KIN 335 - Biomechanics

LAB: Center of Mass (Center of Gravity) of the Human Body

Reading Assignment: Bishop, R.D. & Hay, J.G. (1979). Basketball: the mechanics of hanging in the air. *Medicine and Science in Sports*, **11** (3), 274-277.

Introduction: When a body is acted upon by gravity, all of the mass particles of which the body is composed experience a force of attraction directed toward the Earth's center. The resultant force of all of these small attractive forces is the body's weight and the location at which the resultant force is assumed to act is the center of gravity (CG) of the body. Looking at the CG differently, it is the theoretical location that represents the balance point of the body in a gravitational field (i.e., the point about which all mass particles that make up the body will be balanced in Earth's gravity). In some simplified analyses of movement, the CG is the location at which all of the body's weight is sometimes assumed to be concentrated and is the point that reflects the general motion of the body as a whole (Figure 1). Because the CG of a body is dependent on the distribution of its mass, the CG location for a rigid body (i.e., one that does not experience any change in shape) will be fixed. In contrast, the CG of a body whose mass distribution can change (i.e., the human body) will not have a fixed location. In addition, it is important to keep in mind that the CG location may sometimes fall outside of the body. A doughnut, for example, has its CG in the "hole" in its middle.

For human motion analysis, two methods have been traditionally used to assess CG location: a) a reaction board technique which is easily applied to static positions, and b) a segmentation method, the more versatile of the two since it can be applied to dynamic situations, which involves an estimation of individual segment masses and positions. In this lab, you will be introduced to both methods.

Purpose: 1) To compute the CG location along the longitudinal axis of the body in a supine position using the reaction board technique, and 2) to compute the CG location of an individual captured in a still photograph using the segmentation method.

Part 1. Reaction Board Method

The direct method of calculating the CG involves a device known as a reaction board. The reaction board consists of a long rigid board which is supported as each end on "knife edges" (see Figure 1). Under one end of the board is a scale. The other end is simply elevated such that the board is level. Measurement of the CG location is based on the principle of static equilibrium (i.e., analysis of a static or stationary position of objects) in which the sum of all moments or torques acting on a system about a reference axis of rotation (A) equals zero. When the reaction board is unloaded (refer to Figure 1), the equation of static equilibrium is:

$$\sum M_A = 0 \tag{1}$$

The equation used to calculate the location of the CG relative to the reference axis is derived as follows:

$$\sum M_A = (R_1 d) - (w_b x_b) = 0 \tag{2}$$

where R_1 equals the scale reading when the board is not loaded; d is the distance between the supporting knife edges (i.e., the moment arm of R_1 with respect to axis A); w_b is the weight of the board; and x_b is the distance from axis A to the center of gravity of the board (i.e., the moment arm of w_b with respect to axis A).

When a person assumes a prescribed position on the reaction board (see Figure 2), the equation of static equilibrium becomes:

$$\sum M_A = (R_2 d) - (Wx) - (w_b x_b) = 0 \qquad (3)$$

where **W** equals the person's body weight and **x** is the distance from axis A to the CG of the person's body (i.e., the moment arm of **W** with respect to axis A).

Rearranging equation 2, we can show that:

$$(R_1 d) = (w_b x_b) \qquad (4)$$

Substituting **(R₁d)** for **(w_bx_b)** in equation 3, the equation of static equilibrium when a person is in a prescribed position can be rewritten as:

$$(R_2 d) - (Wx) - (R_1 d) = 0 \qquad (5)$$

Finally, solving for **x** (i.e., the location of the CG with respect to axis A),

$$x = \frac{(R_2 - R_1)}{W} \cdot d \qquad (6)$$

Therefore, in the case of the reaction board technique shown in Figure 2 (see the following page), it is not necessary to measure the weight and location of the center of gravity of the board. The contribution of the weight of the board to the moments produced about axis A is accounted for by the scale reading taken from the system when the board is unloaded **(R₁)**.

Consequently, determination of the CG location of a body with respect to a reference axis of rotation involves four steps:
1. A scale reading is taken when the reaction board is unloaded **(R₁)**.
2. Subject assumes the desired position on the reaction board.
3. A second scale reading is taken **(R₂)** with the subject maintaining the desired position.
4. The CG location **(x)** with respect to the reference axis is calculated using equation 6.

