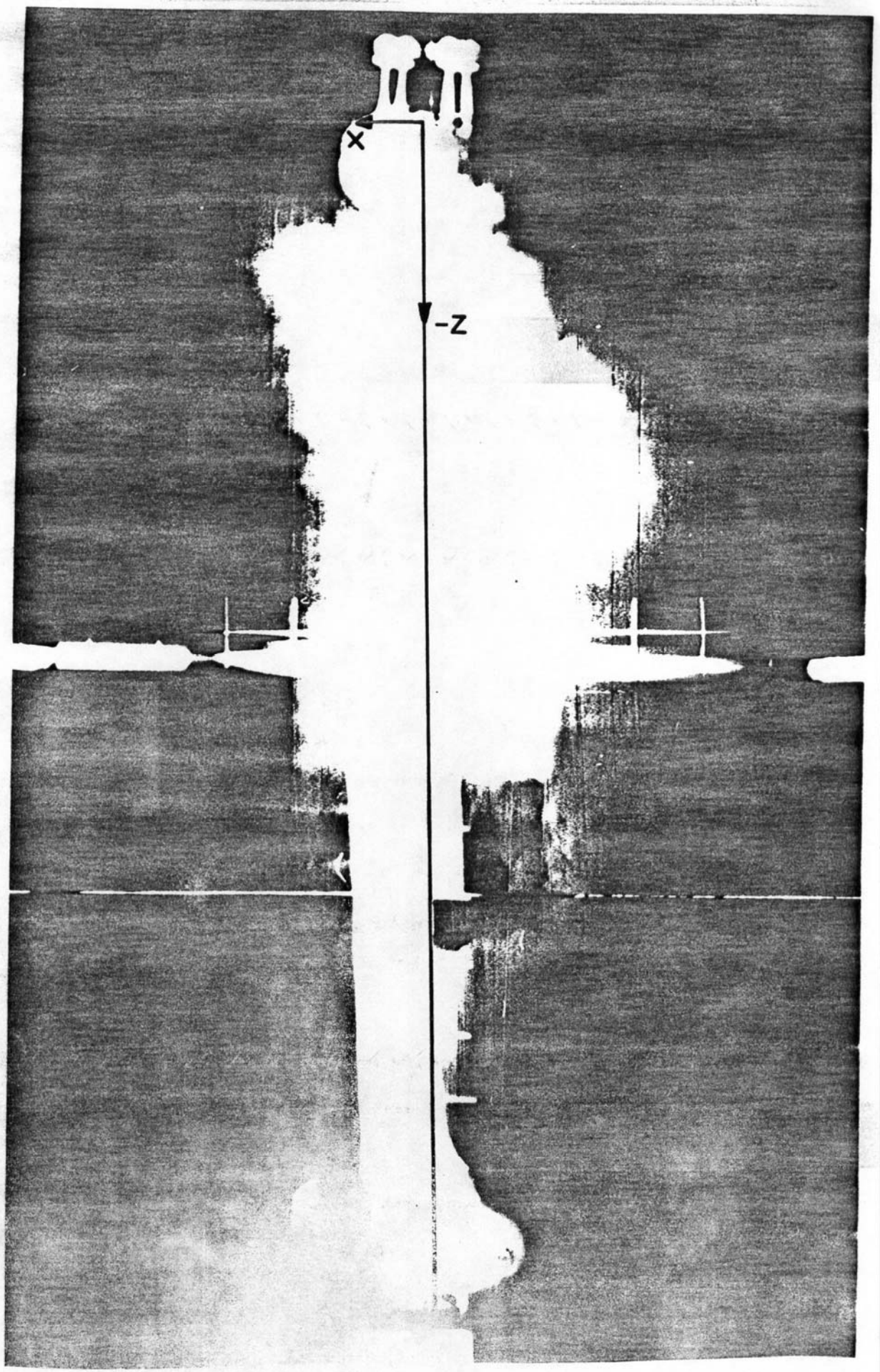


FIG. 13. An Anatomical [illegible] the Human Upper Leg, X-Z (Lateral) View, (Right Leg)

