Eur J Appl Physiol (1985) 54:109—115

European Journal of
Applied
Physiology
and Occupational Physiology

Alignment of the human body in standing

A. M. Woodhull, K. Maltrud, and B. L. Mello

School of Natural Science Hampshire College Amherst, Amherst, MA 01002, USA

Summary. Alignment of the body in typical symmetrical standing was studied by photographing fifteen subjects in profile on a reaction board. Two aspects of alignment were studied: (1) the anteroposterior position of the body landmarks of knee joint, hip joint, shoulder joint, and ear, compared to the ankle joint; and (2) the positions of the partial centers of gravity above the knee and hip, as a measure of how the body is balanced above these joints.

The knee, hip, shoulder, and ear were forward of the ankle in all subjects. On average, the knee was 3.8 (±2.0), the hip 6.2 (±1.3) the shoulder 3.8 (±1.9), and the ear 5.9 (±1.6) cm (±S.D.) anterior to the ankle. The positions of landmarks were positively correlated with one another but not highly. The position of the center of gravity could be predicted well from the positions of the landmarks within individual subjects' data, but not across subjects.

The centers of gravity above the knee and hip were calculated by subtracting the mass and position of the segments below the joint from the whole-body center of gravity. The center of gravity above the knee was located on average 1.4 (±1.1) cm in front of the joint, and that of the hip 1.0 (±1.6) cm behind the trochanter. Thus, at both knee and hip in typical standing, there exist slight gravitational torques tending to extend the joints.

Key words. Posture — Center of gravity — Biomechanics — Standing

Offprint requests to: A. M. Woodhull at the above address

Introduction

Good posture is often idealized as the perfect alignment of the weight-bearing segments, each balanced atop the other. Yet it is wellknown that the center of gravity of the whole body is not above the ankle joint (Hellebrandt 1938; Joseph and Nightingale 1952; Smith 1957) but approximately midway in the foot's base of support, so it is unlikely that the upper joint centers could be directly above the ankle as they are often depicted (Fig. 1).

The idea of alignment has two aspects: the actual position (anterior-posterior) of the joint centers, and the position of the partial centers of gravity above the knee and hip. The position of these partial centers of gravity is important biomechanically, since the torque exerted by the segments above that joint is the product of the weight of the segments and the displacement of their center of gravity.

Despite the numerous assertions about alignment of joint centers and about balancing of body segments, few data are available on these points (Table 3). Knee and hip position (relative to the ankle joint) from two different sets of subjects are reported by Akerblom (1948). We were not able to find any studies of partial centers of gravity above the knee and hip; only Akerblom (1948) and Fox and Young (1954) presented comparisons of the whole-body center of gravity with the positions of these joints.

The partial center of gravity (c.g.) of the portion of the body above a weight-bearing joint can be found in three ways. (1) Partial c.g. can be calculated from the vector sum of the estimated mass and c.g. of each segment above the joint. Flexibility of the torso and neck create problems in this method (Hay 1973). (2) Immersion of the subject

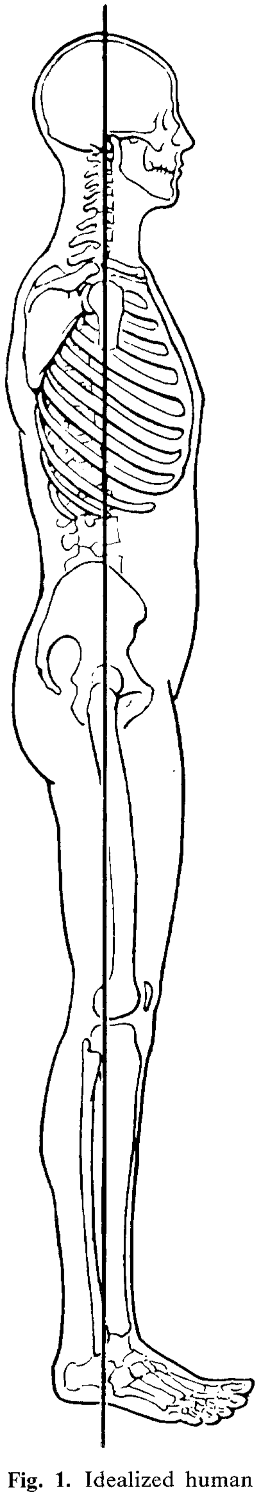

Fig. 1. Idealized human figure from kinesiology text (Wells and Luttgens 1976). Note alignment of knee, hip, shoulder and ear in perfect vertical above ankle

