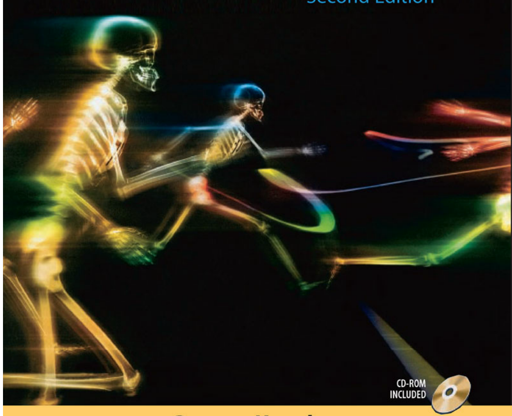
Fundamentals of

Biomechanics

Second Edition



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Springer

Equilibrium and angular kinetics are the mechanical tools most often used in the study of balance. We will see in the next two sections that the center of gravity of the human body can be calculated by summing moments in a static equilibrium form, and these kinds of data are useful in examining the state of mobility and stability of the body. This control of stability and ability to move is commonly called *balance*. What mechanics tells us about balance is summarized in the Principle of Balance.

CENTER OF GRAVITY

A natural application of angular kinetics and anthropometrics is the determination of the center of gravity of the body. The **center of gravity** is the location in space where the weight (gravitational force) of an object can be considered to act. The center of small rigid objects (pencil, pen, bat) can be easily found by trying to balance the object on your finger. The point where the object balances is in fact the center of gravity, which is the theoretical point in space where you could replace the weight of the whole object with one downward force. There is no requirement for this location to be in a high-mass area, or even within or on the object itself. Think about where the center of gravity of a basketball would be.

The center of gravity of the human body can move around, because joints allow the masses of body segments to move. In the anatomical position, the typical location of a body's center of gravity in the sagittal plane is at a point equivalent to 57

Interdisciplinary Issue: The Spine and Low-Back Pain

One of the most common complaints is low-back pain. The medical literature would say that the etiology (origin) of these problems is most often idiopatic (of unknown origin). The diagnostic accuracy of advanced imaging techniques like magnetic resonance imaging (MRI) for identifying spinal abnormalities (e.g., disk herniation) that correlate with function and symptoms of low-back pain is poor (Beattie & Meyers, 1998). The causes of low-back pain are complicated and elusive. Biomechanics can contribute clues that may help solve this mystery. Mechanically, the spine is like a stack of blocks separated by small cushions (McGill, 2001). Stability of the spine is primarily a function of the ligaments and muscles, which act like the guy wires that stabilize a tower or the mast of a boat. These muscles are short and long and often must simultaneously stabilize and move the spine. Total spine motion is a summation of the small motions at each intervertebral level (Ashton-Miller & Schultz, 1988). Biomechanical studies of animal and cadaver spines usually examine loading and rotation between two spinal levels in what is called a motion segment. Individuals even exhibit different strategies for rotation of motion segments in simple trunk flexion movements (Gatton & Pearcy, 1999; Nussbaum & Chaffin, 1997), so that neuromuscular control likely plays an important role in injury and rehabilitation (Ebenbichler, Oddsson, Kollmitzer, & Erim, 2001). Occasionally a subject is unfortunate and gets injured in a biomechanical study. Cholewicki and McGill (1992) reported x-ray measurements of the "buckling" of a single spinal segment that occurred during a heavy deadlift. Biomechanics research using computer models and EMG are trying to understand how muscles and loads affect the spine, and the nature of this motion segment buckling (Preuss & Fung, 2005). This information must be combined with occupational, epidemiological, neurologic, and rehabilitative research to understand the development and treatment of low-back pain.

and 55% of the height for males and females, respectively (Hay & Reid, 1982). Can you name some structural and weight distribution differences between the genders that account for this general difference? Knowing where the force of gravity acts in various postures of the human body allows biomechanists to study the kinetics and stability of these body positions.

There are two main methods used to calculate the center of gravity of the human body, and both methods employ the equations of static equilibrium. One lab method, which requires a person to hold a certain body position, is called the **reaction change** or *reaction board* method. The other method used in research is called the *segmental method*. The **segmental method** uses anthropometric data and mathematically breaks up the body into segments to calculate the center of gravity.

