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TECHNICAL NOTE

ADJUSTMENTS TO ZATSIORSKY-SELUYANOV'S SEGMENT INERTIA PARAMETERS

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Abstract—Zatsiorsky *et al.* (in *Contemporary Problems of Biomechanics*, pp. 272–291, CRC Press, Massachusetts, 1990a) obtained, by means of a gamma-ray scanning technique, the relative body segment masses, center of mass (CM) positions, and radii of gyration for samples of college-aged Caucasian males and females. Although these data are the only available and comprehensive set of inertial parameters regarding young adult Caucasians, they have been rarely utilized for biomechanical analyses of subjects belonging to the same or a similar population. The main reason is probably that Zatsiorsky *et al.* used bony landmarks as reference points for locating segment CMs and defining segment lengths. Some of these landmarks were markedly distant from the joint centers currently used by most researchers as reference points. The purpose of this study was to adjust the mean relative CM positions and radii of gyration reported by Zatsiorsky *et al.*, in order to reference them to the joint centers or other commonly used landmarks, rather than the original landmarks. The adjustments were based on a number of carefully selected sources of anthropometric data. Copyright © 1996 Elsevier Science Ltd.

Keywords: Segment inertia parameters; Living subject; Adjustment; Joint center; Reference point.

NOMENCLATURE AND DEFINITION OF TERMS

ACR	acromion—the most lateral point on the lateral margin of the acromial process of the scapula.
AJC, EJC, HJC, KJC, SJC, WJC	respectively, the joint centers of ankle, elbow, hip, knee, shoulder, and wrist (see de Leva, 1996).
BB	bispinous breadth—the distance between the two iliospinales.
CERV	cervicale—the superior palpable point of the spine of the seventh cervical vertebra (Gordon *et al.*, 1989).
DAC3	3rd dactylion—the tip of the 3rd digit.
GON	gonion—the most lateral point on the posterior angle of the mandible (jawbone; Gordon *et al.*, 1989)
HEEL	(pternion)—the posterior point of the heel (Gordon *et al.*, 1989).
HSP int.	the intersection of the projections on the frontal plane of the hip segmentation planes (HSPs; Zatsiorsky *et al.* 1990a).
HSPs	hip segmentation planes—the boundaries between thighs and trunk, defined as planes passing through the respective iliospinales, parallel to the trunk sagittal axis, and forming a 37° angle with the sagittal plane (Zatsiorsky *et al.*, 1990a).
ILIO	iliospinale (or anterior iliospinale)—the inferior point of one of the anterior superior iliac spines.
LMAL	lateral malleolus—the most lateral point on the lateral malleolus.
MET3	3rd metacarpale—a point on the dorsal sulcus between the tip of the third metacarpal (knuckle) and the base of the third finger.
MIDG, MIDH, MIDS	mid-gonion, mid-hip, and mid-shoulder—the points midway between the gonions, hip joint centers, and shoulder joint centers, respectively.
OMPH	omphalion—the center of the navel (Gordon *et al.*, 1989).
RAD	radiale—the most proximal point on the lateral edge of the radius (Gordon *et al.*, 1989).
SPHY	sphyrion (or tibial sphyrion)—the distal tip of the tibia.
STYL	stylion—the distal tip of the styloid process of the radius.
SUPR	suprasternale—the most caudal point on the margin of the jugular notch of the sternum (breastbone).
TIB	tibiale—the most proximal point on the medial margin of the head of the tibia.
TTIP	(acropodion)—the tip of the longest toe (first or second; Gordon *et al.*, 1989).
VERT	vertex—the most cranial point of the head, when the head is oriented in the Frankfort plane.
XYPH	xyphion (or substernale)—the midpoint of the sulcus between the body of the sternum (breastbone) and the xyphoid process (Zatsiorsky, personal communication, 1991).

Note: Except for MIDG, MIDH, MIDS, and unless otherwise specified, the definitions correspond to those given by Chandler *et al.* (1975).

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INTRODUCTION

Quantitative biomechanical analyses of human movement typically require the estimate of the body segment inertia parameters (BSIPs: mass, position of the center of mass, and principal radii of gyration, or moments of inertia). When body mass and stature are the only known anthropometric parameters for a subject, mean BSIPs obtained measuring cadavers of elderly males (e.g., Clauser *et al.*, 1969, partly adjusted by Hinrichs, 1990) are widely used for estimating the subject's inertial characteristics. Due to lack of other sources, even female subject's inertial characteristics are sometimes estimated using the same mean BSIPs. Yet, de Leva (1993) showed that generalization of cadaver data to college athletes is likely to cause large errors in the calculated position of their body centers of mass (CMs). For instance, when the Clauser *et al.* BSIPs, partly adjusted by Hinrichs (1990), were used for locating the CMs of both female and male athletes in layout position, the mean errors in the longitudinal direction were, respectively, 53 mm (S.D. = 18) and 38 mm (S.D. = 13), with respect to the true CM positions determined with a high precision reaction board. On the contrary, the mean BSIPs reported by Zatsiorsky *et al.* (1990a) were found by de Leva to be validly generalizable to college athletes: using the latter parameters, the errors described above were reduced to 16 mm (S.D. = 17) and − 4 mm (S.D. = 13), respectively. Similar results were obtained for other body positions.