in water up to the joint in question allows buoyancy largely to cancel the weight of the lower segments, so the c.g. of the remainder can be calculated directly by the reaction-board method (Klausen and Rasmussen 1968). (3) The contributions of the lower segments can be subtracted from the measured whole-body c.g., as in the present study. As these lower segments are rigid and their bony landmarks are easy to find, the method should be more accurate than the first method and is easier than the second.

In the studies reported here, we aimed to ascertain the anteroposterior positions of body landmarks and center of gravity in a healthy young population, with measures of the variability of each subject, and to look at statistical correlations among these measures. Additionally, we found the partial centers of gravity above the hip and knee by subtracting the antero-posterior (x-) components of the masses and positions of the lower body segments from the c.g. of the whole body.

Methods

Subjects. The main subject population consisted of fifteen normal volunteers, mostly college students, ranging in age from 18 to 29. Some had training in various sports, but none in the main group were dancers or gymnasts (i.e., they had taken one or fewer semesters of dance and were not currently enrolled in a dance or gymnastics class). Of the fifteen, nine were females, six males. The subjects were screened for gross asymmetries (two additional volunteers were rejected because of scoliosis), and none had had back surgery or other major health problems.

Some comparisons were made on a sample of dancers of similar ages. The dancers had been studying dance (of one form or another) for two years or more were enrolled in or teaching advanced technique. Six female and two male dancers were studied.

Equipment. All data were recorded photographically. The equipment consisted of a short (40 cm) reaction board, one end of which rested on a support, the other end on a digital scale. The subject was photographed in place on the board, from a distance of 4.5 meters, with the digital readout and a plumbline in the camera's view. The center of gravity of the body relative to the ankle joint was then calculated from the digitized data.

Protocol. The five body landmarks were located as follows: the ankle, 1 cm in front of the posterior edge of the lateral malleolus; the knee, at the lateral epicondyle (checked by eye to lie about one-half way across the side view of the knee, in standing); the hip, at the most lateral projection of the greater trochanter; the shoulder, at the center of the head of the humerus, as seen by the camera; the ear, vertically below the external meatus. The lateral epicondyle is a good marker of the joint center of the knee (cf. Figs. 8 and 9, Soudan et al. 1979). The true joint center of the hip is anterior to the trochanter by about one centimeter, because of the anteversion of the neck of the femur. Each point was tabbed with a small black dot for consistency of location in the photographs.

The subjects were instructed to assume a "typical" stance, described as the posture "you stand comfortably in, with weight on both feet" (i.e., symmetrical); we emphasized that the posture was to be individual, not ideal. The hands were at the subjects' sides, and the feet were about 20 to 30 cm apart, slightly turned out as suited the subjects, who were barefoot. Six or more "typical" photographs of each subject were taken; subjects were encouraged to exhibit a normal range of "typical" postures.

Data analysis. The photographic data were entered into a computer by projecting the negatives onto a BitPad 1 digitizer (Summagraphics Corporation) and encoding the x-coordinated of the markers, including the ends of the plumb line.

The partial centers of gravity above the knee and hip were calculated by taking the c.g. of the whole body, and subtracting the quantity (mass times center of gravity position) of each segment below the joint in question. The percentage of body mass in each segment was obtained from Kjeldsen and Plagenhoef's data (Plagenhoef 1971) on young females, since that population best matched ours. We did not use different values for our male subjects, since the data of Bernstein (as cited in Hay 1973), which provide a direct comparison of male with female segment weights, gave male-female differences that would affect our calculations by 0.1 cm or less.