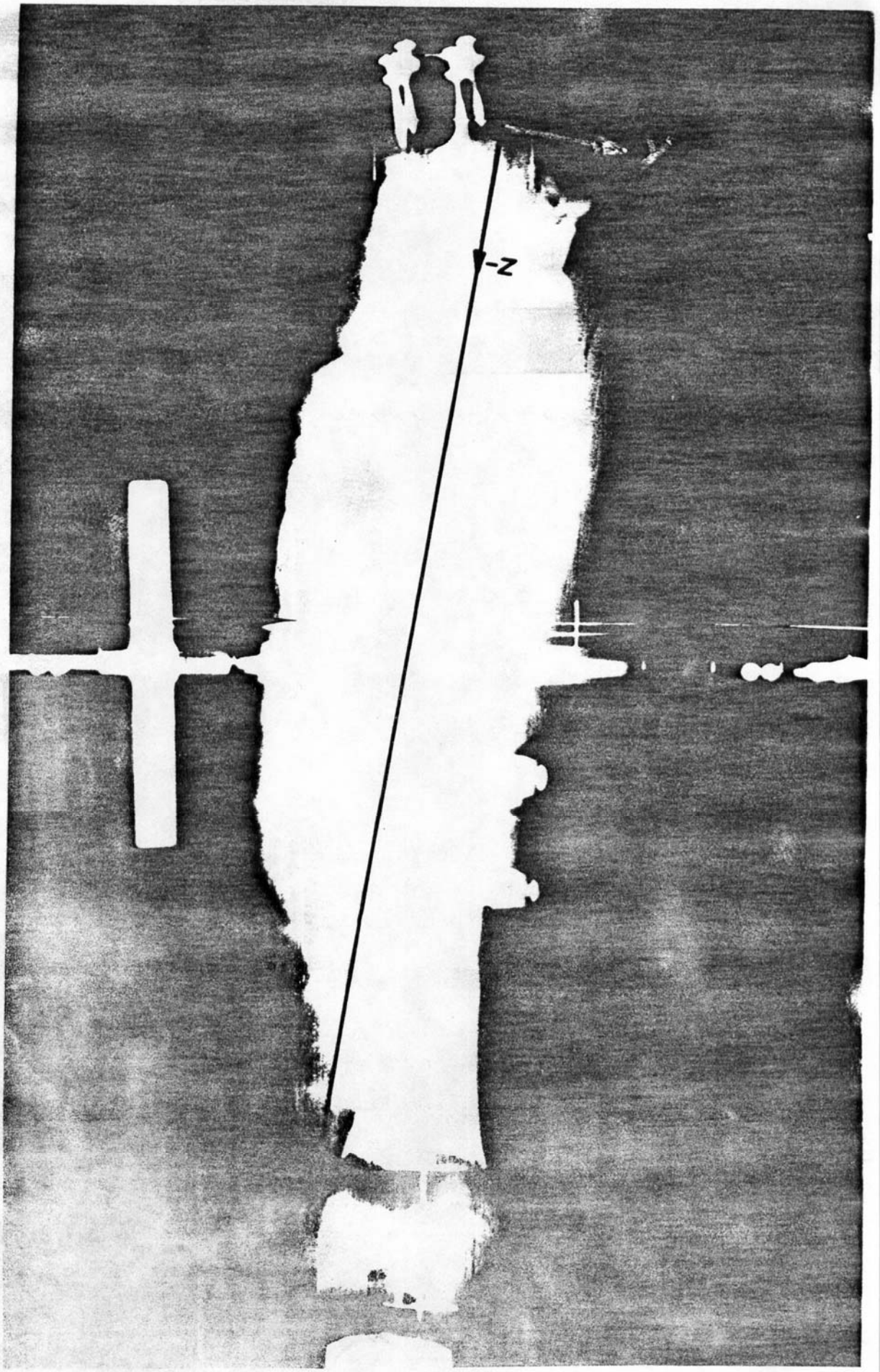


FIG. 14 ... Coordinate System for the Human Upper Leg, Y-Z (A-P) View,

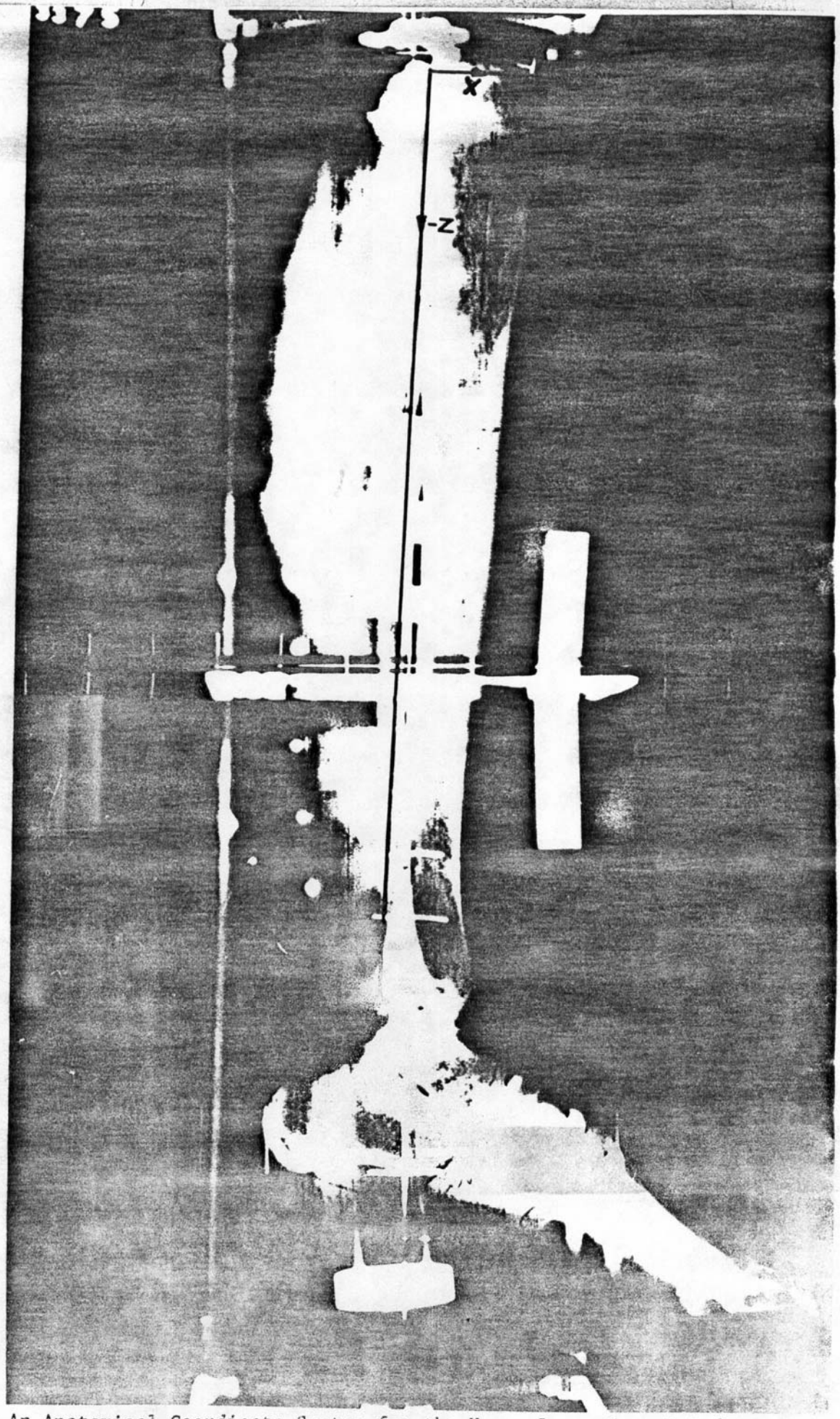


FIG. 15. An Anatomical Coordinate System