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Anatomical Data for Analyzing Human Motion

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Anatomical data necessary for the analysis of human motion are presented on the total living body segmented into sixteen parts. Cadaver data from Dempster (1955) are applied to water displacement data obtained on 135 living subjects (35 men and 100 women) to obtain the weight, center of gravity, and radius of gyration for the segmented extremities. Thirty-three of these subjects (15 men and 18 women) were used to obtain the weight of the segments of the trunk, using the water displacement method, and sixteen of these subjects (7 men and 9 women) were used to locate the center of gravity of each trunk segment. A lead model was constructed using the trunk data to obtain the radii of gyration in both the sagittal and frontal planes. A single male cadaver was dissected to compare the trunk measurements with the lead model results.

Key words: living segmented anatomy, center of gravity, radius of gyration, water displacement, analysis of human motion, link action.

The biomechanical analysis of a total body motion requires the proper anatomical data on all body segments that may be classified as "rigid." All body parts have soft tissue displacement that takes place especially during fast motions where high accelerations and decelerations occur. Soft tissue movement has not been dealt with successfully in the analysis of body motions, and so has been disregarded by biomechanists when calculating forces due to motion. The skeletal structure determines the segments to be considered "rigid" due to the movement at the joints with masses of relatively unchanging length between the joints. The body segments classified as "rigid" are the hands, forearms, upper arms, feet, shanks, thighs, head and neck, and trunk. The trunk presents special problems because it is so massive and mobile, and must be further subdivided to minimize the calculation error of a force analysis.

The trunk may be divided into the pelvis, abdomen, and thorax segments, which gives the total body sixteen "rigid" segments. The movement patterns of these sixteen segments must be analyzed separately to obtain kinematic and kinetic data, and the anatomical input is one of the major contributors to calculation errors of this extremely complex pendular system even if soft tissue motion is considered negligible.

The Anatomical Data Needed

The human body moves by rotating each segment about one of its ends or about its long axis. If any point or segment of the body has translatory motion, it is a result of a combination of compensating rotational motions. The forces of motion about the long axis have been ignored by biomechanists when analyzing a total body motion where the body is treated like a sixteen link pendular system. Ignoring soft tissue motion and motion of the extremities about their long axes, the anatomical data needed on each segment are weight, length, center of gravity, and radius of gyration from each end. These data are relatively easy to obtain on the extremities because the joint centers are the pivot points, and the centers of gravity are close to the line connecting the joint centers. The joint pivot points actually change slightly during movement (Steindler, 1962), but this also has been disregarded in biomechanical work because of the difficulty of selecting joint centers from superficial landmarks.

Obtaining proper anatomical data on the trunk is a major problem because the vertebral column allows many variations of motion, and the pivot points are not easily defined. There is also considerable movement of the whole shoulder girdle during arm motion which requires a center of gravity correction factor within the thoracic segment (Plagenhoef, 1971). Due to the lack of data on the segmented trunk of the living and a lack of data on women, this study was aimed mainly at obtaining those data.

Available Data From Cadavers

Krogman and Johnston (1963) compared the cadaver data of four major monographs in *Human Mechanics*. Only Dempster's (1955) work fully explained the planes of the dissections, which made it difficult to closely compare the centers of gravity and moments of inertia with Braune and Fischer, Fischer, and Amar (Krogman & Johnston, 1963). Because Dempster's (1955) work was explicit and data were collected on the most cadavers (8), his density data were the only data used after obtaining water displacement volumes to calculate each segment weight of the living. Each segment's density thus corresponded to the volume of the segment because the living body was submerged to Dempster's (1955) defined planes of the joint centers (Tables 1 and 2). Contini (1972), Drillis and Contini (1966), and Santschi, DuBois, and Omoto (1963) have done work on the living, but all density and center of gravity data are on the whole body. It is not possible to get accurate density data on living subjects, so cadaver data must be used.

Clauser, McConville, and Young (1969) made a major contribution when they quantified the discrepancy between the mid-volume level of a submerged limb and the actual center of gravity. Their correction factor moves the center of gravity distally from the mid-volume position as shown in Table 3. For example, the volume measurement to obtain the center of gravity of the lower leg, is 45.1% rather than 50%.

Table 1
Dempster's Planes of Joint Center (Dempster, 1955)

For the hand: (1) the mid-point of the pisiform bone, (2) the distal wrist crease at the palmaris longus tendon or the mid-point on the volar surface of the navicular bone, (3) the palpable sulcus dorsally between the lunate and capitate bones.

For the hand plus forearm: (1) the lower border of the medial epicondyle of the humerus, (2) eight millimeters above the radiale.

For the whole upper limb: (1) the palpable sulcus above the acromioclavicular joint, (2) the anterior axillary fold at the projection of the thoracic contour, (3) the posterior axillary fold at the projection of the thoracic contour.

For the foot: (1) the superior border of the calcaneus anterior to the Achilles tendon as palpated medially and laterally, (2) the upper border of the head of the talus, (3) the lower tip of the fibula.

For the foot and shank: (1) the mid point of the posterior curvature of the medial condyle of the femur as palpated, (2) the same for the lateral condyle.

For the whole lower limb: (1) the anterior superior spine of the test side, (2) the ischiopubic sulcus between the thigh and the scrotum, (3) the line from the ischium to above the femoral trochanter.