Zatsiorsky *et al.* (1990a) determined with a gamma-ray scanner the BSIPs of 100 male and 15 female Caucasian subjects (mean ages: 24 and 19 years, respectively), most of which were undergraduates in a physical education college. The BSIPs of their male sample have been available since 1983 (Zatsiorsky and Seluyanov, 1983; Zatsiorsky *et al.*, 1990a, b, 1993), and no other comprehensive studies have been published about the inertial characteristics of college-aged Caucasians. Yet, surprisingly the Zatsiorsky *et al.* data have been rarely preferred to cadaver data, even for estimating the inertial properties of healthy young adult Caucasians. The main reason is probably that Zatsiorsky's group used bony landmarks as reference points for locating segment CMs and defining segment lengths (e.g. the iliospinale was the proximal reference point for the thigh). Some of these points are remarkably distant from the centers of the neighboring joints. As a consequence, when a subject flexes his joints the distances of these reference points from the respective proximal or distal segment CMs significantly decrease. These and other related changes, which make it impossible to accurately locate segment CMs, can be minimized only by using joint centers as reference points.

The purpose of this paper was to adjust the mean relative CM positions and radii of gyration reported by Zatsiorsky's group, in order to reference them mainly to the positions of joint centers rather than bony landmarks. In some cases the original landmarks were either considered adequate, or substituted with other commonly used bony landmarks. When possible, readers were offered the possibility to select among different landmarks for defining a reference point.

ADJUSTMENT PROCEDURES AND RESULTS

Segment lengths

Zatsiorsky *et al.* (1983, 1990a, b, 1993) did not report the mean lengths of their subjects' segments. These lengths were needed for the adjustments. They could not be computed from the original data, stored by the authors in a format that is not readable by modern computers (Zatsiorsky, personal communication, 1991), and were estimated as follows:

$$\bar{l} = \bar{r}_{abs}/\bar{r}_{rel}\,, \tag{1}$$

where $\bar{l}$ is the mean length of a segment, $\bar{r}_{abs}$ is the mean absolute radius of gyration of that segment about a given axis, computed as explained below, and $\bar{r}_{rel}$ is the respective mean ratio between segment radius of gyration and length, as reported by Zatsiorsky *et al.* (1990a). Equation (1) is based on the assumption that the individual values of r_{rel} were identical for all subjects.

For each segment, $\bar{r}_{abs}$ could be estimated by applying the following equation:

$$\bar{r}_{abs} = \sqrt{\bar{I}/\bar{m}}, \tag{2}$$

where $\bar{I}$ is the mean segment moment of inertia about the considered axis, and $\bar{m}$ is the mean segment mass (both reported by Zatsiorsky *et al.*, 1990a; for segment masses of males, see also Zatsiorsky and Seluyanov, 1983 and Zatsiorsky *et al.*, 1990b, 1993).

Although for a single segment r_{abs} is, by definition, equal to $\sqrt{I/m}$, equation (2) can be shown to be valid only if the radius of gyration of the considered segment is identical for all subjects. Since the latter condition was not true, and the more massive segments tend to have a longer radius of gyration, equation (2) is likely to overestimate systematically the value of $\bar{r}_{abs}$. However, the error in estimating segment lengths by using equations (1) and (2) is trifling. In fact, the mean segment lengths of the male sample could be also estimated by dividing mean absolute by mean relative segment CM positions. This second method is based on the assumption that, for each segment, the individual relative CM positions were identical for all subjects. The mean relative values were known; the mean absolute values, in centimeters, were obtained by plugging mean body mass and stature into the multiple regression equations reported by Zatsiorsky *et al.* (1990a), unfortunately for the male subjects only (the regression equations reported for the female subjects predict *relative* CM positions). The differences between the segment lengths estimated using equations (1) and (2), and those estimated using multiple regression equations ranged from − 0.8% to 1.9% (mean 0.7%); the absolute differences ranged from − 4.3 to 4.1 mm (mean 1.5 mm). These differences are trifling compared to the errors typically accepted when mean segment inertia parameters from the literature, such as those reported at the end of this note (Table 4), are generalized to an individual subject (de Leva, 1993). For the sake of consistency, the segment lengths of both the male and female samples were estimated using equations (1) and (2).