for the Human Lower Leg, X-Z (Lateral View, (Left Leg)

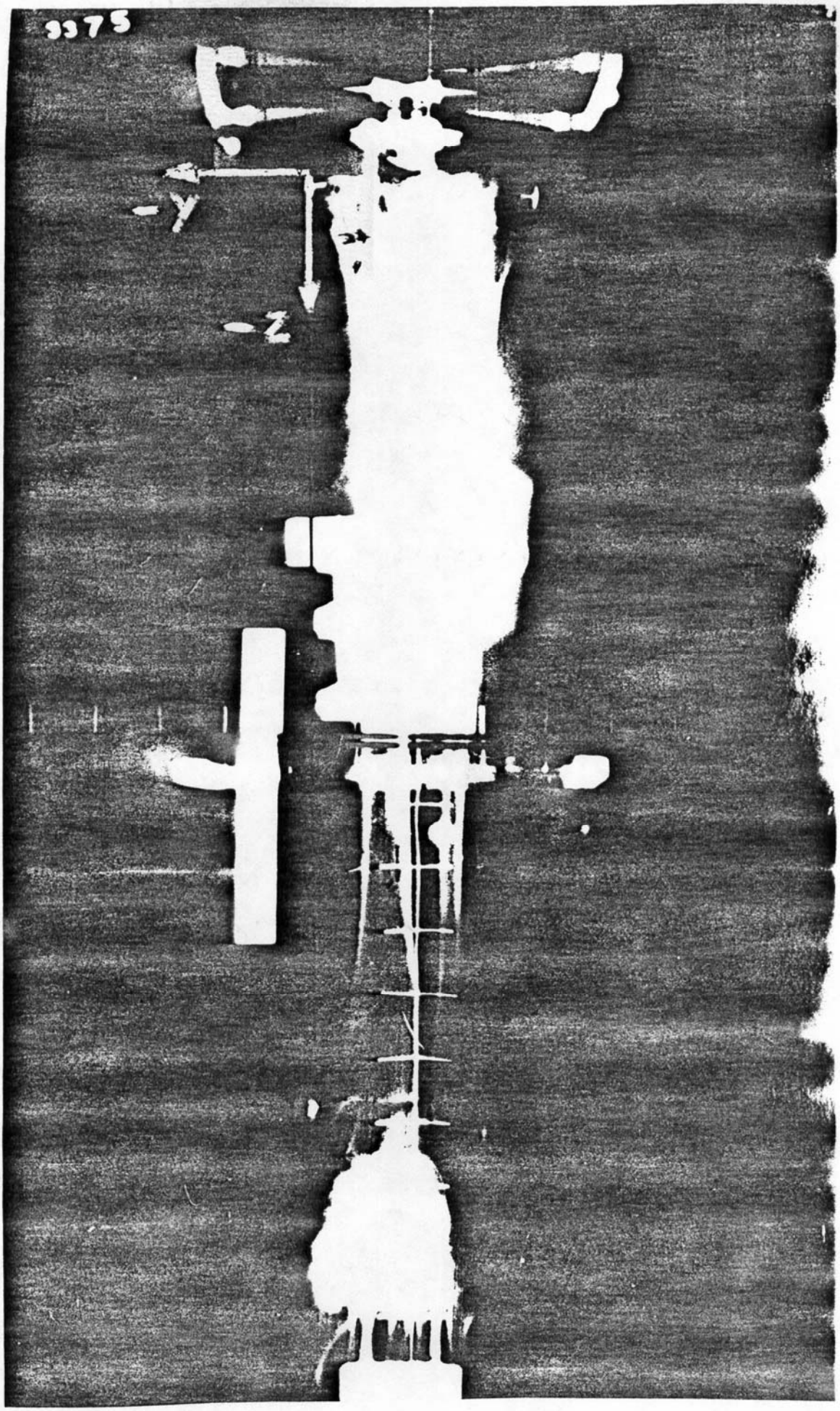


FIG. 16. An Anatomical Coordinate System for the Human Lower Leg, Y-Z (A-P) View, (Left Leg)