For the head and neck: (1) the top of the sterno-clavicular joint, (2) between the 7th cervical and the 1st thoracic vertebra.

For the head: (1) decapitate the skull from the atlas.

For the thorax: (1) the disc between the 10th and 11th thoracic vertebra, (2) the lowest fibers of the pectoralis major or the middle of the xiphoid process.

Between the pelvis and abdomen (not dissected by Dempster): (1) the disc between the 3rd and 4th lumbar vertebra, (2) the umbilicus.

Table 2
Specific Gravity of Body Segments (Dempster, 1955)

Hand	1.16	Forearm	1.13	Upper arm	1.07
Foot	1.10	Shank	1.09	Thigh	1.05
Thorax	0.92	Abdomen	1.01	Pelvis	1.01
Head-Neck	1.11				

Table 3
Water Volume from the Distal End To the Center of Mass (Clauser et al., 1969)

Lower leg	45.1%	Lower leg and foot	46.4%
Thigh	46.5%	Whole leg	42.6%
Forearm	43.7%	Forearm and hand	45.2%
Upper arm	45.6%		

Body Segment Weights

The water immersion technique was performed on 135 college-age athletes (100 women and 35 men) producing a percent of total body weight for each extremity and for the trunk as one segment. Of this group, 18 women and 15 men were selected at random for a four segment analysis of the total trunk. The sixteen segments measured are shown in Figure 1. A small tank

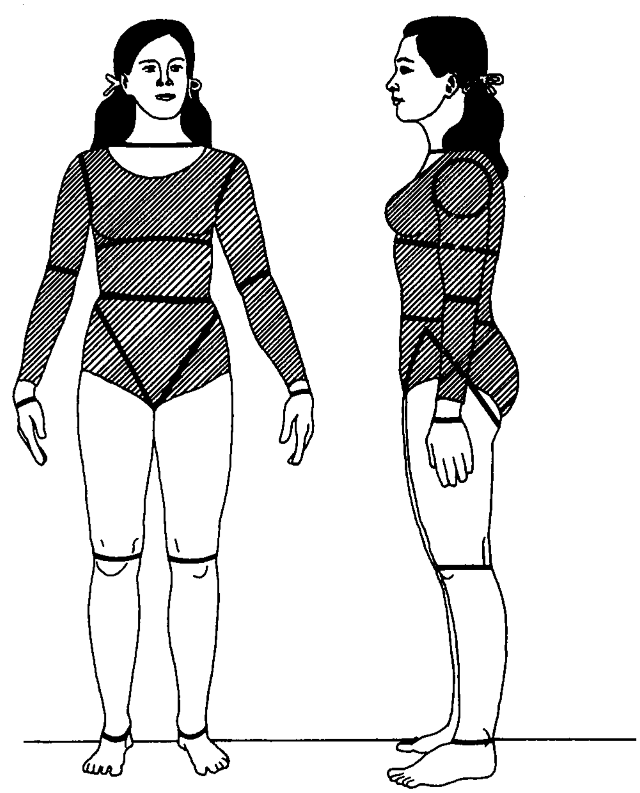

Figure 1—Sixteen body segments.

was used for the whole arm and lower leg, and a tank just large enough for the person to fit into when fully submerged was used for the remainder of the measurements. The larger segments are the most difficult to measure and have the largest standard deviation. Table 4 shows the mean segmented weights as a percentage of the total body weight. This allows the data to be used on any size person.

The cadaver dissection of the trunk by Parks (1959) was used as a guideline for the water displacement landmarks. Figure 2 shows the level of submersion to the umbilicus, xiphoid process at the pectoral line, and the proximal neck line. The total weight is determined by subtracting the extremity weights from the scale reading of the total body weight. It was found that the segmented trunk weights added together always exceeded the actual weight of the trunk. This was due to the extra water displaced by the thorax and abdomen sections because the air could not be completely expelled during the submersion. A correction factor was determined for the thorax and abdomen by resubmerging each subject, segment by segment, with the lungs fully inflated and again with the air expelled as fully as possible. It was found that one-third of the overweight was attributable to the abdomen and two-thirds to the thorax. The overweight of the total trunk was therefore reduced by subtracting one-third of the overweight from the abdomen and two-thirds of the overweight from the thorax. This eliminated any measurement of residual air in the lungs and did not require the lungs to be completely deflated during submersion. When Dempster's (1955) body segment densities were applied to the water displacement data on the living subjects, it was possible to obtain mass distribution data for men and for women, not only on extremities, but on the segmented trunk where none existed previously.