For each segment, equations (1) and (2) were applied twice, using the values of $\bar{r}_{rel}$ and $\bar{I}$ about the sagittal and transverse axes (those about the longitudinal axes were not used because of their lower relative precision, due to their smaller magnitude). The two results were averaged, and reported in Table 1. The differences between the two estimates of the length of each segment ranged from 0.0 to 2.1 mm.

Estimating joint center positions

de Leva (1996) reported the percent longitudinal distances of the main joint centers from neighboring bony landmarks, relative to the lengths of the respective proximal and/or distal segments. de Leva's proportions were multiplied by the respective mean segment lengths of the Zatsiorsky *et al.* subjects, to obtain the absolute distances listed in Table 2. Among the needed segment lengths, only those of the forearm and shank were directly obtained from Table 1. In fact, the definitions given by Zatsiorsky *et al.* for the upper arm, hand, and thigh lengths did not coincide with those given by de Leva. The latter three lengths were estimated for the Zatsiorsky *et al.* samples, according to de Leva's definitions, as explained in the paragraphs dedicated to the respective segments.

Two different estimates were available for the positions of the centers of the elbow, wrist, and knee (Table 2). The respective means were calculated and used for the adjustments to the segment CM percentages.

Selecting the trunk endpoints

Several different couples of reference points can be selected for locating trunk CM and computing trunk length. These points are assumed to lay on the segment longitudinal axis, and represent the cranial and caudal endpoints of the trunk model. The

Table 1. Estimated mean segment lengths for the Zatsiorsky *et al.* male and female subjects. The segment lengths are defined as the longitudinal distances between the respective segment endpoints

Segment	Endpoints	Longitudinal length (mm)	
		Females	Males
Head	Vertex, cervicale	243.7	242.9
Whole trunk	Cervicale, HSP intersection	690.1	709.3
Upper part of trunk	Cervicale, xyphion	228.0	242.1
Middle part of trunk	Xyphion, omphalion	205.3	215.5
Lower part of trunk	Omphalion, HSP intersection	256.8	251.7
Upper arm	Acromion, radiale	235.9*	244.8*
Forearm	Radiale, stylion	247.1	251.3
Hand	Stylion, 3rd dactylion	172.0	189.9
Thigh	Iliospinale, tibiale	496.2	520.2
Shank	Tibiale, sphyrion	393.8	393.4
Foot	Heel, toe tip	228.3	258.1

*Measured with the upper arm abducted by 90°; in this position, the acromion is markedly closer to the radiale than in the standard anatomical position (adducted arm).

Table 2. Estimated longitudinal positions of the main joint centers for the Zatsiorsky *et al.* subjects (the positive sign indicates the proximal direction)

Joint center	Longitudinal position (mm)		Relative to	Calculated using
	Females	Males		
Shoulder	− 33.7	− 34.5	Acromion	Acromion–radiale*
Elbow	13.9	14.3	Radiale	Acromion–radiale*
Elbow	16.6	16.8	Radiale	Radiale–stylion
Wrist	− 1.5	− 1.5	Stylion	Radiale–stylion
Wrist	− 2.2	− 2.4	Stylion	Stylion–3rd metacarpale
Hip	2.8	3.2	Trochanterion	Trochanterion–tibiale
Knee	29.4	33.5	Tibiale	Trochanterion–tibiale
Knee	35.0	35.0	Tibiale	Tibiale–sphyrion
Ankle	− 12.6	− 12.6	Sphyrion	Tibiale–sphyrion

*Estimated for subjects holding their arm in the standard anatomical position (adducted).

trunk length is defined as the distance between the two endpoints. Despite their name, the endpoints do not coincide necessarily with the most cranial and caudal points of the actual trunk, and do not lay necessarily on the segmentation planes selected by Zatsiorsky's group for defining the boundaries between trunk and other segments (see Fig. 1). Zatsiorsky's group used the intersection of the frontal projections of the hip segmentation planes (HSP intersection) as the caudal endpoint of the trunk (Zatsiorsky, personal communication, 1992). Unfortunately, the HSP intersection cannot be easily located on a subject (see definition of HSPs); it is a purely theoretical point, which does not coincide with any physical landmarks. In the author's opinion, the mid-hip (MIDH), a point midway between the hip joint centers (HJCs), is the most convenient choice for defining the trunk caudal endpoint. In fact, it can be easily computed from the positions of the HJCs, the only points of the trunk that can be used as proximal reference points of the thighs as well (de Leva, 1996).

Similarly, the mid-shoulder (MIDS), a point midway between the shoulder joint centers (SJCs), would be the most convenient choice for defining the trunk cranial endpoint, unless the SJCs were free to change their position relative to the chest, to a remarkable extent. Typically, the trunk CM can be located with higher accuracy if the normal projection on the trunk longitudinal axis of either the cervicale or the suprasternale is used as trunk cranial endpoint, rather than MIDS.

