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ABSTRACT

This booklet contains five research works on kinesiology, the study of the principles of mechanics and anatomy in relation to human movement. The first article explains the use of Web graphics in isolating five movements: effort, force, balance, flexibility, and swing. The process for pinpointing values on the Web grid is presented in two sheets of directions (Appendixes A and B). The second article reviews existing methods of three-dimensional cinematography and proposes a new technique that emphasizes the accurate determination of spatial coordinates. The third article discusses the two basic methods used in determining the center of gravity of the human body: a) direct or whole body methods and b) indirect or segmental methods. The article also suggests guidelines which may be used for establishing the most appropriate method for quantitative analysis of human motion. Thirteen tables of data are included. The fourth article analyzes the problems of designing an undergraduate, kinesiology laboratory. The last article investigates the inherent movement patterns of the human body, emphasizing diagonal patterns of the upper and lower extremities and the diagonal patterns used in developmental and sport skills. Each research work presents a list of references. (BRB)

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Web Graphics and the Qualitative Analysis of Movement

GRAPHIC DISPLAYS are frequently found accompanying articles treating a variety of kinesiological topics. Electromyographic recordings, at times combined in novel ways with media like the video tape recorder, help to clarify associated concepts (1). Other examples of the graphic presentation of data range from stick figures extracted from film to light trace photography in which the output of small lights provides an accurate record of intricate bodily action. These and other methods for graphic display are described in detail in a compendium of articles edited by Wartenweiler, Jokl, and Hebbelinck (2).

Graphic display of data is almost without exception presented in connection with experiments that one may describe as "quantitative" in nature. The normal procedure in research demands, after all, some precise measurement of quantity. An absence of quantitative measurement and analysis would tend to limit the scope of knowledge to opinion, abstraction, ideation, and theory construction. These latter behaviors are termed "qualitative." However, it is from this qualitative domain that we form hypotheses about our impressions, many of which are ultimately tested in the quantitative domain of the laboratory.

But why restrict analysis to the quantitative domain? Is it possible to better organize our impressions, perceptions, and concepts of movement qualitatively? This paper is devoted to a qualitative analysis of movement and the exposure of a new method for the graphic display of movement quality. The process has been termed "Web Graphics." Experience thus far with Web Graphics has shown it to be a useful device for organizing qualitative concepts of movement.

The physical educator and the coach are constantly making decisions about the quality (rating) of performance. The ability to make accurate decisions about motor performance should be facilitated when concepts related to movement quality are well organized. In certain sports such as diving, free skating, and gymnastics, scores for performance are often derived in whole or in part by complicated systems of quality analysis. Judges are expected to give their scores momentarily after performance. This is a truly difficult task open to a multitude of sources for error.

The work of Rudolph Laban has given us an initial clue to a method for the qualitative analysis of movement (3, 4). Laban's system for the notation of movement, known as "Kinetography-Laban" (Labanotation), is a system anchored to the quantitative domain. He subsequently appended his basic system to include notations of

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movement quality. Such notations are graphic representations of movement dynamics in terms of time, space, and force. This lesser known system he called "Effort Notation." His "effort" model (Figure 1) displays eight primary notations from which species of quality may be extracted. The "effort" concept was eventually incorporated into the model for Web Graphics as one of five primary sources of qualitative data (Figure 2).

As presented here, the model is in a form called the "Web Grid" or simply the "Web."* Five movement components are isolated, each operating on a full continuum. In addition to the component branch labeled "Effort," the other four branches are labeled "Force," "Balance," "Flexibility," and "Swing." The task associated with Web Graphics is to pinpoint each of five values, one designation for each of the above named prime qualities, that correspond in turn to our notions about movements selected for study. The branches are essentially rating scales with infinite limits defined on a continuum from 0 to 7. Accordingly, Web Graphics was conceived as a medium and a method for the study and graphic display of movement quality. Patterns displayed on a Web can result in meaningful class discussions about basic concepts of movement. The use of Web Graphics has been helpful in the isolation of families of movements resulting in a convenient way to introduce students to the geneology of movement.

The linear graph immediately below the Web in Figure 2 is reserved for a mean value extracted from a combination of the five branch scores. This supplementary graph is useful in describing movement complexity, and as a result, we refer to this graph as "the complexity continuum." The concept of complexity fits in well with the theoretical structure of our qualitative model which in turn is dependent upon an understanding of the concept of "Swing" which will be discussed later in this paper.

When students attempt to use Web Graphics, they are naturally concerned about standards that should be employed as they make judgments about each of the Web's five component branches. In order to facilitate such judgments, it is important to explain the logic employed in the construction of the Web Graph which also serves as a conceptual model.

In addition to its function as a rating scale, the branches of the Web were selected and arranged according to a number of concepts considered tantamount to an understanding of movement quality. Ordinarily, students will have some notions about judging the qualities of force, balance, and flexibility. Time is needed, however, to familiarize them with the "Swing" concept and Laban's Effort Notation.

MAN IS A SWINGER

The component branch called "Swing" is found at the extreme right of the Web. Swing is proposed as an ultimate quality perceived in the movements of animals including man. Man is a swinger not by choice but rather by construction. His bony levers are, more often than not, powered by muscles which in turn are atached to the bones in such a way that the resultant force arms are shorter than the resistance arms associated with them. Therefore leverage in man is either of the first or third class, usually the latter. Such a system of levers cannot have a force advantage. The particular advantage of such a system is that it favors speed and range of movement. The term "swing" was chosen to represent this speed-range quality. Speed and range may be defined and measured in quantitative terms, but the concept of swing appears to be more appropriate for qualitative analysis. The presence of swing in skilled movements is often obvious or can be easily demonstrated to students with selected films. Unskilled performance by contrast tends to lack sufficient speed and range and is likely to be force oriented. (Note that the com-

* When data extracted from a class is displayed on a single Web grid, the resulting mesh of lines reminds one of a spider's web, hence we were prompted to use the term "Web" to describe the graphic display.

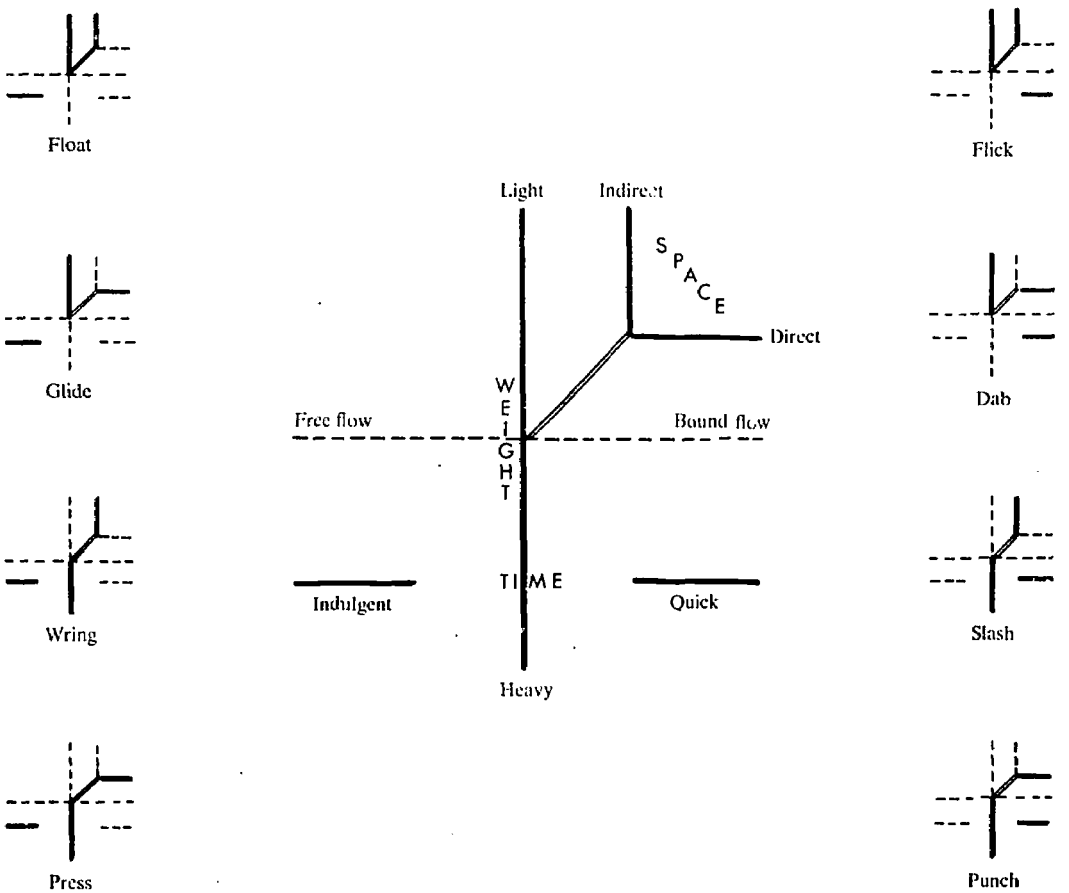


Figure 1. Laban's effort model.

ponent branch labeled "Force" is nearer the left — opposite — side of the complexity index.) Skilled and unskilled tennis players in the act of serving provide one of the many ways that contrast in swing might be demonstrated.

Verbal expressions denoting a swingful performance such as "Effortless," "Graceful," or simply "Wow!" confirm the fact that men are able to recognize swing as an ultimate quality of movement. At times such expressions are closely related to aesthetics and are heard as often at basketball games as at the ballet. The quality perceived is the same — Swing. The "Swing" component branch is placed at the right side of the model which coincides with the complexity continuum, graphed as a supplementary index below the Web. Performances which are not swingful in nature are therefore theorized to be less complex, such movements reflecting litle more than one quality.

An archetype for a correctly executed, nonswingful, force-oriented movement is the "Olympic Cross" performed by the gymnast (Figure 4A). Other activities may be oriented toward balance or flexibility. These qualities are all incorporated in the Web. They are defined: (1) in terms of their relationship to swing, and (2) as specific qualitative entities in their own right.

The qualities of force, balance, and flexibility are always subsumed under Swing. A skilled runner may be perceived as a swinger, but he is certainly exerting muscular force, is constantly compensating for a

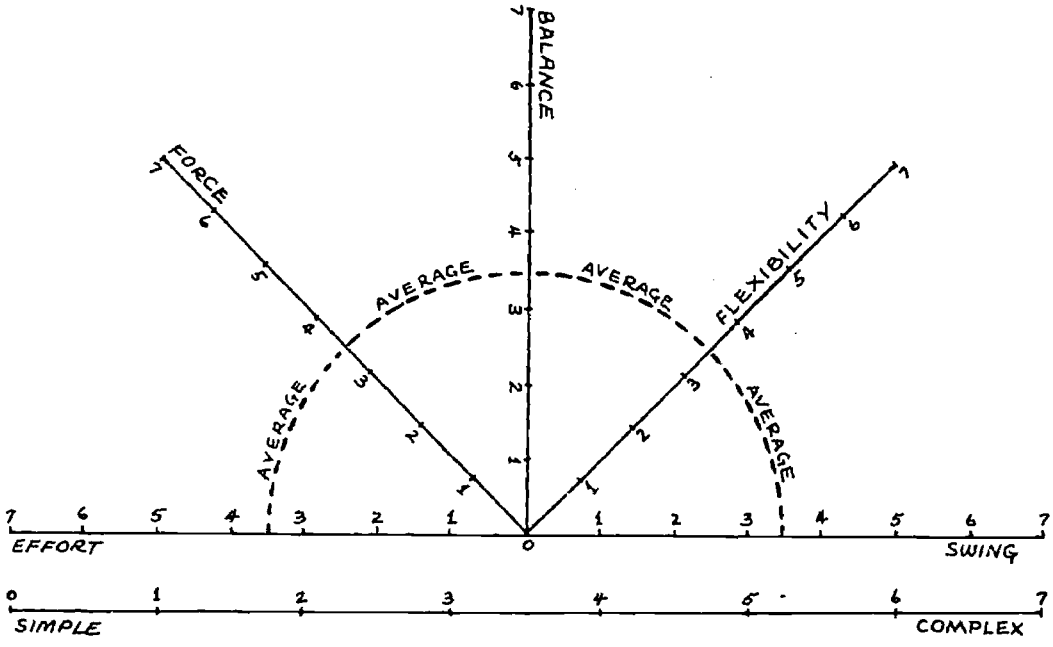


Figure 2. Model and grid for Web graphics.

loss of balance in the direction of the finish, and is stretching his muscles when he achieves maximum joint range.

EFFORT NOTATION

Unlike Labanotation, effort notation is easily grasped by students. If you have not yet been introduced to this convenient notation method, you may consult the original text on the subject by Laban and Lawrence (5) and the more recent work by Bartenieff (6, 7). The use of effort notation and the concept of effort permits one to condense qualitative notions of movements into eight primary species (Figure 1). Effort notation provides a miniature linguistic system of sorts. Students are encouraged to think in effort terms; past experience indicates that they are able to do so. Once they understand the effort model, they are able to generate the words that describe the primary species of effort ("Punch," "Float," "Glide," etc.) and can use these words in subsequent discusions of movement in a meaningful way.

The Effort component branch is placed on the simplicity side of the model because it is the first source of qualitative data. Students are encouraged to consider this aspect first in the analysis process. The concept of effort denotes "flavor" of movement. The number and nature of the effort species that can be extracted in this primary assessment of quality helps with the judgment of the other four component branches and gives an indication of the complexity of the movement.

A push-up has one effort species — a press. It is force oriented, and it is lacking in swing. It would therefore be classified as "simple" on the complexity index. A forward handspring, on the other hand, has at least four effort species (glide, punch, slash, and press) and it is swing oriented. Flexibility of the spine is necessary for a swingful handspring, and balance in landing is a key factor. The effort species detectable in the handspring show that force plays a definite role, but upon observing a skilled performance, the qualities of force, balance, and flexibility often go undetected because of the

swingful nature of the movement; that is to say that these qualities are subsumed under Swing. All swingful movements generally contain more qualitative elements and are therefore more complex.

Complexity should not be confused with difficulty. An "Iron Cross" is difficult but is certainly not complex. Therefore, the terms "primitive" and "aesthetic" are occasionally used to describe the range of a complexity continuum. Force oriented movements are in most instances more primitive than swingful, aesthetic movements. For this reason the Force component branch is placed on the Web to show its tendency to lean toward the simplicity end of the complexity index.

FLEXIBILITY AND BALANCE

A performer with limited flexibility in the muscles and joints is restricted in his ability to swing and must rely on force to accomplish various kinds of movements. Accordingly, the Flexibility component branch of the Web is placed adjacent to Swing. It leans toward (facilitates) swing just as Force leans toward simplicity. But flexibility is often the only major quality detected in certain movements. When flexibility is the primary quality, it is less complex and therefore more primitive than when subsumed with other values. A slow backbend is flexibility oriented. It has one primary effort species (Press) and depends upon a sufficient range of motion in the spine and the shoulder joints. Balance and force are present but are of lesser importance.

Balance is given a central position on the Web because in either its dynamic or static modes it is present qualitatively in all movements. Since it is less apparent in swing, usually assuming only a minor role (there are exceptions), it is more closely associated with force. Unskilled performers often lose their balance in learning movements and rely heavily on force to complete an act. When a baby first learns to walk he moves in a primitive fashion often falling out of balance. But the swingful gait of the adult is taken for granted with little or no attention given to the balance required. The terms "swingful" and "efficient" tend to be synonymous with respect to human movement.

Like flexibility. balance may have a pure form. Static positions such as the handstand or simply standing upright are balance oriented acts. Normal standing postures could be classified without question as primitive in nature. Most commonly known, static postures are classifiable on the simplicity side of the complexity index although some may be most difficult (standing on one hand); others are often associated with aesthetic movements (Arabesque).

THE TECHNIQUE OF WEB GRAPHICS

Having exposed students to the concepts related to the conceptual model contained in the Web, the process of pinpointing values on the Web grid is begun. A concise set of directions is presented to the students on two sheets. These sheets are appended to this paper (Appendixes A and B). The process proper is presented in Appendix A entitled "Pinpointing Values on a Web Graph," and specific questions related to each of the five component branches are found in Appendix B entitled "Questions to Ask in Pinpointing Values."

Since each of the component branches represents an infinite continuum on a scale from 0 to 7, these extreme scores will never appear. We also recommend the use of no finer rating division than quarters of points on the scales of each of the component branches so the actual range of values is in reality from .25 to 6.75. Students are encouraged to record a different score for each component branch, thus forcing them to make a distinction between components. This judgment is difficult to make in the absence of quantitative measures. The result is often a suggestion that some more objective evidence be sought to test the comparative value of quality. Evidence for the confirmation of ideas is frequently gathered by

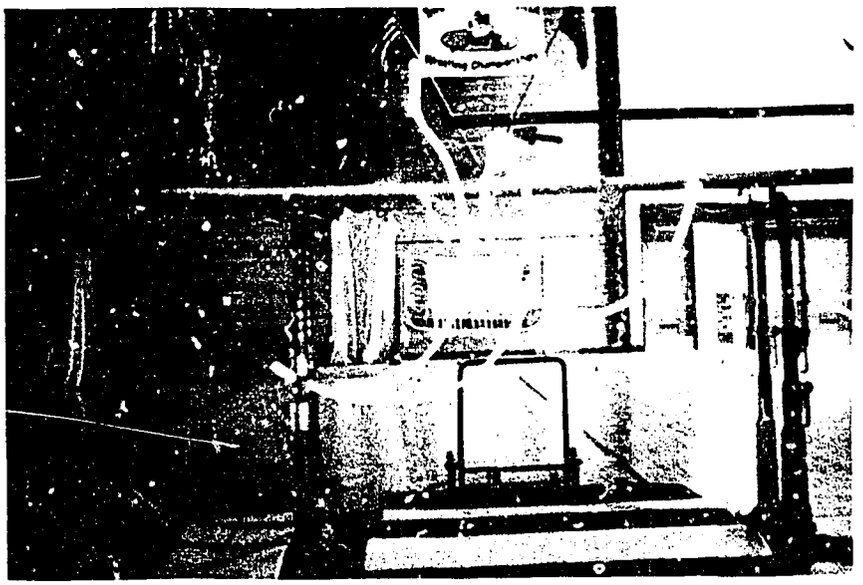
film analysis or library resources when such are available. To say the least, the process of Web Graphics is stimulating. The pinpointing process demands thinking, an admirable goal for any student of movement.