The reaction board method requires a rigid board with special feet and a scale (2D) or scales (3D) to measure the ground reaction force under the feet of the board. The "feet" of a reaction board are knife-like edges or small points similar to the point of a nail. A 2D reaction board, a free-body diagram, and static equilibrium equations to calculate the center of gravity in the sagittal plane are illustrated in Figure 7.11. Note that the weight force of the board itself is not included. This force can be easily added to the computation, but an efficient biomechanist zeros the scale with the board in place to exclude extra terms from the calculations. The subject in Figure 7.11 weighs 185 pounds, the distance between the edges is 7 feet, and the scale reading is 72.7 pounds. With only three forces acting on this system and everything known but the location of the center of gravity, it is rather simple to apply the static equilibrium equation for torque and solve for the center of gravity ($\mathbf{d}_\perp$). Note how the sign of the torque created by the subject's body is negative according to convention, so a negative $\mathbf{d}_\perp$ (to the left) of the reaction board edge fits this standard, and horizontal displacement to the left is negative. In this case, the

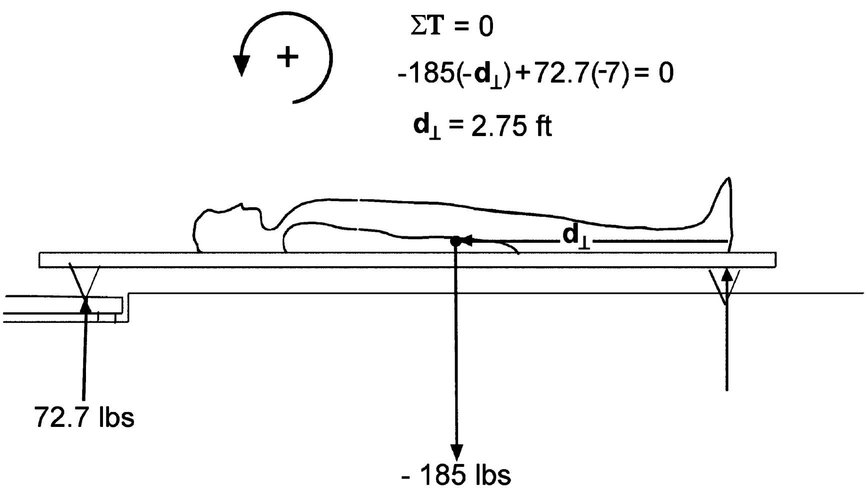

Figure 7.11. Application of static equilibrium and a reaction board to calculate whole body center of gravity. Summing torques about the reaction board edge at the feet and solving for the moment arm ($\mathbf{d}_\perp$) for gravity locates the center of gravity.

subject's center of gravity is 2.75 feet up from the edge of the reaction board. If the subject were 5.8 feet in height, his center of gravity in this position would be 47% of his or her height.

In the segmental method, the body is mathematically broken up into segments. The weight of each segment is then estimated from mean anthropometric data. For example, according to Plagenhoef, Evans, & Abdelnour (1983), the weight of the forearm and hand is 2.52 and 2.07% for a man and a woman, respectively. Mean anthropometric data are also used to locate the segmental centers of gravity (percentages of segment length) from either the proximal or distal point of the segment. Figure 7.12 depicts calculation of the center of gravity of a high jumper clearing the bar using a three-segment biomechanical model. This simple model (head+arms+trunk, thighs, legs+feet) illustrates the segmental method of calculating the center of gravity of a linked biomechanical system. Points on the feet, knee, hip, and shoulder are located and combined with anthropometric data to