For allowing readers to select their preferred reference points, the adjustments to the trunk parameters were performed using three different couples of reference points: cervicale projection and MIDH, suprasternale projection and MIDH, and MIDS and MIDH (see Table 4). The adjustments for the upper and lower parts of the trunk followed the same rationale (see Table 4). The parameters for the middle part of the trunk did not require adjustments.

Combining anthropometric data from different sources

Besides the segment lengths and the joint center positions reported in Tables 1 and 2, other anthropometric data were needed for the adjustments to the inertial parameters of trunk and thigh.

The subjects analyzed by Zatsiorsky *et al.* were ethnically Russian. No data were found in the literature concerning the specific anthropometric characteristics of the Russian population, mainly composed of Caucasian (white) individuals. However, the anthropometric parameters relative to several other Caucasian ethnic groups were available in a comprehensive reference publication edited by a staff of the Webb Associates

(1978), summarizing the results of 61 surveys performed throughout the world. The Caucasian samples for which at least the mean stature and trochanteric height were reported in the Webb Associates' book were selected (the two parameters were needed for normalizing the data). Among them, nine male samples (98% white U.S. Air Force personnel, Greek and Italian military, French Army, German Air Force, British and New Zealand Royal Air Force, Czechoslovakian lumbermen, Swedish industrial workers) and four female samples (100% white U.S.A. citizens, 100% white U.S. Air Force personnel, British and Swedish citizens) were selected. The mean ages ranged from 21 to 36 yr for the female samples, and from 22 to 33 yr for six of the male samples (they were not reported for the German, Czechoslovakian, and Swedish samples). The sample sizes ranged from 87 to 10 042 subjects.

The anthropometric parameters needed for the adjustments were the mean stature, the mean cervicale, acromion, suprasternale, iliospinale, and trochanterion heights, and the mean bispinous breadth (BB). Except for stature and trochanterion height, none of these parameters was measured for all of the selected male or female samples. Indeed, the BB was not reported in any of the surveys of male populations summarized in the Webb Associates' book; it was found in a report by Clauser *et al.* (1969), based on the analysis of 13 male cadavers (mean age: 49 yr).

The positions of the trunk landmarks (cervicale, acromion, suprasternale, iliospinale, and trochanterion) were originally reported as heights relative to the floor for standing subjects. For each sample, the longitudinal positions of the landmarks relative to the trochanterion were obtained by subtracting the trochanterion height from the landmark heights. The positions relative to trochanterion were then normalized, to ensure comparability between the different sources, by expressing them as percentages of the respective trochanterion–vertex longitudinal distance. The latter distance was obtained by subtracting trochanteric height from stature. The BB, which was the only considered transverse dimension, was normalized with the same method. The distances between trochanterion and cervicale or suprasternale, theoretically best suited to be used as yardsticks for normalizing trunk data, were not considered due to lack of data. For the same reason, it was not possible to use a transverse dimension for normalizing the BB.

Eventually, the normalized values available for each distance (landmark positions and BB) were averaged, separately for females and males. The results were reported in Table 3.

Scaling the anthropometric data from the literature

The mean normalized distances reported in Table 3 were multiplied by a scaling coefficient for estimating their absolute value for the Zatsiorsky *et al.* subjects. The scaling coefficient was determined, separately for males and females, using the following equation:

$$s = \bar{l}_0/\bar{l}_1, \tag{3}$$

where $\bar{l}_0$ and $\bar{l}_1$ are trunk lengths defined and computed as follows:

(a) For both males and females, the mean trunk length $\bar{l}_0$ could be easily determined by summing the mean lengths of the three parts of the trunk, obtained from Table 1. It was therefore defined as the distance between the cervicale (cranial endpoint of the upper part of the trunk) and the HSP intersection (caudal endpoint of the lower part).

(b) The mean trunk length $\bar{l}_1$ was computed for the female and male subjects by adding the percent distance between cervicale and iliospinale ($\bar{d}_1$) to the percent distance between iliospinale and HSP intersection ($\bar{d}_2$). In turn, $\bar{d}_1$ was equal to the difference between the trochanterion–cervicale and trochanterion–iliospinale normalized distances reported in Table 3; $\bar{d}_2$ was calculated as follows, according to the definition of the HSP intersection:

$$\bar{d}_2 = \bar{b}/(2\tan 37^\circ), \tag{4}$$

where $\bar{b}$ is the percent bispinous breadth reported in Table 3. The computed values of $\bar{d}_2$ were included in Table 3.

The scaling coefficients computed with equation (3) were $s = 690.1/79.95\% = 863.2$ mm for females and $s = 709.3/81.57\% = 869.6$ mm for males. The scaled distances between trunk landmarks were reported in Table 3.