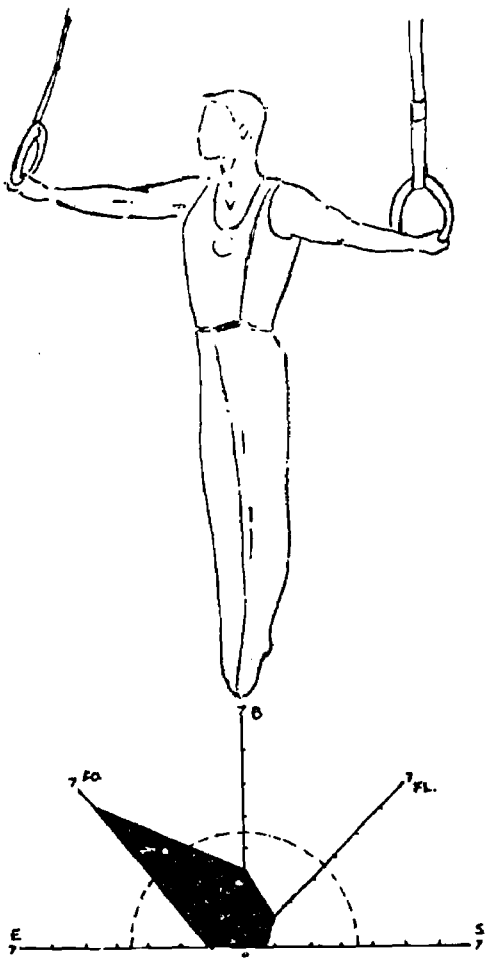
Analysis begins with a few simple questions. "Is the movement swing oriented or force oriented?" "Is it static or dynamic?" Next, an attempt is made to isolate the most prominent and the least prominent component branch. Experienced students do very well in matching the instructor's views in this exercise. If a student becomes confused at this stage, it is probably a good idea to review the concepts associated with the model.

Next, one attempts to isolate the number and kind of effort species which are prominent in the movement. Efforts are never passive and thus are revealed on light trace photographs as changes in direction or variations in the paths of movements. In Figure 3 the reader will find a light trace photograph of the path of the hips during a movement on the parallel bars showing where efforts are most likely occurring.

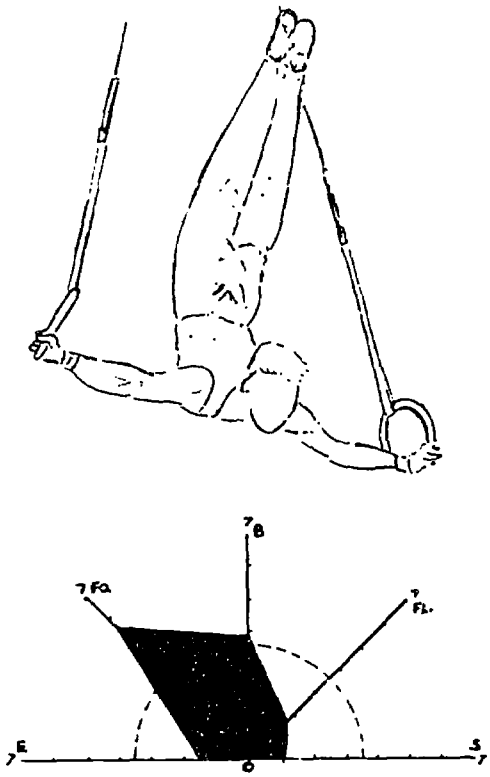
In the next phase, there is an attempt to rate each of the component branches as "above average," "average," or "below average" in value. Numerical values are then assigned for the most prominent and least prominent branches. Next, the values for the remaining three component branches are assigned. This is the most difficult phase of the pinpointing process since it is usually easier to equate the remaining items than to differentiate between (or among) them. Eventually tied values are broken and a rank order is established for the component branches. These values are recorded on the Web's grid and lines connecting the five points are drawn revealing a pattern. Some typical patterns associated with more obvious examples of isolated components of quality are found in Figure 4(A–F).

Figure 3. Light trace of a gymnastic movement (Peach-glide) showing points where efforts result in change of direction and other interruptions of the curves. (Movement is performed from right to left.)

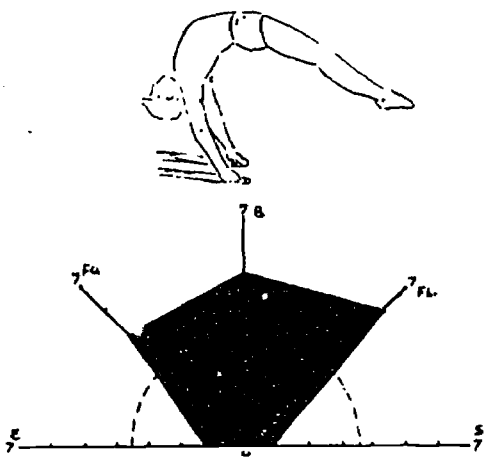




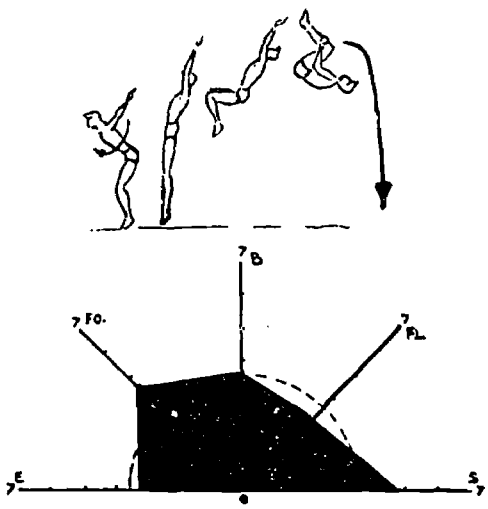
A. Force Olympic cross.



B. Force-balance inverted areas.

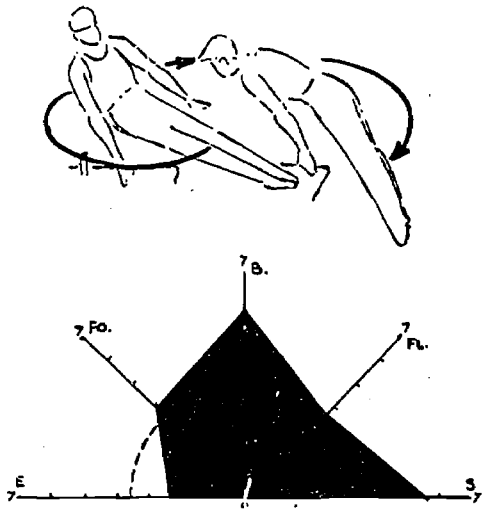


C. Force-balance-flexibility back planche.



D. Swing-force back somersault from stand.

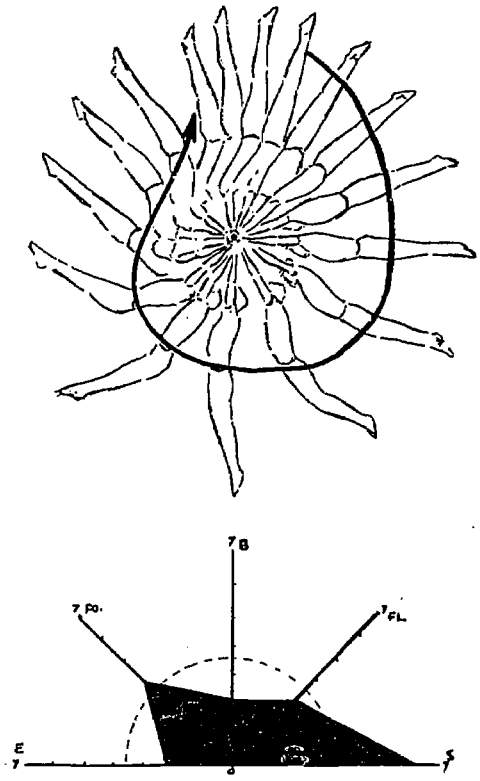
Figure 4.



E. Balance-swing double leg circle to loop on end of pommel horse.

When the instructor finds student deviations from his own scores as high as a point or more in either direction, it is a good idea to review the pinpointing process in class. We concede that we have only our own experience with which to judge the quality of movements, but teacher experience is probably a great deal better than that of the students. Serious research to elicit the mean values of a number of experienced teachers will provide a more reliable baseline for judging the accuracy of the qualitative analysis of movements. Some investigation of this sort has been started. Initial indications reveal that experienced instructors do tend to pinpoint values that have fairly consistant Web patterns for selected movements which are familiar to them.

Appendix B consists of a number of key questions one might ask about each of the five component branches of the Web. The questions serve as cues which help to make the pinpointing process a more precise evaluation.



F. Swing. Regular grip giant swing.

AN EXAMPLE—THE FORWARD ROLL

An example, the forward roll from feet to feet (Figure 5), is now offered so the reader might experience the pinpointing process for a familiar movement. The use of a sequence drawing extracted from film as presented in Figure 5 is helpful in defining the exact nature and limits of the movement. The steps presented in Appendix A are followed below.

1. Students should have little difficulty recognizing the movement as a dynamic rather than static one.

2. The movement is swing rather than force oriented. Since a force oriented forward roll can be performed and depicted in a sequence similar to the one in Figure 5, it is helpful for the students to see an actual

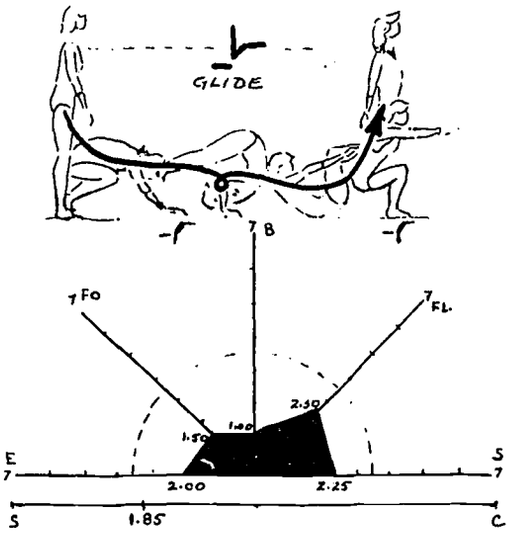


Figure 5. Web graph for the forward roll.

demonstration or film sequence of the movement they are asked to analyze.

3. & 4. The graph indicates that Flexibility (2.50) is most prominent while Balance (1.00) is least prominent in this movement. Reasoning for these values is offered below.

5. Two pressing efforts seem obvious and are notated on the sequence. The overall pattern is estimated to be a glide in terms of general impression.

6. Note that all values for all component branches are rated at below average (Below 3.50) levels.

7. Values derived for each component branch are discussed below.

8. Refer to Figure 5.

Effort (2.00). Considered en toto the movement shows directness, lightness, and slowness characteristic of the effort species known as "Glide." Within the movement there are two obvious pressing efforts provided first by the hands and then through the legs. (See notations on Figure 5.) A punch or more likely a dab would be appropriate for the tucking action and could account for the presence of a third effort. Therefore, values between 2.00 and 3.00 are acceptable. It is important that the student make an attempt to defend the number and the nature of the effort species he extracts. Such activity often results in some very interesting discussions.

Force (1.50). Some minimal amounts of muscular force are required at two points which coincide with the pressing efforts already noted. Muscular force is transient at these points and thus is rated very low. For the most part, the performer exhibits efficient use of gravitational force ("Swings").

Balance (1.00). Since the action of the forward roll is dynamic rather than static, we must be concerned about the stability factor of the roll. A low center of gravity demands less control. The same is true when the base of support is proportionately large. Some side-to-side control is exhibited but is not critical in the swingful roll. The tendency to go crooked is more marked during rolls which are slow and bound (controlled).

Flexibility (2.50). Flexible wrists and the ability to tuck as well as neck flexibility are considerations here. Inability to stretch the legs fully as shown in the third from the left figure of the sequence in Figure 5 (hamstrings) would cause too rapid a movement in some instances often resulting in a jerky or noisy roll.

Swing (2.25). One might easily make a good argument for the prominence of swing over flexibility for the movement in question. The estimate given only favors flexibility by one quarter of a point. The forward roll is an example of a swing fundamental whose flexibility requirement is a key element. Angular momentum is conserved by virtue of the leg extension referred to above and is ultimately utilized in a smooth transition to a standing position at the end of the roll.

Complexity (1.85). The average value extracted from a summation of those given for each component branch reveals the forward roll to be a simple movement which is swingful in nature and dependent upon some key flexibility requirements. The movement is less dependent upon muscular force and like most dynamic movements has a minimal balance requirement.

Within the rationale presented above, class discussions may be conducted with

reference to some of the reasons why forward rolls are often poorly executed. For example, an inflexible, overweight child might easily roll crooked (if at all) and may be exposed to injuries if certain precautions are not taken. In such a case, a rolling experience might be devised which holds the flexibility requirement to a minimum The child might simply lie on his back and attempt to roll rhythmically forward and backward in a rocking action. The example given here is simply a springboard for more sophisticated measurements that can results from class discussions.

THE FUTURE OF WEB GRAPHICS

The value of Web Graphics thus far has been limited to the introduction of kinesiological concepts and to a feedback device for the teacher. The latter technique often exposes, in a graphic way, analysis misconceptions of students, especially the way in which their values for prime components of a movement either coincide or differ with values pinpointed by the instructor. The process itself is much like the "advance organizer" concept proposed by Ausubel (8).

Web Graphics can provide a qualitative overview of the total field of movement. Associated concepts are progressively reinforced as students are confronted with the more traditional content of kinesiology. They employ the concept of swing when examining the structure and function of the muscle-joint complexes of the body. Mechanical principles derived from Newtonian laws are introduced in force-time-space relationships associated with the study of effort notation. The concept of effort and the asociated model provides a convenient movement language of eight prime "words." The use of such a miniature linguistic system has already facilitated the use of a technique called audiotonal rhythm in which sounds corresponding to movement sequences provide feedback for the learner.

The complexity continuum provides some insight to the initial identification of a hierarchy of movement. What makes one movement more complex than another? How is complexity related to difficulty? What do we mean by "aesthetic" or "efficient" movement?

The classification of movements into easily identifiable family groups is important in the design of movement progressions. Patterns exposed on the Web are grouped according to their perceived qualities into prime families each associated with a different movement component (force, balance, flexibility, and swing) and in complex movements with a variety of combinations of these prime families. Such a classification should prove useful in the study of the genealogy of movement.

Students who are exposed to the concepts of the qualitative analysis of movement should be better equipped to deal with problems associated with the observation and subsequent correction of motor skill errors. This might be a fertile area for research. Web Graphics helps students to ask questions about movement and very often such questions lead to miniprojects within the scope of the undergraduate.

Web Graphics exposes one to a subjective process based on a theoretical hierarchy of concepts. It is a tool with which one may cultivate the ability to judge the quality of movement and such a skill corresponds very well with the ordinary tasks of the physical educator and the coach. It is recognized that on-the-spot movement observation and analysis cannot result in the precision of laboratory measurement. The system of Web Graphics has been designed to improve the subjective judgments one is often called upon to make about motor performance. The goal is to provide an analysis with all of the objectivity that can be mustered outside the laboratory.

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APPENDIX A

Pinpointing Values on a Web Graph

You have been asked to make some qualitative decisions about selected movements which you are about to record on a WEB Graph. The following notes and series of progressive steps should make the pinpointing task easier to accomplish.

Notes

A. Since each branch of the WEB Graph represents an infinite continuum, you will never record a zero (0) or a seven (7).

B. Only quarter steps will be utilized. (e.g., 2.25, 3.00, 1.75, etc.) According to note "A" therefore the widest range of scores will be from 0.25 to 6.75.

C. Values for each branch must be different. (e.g., 3.00, 3.50, 3.75, 1.50, and 3.25.) If two or more are the same value, your evaluation will be much more difficult to score.

D. If you believe the movement is "Swing" oriented, "Force" values tend to be lower and vice versa.

E. Static movements or balances are usually either "Force" oriented or "Flexibility" oriented. When this is true in one direction or another a difference should be noted in branch values.

F. As linear or rotational speed is increased, the "Balance" branch will tend to be lower than those movements which are similar but lack speed.

Steps

1. Is the movement (a) Static or (b) Dynamic? (Designation "S" or "D")

2. Is the movement "Force" oriented or "Swing" oriented? (Designation "F" or "S")

3. Which component branch is most prominent in the movement? (Designation "Effort" = E, "Force" = Fo, "Balance" = B, "Flexibility" = Fl, and "Swing" = S.)

4. Which component branch is least prominent in the movement? (Use the same designation as in Step 3.)

Note: Thus far you may have the following designation . . . S–F–B–Sw. This would indicate a static movement which is force oriented with "Balance" the major component and "Swing" the minor component.

5. Estimate the number of "Effort" patterns obviously displayed in the movement. (See Figure 1).

Punch Press Flick Float Slash Wring Dab Glide

Record your estimate on the "Effort" component branch.

6. Estimate next a value for each of the four remaining component branches. It is best to begin by estimating whether your values should be above average (+), below average (−), or average (0). This will help you place the components in what you believe to be a progressive order.

7. Assign values you believe to represent the strength of each component branch and then check to see if all five values are different. If they are not, make all your final decisions in terms of quarter steps (e.g., If you nave two values rated at 3.00, decide in favor of one and change one or both scores so that their new value separates them only by one quarter step. You might record 2.75 for one and 3.00 for the other.)

8. Record all values on the WEB Graph.

APPENDIX B

The Web

Questions to Ask in Pinpointing Values

Effort

What is the overall flavor of the movement? What minor efforts are present?