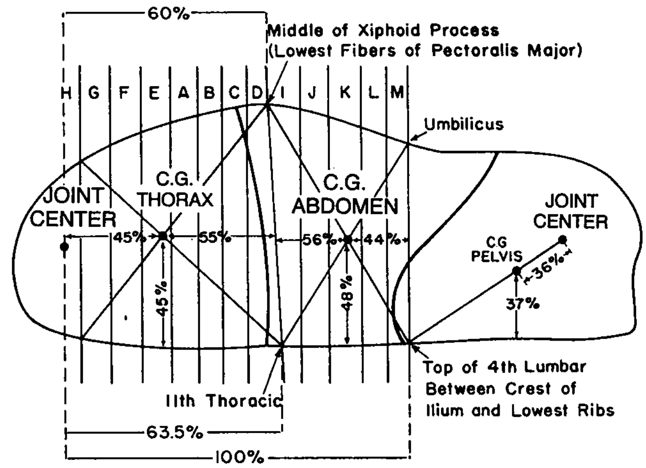

Figure 2—Trunk dissection from Parks

Table 4
Segment Weights as Percentages of Total Body Weight

	Men N = 35		Women N = 100	
One segment	Mean	SD	Mean	SD
Hand	0.65%	0.06%	0.5%	0.026%
Forearm	1.87	0.2	1.57	0.1
Upper arm	3.25	0.49	2.9	0.32
Foot	1.43	0.13	1.33	0.02
Shank	4.75	0.53	5.35	0.47
Thigh	10.5	1.21	11.75	1.86
Whole trunk	55.1	2.75	53.2	4.64
Head and neck	8.26		8.2	
Thorax	20.1		17.02	
Abdomen	13.06		12.24	
Pelvis	13.66		15.96	

Trunk Segments as a Percentage of Trunk Weight

	Men N = 15		Women N = 18	
Head and neck	15.2	1.96	14.8	1.85
Thorax	35.8	1.1	31.9	2.91
Abdomen	24.2	1.6	23.5	1.4
Pelvis	25.5	1.8	30.9	1.5
Abdomen and pelvis	49.6	2.1	48.83	2.45

Body Segment Centers of Gravity

The centers of gravity of each segment were also obtained on seven men and nine women by resubmerging each limb segment to the percentage level given in Table 3 for each segment. All extremities have the true center of gravity slightly distal to the 50% volume level. Trunk segments have a more even distribution about the center of mass, so the mid-volume plane of the total water displaced was used to obtain the center of gravity of the pelvis, abdomen, and thorax segments. With the body almost totally submerged, the measurement of the center of gravity of the head and neck was very difficult, so the location is from Dempster's (1955) cadaver data. Table 5 lists the sixteen body segment centers of gravity as a percentage of the segment length to allow the data to be applied to any size person.

Radius of Gyration

The radius of gyration of the extremities, obtained from Dempster's (1955) cadaver data, was corrected relative to the center of gravity determined for the living. The consistency of the geometric shape of each extremity produces a nearly constant radius of gyration relative to the location of the center of mass. Therefore, this difference was maintained but applied

Table 5
Location of the Segment Center of Gravity As a Percentage of the Segment Length

	Men N = 7		Women N = 9	
	Proximal	Distal	Proximal	Distal
Hand	46.8%	—	46.8%	—
Forearm	43.0	57.0	43.4	56.6
Upper arm	43.6	56.4	45.8	54.2
Foot	50.0	—	50.0	—
Shank	43.4	56.6	41.9	58.1
Thigh	43.3	56.7	42.8	57.2
Whole trunk[a]	63.0	37.0	56.9	43.1
Pelvis[b]	5.0	95.0	5.0	95.0
Abdomen	46.0	54.0	46.0	54.0
Thorax[c]	56.7	43.3	56.3	43.7
Head and neck[d]	55.0	45.0	55.0	45.0
Abdomen and pelvis[e]	44.5	55.5	39.0	61.0

[a]Hip joint to shoulder joint = 100%
[b]Hip joint to plane of umbilicus = 100%
[c]Pectoral line to shoulder joint (gleno-humeral) = 100%
[d]Top of the head to 7th cervical = 100%
[e]Hip joint to T-11 = 100%

Table 6
Radius of Gyration as a Percentage of Segment Length

	Men N = 36		Women N = 100	
	Proximal	Distal	Proximal	Distal
Hand	54.9%	—	54.9%	—
Forearm	52.6	64.7	53.0	64.3
Upper arm	54.2	64.5	56.4	62.3
Foot	69.0	—	69.0	—
Shank	52.9	64.2	51.4	65.7
Thigh	54.0	65.3	53.5	65.8

to the living center of mass. Table 6 gives the radius of gyration as a percentage of the length from the joint center of rotation for the extremities.

Lead Models

The radius of gyration data needed for the segmented trunk were not available from cadavers, so two lead models were constructed to correspond to the living data obtained. The lead cut-out was proportioned to the mass distribution of the body as given by Dempster (1955) but to the size, weight, and center of gravity of the living segments. Figure 3 shows the proportions of the lead model for the frontal and sagittal planes from which a male and female model were constructed using data presented in Tables 4 and 5.

Swinging the lead models allowed the calculations of the radius of gyration for each segment, and for combinations of two or three segments that might be needed for kinetically analyzing different total body motions. The period of oscillation was obtained from different joints for several combinations of segments, so several models were constructed to make this possible. Figures 4 a-h give the axis of rotation, the center of gravity, and the radius of gyration from both the distal end (r_d, k_d) and the proximal end (r_p, k_p) for both the male and female.

Figure 4a gives the data for motion in the sagittal plane when the axis of rotation goes through both shoulders (k_d) and both hips (k_p), or at the level of the 4th-5th lumbar. Axes in the frontal plane show a diagonal axis from one hip to the opposite shoulder, an axis from a hip joint to the shoulder on the same side, and an axis from the 4th-5th lumbar junction to either shoulder. All numbers are percentages of the joint-to-joint length. Figure 4b shows the same measurements as in 4a with the pelvis removed, 4c shows only the thoracic section, 4d only the abdominal section, and 4e only the pelvic section. Figure 4f combines the abdomen and pelvis and shows the head and neck only, 4g combines the thorax and abdomen, and 4h combines the head and neck, and thorax. All these combinations are presented so the data are available for almost any motion. A total link system analysis explaining the axes of rotation of the separate body parts is fully covered in Plagenhoef (1973).