Figure 1.

(b)

Figure 2.

(c)

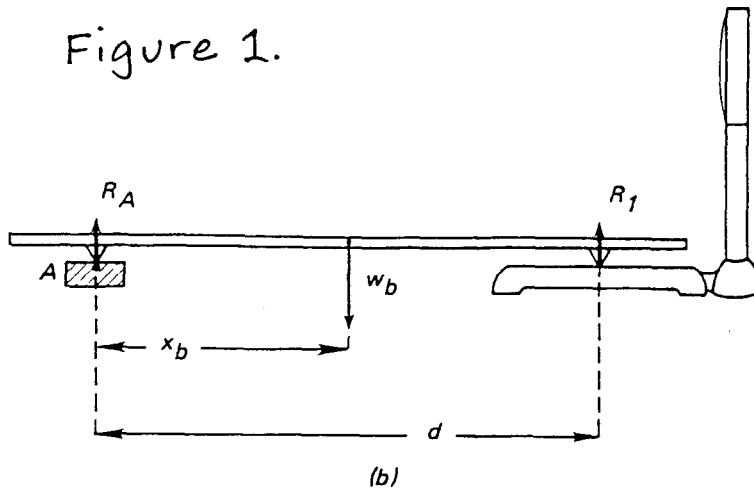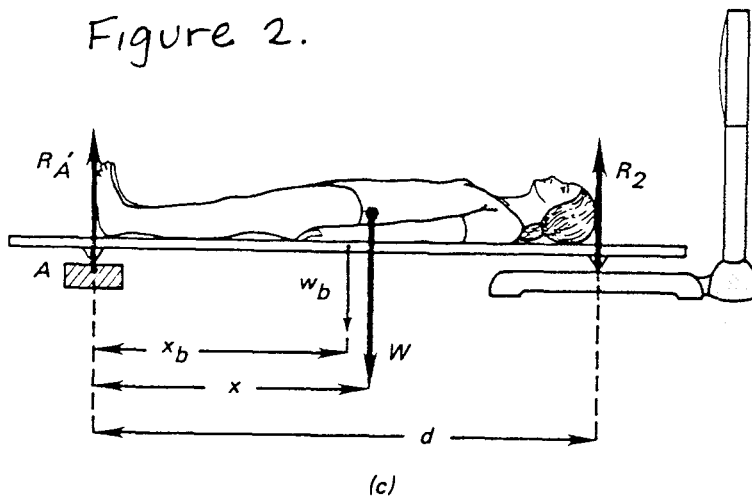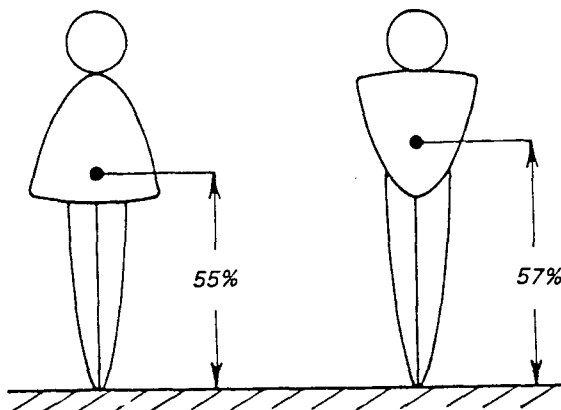## Figure 3.

Differences in the physique of men and women—most notably, in the breadth of hips and shoulders—result in women having slightly lower centers of gravity than men when both assume an erect standing position.

Procedures:
1. Identify one person in your group who will be tested. Obtain an accurate measure of height **(h)** and weight **(W)** using the same scale which will be used for the reaction board:

Weight **(W)** = _____ lb   Height **(h)** = _____ in

2. Record the initial scale reading **(R₁)** and the distance between the knife edges of the board **(d)**.

R_1 = _____ lb   Length **(d)** = _____ in

3. Instruct the participant to lie supine on the reaction board taking care to align the soles of the participant's feet with axis A (see Figure 2).

a. Record scale reading, R_{2A}, while the participant lies on the board with arms at sides.

R_{2A} = _____ lb

b. Record scale reading, R_{2B}, while the participant lies on the board with one arm raised overhead.

R_{2B} = _____ lb

c. Record scale reading, R_{2C}, while the participant lies on the board with both arms raised overhead.