Float? (Sustained, light flexible)	Punch? (Heavy, direct, quick)
Press? (Sustained, heavy, direct)	Flick? (Light, flexible, quick)
Glide? (Sustained, light, direct)	Slash? (Flexible, heavy, quick)
Wring? (Sustained, flexible, heavy)	Dab? (Light, direct, quick)

Force

Are efforts known as press, punch, wring, or slash detected?

Is the action static or dynamic? Is it a posture or a movement? Is it ordinarily called a balance?

What kind (s) of force is (are) detected in the movement as it is initiated? As the movement ends? Which muscles are involved? Which joints? Combinations of muscles and joints.

Is the movement primarily force oriented? (Rated higher) Swing oriented? (Rated lower).

What forces are prominent during the movement? Are they performer produced or environment produced?

Balance

What is the size of the base of support? The smaller the base the higher the value.

How far from the base is the center of gravity? The greater the distance the higher the value.

Is there a tendency for the line of gravity to rotate about the base of support? The greater the tendency the higher the value.

Does the distribution of the body's mass tend to make balance more difficult? Inverted position? Is some object being carried?

How much rotary motion is detected? The more rotary action, the lower the value.

Does apparatus (if used) pose some additional problems in balance? Balance beam? Parallel bars?

Is the action static or dynamic? (Static positions rated higher.)

Flexibility

Are the efforts known as slash, wring, or press detected?

Is the action momentary or continuous?

Does one part of the body bend back upon another part? Trunk on legs, forearm on upper arm, calf on thigh, chin on chest? To what degree?

Do members of a joint move through maximum ranges (anatomically) during a movement? Arms or legs fully stretched, splits, toe point, backbending?

Swing

Is the effort known as slash detected? Glide?

How many parts do the swinging? One big part? Many little parts? Arms only? One leg? One small part?

DORIS I. MILLER
KENNETH L. PETAK

Three-Dimensional Cinematography

WITHIN RECENT YEARS, significant technological progress has been made in methods of studying the human organism. Despite the increasing use of electronic transducers to monitor various aspects of man's movement, film still remains an extremely important medium for recording motor performance. With cinematographic procedures, the subject is unhampered in his movement and can be filmed under either natural or laboratory conditions. This technique also makes it possible to evaluate the external mechanics of a rather complex motion in both qualitative and quantitative terms.

A major difficulty encountered in studying human movement cinematographically has been that of obtaining spatial coordinates. Since virtually all human motion occurs in three dimensions, a single camera and planar film analysis methods cannot provide an adequate basis for a complete quantitative description of the performance. While they may suffice for such activities as running, which take place predominantly in one plane, they are unquestionably inaccurate for skills in which twisting is an important element. The latter require some means of determining X, Y, and Z coordinates from film. These coordinates, in turn, serve as a basis for displacement, velocity, and acceleration calculations.

The purpose of this paper is to review existing methods of three-dimensional cinematography and to present a new technique which has certain advantages over those proposed previously.

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EXISTING METHODS

Single camera techniques

In seeking to avoid the "three-dimensional problem," many investigators have chosen to study movements occurring primarily in one plane and have felt justified in considering any movement out of that plane as inconsequential. By using telephoto lenses which permit large camera-to-subject distances, they have attempted to minimize the perspective error inherent in planar analysis. Others have utilized two or three cameras and have conducted an independent analysis of each view.

At the University of Wisconsin, "body belts" were constructed from heavy elastic upon which Styrofoam projections or fins were fixed by means of light aluminum holders (11). These belts, attached to the pelvic girdle and thorax of the subject, were utilized to investigate spinal rotation during the performance of different sports skills. The angles of rotation were obtained directly from an overhead camera or calculated from the film of the side camera by

comparing the length of the Styrofoam fin when in the picture plane with its apparent length measured from the film. One of the problems encountered, however, was oscillation of the fins independent of subject movement (3). Care must also be taken to ensure that the presence of the belts does not influence the patterns of motion of the performer.

The general method for estimating a nonplanar angle of a limb from the relationship:

Angle = Arc cos (Apparent length of the limb as measured from the film/ True length of the limb as it would be measured from the film if it were at right angles to the optical axis of the camera.)

has several limitations. Since the precise distance between the plane in which the subject is moving and the camera lens may not always remain constant, it is difficult to specify what the exact film length of the segment would be if it were positioned at right angles to the optical axis of the camera. In addition, the technique is based upon the assumption of parallel projection which is only tenable for extremely large subject-camera distances. Despite Plagenhoef's attempts (15) to calculate a correction factor to overcome the latter difficulty, this method at best provides a rough approximation of nonplanar angles.

Mirror techniques

The inclusion of a mirror in the photographic field can be used to record a second image of the subject on the same frame of the film or the occurrence of an event outside the camera's normal field of view. The photograph taken by a camera positioned with its optical axis at a 45° angle with the plane of the mirror is equivalent to superimposing the images from two identical, perfectly synchronized cameras with optical axes intersecting at right angles. Although most research studies employing such techniques have limited the analysis of the mirror image to the qualitative or temporal level, Bernstein (5) was able to derive spatial coordinates for points visible in both the real and mirror images. Using a single camera and a plane mirror, he established the origin of his rectangular reference frame at the point of intersection of the optical axes of the real and mirror cameras. Then, taking advantage of similar triangles and tetrahedrons formed by various projections, he developed formulae for determining X, Y, and Z coordinates. If such quantitative data are to be obtained, careful camera and mirror positioning are essential. Good quality mirrors with a front silvered surface are recommended to reduce distortion. These are expensive and fragile and not the type commonly found in dance studios or exercise rooms. Although having both images on one frame obviates the problem of camera synchronization, the presence of a mirror may restrict the range of movement of a performer. It is not always feasible to have a large mirror at the filming site.

Stereometric systems

The stereometric method of creating the three-dimensional effect in photography employs a special stereocamera or two cameras placed side by side with their optical axes parallel. Since an established base distance separates the lenses, each records a slightly different view of the object. Standard equations for the calculation of X, Y, and Z coordinates of desired points on the stereopair (10, 12) have been applied to the study of human motion by Gutewort (8, 9) and Ayoub *et al.* (4). With this method, the base distance between the two lenses influences the magnitude of the error in estimating the depth coordinate. Although a large base is desirable, there is a limit to which it can be increased while still maintaining an area which is in the field of both lenses. Only within this common area can spatial coordinates be determined for points on the image. If two independently operating 16 mm cameras are employed, the frequency pulsation method for identifying the simultaneous exposure of frames proposed by Garnov and Dubovik (7) may be useful in locating stereopairs.

Multiple camera methods

A number of researchers have concluded that more than one camera must be utilized to accurately determine spatial coordinates from film. Both Atwater (2) and Anderson (1) presented methods in which one camera was sighted along each of the three coordinate axes. While the X, Y, and Z values were calculated from two of the cameras, the third was used to compute appropriate conversion factors to compensate for perspective error. Duquet *et al.* (6), on the other hand, developed a tridimensional analysis technique which required only two cameras at right angles, one being at the side and the other overhead. If a point were visible in the films of both cameras, it could be manipulated graphically to a common plane where its location could be subsequently determined. Like those of Atwater and Anderson, this method required the calculation of a distance conversion factor. Susanka (16, 17) and Walton (19) have also proposed the positioning of two cameras at right angles to determine spatial coordinates.

A somewhat different approach was taken by Noble (13) who located one camera along each of the conventional X, Y, and Z axes. A horizontal and a vertical coordinate were obtained from each of the three films resulting in a total of six (two x, two y, and two z) for each point visible in the corresponding frames of all three cameras. The mean of each pair was taken to be the true value. Noss (14) had earlier proposed a similar technique in which the angles recorded by three similarly positioned cameras were averaged to calculate the true angle.

In many of the multiple camera techniques cited, landmarks must be filmed by all cameras if their spatial coordinates are to be derived. Because of the solid, irregular, and opaque nature of the human body, the number of segmental endpoints for which X, Y, and Z values can be determined by these methods is therefore limited. Other techniques require the calculation of a conversion factor to compensate for the effect of perspective error. This conversion must be continually recomputed to account for changes in subject position in relation to the cameras. In an attempt to overcome these problems, a technique in which the coordinates of a point can be determined from any two of three cameras was developed.

PROPOSED METHOD

Theoretical basis

The theory underlying the proposed method of determining spatial coordinates is based upon the fact that the ratio of the image size to the lens-to-film plane distance is equal to the ratio of the object size to the object-camera distance (Figure 1). This relationship between similar right triangles can be extended to the three-dimensional case (Figure 2) in order to determine X, Y, Z coordinates. An arbitrary point P (X, Y, Z) is photographed by Cameras One, Two, and Three. The point of intersection of their optical axes, which is also the origin of the rectangular coordinate system, is designated O; D refers to the distance from the center of the lens of the camera to the origin; F represents the lens-to-film plane distance; and, p (x, y) is the film image of P where the coordinates are taken with respect to the origin and are expressed in film dimensions. A rifle target, carefully positioned beyond the origin and aligned with the optical axis of the camera, provides reference film coordinates of the origin (Figure 3).

From similar tetrahedrons on both sides of the lens (Figure 2), it can be seen that:

$$\frac{x}{X} = \frac{F}{D+Y} \quad \text{and} \quad \frac{y}{Z} = \frac{F}{D+Y}$$

These relationships apply to Cameras One, Two, and Three. Thus, using capital letters and numbers to indicate the real coordinates of the point as viewed by a particular camera and small letters for the respective image coordinates, the following ratios can be obtained:

From Camera One:

$$\frac{x1}{X1} = \frac{F1}{D1+Y1} \quad (1) \qquad \frac{y1}{Z1} = \frac{F1}{D1+Y1} \quad (2)$$

From Camera Two:

$$\frac{x2}{X2} = \frac{F2}{D2 + Y2} \quad (3) \qquad \frac{y2}{Z2} = \frac{F2}{D2 + Y2} \quad (4)$$

From Camera Three:

$$\frac{x3}{X3} = \frac{F3}{D3 + Y3} \quad (5) \qquad \frac{y3}{Z3} = \frac{F3}{D3 + Y3} \quad (6)$$

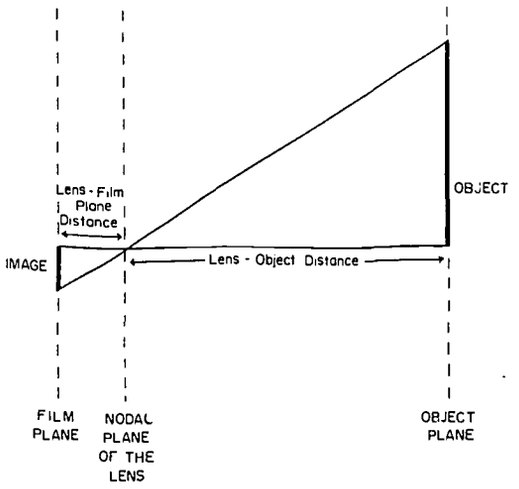

Figure 1. Geornetry of object-image relationship.

$$\frac{\text{Image size}}{\text{Lens-film plane distance}} = \frac{\text{Object size}}{\text{Lens-object distance}}$$

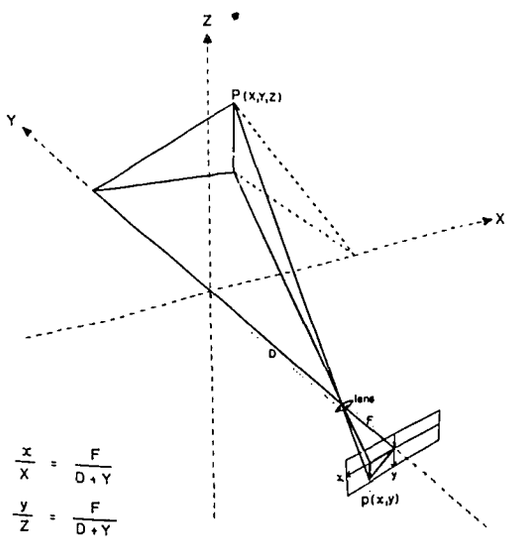

Figure 2. Spatial coordinate relationships.

The cameras must be positioned so that their optical axes are horizontal and intersect at a single point. The optical axes of Cameras One and Two, and One and Three form 120° angles with one another as do those of Cameras Two and Three (Figure 3).* Each camera is sighted along its own positive Y axis. The right-handed coordinate system of Camera One is taken to be the main reference frame and the other two systems are rotated through 120° to conform with it. Applying these transformations:

$$\begin{aligned} X2 &= -X1 \cos 60 - Y1 \cos 30 \\ Y2 &= X1 \cos 30 - Y1 \cos 60 \\ Z2 &= Z1 \end{aligned}$$

$$\begin{aligned} X3 &= -X1 \cos 60 + Y1 \cos 30 \\ Y3 &= -X1 \cos 30 - Y1 \cos 60 \\ Z3 &= Z1 \end{aligned}$$

Appropriate substitutions are then made for $X2$, $Y2$, and $Z2$ into equations (3) and (4) and for $X3$, $Y3$, and $Z3$ into equations (5) and (6). Thus, for any two of the three cameras, there are four equations from which to solve for the three spatial coordinates $X1$, $Y1$, and $Z1$. Although there are four different combinations of the three equations which can be derived from each pair of cameras, only two of these combinations are linearly independent. They are equations (1), (2), (3) and (1), (3), (4) from Cameras One and Two; equations (1), (2), (5) and (1), (5), (6) from Cameras One and Three; and equations (3), (4), (5) and (3), (5), (6) from Cameras Two and Three. Linear independence implies that the equations have a solution which is not extremely sensitive to small variations in their coefficients.

* An angle of 120° between the optical axes is assumed throughout the derivation. It is felt that this positioning of the cameras will maximize the number of points visible in the films of any two of the three cameras. Other camera separation angles are also possible provided that their magnitudes are known and are substituted into the appropriate places in the equations.

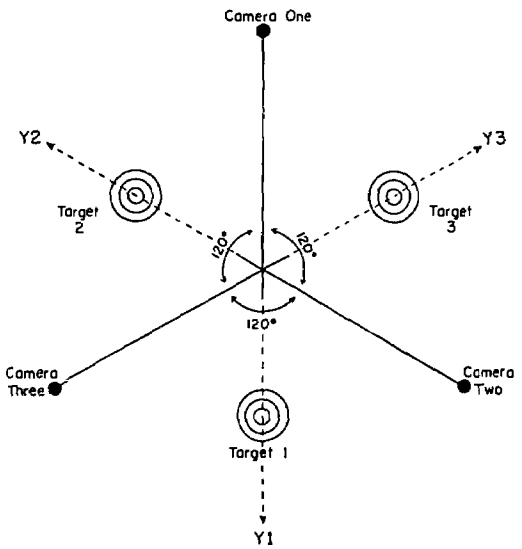

Figure 3. Orientation of the cameras in the X–Y plane.

Practical implementation

To obtain accurate results using the proposed three-dimensional method, a number of procedures must be carefully observed in preparing the filming site. If the study is to take place in a gymnasium or on a playing field, a surveyor's transit should be set up at the specified origin of the spatial coordinate system. The location of the cameras and their corresponding sighting targets (Figure 3) can then be determined following well-established surveying procedures. All cameras and targets must be on the same level. Further, the optical axes of the cameras must be horizontal and intersect at the origin of the coordinate system. A plumb bob suspended from the center of each lens and target; spirit levels on the cameras; reflex or through the lens viewing; and sturdy, continuously adjustable tripods help to achieve correct positioning. Identification information specifying the camera, subject, trial, and experimental condition as well as some type of precision timing display similar to that proposed by Walton (18) must be included in the field of view of each camera. Before commencing the actual study, a range pole must be held in a vertical position at the origin and filmed by all cameras. Since the contrasting sections of the pole are of known length, they provide a ready means for calculating the lens-to-film plane distance (Figure 1).‡

A good quality motion analyzer should be used to extract the raw data from the film. Frames exposed at corresponding instants of time have to be matched with the aid of the timing display visible in the field of each camera. Correct vertical alignment of the selected frames is then obtained from the plumb line suspended from the center of the sighting target which appears in the background of the picture. The coordinates of center of this target, which represent the origin of the system, must be recorded in addition to the x and y coordinates of specific points on the film image. Provided a point is visible in any two of the three cameras simultaneously, its spatial coordinates can be determined.

A digital computer should be programmed o perform the rather lengthy calculations required to convert the raw data to spatial coordinates. Input to the program must include horizontal and vertical film coordinates of the desired points and the target center. The camera-origin distances and the information necessary to determine the lens-to-film distances must also be specified. The program should subtract the coordinates of the target from those of the designated points on the film image and subsequently divide them by the projector magnification. This operation will express the horizontal and vertical coordinates in film dimensions with respect to the origin of the system. Substitution of these data into the appropriate equations will yield the X, Y, and Z coordinates.

A validation study indicated that the method outlined was both sufficiently accurate and feasible for investigating human

‡ The lens-to-film plane distance is usually slightly larger than the focal length of the lens and must be calculated from the relationship shown in Figure 1.

movements of a three-dimensional nature. The positioning of the cameras is arbitrary provided that: (1) their optical axes are horizontal and intersect at a common point which serves as the origin of the system, and (2) the location of the cameras with respect to the origin and the angles between their optical axes are known. Lenses of any suitable focal length and distance setting may be used. Because this method makes it possible to determine the X, Y, and Z coordinates of data points visible in any two cameras and automatically eliminates perspective error without the necessity of continually recalculating conversion factors, it is more flexible than those previously proposed and, therefore, should have wider application.

Conclusion

Several techniques have been proposed to solve the "three-dimensional problem" in the analysis of human motion. In general, those requiring only one camera have proven inferior to multiple camera methods. The latter, however, necessitate precise camera positioning and involve rather extensive calculations. In addition, the difficulty of identifying frames exposed simultaneously by more than one camera cannot be overlooked. Regardless of which technique he selects, the investigator should always verify its accuracy by estimating the spatial coordinates of an object of known dimensions and position. Such calibration data should be reported along with the results of the particular study.