Adjustments to the CM percentages

The main adjustments to the segment CM percentages for males were performed as graphically shown in Fig. 1. Some calculations were too complex to be described in detail in Fig. 1, and will be explained in the ensuing paragraphs. Identical procedures were used also to adjust the CM percentages for females. With similar methods, secondary adjustments were performed for the whole trunk, forearm, hand, and calf, using alternative sets of reference points. The calculations shown in Fig. 1 were similar to those performed by Hinrichs (1990) for adjusting the Clauser *et al.* (1969) percentages. The results for both females and males were reported in Table 4.

Head. For estimating the longitudinal position of the gonion, used as caudal endpoint for the head, the ratio between the gonion–cervicale and the vertex–cervicale longitudinal distances was needed. It was obtained, separately for females and males, from the anthropometric data of Gordon *et al.* (1989), collected on two mixed-race samples of U.S. Army personnel, composed of 2208 females (51.6% white) and 1774 males (66.1% white). The computed ratios were 0.1784 for females, and 0.1629 for males.

Table 3. Means and scaled means of some normalized distances between trunk landmarks. The normalized values were calculated using data from different anthropometric surveys of Caucasian populations. The scaling coefficients for females and males were proportional respectively to the mean trunk lengths of the Zatsiorsky *et al.* female and male samples (N = number of surveys, S.D. = standard deviation)

	Means for females		Means for males	
Distance	Normalized (% of troch.–vertex)	Scaled (mm)	Normalized (% of troch.–vertex)	Scaled (mm)
Troch.–cervicale*	71.55 (N = 3, S.D. = 0.3)	617.6	69.75 (N = 7, S.D. = 0.9)	606.5
Troch.–acromion*	61.91 (N = 2, S.D. = 0.0)	534.4	63.62 (N = 8, S.D. = 2.5)	553.2
Troch.–suprasternale*	61.64 (N = 2, S.D. = 0.5)	532.1	61.53 (N = 9, S.D. = 0.6)	535.1
Troch.–iliospinale*	11.39 (N = 1)	98.3	7.69 (N = 2, S.D. = 0.6)	66.9
Bispinous breadth	29.83 (N = 1)	257.5	29.40 (N = 1)	255.7
Iliospinale–HSP int.*	19.79†	170.8	19.51†	169.7

*Projection on the trunk longitudinal axis.
†Determined by dividing the normalized bispinous breadth by 2tan37° (see text).