R_{2C} = _____ lb

4. Using equation 6, compute the distance from axis A to the participant's CG in absolute terms (inches) and then as a percentage of the participant's standing height. Perform these calculations for each measure of $R_{2(A,B,C)}$.

Arms at sides (A):	**x** = _____ in	**x** = _____ % height
One arm elevated (B):	**x** = _____ in	**x** = _____ % height
Both arms elevated (C):	**x** = _____ in	**x** = _____ % height

Discussion Questions: (Note: These are not to be handed in. Use these to help you study for upcoming quizzes and examinations.)

1. What might account for gender differences in the location of the CG?
2. Why does the CG shift upward when the arms are raised above the head? (You should include a discussion of moments).
3. Do you think the position of the CG is higher, lower, or at the same level within the body when a person is standing up as when a person is lying down? Why or why not?
4. Assuming that the gymnast in Figure 4 is maintaining a static position, where would you expect the position of his CG to lie relative to his base of support? Explain.
5. In order to reach as high as possible in a vertical jump, what position should an athlete adopt at takeoff and at the peak of the jump? (Hint: which body position will result in the greatest distance between the fingertips and the center of mass at the peak of the jump?).

Part 2. Segmentation Method

The segmentation method is based on a simple principle that states that the sum of the moments of the individual body segments defined relative to an arbitrary axis must equal the moment of the sum (i.e., the moment of the total body mass) relative to the same axis:

$$\sum (m_i x_i) = M_B X_B \qquad (7)$$
$$\text{and}$$
$$\sum (m_i y_i) = M_B Y_B \qquad (8)$$

where m_i represents the mass of the segment i, x_i and y_i represent the Cartesian (XY) coordinates of the CG of segment i, M_B equals the total body mass, and X_B and Y_B represent the Cartesian (XY) coordinates of the total body CG. Since X_B and Y_B represent the final X, Y coordinates for the whole body center of mass, equations 7 and 8 should be solved for these variables explicitly.

Procedures: Compute the whole body location for an eight-segment representation of the person in Figure 5, following the general procedures provided below. Use only the right side of the figure for your measurements.

1. Make two or three photocopies of Figure 5 and save the original in case you make a mistake.
2. Make an educated guess as to the location of the whole body CG. Mark this location with a distinctive pen color on one of your photocopies (call this your "working photocopy"). You will compare this estimate of the CG with the calculated location.
3. Carefully mark on your working photocopy the position of the segment endpoints (see "skeleton figure"). Also refer to Figures 6 and 7 for more information on segment endpoints. If you make errors in marking segment endpoints, begin the marking process over on another photocopy.
4. Construct a stick figure representation of the figure by drawing straight lines between appropriate segment endpoints.
5. Measure the length of each segment (in mm) and record the values in Table 1. Using these lengths, and the data expressing the locations of the body segment CG's as a percentage of segment length from the noted reference point (provided in Table 1), compute the distance of the CG of each body segment from the same landmark. Using these computed distances, mark the segment CG locations on your working photocopy.
6. Draw on your working photocopy arbitrary horizontal and vertical axes, one to the left of the stick figure and one below the stick figure.
7. For each segment, measure the horizontal and vertical perpendicular distances from the CG to each axis in millimeters (i.e., the x and y coordinates of each segment CG), and record these values in Table 2. Note: the x coordinate is the perpendicular distance from the y-axis (i.e., vertical axis), the y coordinate is the perpendicular distance from the x-axis (i.e., horizontal axis).
8. To find the segment moments about each axis, multiply the relative weight of each segment by its distance from the axis. Do this for both the horizontal and vertical axes and record the results in Table 2.
9. For each axis, sum the segment moments and record the result in Table 2.
10. Compute the location of the total body CG relative to the horizontal and vertical axes by dividing the sum of segment moments about each axis by the total relative body weight (i.e., 100, which represents 100% of body weight). Record these values in Table 2 and then mark this location (X_B, Y_B) on your working photocopy.
11. Double check your segment markings and computations, especially if the computed location of the total body CF does not agree with your estimated guess from step 2. Common errors include

measuring segment CG locations from the wrong end of the segment (for nearly all segments, the segment CG lies closer to the proximal endpoint).