The positions of the centers of gravity of the foot, lower leg and thigh were calculated using the assumption (Dempster 1955) that the center of gravity is located on the axis between joint centers, 0.43 of the distance from the proximal to distal joint for the thigh and lower leg, and 0.5 of the distance from ankle to the distal end of the second metatarsal for the foot (Hay 1973). The regression equations given by Clauser et al. (1969) would have made very small differences in the results we found on a pilot group of subjects, so we used the simpler Dempster assumptions.

The position of the center of gravity of the body above the hip (relative to the hip) was calculated by the formula

$$C_H = \frac{[c.g. - M_F X_{CF} - M_L X_{CL} - M_T X_{CT}]}{(1 - M_F - M_L - M_T)} - X_H \qquad (1)$$

where

c.g. = the center of gravity of the whole body

M_F = the relative mass (% of whole body mass) of the two feet

X_{CF} = the x-coordinate of the center of mass of the foot (relative to the ankle)

X_K = the position of the knee joint center

M_L = the relative mass of the lower leg

X_{CL} = x-coordinate of the center of mass of the lower leg

M_T = the relative mass of the two thighs

X_{CT} = x-coordinate of the center of mass of the thighs (relative to the ankle.

The center of gravity of the body above the knee, relative to the knee, was similarly calculated by subtracting the masses and positions of the foot and lower leg.

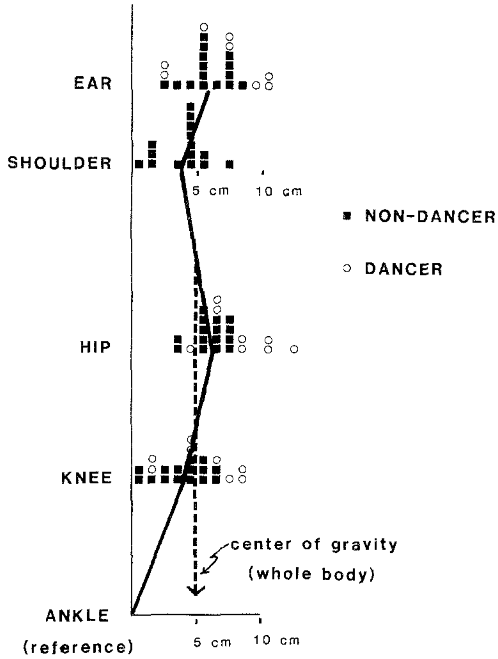

Fig. 2. Alignment of body landmarks of our subjects. Heavy line is group mean (N = 15, not including dancers). Histogram points are individual subjects' mean positions of landmarks. Dancers' data (N = 8) are shown for comparison. Horizontal scale is exaggerated

Table 1. Mean positions of body landmarks and centers of gravity in cm ± standard deviation

	Main Subject group	Dancers
N	15	8
Position of:		
Knee	3.8±2.0	5.3±3.1
Hip	6.2±1.3	8.8±2.8
Shoulder	3.8±1.9	
Ear	5.9±1.6	7.4±3.8
Center of gravity		
Whole body	4.9±1.3	6.0±2.2
Above knee	1.4±1.1	1.0±2.2
Above hip	−1.0±1.6	−2.0±2.1

Results

Alignment of landmarks

The knee, hip, shoulder and ear are always located forward of the ankle joint in typical standing (Fig. 2 and Table 1); only the knee and shoulder sometimes approach being directly over the ankle. Averaging across individuals in our population, the knee is 3.8 cm (±2.0 cm S.D.), the hip is 6.2 cm (±1.3 cm), the shoulder is 3.8 cm (±1.9 cm) and the ear is 5.9 (±1.6 cm) in front of the ankle. Some individuals are more variable than others, but the between-subject variations are large compared to variations within subjects (ANOVA, $p < 0.0001$ for each variable).

The positions of the landmarks and centers of gravity are in general positively correlated, but not highly, indicating that the body to some extent tends to be carried either forward or backward as a whole, but that individual parameters vary independently (Table 2). Correlations within individuals sometimes differ from the population trends. A look at the individual patterns superimposed reveals no consistent pattern or types of posture (Fig. 3).

photograph per subject), followed by the ear (c.g. = $0.47X_E+1.90$; R^2 = 0.41), and hip (c.g. = $0.39X_H+2.33$; R^2 = 0.19). Simply using the fixed value of 4.9 cm for the c.g. is slightly better than assuming that c.g. = X_E, as the residual sum of squares for c.g. = 4.93 cm is 199.3, while that for c.g. = X_E is 215.7.