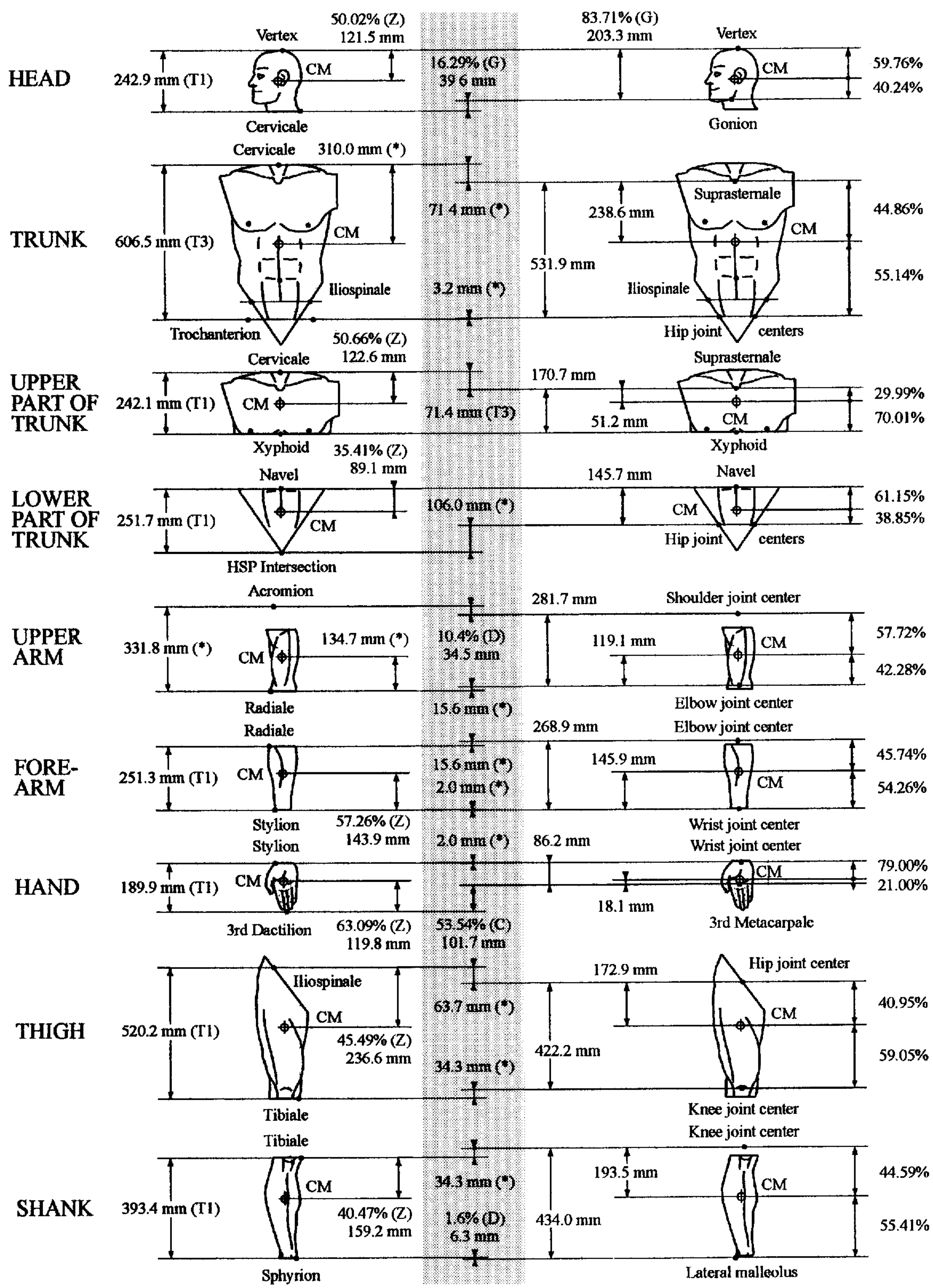

Fig. 1. A graphic description of the main adjustments to the relative CM positions for males. The adjusted distances are shown on the right of the shaded area. For all segments, except trunk and upper arm (see text), the shaded area indicates the longitudinal distances between original (on its left) and new (on its right) reference points. All percent values are relative to the segment lengths indicated on their left. (* = see text; C = Clauser *et al.*, 1969; D = de Leva, 1996; G = Gordon *et al.*, 1989; T1 = Table 1; T3 = Table 3; Z = Zatsiorsky *et al.*, 1990a).

Table 4. Adjusted parameters for females (F; body mass = 61.9 kg, stature = 173.5 m) and males (M; 73.0 kg, 1.741 m). Segment masses are relative to body mass; segment CM positions are referenced either to proximal or cranial endpoints (origin). Both segment CM positions and radii of gyration (*r*) are relative to the respective segment lengths. A set of easy-to-use endpoints is considered in the first part of the table; for some segments, alternative endpoints are considered in the second part (UPT, MPT, and LPT are the Upper, Middle, and Lower Parts of Trunk)

	Endpoints		Longitudinal length (mm)		Mass* (%)		Longitudinal CM position (%)		Sagittal *r* (%)		Transverse *r* (%)		Longitudinal *r* (%)	
Segment	Origin	Other	F	M	F§	M¶	F	M	F	M	F	M	F	M
Head	VERT†	MIDG†	200.2	203.3	6.68	6.94	58.94	59.76	33.0	36.2	35.9	37.6	31.8	31.2
Trunk	SUPR†	MIDH‡	529.3	531.9	42.57	43.46	41.51	44.86	35.7	37.2	33.9	34.7	17.1	19.1
UPT	SUPR†	XYPH†	142.5	170.7	15.45	15.96	20.77	29.99	74.6	71.6	50.2	45.4	71.8	65.9
MPT*	XYPH†	OMPH†	205.3	215.5	14.65	16.33	45.12	45.02	43.3	48.2	35.4	38.3	41.5	46.8
LPT	OMPH†	MIDH‡	181.5	145.7	12.47	11.17	49.20	61.15	43.3	61.5	40.2	55.1	44.4	58.7
Upper arm	SJC‡	EJC‡	275.1	281.7	2.55	2.71	57.54	57.72	27.8	28.5	26.0	26.9	14.8	15.8
Forearm	EJC‡	WJC‡	264.3	268.9	1.38	1.62	45.59	45.74	26.1	27.6	25.7	26.5	9.4	12.1
Hand	WJC‡	MET3†	78.0	86.2	0.56	0.61	74.74	79.00	53.1	62.8	45.4	51.3	33.5	40.1
Thigh	HJC‡	KJC‡	368.5	422.2	14.78	14.16	36.12	40.95	36.9	32.9	36.4	32.9	16.2	14.9
Shank	KJC‡	LMAL†	432.3	434.0	4.81	4.33	44.16	44.59	27.1	25.5	26.7	24.9	9.3	10.3
Foot*	HEEL†	TTIP†	228.3	258.1	1.29	1.37	40.14	44.15	29.9	25.7	27.9	24.5	13.9	12.4
Using alternative endpoints:														
Head*	VERT†	CERV†	243.7	242.9	6.68	6.94	48.41	50.02	27.1	30.3	29.5	31.5	26.1	26.1
Trunk	CERV†	MIDH‡	614.8	603.3	42.57	43.46	49.64	51.38	30.7	32.8	29.2	30.6	14.7	16.9
Trunk	MIDS‡	MIDH‡	497.9	515.5	42.57	43.46	37.82	43.10	37.9	38.4	36.1	35.8	18.2	19.7
UPT*	CERV†	XYPH†	228.0	242.1	15.45	15.96	50.50	50.66	46.6	50.5	31.4	32.0	44.9	46.5
Forearm	EJC‡	STYL†	262.4	266.9	1.38	1.62	45.92	46.08	26.3	27.8	25.9	26.7	9.5	12.2
Hand	WJC‡	DAC3‡	170.1	187.9	0.56	0.61	34.27	36.24	24.4	28.8	20.8	23.5	15.4	18.4
Hand*	STYL†	DAC3‡	172.0	189.9	0.56	0.61	35.02	36.91	24.1	28.5	20.6	23.3	15.2	18.2
Hand	STYL†	MET3†	79.9	88.2	0.56	0.61	75.34	79.48	51.9	61.4	44.3	50.2	32.7	39.2
Shank	KJC‡	AJC‡	438.6	440.3	4.81	4.33	43.52	43.95	26.7	25.1	26.3	24.6	9.2	10.2
Shank	KJC‡	SPHY†	426.0	427.7	4.81	4.33	44.81	45.24	27.5	25.8	27.1	25.3	9.4	10.5