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JAMES G. HAY

The Center of Gravity of the Human Body

THE CENTER OF GRAVITY OF THE HUMAN BODY

DETAILED QUANTITATIVE ANALYSES of human motion require a knowledge of the location of the center of gravity of the body (or bodies) whose motion is being studied. Scores of attempts have been made to develop suitable methods of determining the location of this elusive point — some for the purpose of solving a particular problem, others in the hope of providing methods or data suitable for the solution of a wide range of problems. The result of all these attempts is a somewhat bewildering array of alternative methods and numerous sets of data which have been derived using these methods.

The purposes of this paper are: (1) to review the work of the major contributors to knowledge in the area of center of gravity determination; and (2) to suggest guidelines which might be followed in determining the most appropriate method to use in a given quantitative analysis of human motion.

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METHODS FOR DETERMINING CENTER OF GRAVITY LOCATION

There are basically two methods of approach which have been used in determining the location of the center of gravity of the human body — *the direct (or whole body) approach*, in which the body under consideration is considered as a whole, and *the indirect (or segmental) approach* in which various parts or segments of a body are considered separately and the results used to compute values for the whole body.

The direct (or whole body) approach

Borelli (9) is generally credited with being the first person to attempt to locate the center of gravity of a human body. To do this he placed his subject in a supine position on a board and then moved the board back and forth on a triangular-sectioned support until a position of balance was obtained. However, he failed to realize that the vertical plane passing through the edge on which the board was supported contained the center of gravity of the subject-plus-board system and not necessarily that of the subject alone. His conclusion that the center of gravity of the human body lies "inter nates & pubim" was therefore, understandably, inaccurate.

During the 19th and early 20th centuries numerous methods were developed for the

purpose of locating either the transverse or the frontal plane containing the center of gravity [W. and E. Weber (72), Meyer (50), Mosso (53), Demeny (20), Richer (65), Haycraft and Sheen (39), Croskey *et al.* (19)]. Although there were considerable differences between these methods in terms of the equipment used and the experimental procedures followed, they all had at least one thing in common. Like the method of Borelli, they all depended on adjusting the position of the subject, and/or the apparatus until the system (subject-plus-apparatus) came to rest with its center of gravity in the same vertical plane as the fulcrum upon which it was supported.

As an alternative to the method of Haycraft [and Sheen] (39)—which he described as "unnecessarily complicated" — du Bois-Reymond (26) developed a new technique for locating the frontal plane containing the center of gravity. He described this method (based on the Principle of Moments) in the following terms:

> A board is supported at one end by two points and at the other end by an ordinary spring scale. The subject stands close to the first end and thus weighs down the scale according to the ratio of the distance of the CG projection to the length of the board. If one knows the weight P of the subject, and if at a given position the scale shows a weight of p, then the distance e of the CG projection from the connecting line of the two points can easily be computed according to the formula $e = (p/P)E$, where E is the length of the board, or more exactly the distance of the connecting line of the points from the scale. The weight of the board can easily be eliminated by computation or by suitable adjustment of the scale [26, p. 563].

The method of du Bois-Reymond, has been extensively used by subsequent investigators to determine the location of the frontal plane containing the center of gravity when a subject assumes various postures involving support on the feet [e.g., Reynolds and Lovett (63), (64); Basler (3), (4) — each of whom are occasionally credited with originating the method — and Klausen and Rasmussen (45)] and the location of the corresponding transverse plane when the subject assumes a supine position [e.g., Scheidt (67), Cotton (17), Bober (8), and Yamakawa (77)].

Cotton (17) devised a method (his Differential Method) involving the use of a board balanced on a single central support and held in a horizontal position by a spring scale attached to one end. When the subject took up his position on the board, the scale recorded the force necessary to maintain the system in a horizontal position. The location of the transverse plane containing the subject's center of gravity was then readily obtained by computing moments about the fulcrum provided by the central support. Although Cotton obtained better results with this method than with the method of du Bois-Reymond, it seems likely that this was more due to differences in the recording devices used (with a view to increasing the accuracy of the method, Cotton attached a writing point to the index of the spring balance and recorded its movements on the surface of a moving drum) than to any major differences in the methods.

Palmer (56) (57) developed a method to determine the location of both the transverse and the frontal planes containing the center of gravity. This method, which relied on the same computational principle as did the methods of du Bois-Reymond and Cotton, consisted of determining the vertical plane containing the center of gravity when the subject lay in a supine position on a horizontal platform and again when one end of the platform was subsequently elevated. The line of intersection between the two planes, determined in this fashion, fixed the location of the center of gravity with respect to the transverse and frontal planes of the body.

To establish the "accuracy" of the results obtained in this manner, Palmer conducted a number of tests using: (1) two large wooden blocks, and (2) a sample of five young children (ages 30–46 months). He concluded that "the true center of gravity in inert objects can be located within a circle of a radius of 5 mm."

In the course of his tests on the children, Palmer noted that when the antero-posterior

location of the center of gravity was determined using a 45° angle of tilt, the center of gravity of the subject was almost always computed to be closer to the surface of the platform than when a 30° angle of tilt was used. Palmer attributed these slight differences to changes in the disposition of the body parts and especially of the "various fluid accumulations and movable viscera within the body."

Having developed methods for determining the location of the transverse plane containing the center of gravity, Cotton (18) next turned his attention to devising a method for locating the equivalent frontal plane. After considering and discarding the method of Palmer — "Since these degrees of tilting [the 30° and 45° used by Palmer] must inevitably cause an unknown degree of displacement of the movable viscera both forwards and downwards. . . ." — Cotton evolved a technique which involved "a minimum alteration in the position of the subject." This technique, an adaptation of his Differential Method, required the subject to lie on a second board placed at right angles across the board to which the support and spring scale were attached. The vertical plane containing the center of gravity was then determined with the system tilted upward slightly toward the spring scale end, and then again with the system tilted upward toward the other end. (The difference between the angles of inclination of the board was of the order of 4°–6°.) The antero-posterior location of the center of gravity was then computed in a manner similar to that employed by Palmer.

To obtain a measure of the "accuracy" of his procedure, Cotton made: (1) four determinations of the antero-posterior location of the center of gravity of a heavy rectangular beam, and (2) successive determinations of the antero-posterior location of the center of gravity of one subject. In the first instance, he found a mean error of 0.475 percent when the results of his determinations were compared with those obtained by suspending the beam from a number of points in turn. In the second instance, he obtained a mean error of 0.7 percent, or less than 1 mm — results he suggests which are "of a distinctly higher order of accuracy than (those obtained with) the methods previously described."

(Note: The tests of "accuracy" conducted by Palmer and Cotton provided a measure of the *validity* of their methods for locating the center of gravity of an inert object or objects and a measure of the *reliability* of their methods for locating the center of gravity of a human subject. The latter measure does not, as each has implied, reflect the *validity* of their methods when used with human subjects.)

Basler (5) is generally credited with the next major development in techniques involving the use of a balance, or reaction board. The method devised by Basler required the use of a large triangular board supported in a horizontal position by two metal spikes each of which rested on the platform of a spring scale and a third spike which rested on a fixed support. After due account had been taken of the weight of the board supported by each scale, the subject took up the required position on the board and the readings on the scales were noted. These readings, together with the known weight of the subject, were then used in determining the moments about each of two axes through the points of support. Solution of the resulting moment equations yielded the location of the center of gravity of the subject in two planes — transverse and sagittal planes for a subject in a back-lying position; transverse and frontal planes for a subject in a side-lying position.

[Several modifications of Basler's method have been reported. Groves (36), McIntosh and Hayley (49), and Payne and Blader (58) have each used systems involving a rectangular board and four sets of scales; Rasch and Burke (62) have described a system in which a third set of scales is used as "an accuracy check"; Willems and Swalus (75) have developed an electronic system for recording the supportive forces and computing the location of the center of gravity; and Waterland and Shambes (71) have used a small triangular board to determine the location of the sagittal and frontal

planes containing the center of gravity of a standing subject.]

The pioneer work of Palmer and Cotton was later continued by Swearingen (70) who developed an elaborate five-tiered balancing apparatus to determine the location of two orthogonal planes containing the center of gravity. His approach to the problem like that of his predecessors, took no account of the effect produced by shifts in the disposition of body fluids, viscera, fat, etc. The reliability of the method was again determined by taking repeated readings using the same subject. These readings did not vary by more than 0.25 in. (= 6 mm).

A number of whole-body techniques, quite different from those already discussed, have also been used to determine the location of the center of gravity of a human being.

Santschi, Du Bois, and Omoto (66) determined the location of the transverse and frontal planes containing the center of gravity using a method primarily devised for the purpose of obtaining the moments of inertia of a human body in a variety of positions. The method involved strapping the subject into a large compound pendulum which was then set to oscillate through an angle of $\pm 1°$. After the period of the pendulum had been determined, the location of the point of support was adjusted and the process repeated. The location of the center of gravity of the subject in one plane was then computed using a lengthy equation involving the two periods, the weight and volume of the subject, the ambient air density, and the known physical characteristics of the pendulum itself. The whole process was repeated with the subject strapped into a second compound pendulum to locate a second plane containing the center of gravity.

The authors noted that with this procedure "the center of gravity measurement is made in proper relationship with the gravity vector as contrasted with other methods [those of Hertzberg and Daniels (40) and Swearingen (70) were cited] in which the displacement of subcutaneous fat and viscera is orthogonal to the direction of measurement." They also state that provided the crucial experimental variables are carefully controlled, the distances of the center of gravity from the top of the head and from the plane of the back can be located to within ± 0.5 percent or better. However, they present no evidence that this (or any other) degree of accuracy was achieved.

Weinbach (73) described a method for determining the height of the center of gravity of a subject standing in an erect position, using measurements taken from photographs or taken directly from the subject. The method was based on the assumptions (1) that successive horizontal cross-sections through the body were elliptical in shape and thus their areas could be computed using the formula:

$$a = \frac{\pi}{2} f \cdot s \text{ sq mm}$$

"where f is the number of mm in one-half the front view, and s is the number of mm in the side view section," and (2) that the body was of uniform density. The first steps in the photographic version of the method — unquestionably the more versatile of the two — involved taking front and side view photographs of the subject, accurately measuring the distances f and s at preselected heights from the ground, and computing the corresponding cross-sectional areas. Next a "volume contour map" was drawn by plotting the cross-sectional areas as ordinates against the heights of the cross-sections for the ground as abscissae. From the resulting curve, a second curve was derived using a series of geometric constructions. Finally, the areas under the two curves were measured with a planimeter and the ratio of one (representative of the volume of the body below the center of gravity) to the other (representative of the volume of the whole body) was used in computations to determine the height of the center of gravity above the soles of the feet.

While Weinbach apparently made no attempt to establish the "accuracy" of his technique, Dempster (21) has subsequently considered it from this standpoint. Dempster compared cross-sectional areas using the Weinbach technique with those determined

directly using a "pantograph-planimeter technique" and found that the Weinbach method was very good at certain levels (e.g., head, neck, waist, and ankles) but less good at others (e.g., shoulders). He also observed that while the Weinbach technique gave generally satisfactory information on the regional distribution of volumes, "estimated mass based on density 1.0 should be less good."

Photographic techniques for determining body volume have also been reported by Hertzberg, Dupertuis, and Emanuel (42) and Pierson (59), (60), and it is conceivable that these techniques — stereophotogrammetry and monophotogrammetry, respectively — could also be used with assumed values for density, or specific weight, to determine the location of the center of gravity of a human body or its segments. To date, however, there appear to have been no serious attempts to employ these techniques for this purpose.

The indirect (or segmental) approach

In this approach, the body is considered to be composed of an arbitrary number of segments, whose weights and center of gravity locations are known. The moments of the individual segments about an arbitrary axis are computed, summed, and equated to the moment of the whole body about this same axis:

$$Wx = w_1x_1 + w_2x_2 + w_3x_3 + \ldots + w_nx_n$$

where $w_1, w_2, w_3 \ldots w_n$ are the weights of the n segments; W is the weight of the body (i.e., $w_1 + w_2 + w_3 + \ldots w_n = W$); and $x_1, x_2, x_3 \ldots x_n$ and x are the respective distances of the centers of gravity of the segments and the whole body from the chosen axis. A simple rearrangement of this equation yields the distance of the center of gravity of the whole body from the axis and thus fixes its location in one dimension.

$$x = \frac{w_1x_1 + w_2x_2 + w_3x_3 + \ldots + w_nx_n}{W}$$

A similar computation of the moments about a second axis (not parallel to the first) fixes the location of the whole-body center of gravity in a second dimension:

$$y = \frac{w_1y_1 + w_2y_2 + w_3y_3 + \ldots + w_ny_n}{W}$$

The accuracy of the results obtained using this approach obviously depends in large part on the validity of the available data concerning the weight and the location of the center of gravity of each of the body segments. Numerous studies have been undertaken with a view to obtaining suitable data. These may be classified under five broad headings: (1) *cadaver studies*, (2) *immersion studies*, (3) *reaction board studies*, (4) *mathematical modelling studies*, and (5) *miscellaneous studies*.

Cadaver Studies

Harless (38) dissected the cadavers of two executed criminals — Graf, (age not available) 172.685 cm (67.97 in.) and 63.97 kg (141.05 lb), and Kefer, 29 yr, 167.7 cm (66.02 in.) and 47.087 kg (103.83 lb). Each of the limbs was dissected into three segments: the arm, forearm, and hand for each of the upper limbs and the thigh, shank, and foot for each of the lower limbs. In each case, the separation of adjoining segments was made "tangent to their planes of articulation" and the soft tissues at the end of each segment sutured over the bone ends (as with an amputation stump) to "prevent the uneven contraction of the soft parts at the two ends from exerting an excessive detrimental influence on the center of gravity determination." Each limb segment was weighed on a precision balance, and its center of gravity determined by means of a specially constructed balance device. The head, neck, and trunk were considered as three segments of which the uppermost segment (the head and neck) was treated in essentially the same manner as the limb segments. The weight and center of gravity location of each of the remaining two segments — one consisting of the pelvis up to and including the fifth lumbar vertebra, and the other the remainder of the trunk — were determined by computing the equivalent values for similar geometric solids using an

assumed specific gravity of 1.066. For the first of the two cadavers examined (Graf) the upper trunk segment was regarded as a truncated cone and the lower trunk segment as an elliptical-ended solid. For the second cadaver (Kefer) both these segments were considered to be elliptical-ended solids — a procedure which, so Harless claimed, approximated "more exactly to the given shape relationships of the trunk."

With a view to establishing the validity of the segmental data which he had obtained for Graf, Harless computed the moments of the segments about a transverse axis "tangent to the top of the head," and thence determined the distance of the whole-body center of gravity from this axis. He then compared the result obtained with that obtained by the Weber brothers in an earlier study [the center of gravity of a supine subject was "found . . . to be vertically above the promontorium" (the prominent anterior border of the first sacral vertebra)] and concluded that his results were "in full agreement" with those of the Webers.

A second comparison in which the locations of the centers of gravity of an entire leg and an entire arm of a cadaver were determined; (1) by the balancing method devised by the Webers, and (2) by computation using the data obtained for Graf, revealed a difference of 1.6 cm (0.6 in.) in the locations of the centers of gravity for the leg. (Harless did not report the magnitude of the difference in the case of the arm, but instead simply observed that "calculation and observation also agree . . . as closely as may be expected.")

Braune and Fischer (10) obtained four male cadavers (Table 1), placed them on a horizontal board in a symmetrical supine position (legs extended and rotated laterally, elbows slightly flexed, forearms in midrange position), and froze them solid. They then drove three thin, metal rods through each cadaver at right angles to its three cardinal planes,* suspended it from each of the three rods in turn and, once equilibrium had been established each time, scratched lines on it to indicate the positions at which the vertical plane containing the supporting rod intersected the trunk. (This last process was facilitated by the use of two plumb lines attached, one on each side of the body, to the supporting rod.) The point of intersection of the three planes determined in this manner was taken to be the center of gravity of the body. To fix the location of this point relative to adjacent skeletal landmarks, the body was then sawn in two with a transverse cut at the level of the center of gravity. [In view of the findings of the Webers and Harless, it is of some interest to note that the center of gravity of each of the four cadavers was found to lie below the promontorium — i.e., relative to an erect-standing position — and was as much as 4.5 cm (1.8 in.) and 2.1 cm (0.8 in.) below this point in two instances, cadavers I and IV, respectively.]

Cadavers II, III, and IV were then divided into 14 segments with sawcuts made through the appropriate joint centers. After each of these segments had been carefully weighed, the location of its center of gravity was determined using essentially the same process as that used to determine the location of the center of gravity of the whole body. These data on segment weights and center of gravity locations (Tables 2a and 2b) have been very widely quoted (11), (23), (28), (68) and extensively used (16), (29), (30), (31), (34), (35), (47).

To determine the relationship between the body alignment exhibited by a supine cadaver and the erect posture of a living subject, Braune and Fischer constructed two life-size drawings of cadaver IV (side and front views) and marked in the position of the segmental centers of gravity which they had determined previously. They then posed a muscular male subject of similar dimensions to those of cadaver IV in an erect position that closely approximated that depicted in the drawings of the cadaver. The height of the center of gravity of the live subject above the ground was then computed using the segmental data from cadaver IV and the result compared with the corresponding height indicated on the drawings. The differ-

* In the case of cadaver IV the metal rods were driven into place before the body was frozen.

TABLE 1. CADAVERS USED IN BRAUNE AND FISCHER'S STUDY

	Age	Supine height	Weight	Build	Cause of death
I[a]	18	169 cm (66.5 in.)	Not reported	"well-built"	Suicide—shooting
II[b]	45	170 cm (66.9 in.)	75,100 g (165.6 lb)	"muscular"	Suicide—hanging
III	50	166 cm (65.4 in.)	60,750 g (134.0 lb)	"muscular"	Suicide—hanging
IV	Not reported	168.8 cm (66.5 in.)	56,090 g (123.7 lb) p. 595 55,700 g (122.8 lb) p. 594	"good muscular build"	Suicide—hanging

[a] Cadaver I could not be dissected.
[b] Cadaver II began to thaw before all measurements could be completed.

ence between the two values was 0.8 cm (0.3 in.) — the computed height was 93.3 cm (36.7 in.) and the equivalent figure for the cadaver 92.5 cm (36.4 in.) — a result which prompted Braune and Fischer to observe "Because of saw cuts and variable positioning absolute accuracy is impossible."