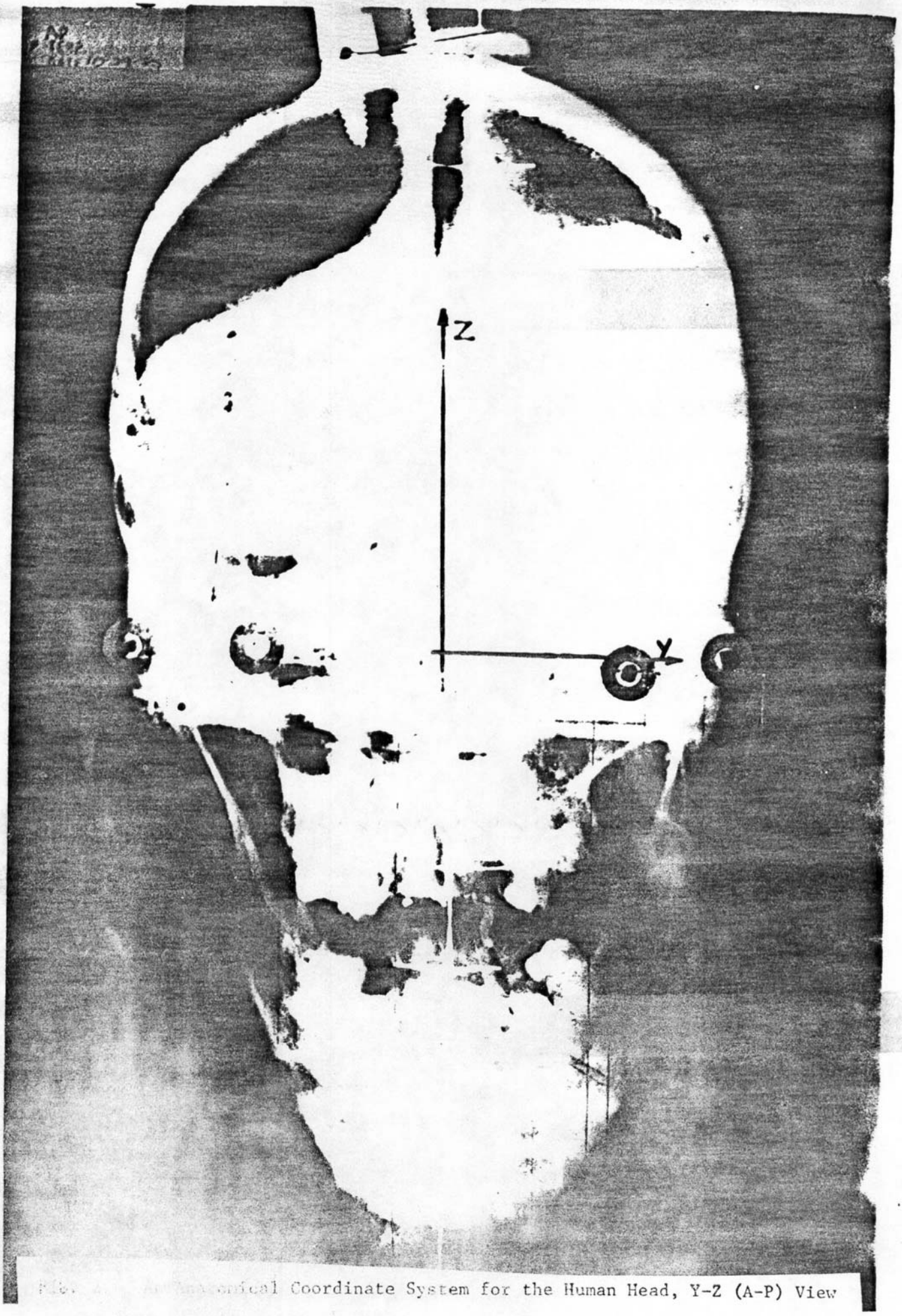


Fig. [illegible] Anatomical Coordinate System for the Human Head, Y-Z (A-P) View

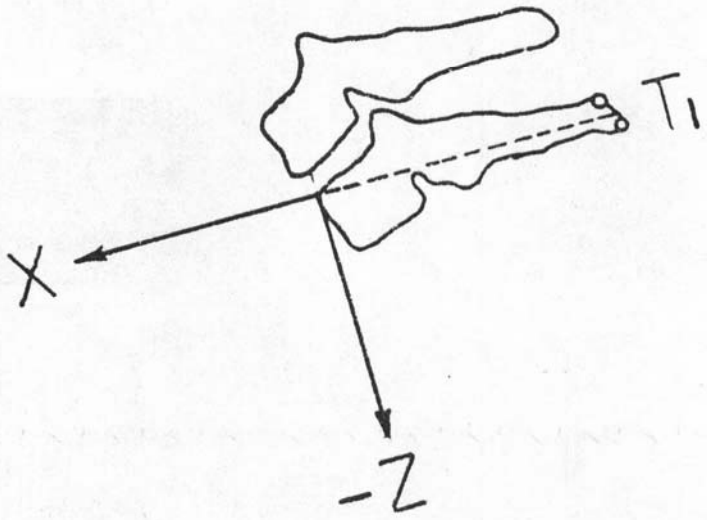


FIG. 3. An Anatomical Coordinate System for the Human Neck, X-Z (Lateral) View