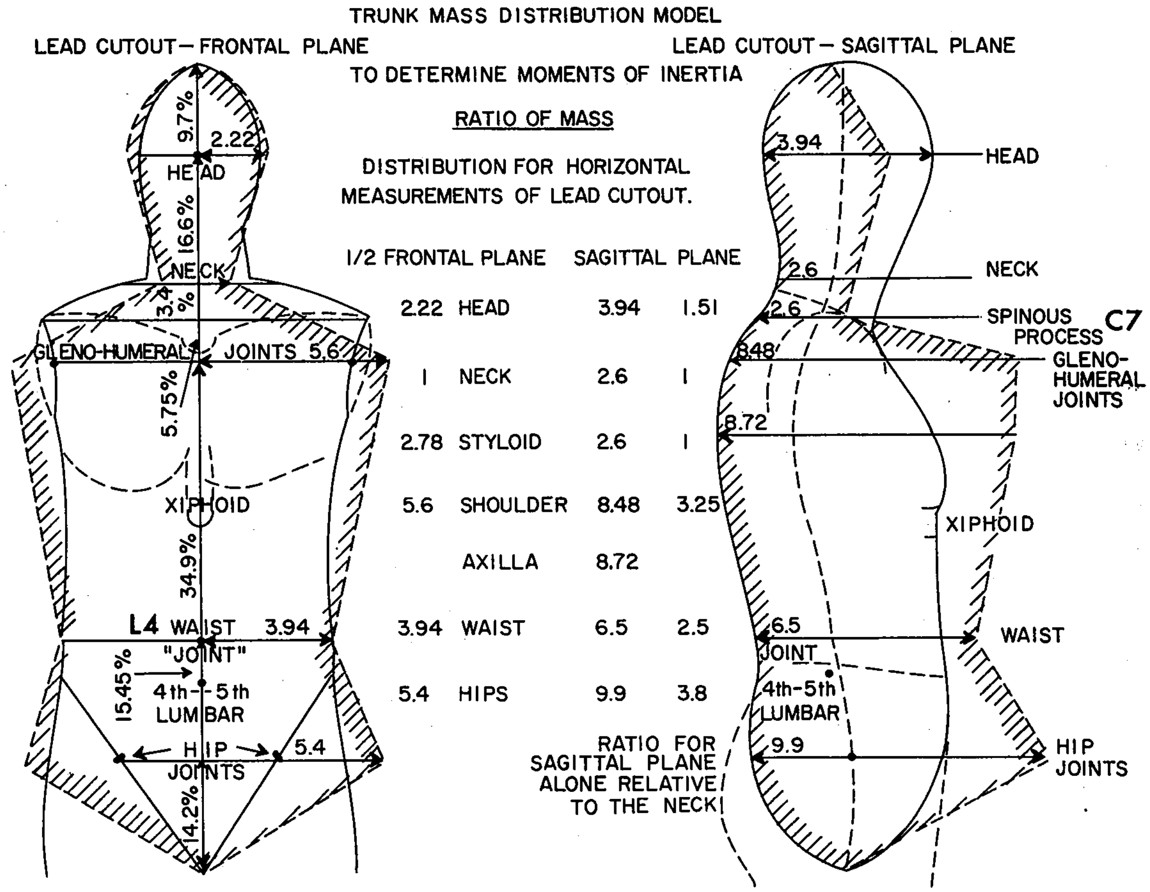

Figure 3—Lead model.

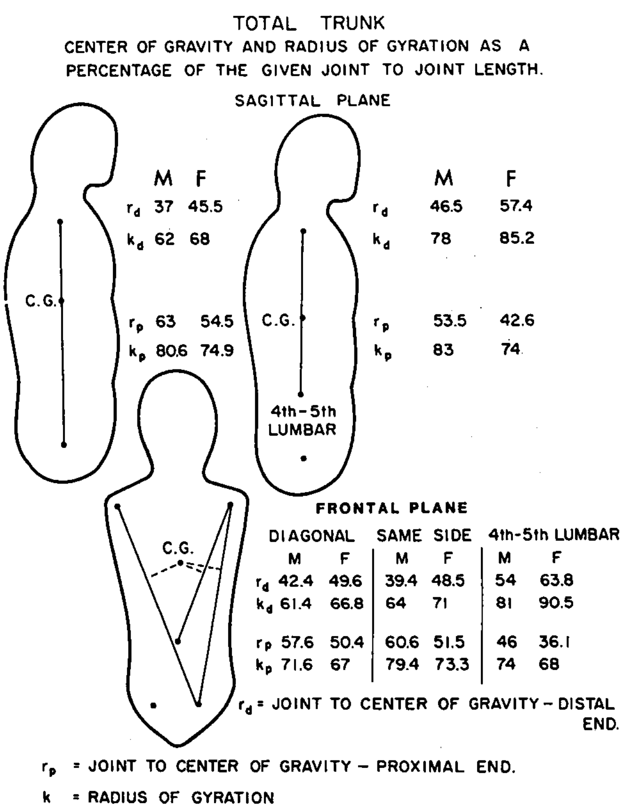

Figure 4a.