[Note: Since Braune and Fischer did not compare their computed value with a direct (criterion) measurement *on the same subject,* the small difference obtained cannot justifiably be taken as an indication of the validity of their segmental data.]

The applicability of the results obtained by Braune and Fischer has been called into question by the observations of Duggar (27, p. 148) who noted that

> Braune and Fischer's measurements of whole body CG for their cadaver Number 4 in a standing position falls outside Swearingen's 'range' [i.e., the range of locations determined by direct measurements on living subjects]. We have calculated a seated CG location based on this cadaver data and found that it too falls outside Swearingen's measured range for a seated position.

Duggar contends, and with some justification, that "This discrepancy is particularly important since the data from Braune and Fischer's cadaver Number 4 have been widely quoted."

In the course of a further study of the inertial characteristics of the human body, Fischer (32) dissected a small cadaver [150.0 cm (59.3 in.), 44.057 kg (97.1 lb)] and determined the weights and center of gravity locations of 14 individual body segments. The methods employed appeared to be the same as those reported by Braune and Fischer.

A period of almost 50 years elapsed before the next major cadaver study was conducted. Then, as part of a comprehensive 3-year project undertaken on behalf of the U.S. Air Force, Dempster (21) obtained eight white, male cadavers "of more or less medium build" (details of these cadavers are presented in Table 3), positioned their limb joints at the midpoints of their ranges and froze them by packing them with dry ice. He then bisected the joint angles with cuts through the joint centers, weighed each segment, and determined the "linear location" of its center of gravity using a balance plate—a square metal plate positioned to pivot about the turned-down ends of one of its diagonals. The "anatomical location" of the center of gravity of each segment (i.e., the location relative to adjacent anatomical landmarks) was determined by drilling small transverse holes in the direction of the center of gravity (the latter determined by an appropriate suspension or balance technique),

TABLE 2. SEGMENT WEIGHTS AND CENTER OF GRAVITY LOCATIONS
(after Braune and Fischer)

(a) *Segment Weights*

Segment		*Weight of segment relative to total body weight*			Mean
		Cadaver II	Cadaver III	Cadaver IV	
Head		.071	.067	.071	.070
Torso		.480	.475	.427	.461
Arm	R	.066	.058	.063	.062
	L	.064	.057	.067	.063
Upper arm	R	.034	.033	.031	.033
	L	.034	.031	.036	.034
Forearm and hand	R	.032	.026	.032	.030
	L	.030	.026	.030	.029
Forearm	R	.023	.017	.023	.021
	L	.021	.018	.022	.020
Hand	R	.008	.008	.009	.008
	L	.008	.008	.008	.008
Leg	R	.161	.175	.182	.173
	L	.158	.169	.191	.173
Upper leg	R	.102	.110	.110	.107
	L	.097	.102	.121	.107
Lower leg and foot	R	.060	.065	.071	.065
	L	.060	.066	.070	.065
Lower leg	R	.043	.044	.053	.047
	L	.044	.047	.052	.048
Foot	R	.015	.017	.018	.017
	L	.015	.018	.018	.017

(b) *Segment Center of Gravity Locations*

Segment		*Distance of C.G. from proximal axis as fraction of segment length*			Mean
		Cadaver II	Cadaver III	Cadaver IV	
Head				.455[a]	
Torso				.390[b]	
Arm	R	.535	.492	.551	.526
	L	.533	.508	.534	
Upper arm	R		.438	.509	.470
	L		.454	.478	
Forearm and hand	R		.475	.472	.472
	L		.463	.477	
Forearm	R		.414	.422	.421
	L		.406	.441	
Leg	R	.419	.407	.403	.407
	L	.417	.421	.375	
Upper leg	R	.432	.469	.425	.439
	L	.446	.476	.388	
Lower leg and foot	R	.500	.531	.521	.519
	L	.517	.514	.531	
Lower leg	R	.420	.435	.410	.420
	L	.416	.413	.422	
Foot[c]	R	.404	.430	.453	.434
	L	.424	.439	.453	

[a] Distance of C.G. from atlanto-occipital joint expressed as a fraction of the distance from the same joint to the crown.
[b] Distance of C.G. from line joining centers of hip joints, as fraction of distance from this line to atlanto-occipital joint.
[c] Length front to rear reduced to 1.0.

TABLE 3. CADAVERS USED IN DEMPSTER'S STUDY

Number	Somatotype[a] (Sheldon system)	Age[b] yr	Supine height[b] cm (in.)	Weight[b] (kg) lb	Cause of death	Embalmed
14815	4–5–2½	67	168.9 (66.5)	(51.2) 113	Unknown	Yes
15059	3–5–3	52	159.8 (62.9)	(58.3) 128.5	Cerebral hemorrhage	No
15062	4–2–4	75	169.6 (66.8)	(58.3) 128.5	General arteriosclerosis	No
15095	4–3–4	83	135.3 (53.3)	(49.5) 109.25	Unknown	No
15097	4–5–3	73	176.4 (69.4)	(72.3) 159.5	Esophageal carcinoma	No
15168	3–3–4	61	186.6 (73.5)	(71.2) 157	Coronary thrombosis	No
15250	3–3–4		180.3 (71.0)	(60.3) 133	Acute coronary occlusion	No
15251	4–4–2		158.5 (62.4)	(55.8) 123	Chronic myocarditis	No

[a] Determined from front, left side, and rear view photographs of suspended cadaver.

[b] With regard to the physical characteristics of his subjects, Dempster observed that "all the available cadaver material represented individuals of the older segment of the population. The specimens were smaller than either the average white male population or the military populations of special interest, and the weights were below those of average young individuals. Physically, however, the subjects were representative specimens for their age level" (21, p. 47).

inserting pointed dowel sticks in these holes and then making a saw cut through the segment in the plane of the sticks. Upon completion of this transverse bisection, the pointed ends of the sticks indicated the location of the center of gravity of the segment.

The remainder of the body was divided into five segments — (1) head and neck, (2) right shoulder, (3) left shoulder, (4) thorax, and (5) a combined abdominopelvic segment — and treated in similar fashion to the limbs. [Note: "except for Harless' crude calculations" (21, p. 185), the authors of each of the previous cadaver studies cited considered the trunk as a single segment.]

With respect to the accuracy of his methods, Dempster noted that

> Inherent procedural errors are to be expected in measurements of dismembered cadaver parts, especially where methods involve repeated handling and the determining of a variety of measurements. These points are ordinarily missed when the older data are read. Values on parts, like those of Harless, which add up correctly [i.e., the sum of the weights of the segments exactly equals the original weight of the whole body] are most unusual in our experience. [21, pp. 185, 189].

The results obtained by Dempster (Tables 4a and 4b), like those of Braune and Fischer which they have tended to supersede, have been used in numerous studies (1), (22), (46), (54) and have been cited frequently in the literature (16), (61), (76).

Barter (2) attempted to overcome limitations imposed by the small sample sizes in

TABLE 4. SEGMENT WEIGHTS AND CENTER OF GRAVITY LOCATIONS
(after Dempster)

(a) *Segment Weights*

Segment		*Weight of segment as percentage of total body weight*								Mean
		14815	15059	15062	15095	15097	15168	15250	15251	
Trunk minus limbs		61.1	56.4	59.1	58.7	56.0	53.8	52.2	54.3	56.5
Trunk minus shoulders		52.2	45.7	47.3	49.0	46.1	46.8	42.9	45.3	46.9
Both shoulders		8.4	11.2	11.8	11.5	11.1	10.1	9.4	8.8	10.3
Head and neck			6.5	8.9	8.7	7.4	6.8	7.2	7.8	7.9
Thorax			8.2	10.5	10.7	12.1	12.7	10.9	11.9	11.0
Abdomen plus pelvis			31.1	28.0	29.1	22.0	24.1	24.7	25.7	26.4
Entire upper extremity	R	5.1	5.6	4.6	4.3	5.4	5.1	5.0	4.3	4.9
	L	5.3	4.7	4.3	4.3	5.4	4.8	5.1	4.4	4.8
Arm	R	2.4	3.3	2.6	2.3	3.0	2.8	2.7	2.5	2.7
	L	2.3	2.6	2.4	2.3	3.0	2.7	2.8	2.4	2.6
Forearm and hand	R	2.6	2.3	1.9	2.1	2.5	2.4	2.3	1.8	2.2
	L	2.5	2.2	1.8	2.0	2.3	2.1	2.3	2.0	2.1
Forearm	R	1.7	1.7	1.4	1.4	1.7	1.8	1.7	1.3	1.6
	L	1.7	1.6	1.3	1.4	1.6	1.5	1.7	1.4	1.5
Hand	R	0.9	0.6	0.5	0.6	0.7	0.6	0.7	0.5	0.6
	L	0.9	0.6	0.6	0.6	0.7	0.6	0.6	0.6	0.6
Entire lower extremity	R	12.0	16.4	14.2	15.5	16.4	16.7	19.5	15.1	15.7
	L	12.1	16.9	14.4	16.7	16.4	15.6	18.8	15.0	15.7
Thigh	R	6.6	10.5	9.2	9.6	9.9	9.7	11.9	9.2	9.6
	L	6.8	11.1	9.5	10.5	9.8	8.8	12.7	8.3	9.7
Leg and foot	R	5.1	5.9	5.0	5.8	6.7	6.7	6.5	5.9	5.9
	L	5.1	5.8	4.9	6.1	6.7	6.7	6.7	6.1	6.0
Leg	R	3.8	4.6	3.7	4.4	5.4	5.1	4.9	4.4	4.5
	L	3.8	4.5	3.6	4.4	5.3	5.0	4.9	4.6	4.5
Foot	R	1.3	1.4	1.3	1.5	1.3	1.5	1.4	1.4	1.4
	L	1.4	1.3	1.3	1.6	1.3	1.7	1.6	1.4	1.4

(b) *Segment Center of Gravity Locations*

Segment	Center of gravity location with respect to stated reference points, expressed as percentage of total distance between reference points
Upper arm	43.6% to gleno-humeral axis; 56.4% to elbow axis
Forearm	43.0% to elbow axis; 57.0% to wrist axis
Hand	50.6% to wrist axis; 49.4% to knuckle III
Forearm plus hand	67.7% to elbow axis; 32.3% to ulnar styloid
Whole upper limb	51.2% to gleno-humeral axis; 48.8% to ulnar styloid
Shoulder mass	84.0% of clavicular link dimension to sternal end of clavicle (oblique)
	71.2% of clavicular link dimension to gleno-humeral axis (oblique)
Thigh	43.3% to hip axis; 56.7% to knee axis
Lower leg	43.3% to knee axis; 56.7% to ankle axis
Foot	42.9% to heel; 57.1% to toe I[a]
Leg plus foot	43.4% to knee axis; 56.6% to medial malleolus
Whole lower limb	43.4% to hip axis; 56.6% to medial malleolus
Head and trunk minus limbs	60.4% to vertex; 39.6% to hip axes
Head and trunk minus limbs and shoulders	64.3% to vertex; 35.7% to hip axes
Head and neck	43.3% to vertex; 56.7% to seventh cervical centrum
Thorax	62.7% to first thoracic centrum; 37.3% to twelfth thoracic centrum
Abdomino-pelvic mass	59.9% to first lumbar centrum; 40.1% to hip axes

[a] A ratio of 42.9 to 57.1 along the heel to toe distance establishes a point above which the center of gravity lies; the latter lies on a line between ankle axis and ball of foot.

the studies of Braune and Fischer (10), Fischer (32), and Dempster (21) by combining their results for the weights of the various segments and treating them statistically by means of a regression analysis. He acknowledged that such an approach ignored differences in the dismembering techniques used in the three studies but considered that these differences were probably not significant when the magnitude of the errors introduced by other factors were considered. The equations derived by Barter, and which he contends "should provide the engineer with a better means of estimating the masses of segments [than the average values used hitherto]" (2, p. 6) are presented in Table 5.

Mori and Yamamoto (52) dismembered six cadavers — three Japanese males and three Japanese females with average ages of 65.3 years and 59 years, respectively — and determined the weights of the segments. The techniques used in the separation of the body parts were very incompletely reported and, as Clauser *et al.* have suggested, "one can only assume that they followed those of Braune and Fischer" (13, p. 11).

Under Mori's direction, Fujikawa (33) dismembered a further six Japanese cadavers and determined the weight and the location of the center of gravity of each segment. However, because his published report contained several obvious inaccuracies — e.g., the distance from the shoulder joint to the hip joint was reported as ranging from 8.5 cm (3.3 in.) to 11.0 cm (4.3 in.) — and was very incomplete, little significance can be attached to his findings.

Clauser, McConville, and Young (13) used 14 preserved male cadavers, carefully selected to closely approximate the wide range of physical body sizes found in normal populations, in an attempt to answer two basic questions:

> 1. Can body segment parameters [specifically, weight, volume, and center of gravity location] be predicted from one or more anthropometric dimensions with the needed degree of accuracy?
>
> 2. Can predictive equations for estimating the weight and the location of the center of mass of body segments provide accurate estimates for individuals as well as for populations? (13, p. 60)

An extensive series of anthropometric measurements were taken on each cadaver, the whole body center of gravity was located using Swearingen's (70) apparatus and the body was carefully dismembered so that the required segment parameters could be determined. The considerable care that was taken in the determination of these segmental values is typified by the following precautions that were taken:

> Before dismemberment of the cadavers, each plane of segmentation was marked with a thin lead strip and studied under a fluoroscope to assure that it would coincide with the desired reference landmarks [13, pp. 21, 29]. All cuts were made with a paper towel under the area being dissected, and the few grams of tissue that fell on the paper or remained on the saw were weighed and one-half the weight was added to each segment [13, p. 29]. In order to reduce fluid losses to a minimum, each cut was sealed with a waterproof, plastic film applied by an aerosol spray [13, p. 29].

The anthropometric and segmental data was then subjected to a step-wise multiple regression analysis and regression equations were derived for the prediction of segment weight, volume, and center of gravity location from the anthropometric measures. (The equations for segment weights and center of gravity locations are presented in Tables 6a and 6b.) The mean values for the weight of each segment, expressed as a ratio of the total body weight and for the location of the center of gravity as a ratio of the segment length, were also determined (Table 7).

In order to assess which of the two methods of predicting segment weights and center of gravity locations (i.e., using the regression equations or using the mean ratios) provided the most accurate results, Clauser *et al.* compared the values obtained using each method with the actual values, for the cadavers used in their study. They found that use of the regression equations in Tables 6a and 6b generally reduced the average error (actual—predicted) on one-half or less,

TABLE 5. REGRESSION EQUATIONS FOR COMPUTING THE WEIGHT OF BODY SEGMENTS

(after Barter)

Body segment	Regression equation	Standard error of estimate[a]
Head, neck, and trunk	= .47 X Total body wt. +12.0	(±6.4)
Total upper extremities	= .13 X Total body wt. − 3.0	(±2.1)
Both upper arms	= .08 X Total body wt. − 2.9	(±1.0)
Forearms plus hands	= .06 X Total body wt. − 1.4	(±1.2)
Both forearms	= .04 X Total body wt. − 0.5	(±1.0)
Both hands	= .01 X Total body wt. + 0.7	(±0.4)
Total lower extremities	= .31 X Total body wt. + 2.7	(±4.9)
Both upper legs	= .18 X Total body wt. + 3.2	(±3.6)
Both lower legs plus feet	= .13 X Total body wt. − 0.5	(±2.0)
Both lower legs	= .11 X Total body wt. − 1.9	(±1.6)
Both feet	= .02 X Total body wt. + 1.5	(±0.6)

[a] "The average regression value plus or minus one standard error of estimate gives a range within which approximately 67% of all values will lie. Nearly 95% of all values for a given segment mass will be encompassed by the average regression value plus or minus two standard errors" (2, p. 8).

TABLE 6. REGRESSION EQUATIONS FOR COMPUTING THE WEIGHT AND CENTER OF GRAVITY LOCATION OF BODY SEGMENTS

(after Clauser *et al.*)

(a) *Weight of Segments*

Weight in kilograms, body fat in millimeters, all other dimensions in centimeters

Segment	Regression equation	Standard error of estimate
Head and trunk	0.491 (W) +0.504 (Trunk L) +0.370 (Chest D) −31.122	0.93
Head	0.104 (Head C) +0.015 (W) −2.189	0.17
Trunk	0.349 (W) +0.423 (Trunk L) +0.229 (Chest C) −35.460	0.92
Total arm	0.014 (W) +0.182 (Wrist C) +0.083 (Biceps C) −3.041	0.16
Upper arm	0.007 (W) + 0.092 (Arm C, Axillary) +0.050 (Acromion—Radiale L) −3.101	0.09
Forearm and hand	0.103 (Wrist C) +0.046 (Forearm C) +0.043 (Radiale—Stylion L) −2.543	0.08
Forearm	0.081 (Wrist C) +0.052 (Forearm C) −1.650	0.06
Hand	0.029 (Wrist C) +0.075 (Wrist B, Bone) +0.031 (Hand B) −0.746	0.02
Total leg	0.094 (W) +0.146 (Calf C) +0.113 (Upper thigh C) −5.455	0.46
Thigh	0.074 (W) +0.123 (Upper thigh C) +0.027 (Iliac crest fat) −4.216	0.43
Calf and foot	0.130 (Calf C) +0.058 (Tibiale H) +0.103 (Ankle C) −4.915	0.09
Calf	0.111 (Calf C) +0.047 (Tibiale H) +0.074 (Ankle C) −4.208	0.08
Foot	0.003 (W) +0.048 (Ankle C) +0.027 (Foot L) −0.869	0.04

B=Breadth, C=Circumference, D=Depth, H=Height, L=Length, W=Weight.