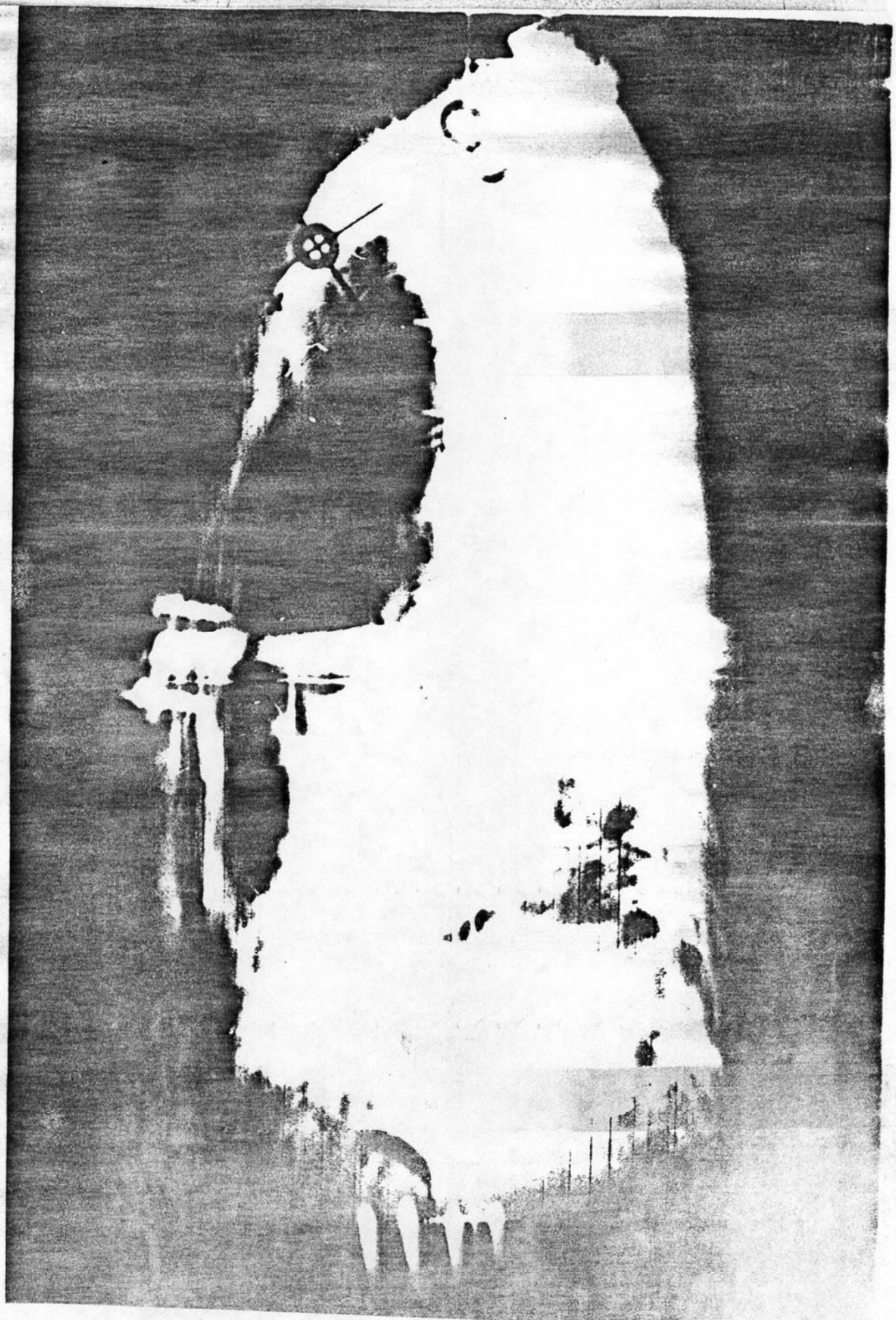


FIG. 4. An Anatomical Coordinate System for the Human Upper Torso, X-
View

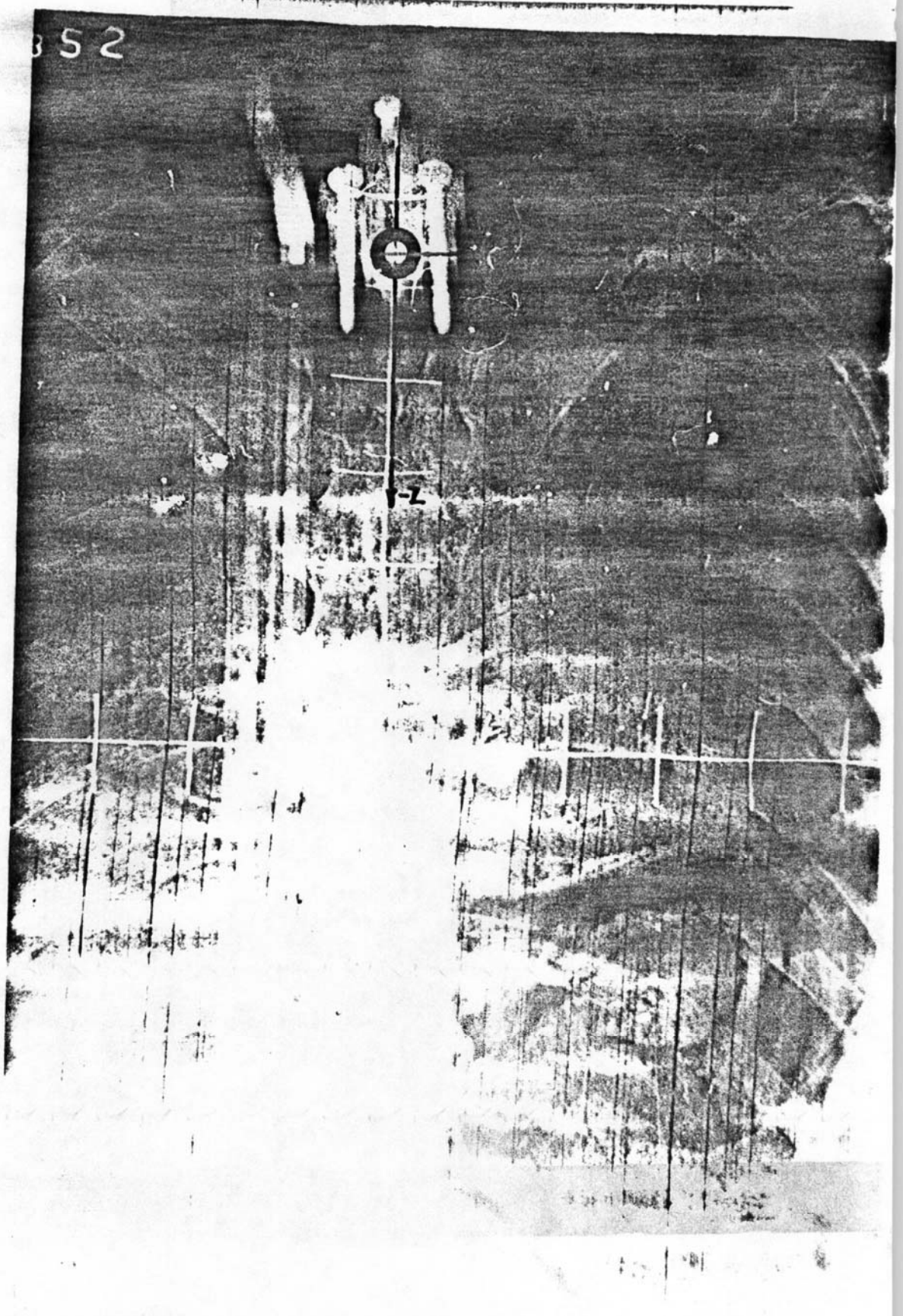


FIG. 5. An Anatomical Coordinate System for the Human Upper Torso, Y-Z (A-P) View