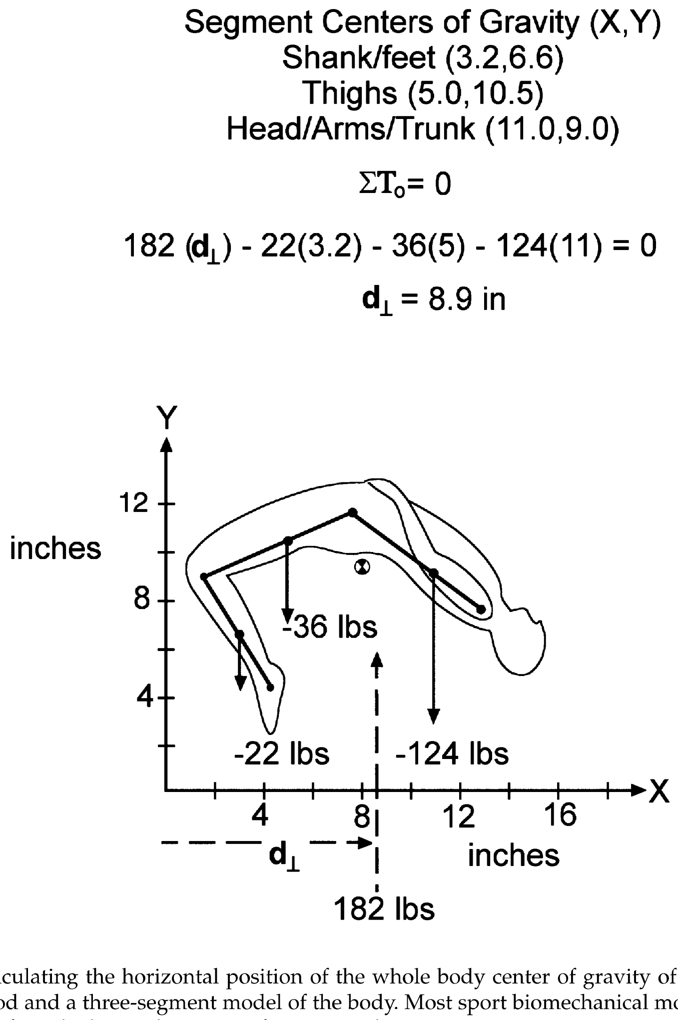

Figure 7.12. Calculating the horizontal position of the whole body center of gravity of a high jumper using the segmental method and a three-segment model of the body. Most sport biomechanical models use more segments, but the principle for calculating the center of gravity is the same.

calculate the positions of the centers of gravity of the various segments of the model. Most biomechanical studies use rigid-body models with more segments to more accurately calculate the whole-body center of gravity and other biomechanical variables. If a biomechanist were studying a high jump with high-speed video (120 Hz), a center of gravity calculation much like this would be made for every image (video snapshot) of the movement.

The segmental method is also based on static equilibrium. The size and location (moment arm) of the segmental forces are used to calculate and sum the torques created by each segment. If this body posture in the snapshot were to be balanced by a torque in the opposite direction (product of the whole bodyweight acting in the opposite direction times the center of gravity location: $182 \cdot \mathbf{d}_{\perp}$), the total torque would be zero. By applying the law of statics and summing torques about the origin of our frame of reference, we calculate that the person's bodyweight acts 8.9 inches from the origin. These distances are small because the numbers represent measurements on an image. In a 2D biomechanical analysis, the image-size measurements are scaled to real-life size by careful set-up procedures and imaging a control object of known dimensions.

Finding the height of the center of gravity is identical, except that the y coordinates of the segmental centers of gravity are used as the moment arms. Students can then imagine the segment weight forces acting to the left, and the height of the center of gravity is the y coordinate that, multiplied by the whole bodyweight acting to the right, would cancel out the segmental torques toward the left. Based on the subject's body position and the weights of the three segments, guess the height in centimeters of the center of gravity. Did the center of gravity pass over the bar? Finish the calculation in Figure 7.12 to check your guess. The segmental method can be applied using any number of segments, and in all three dimensions during 3D kinematic analysis. There are errors associated with the segmental method, and more complex calculations are done in situations where errors (e.g., trunk flexion/extension, abdominal obesity) are likely (Kingma, Toussaint, Commissaris, Hoozemans, & Ober, 1995).

Activity: Center of Gravity and Moment of Inertia

Take a 12-inch ruler and balance it on your finger to locate the center of gravity. Lightly pinch the ruler between your index finger and thumb at the 1-inch point, and allow the ruler to hang vertically below your hand. Swing the ruler in a vertical plane and sense the resistance of the ruler to rotation. Tape a quarter to various positions on the ruler and note how the center of gravity shifts and how the resistance to rotation changes. Which changes more: center of gravity or moment of inertia? Why? What factors make it difficult to sense changes in ruler moment of inertia?

PRINCIPLE OF BALANCE

We have seen than angular kinetics provides mathematical tools for understanding rotation, center of gravity, and rotational equilibrium. The movement concept of balance is closely related to these angular kinetic variables. **Balance** is a person's ability to control their body position relative to some base of support (Figure 7.13). This ability is needed in both static equilibrium conditions (e.g., handstand on a balance beam) and during dynamic movement (e.g., shifting the center of gravity from the