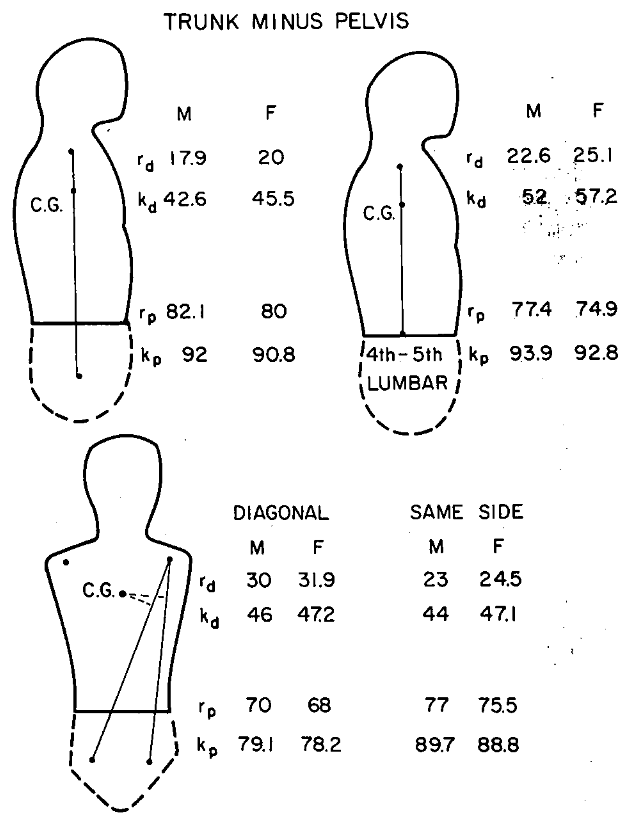

Figure 4b.

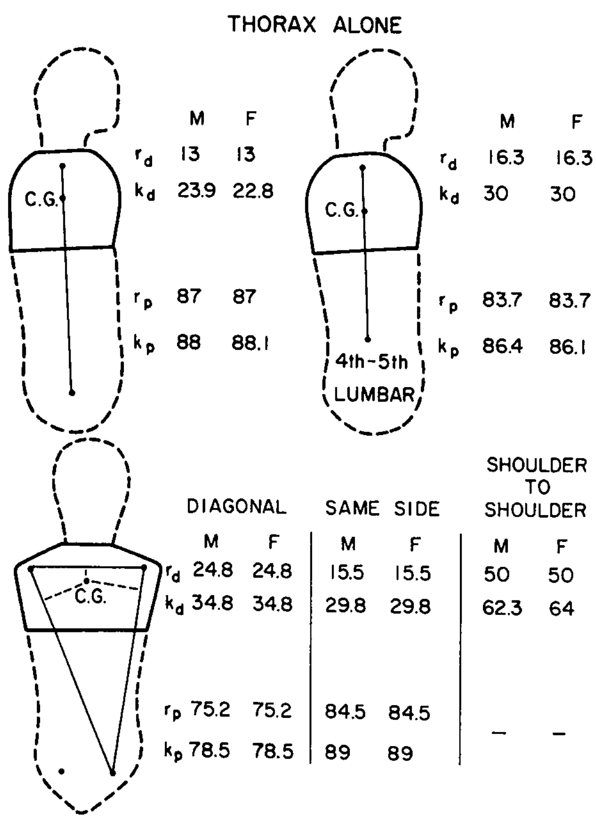

Figure 4c.

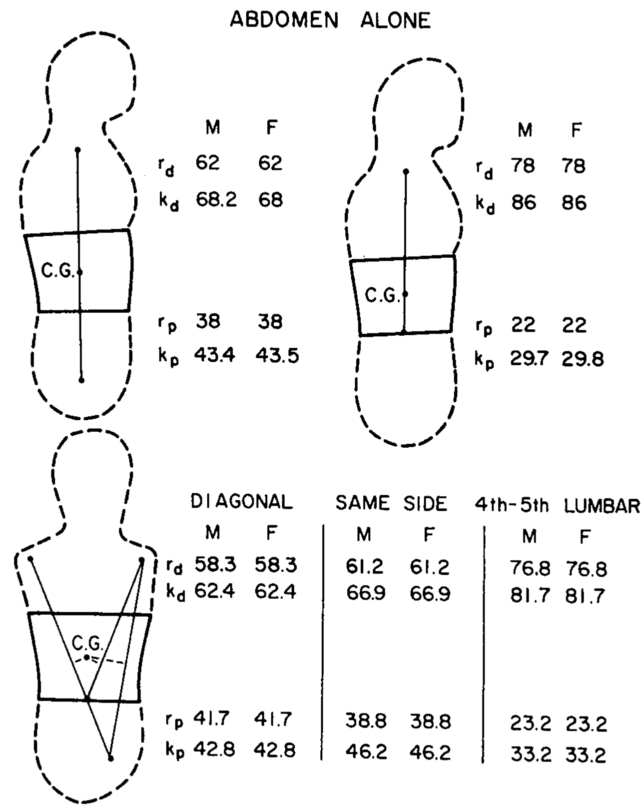

Figure 4d.