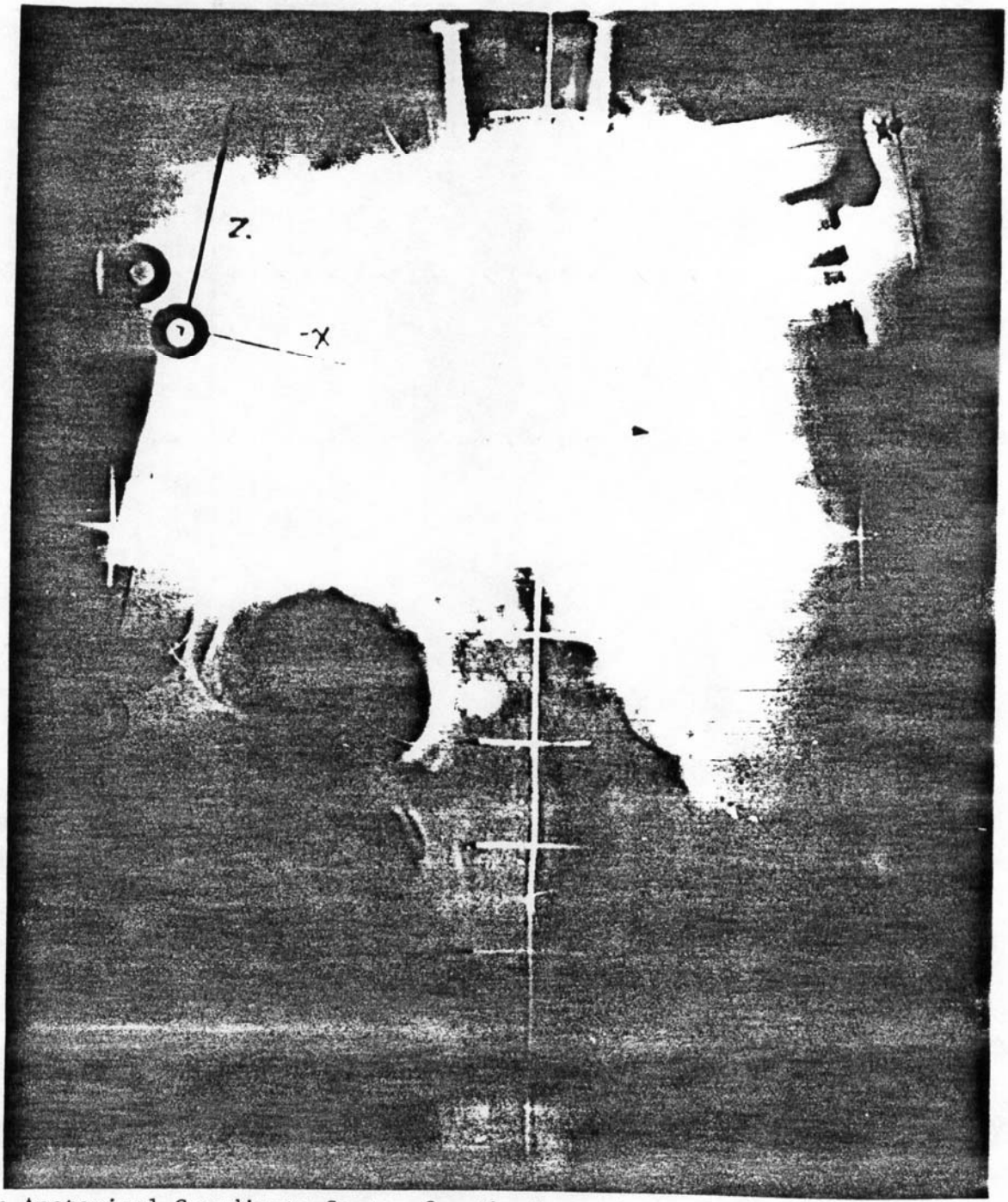


FIG. 6. An Anatomical Coordinate System for the Human Lower Torso, X-Z (Lateral) View