Table 2. Correlations of positions of landmarks and centers of gravity for aggregated data of all individuals in typical standing posture. $N = 100$; 6 to 8 measures for each of 15 subjects

	X_K	X_H	X_S	X_E	c.g.	C_K	C_H
X_K	1.00						
X_H	0.714	1.000					
X_S	0.626	0.608	1.000				
X_E	0.492	0.394	0.504	1.000			
c.g.	0.804	0.622	0.647	0.594	1.000		
C_K	*	−0.447	−0.267	−0.111	−0.145	1.000	
C_H	*	*	−0.0283	0.169	0.336	0.514	1.000

* These measures are calculated from one another, so correlations are omitted

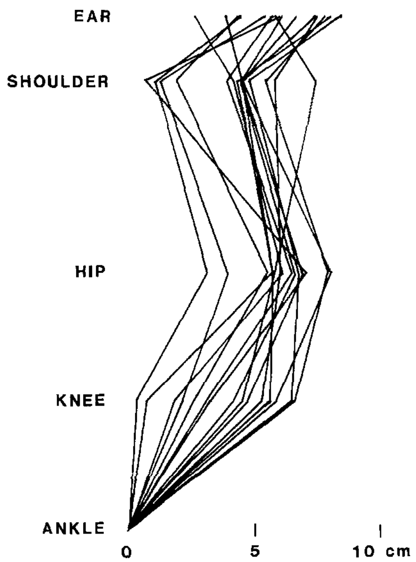

Fig. 3. Individual patterns of alignment. Each subject is represented by a line connecting individual mean landmark positions. Horizontal scale is exaggerated.

Position of the center of gravity in relation to landmarks

In this group of normal subjects, the center of gravity of the whole body lies on the average 4.95 cm (±1.34 cm) in front of the ankle. The position of the center of gravity correlates positively with the position of each landmark (Table 2).

For our fifteen subjects in their typical postures, the best single predictor of c.g. is the knee position (c.g. = $0.52X_K+2.71$; R^2 = 0.71, for one

Centers of gravity above the knee and hip

Figure 4 compares the positions of the centers of gravity above the ankle, knee, and hip. The center of gravity of the portion of the body above the knee falls on the average 1.4 cm in front of the knee joint (Table 1, Fig. 4). Each subject may or may not be consistent (S.D.s ranging from 0.5 to 2.4), but the population is consistent (S.D. = 1.1 cm; S.E.M. = 0.3 cm). Between-subject differences were significantly larger than within-subject differences (ANOVA, $p < 0.0001$).

Above the hip, the center of gravity of the upper body falls on average 1.0 cm (±1.6 cm) be-

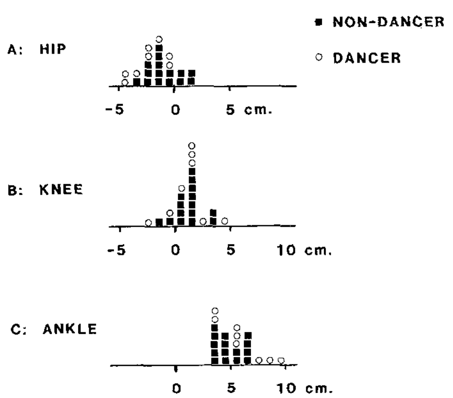

Fig. 4 A-C. Centers of gravity above the hip, knee and ankle, relative to respective joint centers. **A** Center of gravity of the portion of the body above the hip, relative to the trochanter (calculated by equation 1). **B** Center of gravity of the body above the knee, relative to the knee. **C** Center of gravity of the whole body, relative to ankle (ignoring the correction for mass of foot)

hind the trochanter. Again, individuals differ significantly (ANOVA, $p < 0.0001$).

Lack of sex differences

Within this population no significant differences are seen between the sexes in any measure (two-tailed t-tests, $p > 0.6$ in each case), but the number of males is small. Our population means of male x-coordinates are nonetheless consistently very slightly larger than those for females, perhaps because the males are slightly taller.