12. Check your whole body CG locations with the lab instructor's. These will be posted outside the biomechanics lab the day after your laboratory activity.

Discussion Questions: (Note: These are not to be handed in. Use these to help you study for upcoming quizzes and examinations.)

1. Considering the position of the body segments, is your estimate of the computed location of the total body CG reasonable? Explain.
2. The segment mass and CG values provided in Table 1 are based on *male cadavers* (old ones, at that). How do you think a (living) male athlete's values would compare? How do you think a (living) *female* athlete's values would compare? Explain.

Assignment: Segmentation method calculation using a photograph of your choice. Please refer to the additional two page handout for specific details. **This assignment is worth 10 points and is due at the *beginning* of lab period, Wed., November 12.**
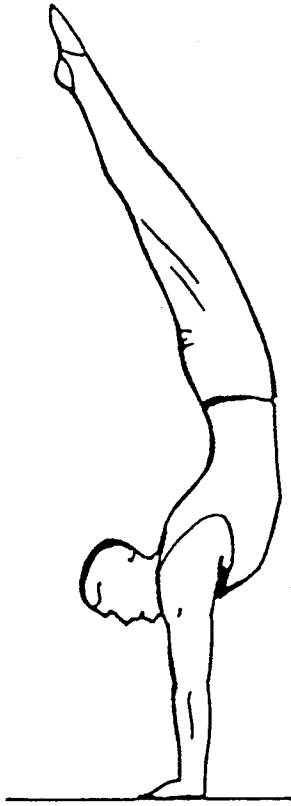
Figure 4
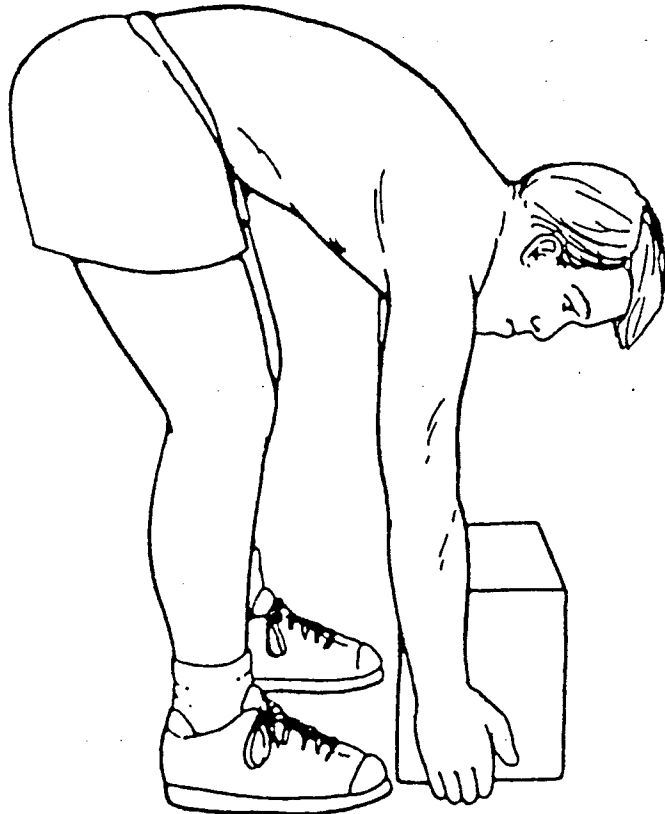
Figure 5

SKELETAL ANTHROPOMETRIC POINTS

Figure 6 (lateral view labels):

- Vertex
- Frankfort Plane
- Chin-Neck Intersect
- Cervicale
- Suprasternal Notch
- Shoulder Axis
- Elbow Axis
- Anterior Superior Spine of the Ilium
- Hip Axis
- Stylion
- Wrist Axis
- Knuckle III
- Knee Axis
- Ankle Axis
- Heel
- Toe

Figure 6

Figure 7 (anterior view labels):

- Vertex
- Chin-Neck Intersect
- Suprasternale (Suprasternal Notch)
- Acromion
- Shoulder Axis
- Substernale
- Radiale
- Elbow Axis
- Anterior Superior Spine of the Ilium
- Trochanterion
- Hip Axis
- Wrist Axis
- Knuckle III
- Midpoint between Hip Joints
- Knee Axis
- Tibiale
- Ankle Axis
- Sphyrion
- Toe
- Heel

Figure 7

Table 1. Segmental lengths and segment CG locations as a percentage of length measured from the proximal endpoint.