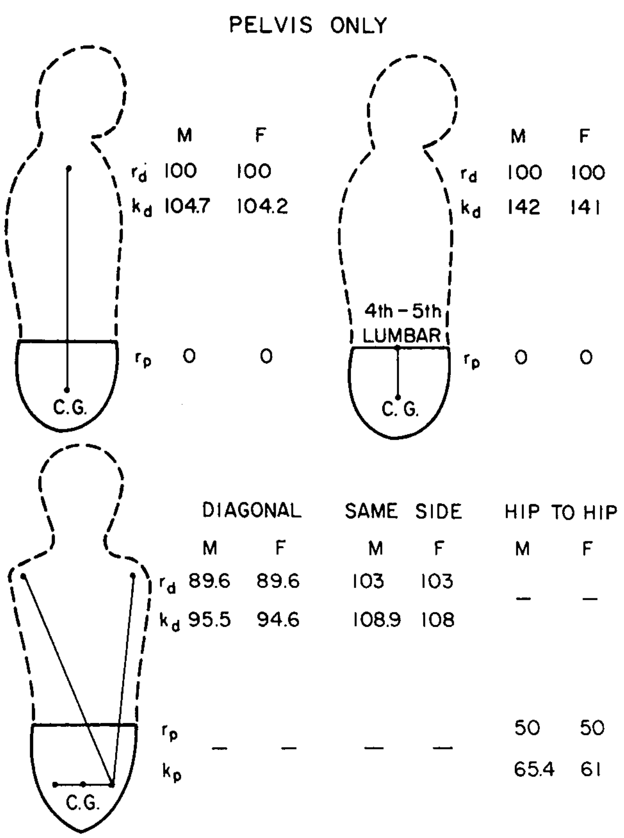

Figure 4e.

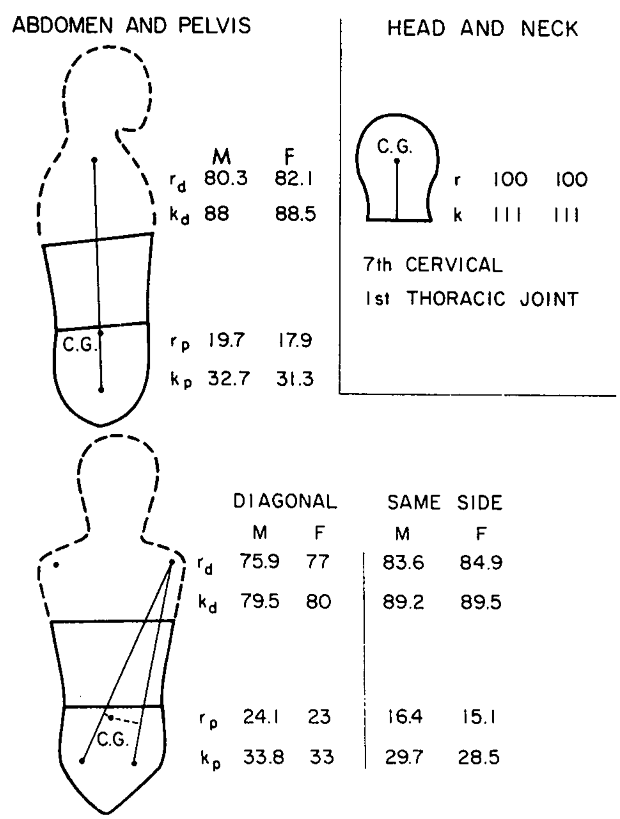

Figure 4f.

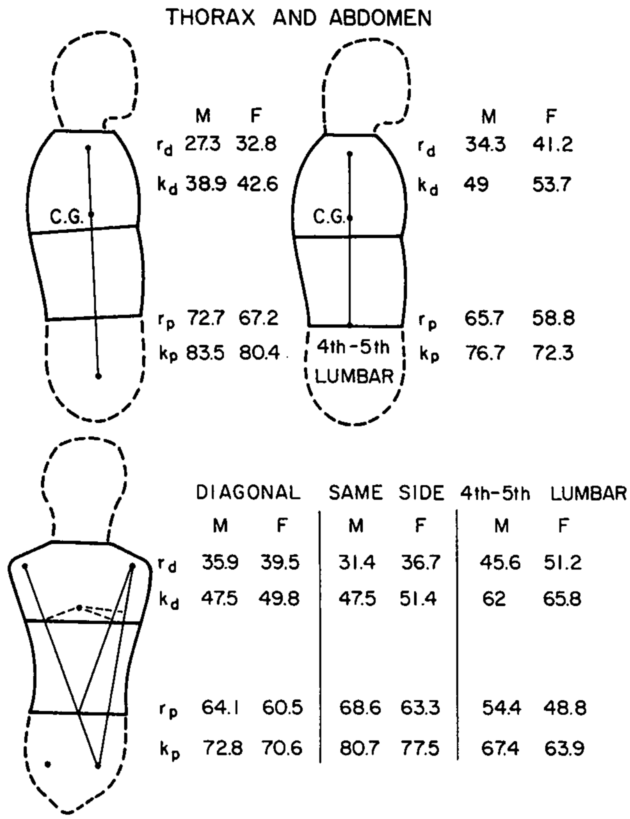

Figure 4g.