Variations within individuals

Individuals differ both in their extent of variability and their patterns of correlation of measures. For nine subjects for whom enough data are available (more than twelve photographs each), high correlations are seen between individual measures of positions of the hip, shoulder and ear and the center of gravity. However, the patterns are very individual, so that a good predictor for one subject is a poor predictor for another, and the knees in particular can have a positive, negative, or no correlation to the c.g.

Comparisons with a group of dancers

The mean positions of landmarks in dancers are slightly farther forward than those of non-dancers (Table 1), differing significantly only in the hip ($p < 0.05$). The individual means for dancers can be seen in Fig. 2 to vary more than those for non-dancers. Accordingly, the variances of the positions of landmarks of the dancers taken as a group are consistently larger than among non-dancers, significantly so for the hip and the ear (F-test, $p < 0.05$ and $p < 0.01$, respectively).

Looking at the partial centers of gravity above hip and knee, the dancers' mean does not differ from non-dancers'; their variance is larger, but not significantly so.

Discussion

Our findings on a healthy young population present a different picture from the "ideal" linear posture usually shown (cf. Fig. 5, Fig. 1). In the instances where other investigators have obtained similar measures, (Table 3), only the very old data of Braune and Fischer (cited by Steindler 1955) differ from ours in most respects. The positions of the partial centers of gravity above the knee and hip compare reasonably to the different types of data obtained by Akerblom (1948) and by Fox and Young (1954), as seen in Table 3.

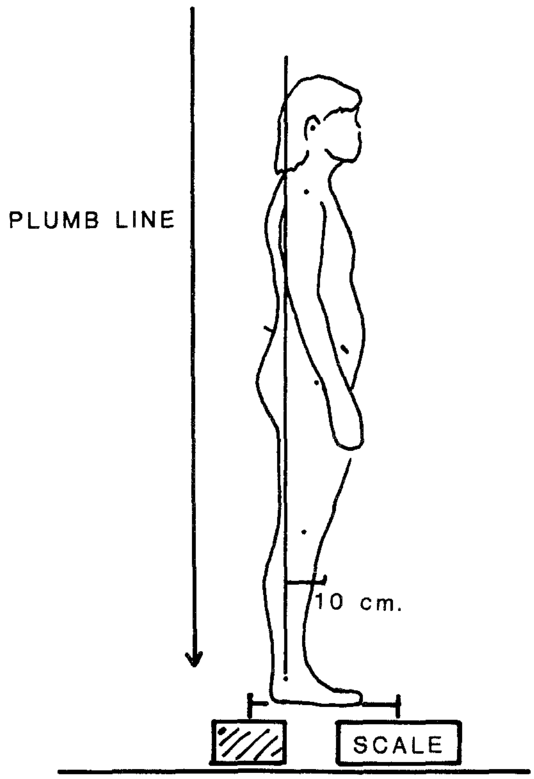

Fig. 5. A typical subject in our population, traced from a photograph. This subject's individual means lie close to the group means (cf. Table 1). Points shown are landmarks as tabbed. Compare to Fig. 1

Although our subjects' knees and hips appear to be appreciably further forward than those studied by Akerblom (1948), we can attribute almost all of this difference to the difference in ankle joint reference point; judging from Akerblom's c.g. measurements, his ankle joint reference point was probably about 2.8 cm forward of other investigators'. Smith (1956) reported that hyperextended knees were typical in his population, but our subjects did not in general have hyperextended knees (Fig. 3).

The relationship between the center of gravity and the bony landmarks can be predicted quite consistently in many individual subjects, but predictions across the population are poor, because people are so individual. In particular, it is not useful to assume that the c.g. is in the same antero-posterior position as the ear (Murphey et al.