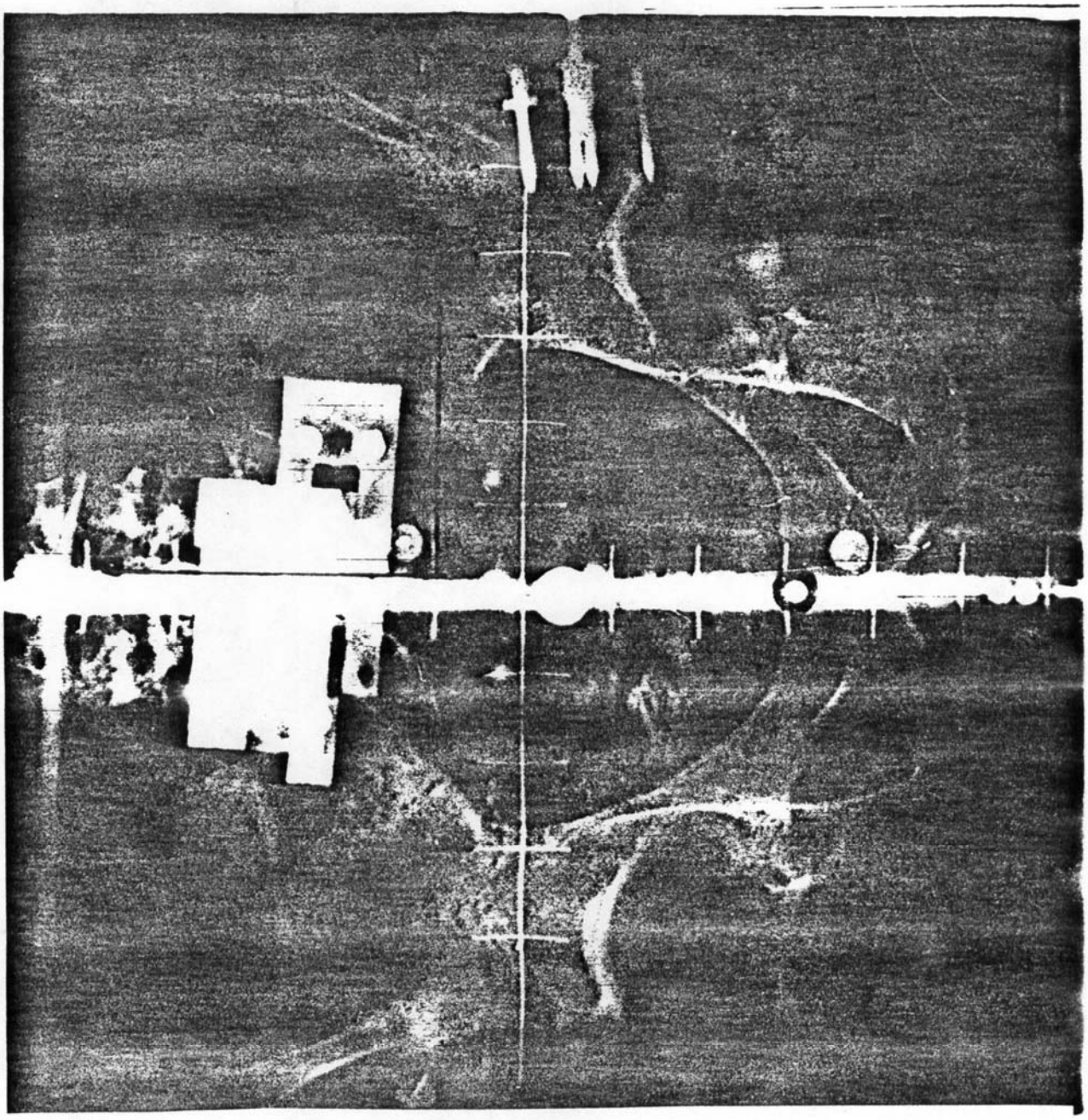


FIG. 7. An Anatomical Coordinate System for the Human Lower Torso, Y-Z (A-P) View

FIG. 8. An Anatomical Coordinate