TABLE 6 (continued)

(b) *Location of Center of Gravity*
Weight in kilograms, body fat in millimeters, all other dimensions in centimeters

Segment	Distance	Regression equation	Standard error of estimate
Head and Trunk	CG—Top of head	0.621 (Bicristal B) +0.582 (Head-Trunk L) −0.181 (Estimated stature) +14.050	0.75
Head	CG—Top of head	0.246 (Head C) +0.159 (H of Head) −6.711	0.55
	CG—Back of head	0.238 (Head C) −0.570 (Head B) +3.376	0.55
Trunk	CG—Suprasternale	0.471 (Bi-spinous B) −0.058 (Iliac crest fat) +0.166 (Trunk H) +1.683	0.61
Total arm	CG—Acromion	0.963 (Humerous-Radiale L) +0.918 (Forearm C) −0.571 (Arm C, Axillary) −4.909	1.35
Upper arm	CG—Acromion	0.329 (Humerous-Radiale L) −0.250 (Arm C, Axillary) +2.827 (Elbow B, Bone) −6.168	0.72
	CG—Anterior aspect	0.444 (A–P Diameter at CG) +0.665	0.23
Forearm and hand	CG—Radiale	1.617 (Wrist B, Bone) +0.585 (Radiale-Stylion L) −0.331 (Forearm C) +0.510	0.46
	CG—Anterior aspect	0.890 (A–P Diameter at CG) −0.313 (Elbow B, Bone) −0.229 (Stylion-Meta III Length) −2.153	0.16
Forearm	CG—Radiale	0.440 (Radiale-Stylion L) +0.761 (Wrist B, Bone) −5.645	0.51
	CG—Anterior aspect	0.790 (A–P Diameter at CG) −2.295	0.35
Hand	CG—Meta III	0.657 (Wrist bone, B) −0.202 (Hand C) +2.130	0.37
	CG—Medial aspect	1.038 (Wrist bone, B) +0.248 (Hand B) −3.271	0.30
Total leg	CG—Trochanter	0.562 (Tibiale H) +0.404 (Calf C) −0.264 (Upper thigh C) +9.061	1.50
	CG—Anterior aspect	0.935 (A–P Diameter at CG) −0.054 (W) −0.050 (Iliac crest fat) +0.408	0.43
Thigh	CG—Trochanter	0.227 (Trochanter H) +0.989 (Knee B, Bone) −0.033 (Iliac crest fat) −13.362	0.49
	CG—Anterior aspect	0.595 (A–P Diameter at CG) −0.956	0.69
Calf and foot	CG—Tibiale	0.335 (Tibiale H) −0.159 (Calf C) +11.267	0.57
	CG—Anterior aspect	0.646 (A–P Diameter at CG) +0.114 (Calf L) −7.044	0.35
Calf	CG—Tibiale	0.309 (Tibiale H) −0.558 (Knee B, Bone) +5.786	0.43
	CG—Anterior aspect	0.503 (A–P Diameter at CG) +0.101 (Calf L) −4.688	0.51
Foot	CG—Heel	0.153 (Foot L) +0.137 (Ankle C) +0.444 (Lateral Malleolus H) +1.403	0.25

A–P=Antero-posterior, B=Breadth, C=Circumference, CG=Center of gravity, H=Height, W=Weight.

TABLE 7. MEAN SEGMENT WEIGHTS AND CENTER OF GRAVITY LOCATIONS (after Clauser *et al.*)

Segment	Segment weight as percentage of body weight	Center of gravity location as percentage of segment length
Head	7.3	46.6
Trunk	50.7	38.0
Total arm	4.9	41.3
Upper arm	2.6	51.3
Forearm and hand	2.3	62.6
Forearm	1.6	39.0
Hand	0.7	18.0
Total leg	16.1	38.2
Thigh	10.3	37.2
Calf and foot	5.8	47.5
Calf	4.3	37.1
Foot	1.5	44.9

of the average error obtained by using the ratios.

In summary, Clauser *et al.* stated that

> The predictive equations developed in this study are believed to provide a better estimate of weight and location of the center of mass of segments of the body for individuals and populations than were previously available. They should not, however, be considered as other than good first approximations until they can be adequately validated on live populations [13, p. 61].

Immersion Studies

Following his work with the cadavers of Graf and Kefer, Harless (38) sought to develop a method for determining the weights of the segments of a living subject. To this end, he obtained a total of 44 limb and head segments from a wide variety of adult corpses — four males, two females, median age 33.5 years, age range 22–68 years — determined the weight of each when it was suspended "in air," W_{air}, and when it was totally immersed in water, W_{water} and then computed its specific gravity using the formula:

$$\text{Specific gravity} = \frac{W_{air}}{W_{air} - W_{water}}$$

He suggested that the weight of a segment of a living subject could be determined in a simple computation involving the volume of the segment — he described a water displacement method "liable to extremely small error" (38, p. 45) for this purpose — and the specific gravity of the equivalent cadaver segment, nearest in volume to the "live" segment.

Several investigators have determined the volumes of the limb segments of living subjects and then computed values for the mass or weight of these segments using assumed values for their density or specific weight.

Dempster (21), selected 39 white, male, college-aged, subjects representative of four body builds (median, rotund, thin, and muscular — see Figure 1) and determined the volumes of their limb segments by immersing them in water and noting the volume of water displaced. The data obtained in this manner (expressed in percentages of the total body volume) are presented in Table 8.

Dempster subsequently compared the results obtained when the location of the center of gravity of his living subjects was determined by two methods — a direct method involving the computation of moments about a given point of support, and an indirect (segmental) method in which he used the volume of the segments determined by water displacement and an assumed uniform specific gravity of 1.0. He reported that "The center of gravity calculated in this way in no instance was separated by more than 1 cm from the center of gravity as derived from the first method involving the balancing of moments . . ." (21, p. 221).

Duggar (27, p. 142) presented a tabulation of estimated weights of body segments (expressed as percentages of the total body weight) based on the volume data in Table 8 and the mean specific gravities of the corresponding segments which Dempster determined in his work with cadavers. While this procedure for estimating the weights of segments would appear to be more logical than that involving an assumed uniform specific gravity of 1.0, Duggar apparently made no attempt to determine its accuracy.

TABLE 8. RATIO OF MEAN VOLUME OF THE LIMB SEGMENTS TO BODY VOLUME[a]
(after Dempster)

Segment	Rotund (%)	Muscular (%)	Thin (%)	Median (%)
Whole upper limb	5.28	5.60	5.20	5.65
Arm	3.32	3.35	2.99	3.46
Forearm plus hand	1.95	2.24	2.23	2.15
Forearm	1.52	1.70	1.63	1.61
Hand	0.42	0.53	0.58	0.54
Whole lower limb	20.27	18.49	19.08	19.55
Thigh	14.78	12.85	12.90	13.65
Leg plus foot	5.52	5.61	6.27	5.97
Leg	4.50	4.35	4.81	4.65
Foot	1.10	1.30	1.46	1.25

[a] Body volume considered as body weight for an assumed density of 1.0.

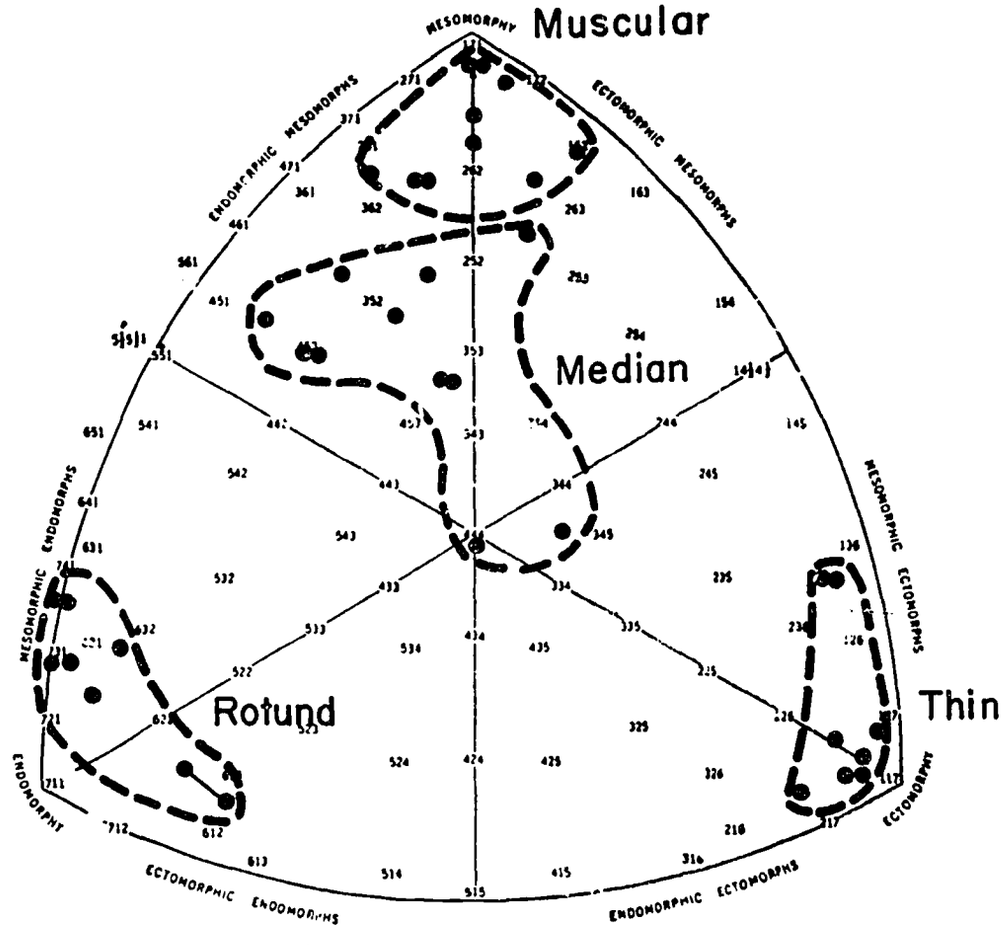

Figure 1. Somatotypes of 30 college-aged males used in Dempster's immersion study of living subjects.

Plagenhoef (61) determined the segment weights of 76 college-aged women and 7 modern dancers using the water displacement technique of Dempster to determine segment volumes and the mean specific gravity values derived from Dempster's cadavers. Kjeldsen (44), under Plagenhoef's direction, extended this work using six women gymnasts and six selected nongymnasts as subjects. Data from these two studies, two of the very few in which the inertial characteristics of females have been studied, are presented in Table 9.

Cleaveland (14) endeavored to locate the transverse planes containing the centers of gravity of 10 body segments, using an underwater weighing method. Each of his subjects (11 college-aged males) was weighed in air, and then again with the segment under consideration immersed in water. The "segment C.G. weight" — a value defined by Cleaveland as ". . . the weight indicated on the scale when one half of the mass of the . . . body part is below the surface of the water" — (14, p. 20) — was then computed using the formula:

$$\text{Segment C.G. weight} = \frac{\text{air weight} - \text{immersed weight}}{2} + \text{immersed weight}$$

The whole body was then raised until the reading on the scale was equal to the computed value and the upper limit of that part of the segment still under water was marked to indicate the transverse plane containing the center of gravity of the segment. The weight of each segment was computed by multiplying its volume by the average specific gravity for the body as a whole.

The procedures employed by Cleaveland were based on the assumption that the human body was of uniform density throughout, and that the center of gravity of a segment, therefore, coincided with its "center of volume." Whether or not the centers of gravity and volume do coincide is a matter of some disagreement in the literature. Bernstein is reported to have conducted a study using frozen cadavers and to have "concluded that for the required accuracy, the center of mass of a body segment can be considered coincident with the center of volume" (15, p. 501). Clauser *et al.*, on the other hand, have shown that "If the mid-volume were to be used to approximate the location of the center of mass of segments, the estimated center of mass would be proximal to its true location" (13, p. 69).

TABLE 9. BODY SEGMENT PERCENTAGES OF TOTAL BODY WEIGHT FOR LIVING WOMEN
(after Plagenhoef and Kjeldsen)

Segment	Subjects		
	College age	Dancers	Gymnasts
Hands	1.0	1.0	1.03
Forearms	3.1	2.9	3.21
Upper arms	6.0	5.8	5.49
Feet	2.4	2.7	2.48
Shanks	10.5	11.0	10.98
Thighs	23.0	24.3	16.52
Whole trunk (including head and neck)	54.0	52.3	60.24

Drillis and Contini (24) employed a wide range of measurement techniques in order to determine the volume, mass, density, center of mass, mass moment of inertia, and radius of gyration of the living human body and its segments. Among these were two immersion-type techniques — the "N.Y.U. Modified Immersion Method" in which the segment being studied was placed in an empty tank which was then filled to the appropriate level, and the "Segment Zone Method" in which the same procedure was followed with the water level raised in small equidistant steps so that the distribution of volume could be determined throughout the length of the segment. These methods have also been described in articles by Contini, Drillis, and Bluestein (15) and Drillis, Contini, and Bluestein (25).

The mean volumes obtained for the limb segments of 12 male subjects (age range 20–39 yr, mean age 27.2 yr) and the location of the segment centers of gravity (based on the assumption that the centers of gravity and volume are coincident) are presented in Table 10.

Drillis and Contini used three methods to establish the mass of each segment — a reaction board method, a volumetric method in which segment volumes were multiplied by the average of the corresponding segment densities reported by Harless, Dempster, and "the N.Y.U. Biomechanics team," and a coefficient method based on the cadaver data of Harless, Braune and Fischer, and Dempster. In reviewing the results obtained using these three methods they concluded "It is evident that neither the volumetric nor the coefficient method are sufficiently accurate and should not be used for scientific studies. They are useful, however, for technical purposes and approximations" (24, p. 70).

[Note: The comparisons upon which this conclusion was apparently based (comparisons between data from several different sources) took no heed of differences in the subjects used (age, physique, living or dead) nor of differences in the segment boundaries defined by the various investigators.]

TABLE 10. SEGMENTAL VOLUME AND CENTER OF GRAVITY LOCATIONS
(after Drillis and Contini)

Segment	Segment volume as percentage of body volume	Location of center of gravity from proximal joint as percentage segment length
Hand	.566	39.2
Forearm	1.702	42.3
Forearm and hand		38.2
Upper arm	3.495	44.9
Whole arm	5.73	43.1
Foot	1.297	44.5
Shank	4.083	39.3
Shank and foot		45.0
Thigh	9.241	41.0
Whole leg	14.620	39.7

Reaction Board Studies

The weight of a body segment (or, alternatively, the location of the center of gravity of that segment) can be determined using a modification of the reaction board technique of du Bois-Reymond. After the subject has taken up his position on the board, the reading on the scales and the horizontal location of the segment center of gravity (usually determined with the aid of cadaver data) are noted. The subject then alters the position of the segment in question and the same two parameters are noted a second time. The weight of the segment is then computed as indicated in the caption for Figure 2. (Assuming knowledge of the segments weights — again from cadaver data or some other source — the location of the center of gravity can be obtained in somewhat similar fashion. It must be noted, however, that it is not possible to determine both parameters of interest — the weight of the segment and the location of its center of gravity — simultaneously. The value for one must be assumed known in order that the value for the other can be computed.)

Although this technique has been described by numerous authors (13), (15), (55), (69), (76), it appears to have been very sparingly used in research investigations.

Bernstein (7) used a sophisticated version of the reaction board procedure shown in Figure 2 to determine the masses and the center of gravity locations of the major limb segments of 152 living subjects (both male and female) ranging in age from 10–75 years. The results obtained are summarized in Table 11. In commenting on these results, Bernstein observed that "the deviations found with sex of subject, contrary to expectation, do not significantly affect the values of the radii obtained" (7, p. 12). However, significant differences were reported between the sexes in terms of the segment masses. "Male thighs are significantly lighter than female thighs . . . but distal portions of the limbs in men are significantly heavier than those of women" (7, p. 13–14).

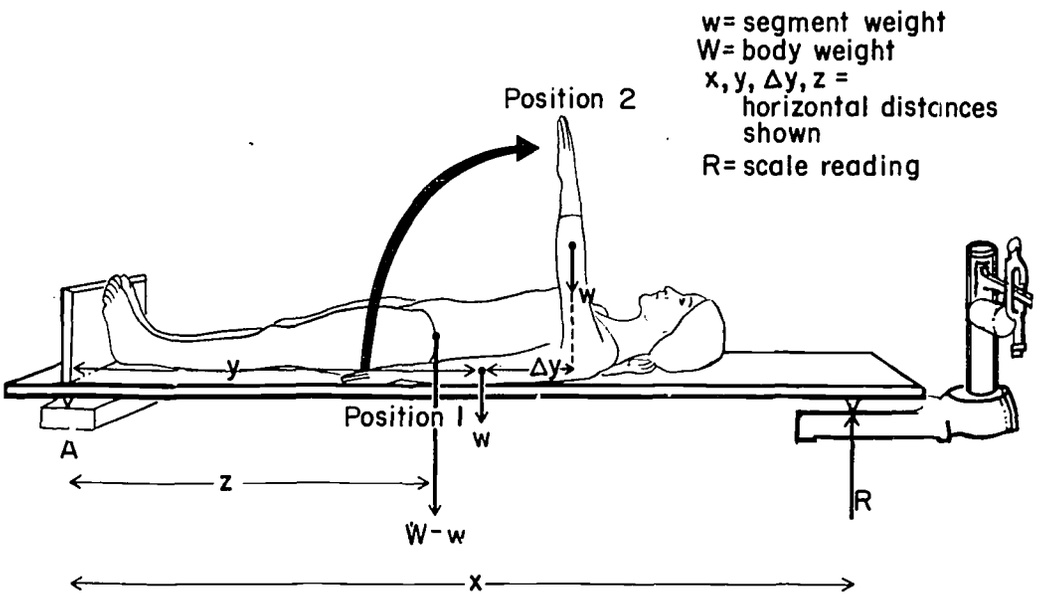

Figure 2. Determination of the weight of a body segment.