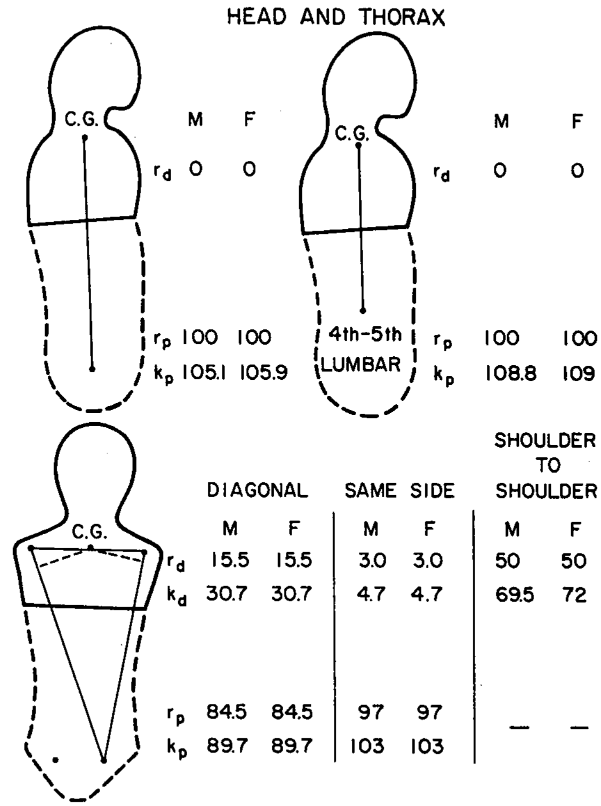

Figure 4h.

Error is introduced into the lead models because a solid form is represented by a non-solid model. Considering the trunk to be an elliptical solid and calculating the moments of inertia for both a solid and the two crossed planes of lead (Figure 3), the errors range from 3% to 9% depending on the location of the axis of rotation. It is 9% when the axis is through the center of the trunk, as it would be for a spinning ice skater, but it is only 3% when the axis is on one side (Figure 4a, frontal plane), which occurs with almost all nonsymmetrical body motions. Constructing lead models (approximately one third life size) and using cadaver mass distribution data was the easiest way to obtain the needed unknown radii of gyration. Obtaining the same information using cadaver dissection would be an enormous undertaking, and some of the axes of rotation would be nearly impossible to obtain. More importantly, the model is based on sixteen living men and women.

Cadaver Dissection

One cadaver was dissected for the specific purpose of obtaining the period of oscillation of the trunk segments for comparison with the lead model data. The cadaver was a male weighing about 77 kg and was about 178 cm in height. After the extremities were eliminated, the trunk was dissected, and the parts weighed and balanced to obtain the centers of gravity. Each part was then swung about several axes to obtain the radii of gyration corresponding to some of those shown in Figures 4a-h. To swing the body parts, holes were drilled and rods inserted at the various axes of rotation. Some comparative results are presented in Table 7. When the whole trunk was swung as in Figure 4a, from the shoulder and hip joints, the radius of gyration was 62% (k_d) and 80.6% (k_p) of the shoulder-to-hip distance. The corresponding cadaver percentages were 60% and 73%. When the thorax alone was swung as in Figure 4c, from the shoulders and hips, the radius of gyration was 23.9% (k_d) and 88% (k_p) of the

Table 7
Comparison of Radii of Gyration of Cadaver and Male Lead Model as a Percentage of Segment Length

	Proximal		Distal	
	Model	Cadaver	Model	Cadaver
Whole trunk	80.6%	73.0%	62.0%	60.0%
Thorax alone	88.0	83.4	23.9	30.5
Shoulder to Shoulder	62.3	57.6	—	—
Abdomen alone	43.4	37.5	68.2	64.8
Pelvis alone	0	14.0	104.7	97.0
Hip to Hip	65.4	61.0	—	—

shoulder-to-hip distance. The corresponding cadaver percentages were 30.5% and 83.4%. When the thorax alone was swung from one shoulder, and taken as a percentage of the shoulder-to-shoulder distance, the radius of gyration was 62.3% versus 57.6% for the cadaver. When the abdomen alone was swung as in Figure 4d, from the shoulders and hips, the radius of gyration was 68.2% (k_d) and 43.4% (k_p) of the hip-to-shoulder distance. The corresponding cadaver percentages were 64.2% and 37.5%. The center of gravity of the pelvis alone was between the hip joints in the model, and above the hips in the cadaver. Therefore, the radius of gyration was 104.7% (k_d) and 0% (k_p) of the hip-to-shoulder distance. The corresponding cadaver percentages were 97% and 14%. When the pelvis alone was swung from one hip, and taken as a percentage of the hip-to-hip distance, the radius of gyration was 65.4% for the model and 61% for the cadaver. In addition to these comparisons, the moments of inertia of the pelvis, abdomen, and thorax were calculated as a whole and again as a unit, but after dissection. Variances were 4% and 7.4% for the model when swung about the hip and shoulders, while the cadaver varied 8.4% and 3%.

The cadaver trunk was very difficult to dissect along the defined planes, and there were differences in the size of the segments relative to the model. The thorax was 9.7% larger and the pelvis 13.7% larger, which made the abdomen section smaller than the model. The high saw cut between the pelvis and abdomen raised the pelvic center of gravity 2½ cm, and this small difference resulted in high percentage differences of the pelvic model and cadaver. The thorax section was cut larger on both the top and bottom, and the center of gravity was 3.5% higher than the model. These differences are reflected in the radii of gyration calculations which are 5%to 8% less for the cadaver. The comparison of one cadaver dissection to a composite model seems like a useless procedure, but the difficulties encountered when dissecting and swinging the cadaver trunk showed that the use of a model was a good selection for obtaining the necessary anatomical data.