* Not adjusted values.
† Normal projection on the segment longitudinal axis.
‡ Assumed to lay on the segment longitudinal axis.
§ Zatsiorsky *et al.* (1990a).
¶ Zatsiorsky *et al.* (1990b, 1993).

Thigh. The thigh length was defined by Zatsiorsky *et al.* as the longitudinal distance between iliospinale and tibiale. However, for locating the hip and knee joint centers (HJC and KJC), the longitudinal distance between trochanterion and tibiale was needed (see Table 2). For both males and females, the latter distance was simply obtained by subtracting from the iliospinale–tibiale distance (Table 1) the scaled trochanterion–iliospinale distance reported in Table 3.

Since the HJC is slightly proximal to the trochanterion (de Leva, 1996), the longitudinal distance between iliospinale and HJC (see Fig. 1) was computed, for both males and females, by subtracting the HJC–trochanterion distance (Table 2) from the scaled trochanterion–iliospinale distance reported in Table 3.

Lower part of trunk. For both males and females, the distance between HSP intersection and MIDH, needed for adjusting the lower trunk CM percentage (Fig. 1), was obtained by subtracting the iliospinale–HJC distance (computed as explained above) from the scaled iliospinale–HSP intersection distance reported in Table 3.

Upper arm. The upper arm length was defined by Zatsiorsky *et al.* as the longitudinal distance between Acromion and radiale. However, that distance was measured with the arm abducted by 90° relative to the longitudinal axis of the trunk (Zatsiorsky, personal communication, 1993). That position was probably required to clearly distinguish the upper arm mass from the trunk mass during the gamma-ray scanning. With the abducted arm the acromion–radiale distance is markedly shorter than in the standard anatomical position (adducted arm). In fact, the acromion is located on the scapula, distant from the SJC; thus, the radiale, located on the elbow, markedly changes its position relative to the acromion when the arm rotates about the SJC, relative to the scapula.

Using the Chandler *et al.* (1975) data, the standard acromion–radiale distance, measured with adducted arm, was found to be highly correlated ($r > 0.8$) to the iliospinale–tibiale and radiale–stylion distances. The ratios between the standard acromion–radiale and the latter two distances were computed using anthropometric data from the same surveys that were selected for estimating the trunk landmark positions (Table 3). The mean ratios between acromion–radiale and iliospinale–tibiale were 0.6401 for females and 0.6551 for males. The mean ratios between acromion–radiale and radiale–stylion were 1.3374 for females and 1.2841 for males. For both females and males, these ratios were multiplied, respectively, by the iliospinale–tibiale and radiale–stylion distances reported in Table 1. Thus, two estimates of the standard acromion–radiale distances were obtained, for both the Zatsiorsky *et al.* female and male subjects. The respective means were 324.1 mm for females, and 331.8 mm for males (Fig. 1). Notice that both these estimated distances were about 90 mm longer than the respective acromion–radiale distances measured by Zatsiorky's group (Table 1).