Taking moments about A in position 1:

$$R_1x = wy + (W - w)\,z$$

Taking moments about A in position 2:

$$R_2x = w(y + \Delta y) + (W - w)\,z$$

Subtracting:

$$(R_2 - R_1)\,x = w\,\Delta y$$

$$\boxed{w = \frac{(R_2 - R_1)\,x}{\Delta y}}$$

Mathematical Modelling Studies

A number of attempts have been made to represent the segments of the body as regular geometric solids of known density and to determine the center of gravity of the whole body by appropriate computations.

Among the first to use this approach was Harless (38) who likened the trunk segments of his cadavers to specific geometric forms, assumed a known specific gravity on the basis of previous research, and determined the weight and the location of the center of gravity of each segment by computation. His efforts were later dismissed by Dempster (21, p. 185) as "crude."

Matsui (48) derived a method for determining the weight and center of gravity location of geometric solids representing 18 body segments "based on the data of somatometry, bone density, and muscle density." The volume of each segment was computed from anthropometric measurements and divided into two parts, the bone volume and the muscle volume. The mass of each segment was then computed by adding the product of the bone volume and the bone density to the product of the muscle volume and the muscle density. For male subjects, 1.418 and 1.076 were used as the "bone density" and "muscle density" values, respectively. These values (determined in a study on rabbits) were used in the absence of "sufficient information concerning the density of bone and muscle [in humans]." The bone and muscle "densities" were adjusted to 1.265 and

TABLE 11. RESULTS FROM BERNSTEIN'S STUDY OF 152 LIVING SUBJECTS

(a) *Relative Masses of the Limbs*

Segment	Men	Women	General mean	Ratio M/W
Upper arm	0.02655	0.02600	0.02632	1.021
Forearm	0.01818	0.01820	0.01819	1.000
Hand	0.00703	0.00550	0.00642	1.279
Thigh	0.12213	0.12815	0.12485	0.948
Lower leg	0.04655	0.04845	0.04731	0.961
Foot	0.01458	0.01295	0.01313	1.126

(b) *Radii of the Center of Gravity*[a]

Segment	Mean value for men	Mean value for women
Upper arm	0.4657	0.4840
Forearm	0.4124	0.4174
Thigh	0.3857	0.3888
Lower leg	0.4130	0.4226

[a]The radius of the center of gravity was defined as the distance from the center of gravity to the center of gravity of the proximal joint with the length of the limb taken as a unit.

TABLE 12. SEGMENT WEIGHTS AND CENTER OF GRAVITY LOCATIONS (after Matsui)

Segment	Segment weight (Body weight = 1.0)		Center of gravity location (Distance from cranial or proximal end of segment. Segment length = 1.0)	
	Male	Female	Male	Female
Head	0.044	0.037	0.63	0.63
Neck	0.033	0.026	0.50	0.50
Trunk	0.479	0.487	0.52	0.52
Arm	0.027	0.026	0.46	0.46
Forearm	0.015	0.013	0.41	0.42
Hand	0.009	0.006	0.50	0.50
Thigh	0.100	0.112	0.42	0.42
Leg	0.054	0.054	0.41	0.42
Foot	0.019	0.015	0.50	0.50
Head and neck	0.078	0.062	0.46	0.45
Head, neck, and trunk			0.63	0.64
Head, neck, trunk and upper extremity			0.65	0.64
Upper extremity	0.050	0.044	0.46	0.44
Forearm and hand			0.48	0.46
Lower extremity	0.172	0.181	0.42	0.39
Leg and foot			0.51	0.50

1.041, respectively, for female subjects. The center of gravity of each segment was assumed to lie on the axis of symmetry of the segment and in a transverse plane bisecting the volume of the segment. (The mean values obtained by Matsui for the mass of each segment and the location of its center of gravity are shown in Table 12.)

Matsui found good agreement between his bone volume measurements (determined using X-rays) and those obtained by a previous Japanese worker (differences ranged from 0.1%–0.3%) and between his computed segment masses and those reported by Braune and Fischer (differences of less than 1%). He also made several comparisons between the location of the whole body center of gravity derived using (a) his segmental data and that of Braune and Fischer (10) and (6) using his segmental data and direct measurements obtained with a variety of reaction board methods. Differences in the "height" of the center of gravity (expressed as a percentage of the total height) when the subject assumed (or simulated) an erect standing position ranged from 0%–3%. When other body positions were investigated similar agreement was found between the results obtained using Matsui's data and those obtained using a reaction board technique similar to that of Basler (5).

King, Patch, and Shinkman (43) assumed that a human body could be represented by a stick figure composed of seven rigid segments free to rotate about seven fixed points of articulation; used the segment masses and center of gravity locations reported by Lay and Fischer (47) [derived from the data of Braune and Fischer]; and determined the extent to which the center of gravity deviated from a standard location when a variety of body positions were assumed. Comparison of results obtained using the model with corresponding results obtained by Swearingen (70), revealed large discrepancies.

Kulwicki, Schlei, and Vergamini (46) developed a model consisting of six right circular cylinders (two arms, two legs, torso, and head) in order to evaluate the effectiveness of certain movements in producing rotation while in a weightless state. The linear dimensions of the model were based on the 50th percentile data obtained by Hertzberg, Daniels, and Churchill (41) in their survey of U.S. Air Force personnel and the weights for each segment were based on the mean weights for Dempster's (21) cadavers. No attempt was made to validate the results obtained using the model.

Whitsett (74) constructed a mathematical model consisting of 14 segments for the purpose of studying "man's mechanical behavior in some selected conditions associated with weightlessness." The dimensions of the segments were determined by direct measurement from the subjects, the masses of the limbs by using Barter's (2) regression equations, and the locations of the segment centers of gravity by using Dempster's (21) cadaver data (upper and lower arms and legs) and by assuming coincidence with the midpoint of the segment length on the axis of symmetry (other segments). Difficulties were encountered in determining the accuracy with which the model could be used to predict the location of the whole body center of gravity. Whitsett concluded that

> The assumption that the human body consists of 14 rigid and homogeneous segments is a convenient, but not too realistic, idealization. However, for the intended application of the model to dynamics problems facing weightless man, this assumption will not produce any great inaccuracies (74, p. 27).

Hanavan (37) designed a 15-segment mathematical model to predict the inertial properties of the human body in any fixed body position. The dimensions and properties of the segments (head, upper torso, lower torso, and 12 limb segments) were calculated using a total of 25 anthropometric measurements taken on the individual subject. The weights of the segments were computed using the regression equations derived by Barter (2) with corrections to ensure that the sum of the segment weights was equal to the weight of the whole body.

In the process of validating his model, Hanavan used the raw data obtained by Santschi *et al.* (66) and computed the location of the center of gravity of each segment (excluding the foot) using the model. He then compared the results obtained with those obtained in Dempster's (21) work with cadavers (Table 13a) and concluded that "The very small deviation between the model and the experimental results indicates that the shape and size of these segments approximate the body segment very well" (37, p. 37). A similar process was followed

TABLE 13. COMPARISON OF RESULTS OBTAINED FROM A MATHEMATICAL MODEL AND FROM DISSECTION OF CADAVERS
(after Hanavan)

(a) *Location of Center of Gravity*[a]

Segment	Model			Cadaver (after Dempster)
	High	Low	Average	
Head and torso	73.2	61.3	64.5	60.4
Upper arm	49.6	44.6	47.3	43.6
Forearm	45.0	39.8	42.8	43.0
Upper leg	45.3	42.0	43.7	43.3
Lower leg	47.6	39.8	41.6	43.3

[a]Distance from upper end in percentage of segment length.

(b) *Specific Gravity of Body Segments*

Head	1.47	.90	1.15	1.11
Upper torso	1.00	.72	.84	.92
Lower torso	1.10	.80	.92	1.01
Hand	1.72	1.02	1.29	1.17
Upper arm	1.22	.79	.97	1.07
Forearm	1.56	1.04	1.30	1.13
Upper leg	1.32	.88	1.13	1.05
Lower leg	1.44	.83	1.19	1.09
Foot	2.14	1.12	1.62	1.09

with regard to the specific gravity of each segment (Table 13b) and the following conclusion was reached: "The average results are within approximately 10 percent of the experimental data. This is exceptionally good considering the number of parameters involved in the calculations and the assumptions of simple geometric shape and uniform density" (37, pp. 37, 39). When coordinates of the whole body center of gravity were determined using the model and then compared with those for the corresponding positions in the study of Santschi *et al.* (66), it was found that generally one half of the predicted values fell within 0.7 in. of the experimental data.

Miller (51) has subsequently used a simplified four-segment version of the Hanavan model in a computer simulation study of the airborne phase in diving and has obtained what she describes as "acceptable accuracy."

MISCELLANEOUS STUDIES

Recently, Baster (6) and Casper *et al.* (12), have been working on a new technique for determining the density, mass, center of mass, and moment of inertia of a body. This technique involves the use of a Gamma Ray Scanner to monitor the radiation (emitted from a cobalt 60 source) passing through the body under investigation. Initial results using dead biological tissues as specimens have yielded encouraging results, and it is anticipated that ultimately this work may be extended to obtain corresponding data for the body segments of living human subjects.

Discussion

The preceding review clearly indicates that there are a wide range of direct methods and a large amount of segmental data that one

might use in determining the location of the center of gravity of a human body. Which of the various methods or sets of data is the best to use in any given instance obviously depends on several factors. Among these are: (1) the degree of accuracy required; (2) the characteristics of the subject, or subjects, involved in the study; (3) the nature of the body positions for which center of gravity determinations are required; (4) the number of coordinates of the center of gravity (or principal planes of the body) which must be determined; (5) the number of subjects and the extent to which they are available for testing.

Accuracy

The accuracy of several of the methods and sets of segmental data reviewed above has been called into question. In some cases because the techniques used were crude, in others because the computations involved were based on false or doubtful assumptions, in others because the reporting of procedures and/or results was incomplete or demonstrably inaccurate, and in still others because of substantial differences in the results obtained compared with those obtained when an apparently highly accurate method was used.* The methods or data reported by Bernstein (7), Borelli (9), Braune and Fischer (10), Cleaveland (14), Fujikawa (33), Hanavan (37), Harless (38), King, Patch, and Shinkman (43), Mori and Yamamoto (52), Weinbach (73), and Whitsett (74) can be seriously questioned on one or more of these grounds and, if the highest possible accuracy is sought, they are probably best dismissed as unsuitable for the purpose.

* The expression "apparently highly accurate" is used advisedly because the whole question of accuracy is clouded by the fact that the location of the center of gravity is affected by movements of the circulatory and respiratory organs; and by changes in the disposition of the body fluids, internal organs, body fat, etc., due to the influence of gravity or due to the accelerative effects experienced by a body in motion. The magnitudes of these several effects (although generally presumed to be fairly small) are largely unknown.

Characteristics of Subjects

Which of the various sets of data should be used in conjunction with the segmental method—whenever conditions suggest that this is the more appropriate method—is a very difficult question to answer. If data gathered in a cadaver study are used, one must assume that the segment weights and center of gravity locations of the cadaver (or cadavers) do not differ significantly from those of the living subject. If data from immersion, reaction board, or mathematical modelling studies are used, assumptions must be made about one or more of: (1) the segment densities, (2) the segment center of gravity locations, and (3) the geometry of the segments. Unfortunately, at the present time there is very little evidence to support or refute any of these assumptions. For example, whether errors resulting from assuming that the segmental characteristics of a living subject and those of a cadaver are identical are of greater or lesser magnitude than errors resulting from assuming that the segments are of uniform density, or that the segment centers of gravity coincide with their volume centroids, is just not known. Therefore, in the absence of any clear-cut guidelines concerning the validity of these assumptions, and to control other factors which probably influence the accuracy of the results obtained, it would seem logical to select the data which has been gathered on subjects who most closely approximate the subjects under investigation in age, height, weight, sex, race, physique, and health status—all factors known, or likely, to influence the location of the center of gravity.

Thus investigators conducting studies with college-aged male subjects might be best advised to use data from the immersion study of Dempster (21); those using college-aged female subjects, the data of Plagenhoef (61), or Kjeldsen (44); and those using older subjects, data from the cadaver studies of Clauser, McConville, and Young (13) or Dempster (21).

Nature of Body Positions

The body positions for which center of gravity determinations are required exert a limiting influence on the methods that may be used. For erect standing, back-lying, and a limited range of other positions, practically any of the available methods may be used. For other more complex body positions, the direct methods are frequently unsuitable—either because the subject cannot put his body in a static position comparable to that which he attains when in motion, or because the flat, hard surface of the testing apparatus makes it very difficult for him to assume an otherwise attainable position. In those cases where it is necessary to resort to the segmental method, care must be taken to select that set of data most appropriate to the body positions being considered. In this respect, the principal consideration is the orientation of the subject's head, neck, and trunk. If these are in an essentially straight line, no special allowance need be made for body position in deciding which set of segmental data should be used (i.e., the decision should be made on the basis of the other factors mentioned here). However, if these segments are not so aligned it seems highly likely that use of data gathered in immersion and reaction board studies (in which the head, neck, and trunk are almost invariably treated as a single, "straight-line" segment) will lead to greater errors than use of data which is less appropriate in terms of similarity of subjects but which makes due allowance for variations in the alignment of these segments.

Number of Coordinates Required

Methods of determining the location of the center of gravity differ in the information they provide. Some, like that of du Bois-Reymond (26), identify one plane containing the center of gravity, while others, like the segmental method and those of Basler (5), Cotton (18), and Palmer (56), (57), identify more than one. Due notice must be taken of these differences when endeavoring to select the best method to use in a given case.

Number and Availability of Subjects

The number of subjects for whom it is desired to determine center of gravity locations, and the availability of these subjects, are factors which must be considered in arriving at the best method to employ.

If there are only a few subjects involved, and if these subjects are readily available, it may be feasible to determine their individual segmental characteristics using an immersion or reaction board technique and to use this data in determining the required center of gravity locations by the segmental method. Alternatively, if the number of body positions involved is also small and such as to permit use of direct methods, one of these might well prove to be even more appropriate.

If there are a large number of subjects involved, or if the subjects are not readily available for extended testing, the segmental method, using data gathered on other subjects, would seem the most practical proposition—albeit one in which some accuracy is probably sacrificed in favor of expediency.

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A Laboratory Design for Undergraduate Kinesiology*

IN THE PAST, laboratories for kinesiology have consisted mainly of a few skeletons, bone boxes, muscle charts, and perhaps, some lever models. Recently, laboratories have been built on a concept of unique stations. This concept provides for a unique experience for a pair of students at each of about 10 stations. For example, the first station might have a force platform, the second a motion picture camera, etc. (1). Students learn the uses of all of these resources and the applications to kinesiology. Work is planned during class and often during uncommitted time. Generally, provision is made for some specialized study, like a term project, using the resources of one or two of the stations. Some of the advantages of such a concept relate to the variety of instrumentation, experience, and imagination possible in such a situation. Some of the disadvantages relate to the brevity of orientation, the brevity of experience prior to specialization, conflicting interests, and the need for practically individualized, rather than class instruction.

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The other kind of design, of course, is the concept of standardized stations. This creates in the laboratory, the traditional situation of the classroom. All students have the same resources and are apprenticed in very basic experiences that widely apply before journeying to the specialized possibilities. Some of the adavntages relate to the management of graduated progress, of readiness diagnosis, and of defined communication. Some of the disadvantages relate to the physical suggestion that culminating or specialized experiences must be standardized. An imaginative teacher would not be overwhelmed with problems such as these. Other disadvantages, however, relate to the cost of having, let's say, ten of everything. For kinesiology, this kind of problem might overwhelm even the imaginative teacher because costs per student in physical education already are high. The purpose of this study was to analyze the problems of design and to build a modern, undergraduate, kinesiology laboratory.

Methods

The main method used was systems analysis. From teaching and research experiences, a list of learning objectives was formulated. The list, reduced to equipment requirements, was applied to various laboratory designs in comparative analyses directed at calculating

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the possible learning return for the money invested. Criteria for each of the analyses were weighted according to the estimated importance with respect to this major economic objective. Principles commonly used in engineering and in management were drawn upon freely. The initial constraints related to the facilities and the time.

Two areas, each approximately 40 feet by 30 feet, had to accommodate the research and the instructional activities for exercise physiology and kinesiology. One of these areas was divided into six rooms and was meant for research. The other area was designed as a large classroom with a concrete podium and laboratory table before a motion picture screen for front projecttion and a blackboard along the north wall. Sundry equipment was stored in the research and the lecture areas. Both areas were used by the kinesiology and the exercise physiology classes at the discretion of the various professors. Some of the early experiments in exercise physiology, for example, had to be done with participants supine on mats for resting measurements in the research area and sometimes students stepped over them on their way to and from the instructional area. With respect to time, the laboratory sessions remained in blocks of 3 hours each week.

In general, results were obtained with the use of several processes. The designated director of research was the principal investigator and took the responsibility for planning, coordinating, and organizing the project. Control and command were shared in various ways with the other professors and the chairman of the department. The meetings, held several times during the school year, helped in the formulation of decisions and their execution.

Results

Results were obtained because all parties concerned wanted progress. A key decision was to designate instructional progress as the major objective of the research program. The design of instructional facilities and equipment was given the highest priority. The decision to separate the instructional and the research areas was made early but was executed in stages. Efforts were made to understand the instructional program as it stood and to provide as completely as possible for it in the instructional area. Additional cabinets were built in the instructional area in order to facilitate this transition (see east wall of Figure 1). Research was done with the instructional equipment available to enhance rather than just duplicate instructional capabilities in the mixed environment. For example, electromyograms were provided in the classroom, from instructional equipment, from four muscles at a time, either as direct or integrated tracings, rather than with the research equipment in the shielded research facility from one muscle at a time as integrated and subsequently displayed on an electronic counter. As the immediate instructional requirements were met and separation progressed, more time was spent on design and execution.