System for the Human Lower Torso, X-Y (I-S) View

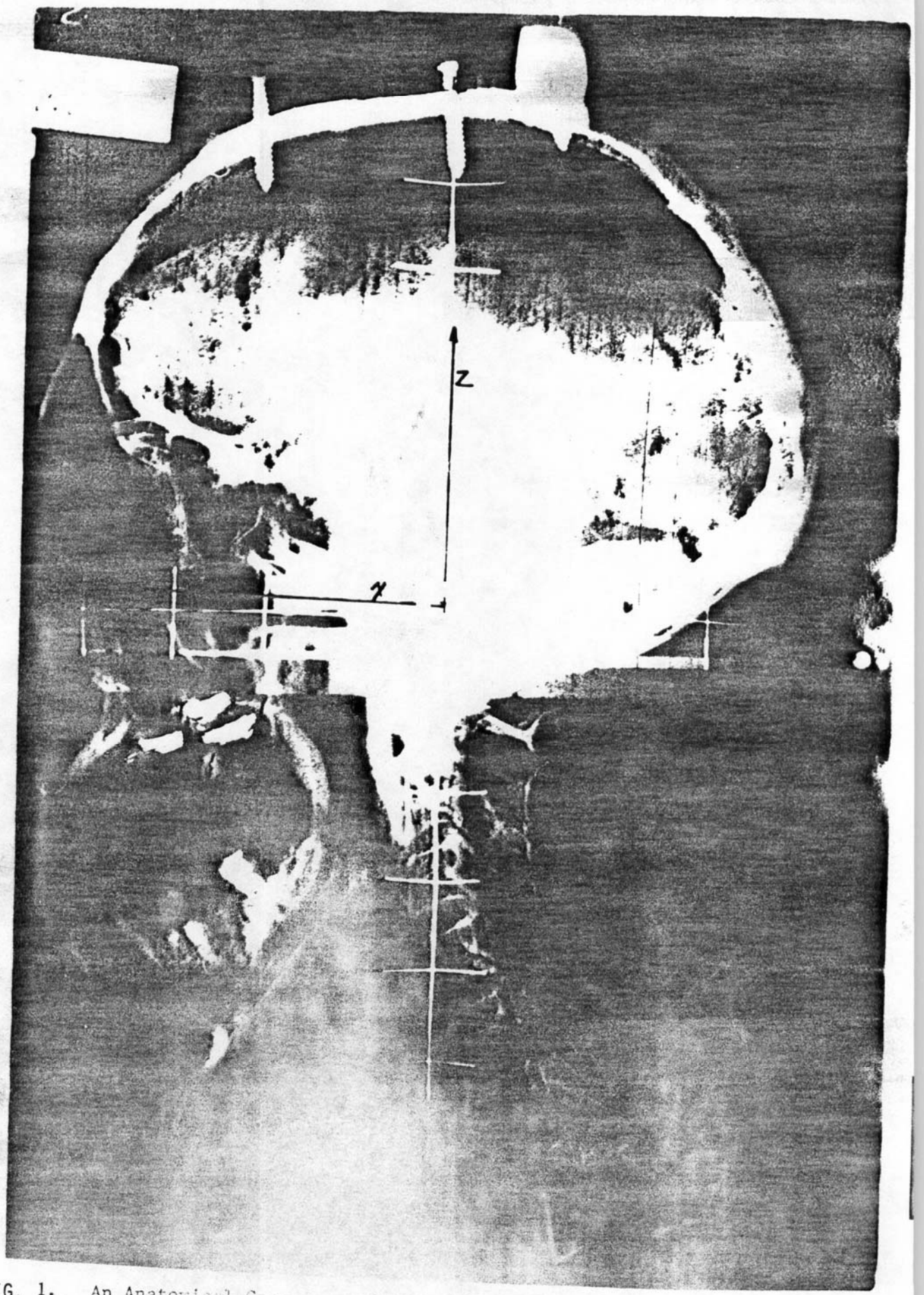


FIG. 1. An Anatomical Co[illegible] the Human Head, X-Z (Lateral) View