Table 3. Comparison of present with previous data on landmarks and center of gravity. Numbers are antero-posterior distances in cm, relative to ankle except where otherwise specified. Standard deviations are given where available; N is in parentheses. Under center of gravity all numbers are comparisons of the position of the whole-body c.g. to the position of the joint named except for the last row which gives partial centers of gravity above the joints calculated by the method of equation (1)

Investigators	X-coordinates of Knee	Hip	Sh.	Ear	Center of gravity, relative to Ankle	Knee	Hip	Shoulder	Ear
Braune and Fischer (1889; from Steindler 1955)	0	0	0	0					
Hellebrandt (1938)[a]					5.0				
Akerblom (1948)[b]	0.8 (23)	4.4 (10)			2.24±0.26 (11)	1.6±0.2 (23)	−1.8 (10)		
Fox and Young (1954)[c]					5.36±1.46 (66)	slightly anterior to joint center (66)		in anterior portion of acromion process (66)	ear lobe (66)
This study[d]	3.8 (15)	6.2 (15)	3.8 (15)	5.9 (15)	4.9±1.3 (15)	1.1±2.4 (15)	−1.3±1.2 (15)	1.2±1.6 (15)	−1.0±1.3 (15)
This study partial c.g.'s					4.9±1.3 (15)	1.4±1.1 (15)	−1.0±1.6 (15)		

[a] Hellebrandt did not specify which part of malleolus was meant.
[b] Joint center was found by x-ray; ankle joint center was "weightbearing trapezium." Subjects were mostly male, different subjects for different measures. Centers of gravity relative to knee and hip are the positions of whole-body center of gravity relative to these landmarks.
[c] Ankle reference point was posterior border of lateral malleolus. Subjects were all female. The data for knee are interpreted from a table in which subjects were grouped into categories
[d] Ankle joint center was taken as 1 cm. forward of posterior border of lateral malleolus

1971) or that the c.g. above the hip is related to the position of the ear (Asmussen 1960; cf. Table 2).

The positions of the centers of gravity of the portions of the body above the knee and hip indicate there is little torque present due to gravity at those joints in typical standing. At the knee joint most individuals have the c.g. a centimeter or two in front of the lateral epicondyle taken as the joint center, so that gravity tends to extend the joint slightly. In a 60-kg subject, the gravitational torque would be about $0.87 \times 60\ \text{kg} \times 9.81\ \text{m/s}^2 \times 0.014$ m, or about 7 Newton-meters. Smith (1956, Fig. 6) measured the passive resistance to extension of the knee, finding about 4.5 ft.-lb. or 6 Newton-meters at 5° before the limit of extension (approximately the extra excursion possible in our subjects whose knees were not already hyperextended). Thus, it is possible that the torque due to gravity at the knee is largely compensated by passive resistance in a typical position in which the knees are not locked back. However, the center of gravity above the knee is variable from individual to individual (Fig. 4). Different patterns of muscular activity might therefore be expected for different individuals; Murphey et al. (1971) found indications of such differences, but they had no measures of the center of gravity.

In the typical standing position, the center of gravity above the hip averages one centimeter behind the greater trochanter, or perhaps two centimeters behind the true joint center. Therefore, gravitational forces tend slightly to extend this joint — i.e., to decrease pelvic tilt and flatten the lumbar lordosis. It seems odd to find such a gravitational torque present in normal standing, since the tendency in the most relaxed position seems to be towards increased pelvic tilt (Wells and Luttgens 1976). It does not seem that the hip is fully "locked" at the end of its possible extension in typical stance, because subjects are able to entend the joint a few degrees farther (as we found, and cf. Akerblom 1948). The case of the hip may be like that of the knee, with slight joint resistance compensating for slight gravitational torque.

The data from dancers were odd, as seen in Fig. 2 and in their significantly higher variances. That dancers differ individually and as a population seems to be an indication of the force of habits in modifying posture.

Although our data were obtained from healthy young subjects, it would be a mistake simply to equate these distributional data with some kind of human "ideal" or "norm" as some have done (Beck and Killus 1973). Our subjects had a range of postures, and probably some were better biomechanically than others. There is no reason to suppose that the average (Fig. 5) is "better" than any one example. On the other hand, it is clear that no subject was close to a linear alignment of joint centers and none is to be expected.

Acknowledgments. We appreciate the extensive help that Albert Woodhull gave us with the BitPad interface and related programming. Michael Sutherland was our patient and flexible consultant on statistics, for which we are grateful.

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Accepted January 22, 1985