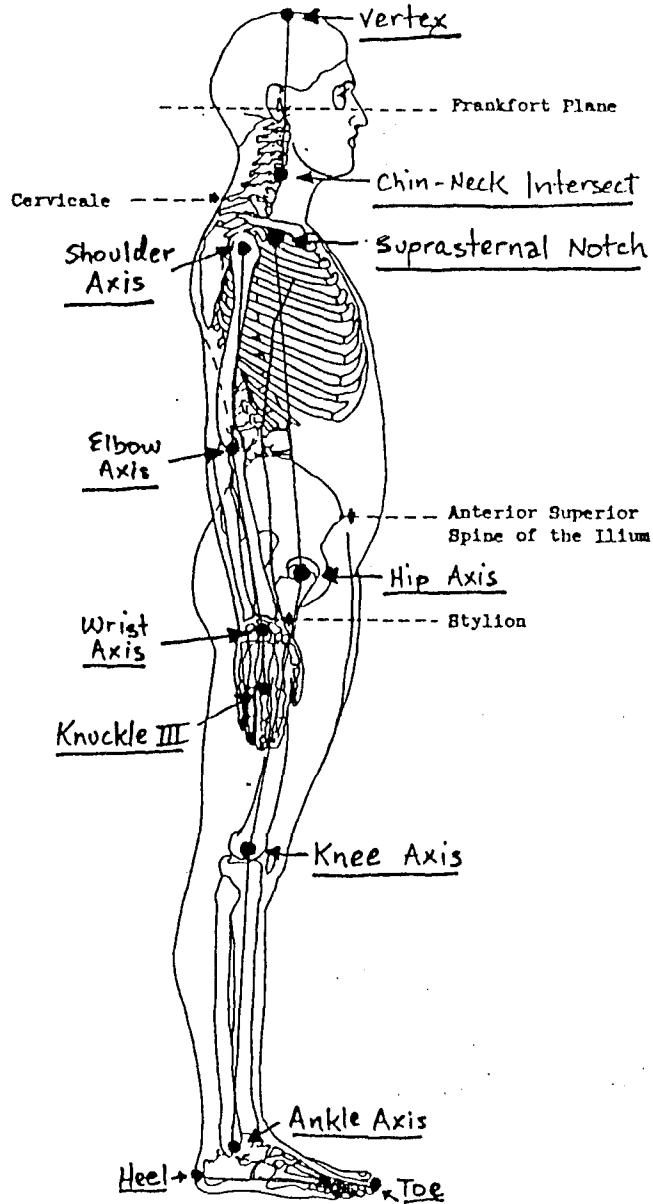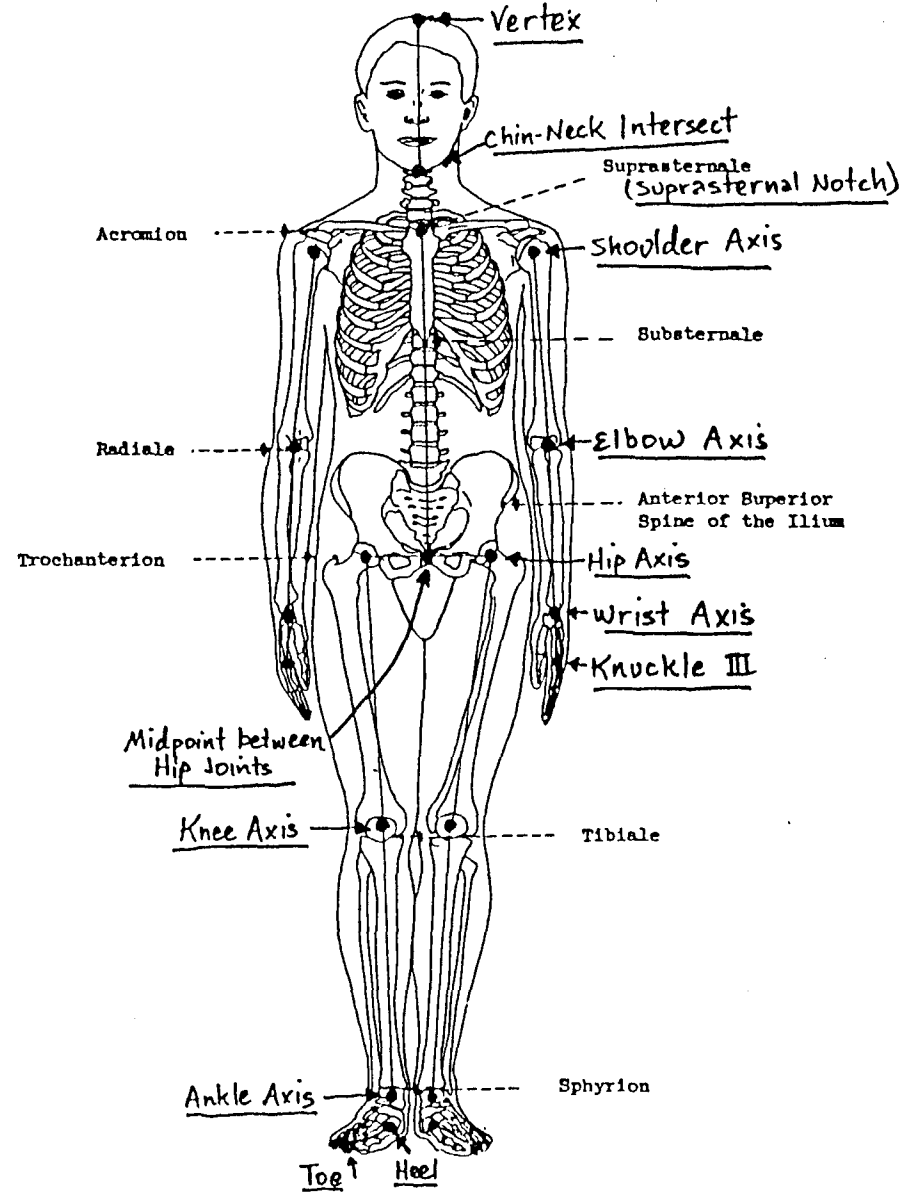| Segment	Length (mm)	CG location (% length)	CG location (mm)
Head	_____	59.8% from vertex	_____
Trunk	_____	44.9% from supersternale	_____
Upper arm	_____	57.7% from shoulder	_____
Forearm	_____	45.7% from elbow	_____
Hand	_____	79.0% from wrist	_____
Thigh	_____	41.0% from hip	_____
Shank	_____	44.6% from knee	_____
Foot	_____	44.2% from heel	_____