Hand. The hand length was defined by Zatsiorsky *et al.* as the longitudinal distance between stylion and 3rd dactylion. However, for locating the wrist joint center, the longitudinal distance between stylion and 3rd metacarpale was needed (see Table 2). For both males and females, this distance was assumed to be equal to 46.46% of the respective hand length, reported in Table 1. This percentage was obtained from the anthropometric data of Clauser *et al.* (1975).

The whole trunk and its parts. Most of the longitudinal dimensions needed for adjusting the CM percentages of the whole trunk and of its upper part were either obtained from Table 2, or determined by simple subtraction, using the scaled values reported in Table 3. A more complex procedure was required to compute the CM percentage for the whole trunk of females.

Zatsiorsky *et al.* (1990a) reported the inertial parameters of the upper, middle, and lower parts of the trunk, for both the male and female subjects; they did not report the parameters of the whole trunk. The latter parameters were reported elsewhere only for males (Zatsiorsky *et al.*, 1990b). However, researchers frequently prefer to model the trunk as a single rigid segment, neglecting the errors caused by trunk flexion (de Leva, 1993). The reason is that the landmaks defining the 'joints' between the trunk subsegments are difficult to locate. Thus, it was important to include in this paper the parameters for the whole trunk, both for males and females.

For the female subjects, the mean longitudinal distance of the trunk CM from the cervicale was obtained as follows:

$$\bar{d}_{CM} = \frac{\bar{d}_{CM_U} \cdot \bar{m}_U + \bar{d}_{CM_M} \cdot \bar{m}_M + \bar{d}_{CM_L} \cdot \bar{m}_L}{\bar{m}_U + \bar{m}_M + \bar{m}_L}, \quad (5)$$

where $\bar{m}_U$, $\bar{m}_M$, $\bar{m}_L$ are, respectively, the mean percent masses of the upper, middle, and lower subsegments of the trunk, reported by Zatsiorsky *et al.* (1990a), and $\bar{d}_{CM_U}$, $\bar{d}_{CM_M}$, $\bar{d}_{CM_L}$ are the mean longitudinal distances of the CMs of the three subsegments from the cervicale. In turn,

$$\bar{d}_{CM_U} = \bar{l}_U \cdot \bar{P}_{CM_U},$$

$$\bar{d}_{CM_M} = \bar{l}_M \cdot \bar{P}_{CM_M} + \bar{l}_U,$$

$$\bar{d}_{CM_L} = \bar{l}_L \cdot \bar{P}_{CM_L} + \bar{l}_L + \bar{l}_M,$$

where $\bar{l}_U$, $\bar{l}_M$, $\bar{l}_L$ are the mean subsegment lengths from Table 1, and $\bar{P}_{CM_U}$, $\bar{P}_{CM_M}$, $\bar{P}_{CM_L}$ are the mean ratios between subsegment CM longitudinal positions and subsegment lengths, reported by Zatsiorsky *et al.* (1990a). The subsegment CM longitudinal positions were referenced to the respective subsegment cranial landmarks (cervicale, xyphion, and omphalion).

The value computed with equation (5) for the female subjects was $\bar{d}_{CM} = 305.2$ mm, which corresponds to 44.23% of the respective total trunk length (690.1 mm, Table 1).

Similar calculations, performed using the parameters reported for males (Zatsiorsky and Seluyanov, 1983; Zatsiorsky *et al.*, 1990b, 1993), gave as the final result a trunk CM percentage of 44.13%, very close to the value of 43.70% reported by Zatsiorsky *et al.* (1990b). The absolute distance between cervicale and trunk CM reported in Fig. 1 is the product of the latter percentage by the total trunk length reported in Table 1 (43.70% of 709.3 = 310.0 mm).

Adjusting the radii of gyration

Zatsiorsky *et al.* (1990a) reported the percent ratios between segment radii of gyration and segment lengths (relative radii of gyration), for both males and females. These parameters were adjusted by multiplying them by the ratios between the respective original (Table 1) and adjusted (Table 4) segment lengths. The results are listed in Table 4.

Since the relative radii of gyration of the whole trunk for females were not reported by Zatsiorsky *et al.* (1990a), it was necessary to compute their adjusted values (Table 4) from the adjusted parameters of the three trunk subsegments (Table 4), using the Parallel Axes Theorem.

Assuming that a subject's segment radii of gyration are proportional to the respective segment lengths, the relative segment masses and radii of gyration reported in Table 4 can be used to estimate the subject's segment moments of inertia. The moment of inertia of a given segment about a given principal axis is

$$I = (M \cdot \bar{m}) \cdot (l \cdot \bar{r})^2,$$

where M is the body mass of the considered subject, $\bar{m}$ is the mean relative mass of the segment (Table 4), l is the segment length, which can be measured from a filmed or videotaped performance, and $\bar{r}$ is the mean relative radius of gyration of the segment about the considered axis (Table 4).

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