Segment Lengths

In addition to the data presented thus far, it is often necessary to obtain segment lengths on subjects not available for measurement. The segment lengths of thirty-five men and seventy-three women were measured with the results given in Table 8. The lengths are given as a percentage of the height so these data may be used on any size person. The standard deviation was one centimeter for approximately every sixteen centimeters, which is 6%. There is a very small variation in both segment lengths and segment weights when expressed as a percentage of height and weight; therefore, no attempt was made to relate these data to somatotypes.

Table 8
Segment Length as a Percentage of Total Height

	Men N = 35	Women N = 73
Hand (to center of gravity)	5.75%	5.75%
Forearm	15.7	16.0
Upper arm	17.2	17.3
Foot (to center of gravity)	4.25	4.25
Shank	24.7	25.0
Thigh	23.2	24.9
Trunk (hip to shoulder)	30.0	29.0
Head and neck (to center of gravity)	10.75	10.75
Thorax	12.7	12.7
Abdomen	8.1	8.1
Pelvis	9.3	9.3
Shoulder to shoulder (gleno-hum)	24.5	20.0
Hip to hip	11.3	12.0

Standardized Data For Biomechanical Analysis

Filming of a person performing a motion that is to be analyzed is usually done under conditions which do not allow body measurements to be taken. The person's height and weight can probably be obtained, so the Tables presented will allow the segment weights and lengths, centers of gravity, and radii of gyration to be calculated. To simplify the work of the analyst, who lacks anatomical data, a standard man and woman are presented in Table 9. This information is especially helpful when comparing motion patterns of two people. Any size person may be chosen and a similar table constructed from the percentages given.

Conclusions

The presentation of anatomical data on the segmented body, and especially the trunk, of both men and women makes it possible to analyze a total body motion kinetically. The inherent errors of the data must be fully recognized and considered in the interpretation of any data. These errors are the soft tissue motion, the choosing of a single point to represent the joint center, the inaccuracy of choosing that point from external landmarks, the omission of motion in the extremities about the long axis, and the actual differences in the segment weight, center of gravity, and radius of gyration to that unknown quantity of what they actually are in the living human body.

Table 9
Standard Man[1] and Woman[2]

Segment	Weight (gm)		Length (cm)	
	Man	Woman	Man	Woman
Foot	1154	812	15.3	14.5
Shank	3848	3279	44.5	42.5
Shank and foot[a]	5002	4091	44.5	42.5
Thigh	8505	7202	41.8	42.3
Hand	526	306	10.4	9.8
Forearm	1519	965	28.3	27.2
Upper arm	2633	1777	31.0	29.4
Forearm and hand[b]	2045	1271	28.3	27.2
Pelvis[c]	11065	9782	20.3	20.4
Abdomen[d]	10578	7502	54.0	49.3
Thorax[e]	16281	10432	44.1	34.0
Head and neck	6695	5063	19.4	18.3
Whole trunk[f]	44631	32606	54.0	49.3

	Man	Woman	Man	Woman	Man	Woman	Man	Woman
	r		r		k		k	
	Prox	Dist	Prox	Dist	Prox	Dist	Prox	Dist
Foot	0.5	0.5	0.5	0.5	0.69	0.6	0.69	0.6
Shank	0.43	0.57	0.42	0.58	0.53	0.64	0.51	0.66
Shank and foot[a]	0.61	0.39	0.6	0.4	0.74	0.57	0.73	0.58
Thigh	0.43	0.57	0.43	0.57	0.54	0.65	0.54	0.66
Hand	0.51		0.5		0.54		0.54	
Forearm	0.43	0.57	0.43	0.57	0.53	0.65	0.53	0.64
Upper arm	0.44	0.56	0.46	0.54	0.54	0.65	0.56	0.62
Forearm and hand[b]	0.68		0.68		0.83		0.83	
Pelvis[c]	0.5		0.5		0.65		0.61	
Abdomen[d]	0.38	0.62	0.38	0.62	0.43	0.68	0.43	0.68
Thorax[e]	0.5		0.5		0.62		0.64	
Head and neck	0.55		0.55		0.61		0.61	
Whole trunk[f]	0.63	0.37	0.55	0.45	0.81	0.62	0.75	0.68

[a]Length of shank alone = 100%
[b]Length of forearm alone = 100%
[c]Hip joint to hip joint = 100%
[d]Hip to shoulder length = 100%
[e]Shoulder to shoulder length = 100%
[f]Hip to shoulder length = 100%
r = Percent of length to obtain center of gravity
k = Percent of length to obtain radius of gyration
[1]Man = 81000 gms or 178½ lbs, and 180 cm or 5 ft 11 in.
[2]Woman = 61290 gms or 135 lbs, and 170 cm or 5 ft 7 in.

It can only be estimated that the anatomical data presented in this paper may be in error by as much as 10% to 15% from the actual living body. The anatomical input is usually not the major cause of error in a kinetic analysis. Many kinesiologists make the mistake of curve fitting with extreme accuracy the large errors of selecting joint centers, which results in extremely poor kinetic data. This paper only fulfills the purpose of presenting anatomical data that have been lacking to make a total body analysis possible.

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