Table 2. Data summary for segmental computation of whole body center of mass. Note: the relative masses for each limb have been doubled to account for each side of the body.

Segment (i)	Relative Mass (m_i: %)	Horizontal CG distance (x_i: mm)	Horizontal moment ($m_i \cdot x_i$)	Vertical CG distance (y_i: mm)	Vertical moment ($m_i \cdot y_i$)
Head	6.94	_____	_____	_____	_____
Trunk	43.46	_____	_____	_____	_____
Upper arm	5.42	_____	_____	_____	_____
Forearm	3.24	_____	_____	_____	_____
Hand	1.22	_____	_____	_____	_____
Thigh	28.32	_____	_____	_____	_____
Shank	8.66	_____	_____	_____	_____
Foot	2.74	_____	_____	_____	_____

$$M_B = 100.0\% \qquad \sum m_i x_i = \underline{\quad\quad} \qquad \sum m_i y_i = \underline{\quad\quad}$$

Center of mass location: $X_B = $ _____ mm; $Y_B = $ _____ mm

Laboratory Assignment 1

Calculate the two-dimensional center of gravity location on a photographed image of your choice using the segmentation method and the instructions provided below. **(10 points)**

1.   Find a photograph of a person in motion that will fit on a piece of 8.5 x 11 inch paper (avoid extremely small photographs as this will make precise measurement very difficult; try to get a photograph at least 50% as large as the page, but not larger than 8 x 10). The best photographs to use are those showing a figure moving in the sagittal plane. Photographed images viewed in other planes can be used, but may be more troublesome. The photograph must show the whole body.
2.   Make two or three good photocopies of your photograph and save the original in case you make mistakes.
3.   Make an educated guess as to the location of the whole body CG. **Mark this location with a distinctive color pen on one of your photocopies (call this your "working photocopy"). Clearly label this mark as "quess"**. You will compare this estimate of the CG with the calculated location.
4.   Carefully mark on your working photocopy the position of the segment endpoints. Positions of endpoints obscured by other body parts should be estimated carefully. Also refer to your CG lab for extra information on segment endpoints. If you make errors in marking segment endpoints, begin marking process again on another photocopy.
5.   Construct a stick figure representation of the athlete by drawing straight lines between appropriate segment endpoints.
6.   Measure the length of each segment in millimeters and record the values in Table 1. Using these lengths and the data expressing the locations of body segment CG's as a percentage of segment length from the noted reference point (provided in Table 1), compute the distance of the CG of each body segment from the same landmark. Using these computed distances, mark the segment CG locations on the photo.
7.   Draw on your photocopy arbitrary horizontal and vertical axes, one to the left of the stick figure and one below the stick figure.
8.   For each segment, measure the horizontal and vertical perpendicular distances from the CG to each axis in millimeters (i.e., the x and y coordinates of each segment CG), and record these values in Table 2. Note: the x coordinate is the perpendicular distance from the y-axis (i.e., vertical axis), the y coordinate is the perpendicular distance from the x-axis (i.e., horizontal axis).
9.   To find the segment moments about each axis, multiply the relative weight of each segment by its distance from the axis. Do this for both the horizontal and vertical axes and record the results in Table 2.
10.   For each axis, sum the segment moments and record in Table 2.
11.   Compute the location of the total body CG location relative to the horizontal and vertical axes by dividing the sum of segment moments about each axis by the total relative body weight (i.e., 100, which represents 100% of body weight). Record these values in Table 2 and then measure and **mark this x,y location on the working photocopy. Clearly label the final CG location as "actual".**
12.   Double check your segment markings and computations, especially if your computed location of the total body CG does not agree with your estimated guess from step 2. Common errors include measuring segment CG locations from the wrong end of the segment (for nearly all segments, the segment CG lies closer to the proximal end than the distal end).
13.   **TURN IN** *your completed Tables 1 and 2, your working photocopy, and your original photo no later than the deadline specified by your instructor.*

Table 1. Segmental lengths and segment CG locations as a percentage of length measured from the proximal endpoint.

Segment	Length (mm)	CG location (% length)	CG location (mm)
Head	_____	59.8% from vertex	_____
Trunk	_____	44.9% from supersternale	_____
R. Upper arm	_____	57.7% from shoulder	_____
R. Forearm	_____	45.7% from elbow	_____
R. Hand	_____	79.0% from wrist	_____
R. Thigh	_____	41.0% from hip	_____
R. Shank	_____	44.6% from knee	_____
R. Foot	_____	44.2% from heel	_____
L. Upper arm	_____	57.7% from shoulder	_____
L. Forearm	_____	45.7% from elbow	_____
L. Hand	_____	79.0% from wrist	_____
L. Thigh	_____	41.0% from hip	_____
L. Shank	_____	44.6% from knee	_____
L. Foot	_____	44.2% from heel	_____

Table 2. Data summary for segmental computation of whole body center of mass.

Segment (i)	Relative Mass (m_i: %)	Horizontal CG distance (x_i: mm)	Horizontal moment ($m_i \cdot x_i$)	Vertical CG distance (y_i: mm)	Vertical moment ($m_i \cdot y_i$)
Head	6.94	_____	_____	_____	_____
Trunk	43.46	_____	_____	_____	_____
R. Upper arm	2.71	_____	_____	_____	_____
R. Forearm	1.62	_____	_____	_____	_____
R. Hand	0.61	_____	_____	_____	_____
R. Thigh	14.16	_____	_____	_____	_____
R. Shank	4.33	_____	_____	_____	_____
R. Foot	1.37	_____	_____	_____	_____
L. Upper arm	2.71	_____	_____	_____	_____
L. Forearm	1.62	_____	_____	_____	_____
L. Hand	0.61	_____	_____	_____	_____
L. Thigh	14.16	_____	_____	_____	_____
L. Shank	4.33	_____	_____	_____	_____
L. Foot	1.37	_____	_____	_____	_____

$M_B = 100.0\%$ $\sum m_i x_i$ = _____ $\sum m_i y_i$ = _____

Center of mass location: X_B = _____ mm; Y_B = _____ mm