The design studies suggested uniform rather than unique learning stations. One of the principles that made this possible was to provide equipment according to utilization. For example, equipment requiring very long study time was provided for each pair of students. Equipment that was used very infrequently was provided singly. For expensive single pieces of equipment, systems were designed to extend utilization. Equipment with long preparation time was provided to each pair of students unless designing a system to abbreviate setup and takedown time seemed economical.

Table 1 shows how some of the basic decisions were made. For example, our experience indicated that our undergraduates required at least 15 minutes to locate motor points, scrub the skin, place adhesive collars on the electrodes, fasten the electrodes over the motor points, stabilize the electrode wires, and connect to the recorder. Most students only take about a minute to obtain the tracing and about 10 minutes to remove, wash, dry, and replace the electrodes so that they are ready for use again. One set of electrodes would require 26 minutes times 20 students, 520 minutes or 8.6 hours, which

TABLE 1. COMPARATIVE ANALYSIS FOR KINESIOLOGY DECISIONS

Datum source	Preparation[a] time (min.)	Takedown time (min.)	Time in use (min.)	System to extend use (cost/student[b])	Display	Cost of supplies	Cost/student[b] One	Cost/student[b] Ten	Decision (1, 3, 10, or 20 of each)
1. EMG	15	10	1	$0.67	Tracing	Low	$0.02	$0.20	10
2. Elgon	5	5	1	Same as EMG	Tracing	Low	$0.01	$0.10	10
3. Force transducer	10	5	1	Same as EMG	Tracing	Low	$0.10	$1.00	10
4. Camera	60	30	0.1	$0.10	Film	High	$1.00	$10.00	3
5. Projector	5	5	3600	$0.77	Screen	None	$0.10	$1.00	10

[a] Preparation time was a criterion. Weighting and scoring are not shown.

[b] Costs were divided by 4500 students, the projected utilization before instructional obsolescence. (This laboratory is used by 415 students/year at present. We projected an average growth of 8.5% for the department(s) over the next 10 years or 4500 students for the next decade. We projected instructional obsolescence in 10 years.)

is inordinately long. Ten sets of electrodes permit assistance from a laboratory partner and 10 students can be ready to record in 15 minutes. With no system to extend the use of the recorder, then about 5 minutes is required to obtain a tracing for each student (connect, performance, and disconnect time). After the first 15 minutes, the eleventh person should be joining the queue and the others should follow one at a time at intervals of 5 minutes. That means that 20 students may obtain tracings in 20 times 5 minutes plus 15 minutes for preparation time and 10 minutes for cleanup time, i.e., 2 hours and 5 minutes. In practice this worked out to about 2 hours with about five repeat tracings for students who had technical difficulties. About 15 minutes were available to introduce the experiment before the tracings were obtained and about 25 minutes were available to discuss results, answer questions, and begin the report at the end of the laboratory period. Students responded, almost without exception, that they learned more from electromyography than from palpation and preferred to do the EMG rather than the palpation experiments.

Table 1 also shows that systems may be designed to extend the use of equipment. For electromyography, electrogoniometry, and force measurements, this consisted of 10 consoles for students providing 6 dedicated channels each (see *D* Figure 1) to a master console and the recorder (planned for the north wall east of the instructor's desk, see Figure 1). This system, presently under construction, should halve the 5 minutes required to obtain each tracing. That would reduce the 2 hours and 5 minutes to 1 hour and 15 minutes because connect and disconnect times are eliminated and more than one experiment can be recorded on separate channels at the same time. Cuing and channel identification will be handled at the master console. This cost was considered justifiable because it will save an hour of student time, 20 student hours per laboratory, and an hour of instructor time. This is time when learning is not going on. That means that the learning efficiency of the

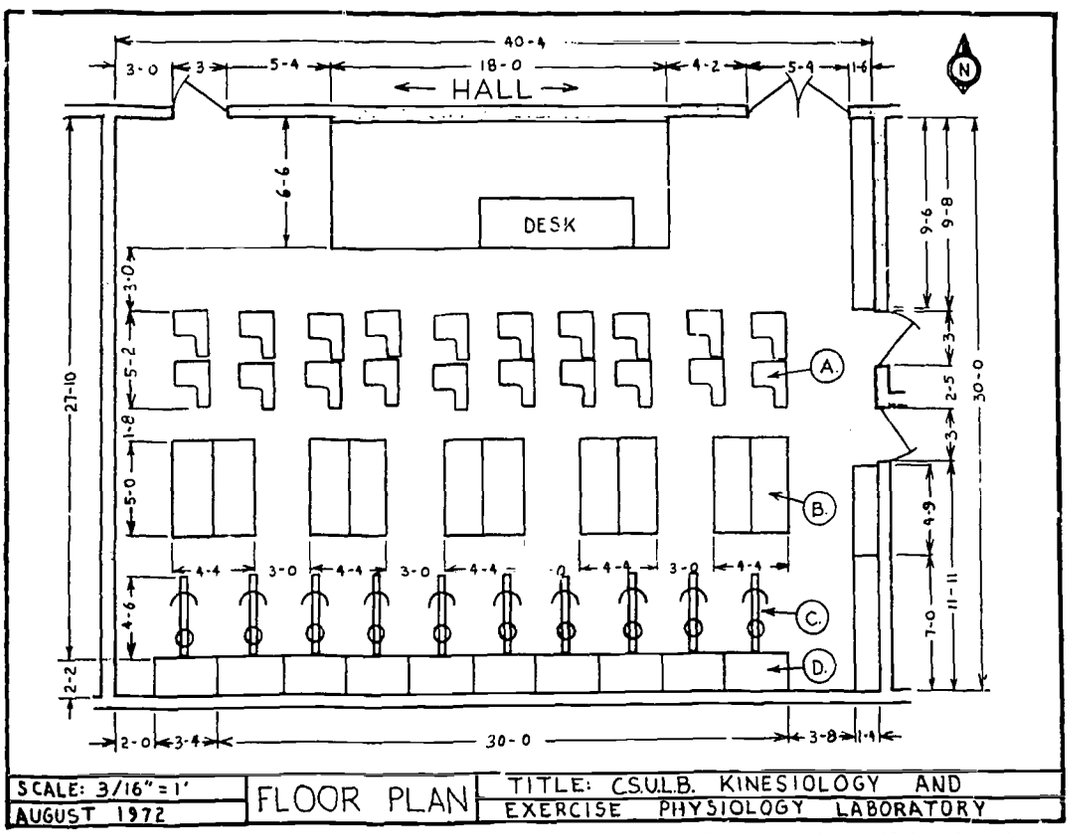

Figure 1. Kinesiology and Exercise Physiology Laboratory at California State University, Long Beach. *A* shows 20 student lecture chairs, which shall be replaced by chairs for viewing and note taking at *B*. *B* shows the 10 projection desks, each accommodating 2 projectors and 2 backlighted viewing screens. C shows 10 bicycle ergometers. *D* shows the 10 consoles for exercise physiology, each accommodating 2 Haldane gas analyzers, 16 gas collectors, the inputs to 6 dedicated recorder channels, and storage for exercise physiology and kinesiology.

laboratory, the instructor, and the course should improve by about 50 minutes or one class hour for each such laboratory experience.

The system to extend the use of the camera is permanent mounting for the camera and the flood light fixtures and roll-away grids. Timers and subjects may be kept in focus simultaneously with split diopters. All lights, camera(s), and timer(s) can be started and stopped with one switch. What is shown in the table, 60 minutes for preparation time, can be reduced to 15 minutes by the elimination of light, distance, and aiming measurements. The filming alley would run parallel to the longer dimension of the room (where the students' lecture chairs are shown, *A* in Figure 1). Takedown time could be reduced to 10 minutes, for a total saving of 45 plus 20 minutes or about another class hour. This saving could justify three cameras to permit simultaneously filming the movement in three dimensions.

Films in one, two, or three dimensions will require considerable analysis time. That is why the decision was made to provide initially for one projector for each pair of students and build the furniture (see *B*, Figure 1) for the viewing, the editing, and the studying. The same reasoning prompted the additional decision to build the furniture so that it might eventually provide one projector and screen for each student.

The advisability of designing one laboratory to serve kinesiology as well as exercise physiology was examined. The disadvantages relate to crowding of equipment and scheduling conflicts. The advantages relate to common requirements for recording, common requirements for extending the use of equipment, economy, and the suggestion that exercise could and should be investigated kinesiologically and physiologically simultaneously. The decision was made for a unified laboratory. What was described here was the kinesiology portion of that laboratory.

Conclusion

For electromyography, electrogoniometry, force transducers, and projectors, the standardized station concept seemed more advantageous than the unique station concept in the design of an undergraduate kinesiology laboratory. For filming and for recording, the unique station concept with systems to extend use seemed most advantageous. For an instructional laboratory of 1200 square feet or larger, a unified laboratory for kinesiology and exercise physiology seemed more advantageous than separate laboratories.

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Inherent Movement Patterns in Man

"MAN DOES NOT CHOOSE his structure; that is an inheritance from species which preceded him . . . Nor does he choose his basic movement patterns; they, too, are inherited. These can be modified but not changed basically . . . The study of movement of man should therefore begin with the attempt to identify his basic patterns" (1:5–6). Basic motor patterns in man may be defined as inherent or inborn combinations of certain movement components organized in various spatiotemporal sequences. In the early 1950's, Kabat, Knott and Voss, researchers and practitioners in the areas of neurology and physical therapy, attempted to identify man's basic motor patterns (2). They were interested in establishing or reestablishing fundamental movement activity in patients with neuromuscular deficits. Before they could formulate therapeutic tenets and techniques for working with these patients, they first had to identify the basic motor patterns found in *normal* man. After extensive observations of man performing various motor activities of everyday living, they identified specific movement patterns which they believed formed the basic substrates or language of movement. These fundamental movement components have been described in the physical therapy literature as "mass movement patterns," "proprioceptive neuromuscular facilitation (PNF) patterns," "irradiation patterns," and most recently as "spiral-diagonal or diagonal patterns" (5). Practitioners and researchers in the areas of physical therapy, occupational therapy, and rehabilitation medicine have subsequently found that successful rehabilitation of patients with neuromuscular disorders can be achieved through the teaching of "diagonal" patterns. It was observed that once the *major* constituents of the diagonal patterns were learned by patients, they could combine or vary the different components of the patterns spatially and temporally according to the specific motor behavior desired. It would appear that these patients were relearning fundamental movement patterns which had been disrupted by disease or injury.

Kabat, Knott and Voss (2) initially made observations of normal man performing such activities as walking, kicking and throwing balls, chopping wood, and swinging a golf club. In addition, Voss (5) later observed that infant developmental sequences such as rolling from prone to supine, creeping, crawling, walking, running, and jumping also were composed of spiral-diagonal combinations. Thus, it appears that many motor skills, whether developmental, sport, or ac-

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tivities of everyday living, possess common movement denominators which can be identified as diagonal patterns.

DIAGONAL PATTERNS OF THE UPPER AND LOWER EXTREMITIES

The patterns of movement identified by Kabat, Knott, and Voss are all spiral and diagonal in direction and these features are associated with the rotatory and diagonal anatomical arrangements and functional capacities of the musculo-skeletal system (2). The topographical alignment of muscle attachments proximally and distally are known to lie in cross-diagonal fashions as shown in Figure 1. Therefore, it would appear that optimal muscle function is achieved through muscles contracting in rotatory and diagonal directions. Joint and muscle movements seldom, if ever, occur in the pure cardinal planes of flexion-extension or abduction-adduction.

According to Knott and Voss (2), there are two diagonals of motion in the upper and lower extremities. The diagonal patterns for the extremities consist of "three components of motion occurring at the proximal joints or pivots of action — the shoulder and hip. Each extremity pattern includes a component of flexion or extension, adduction or abduction, external or internal rotation . . . The intermediate joints, the elbow and knee, may remain straight or they may flex or extend . . . The distal components of motion are consistent with proximal segments regardless of intermediate joint action" (2:9). The four diagonal patterns are usually described by the muscle actions occurring at the proximal or pivot joints.

The *first diagonal* pattern of both the upper and lower extremities consists of shoulder or hip flexion, adduction and external rotation components and its reciprocal actions of extension, abduction and internal rotation. The distal movement components are similar to the proximal patterns and the intermediate joints are either flexed or extended. The first diagonal patterns of the arms and legs appear in Figure 2.

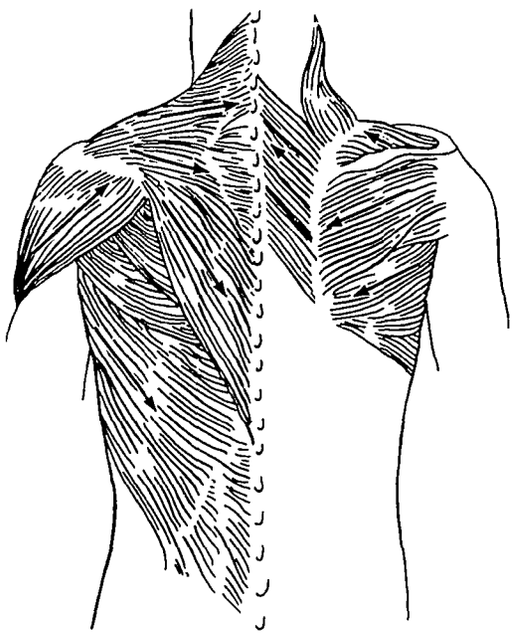


Figure 1. Anatomical arrangement of shoulder and trunk musculature showing lines of muscle pull. (Redrawn from Hollinshead, W. H. Functional anatomy of the limbs and back. Philadelphia: W. B. Saunders Co., 1951.)

The *second diagonal* pattern is different in the upper and lower extremities. The upper extremity second diagonal pattern consists of shoulder flexion, abduction, and external rotation with its reciprocal actions of extension, adduction, and internal rotation. The distal joint movements are again consistent with the proximal joint patterns and the elbow is either flexed or extended. The arm second diagonal flexion and extension patterns are shown in Figure 3.

The second diagonal pattern of the leg is made up of hip flexion, abduction, and internal rotation and its reversed actions of hip extension, adduction, and external rotation. The second diagonal leg patterns are illustrated in Figure 3.

Almost every motor activity employs reversals of movement patterns (2). Reversed or reciprocal muscle actions are utilized in such activities as throwing a ball, rowing a

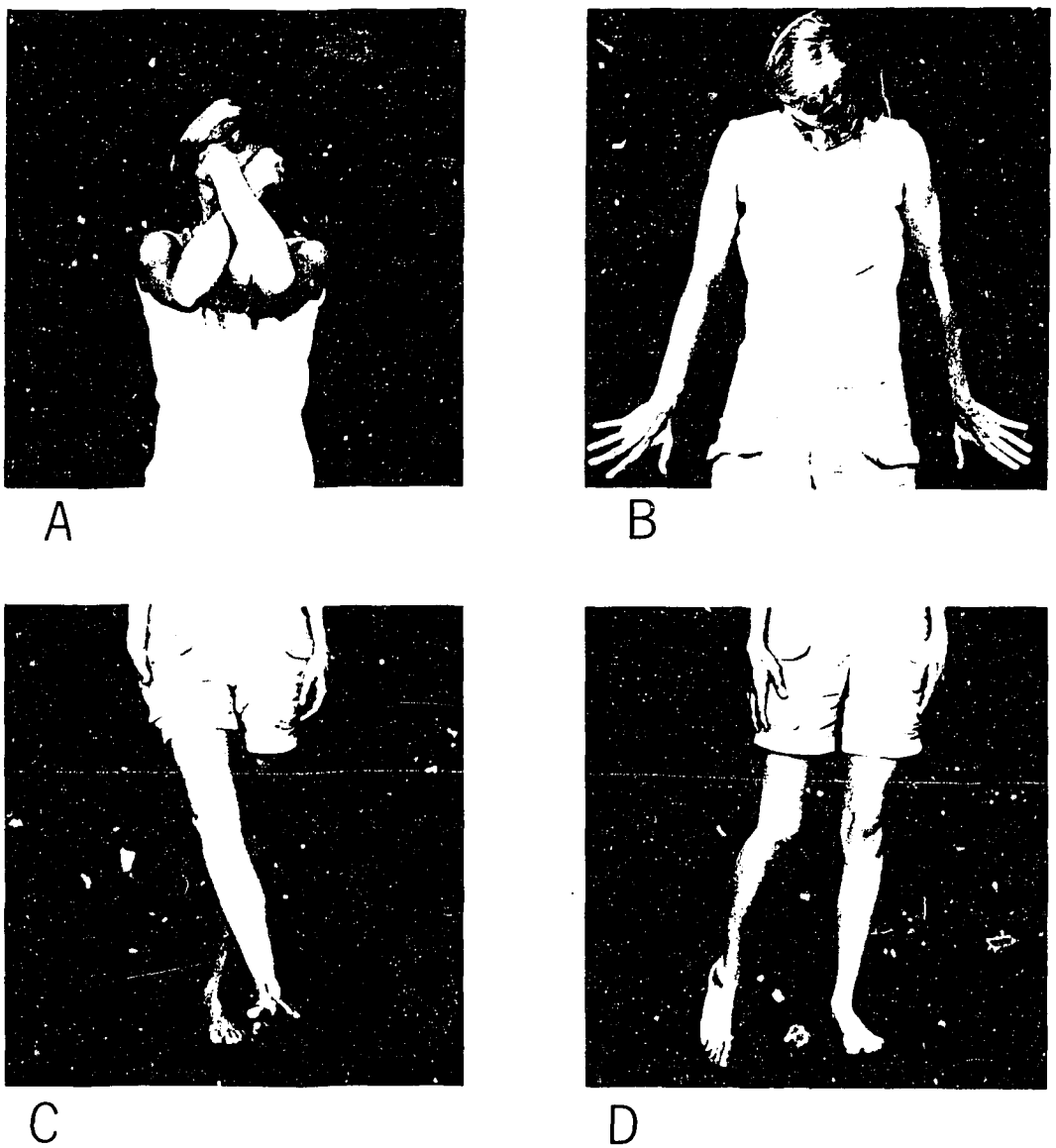


Figure 2. First diagonal arm and leg patterns. (A) First diagonal arm flexion components — shoulder flexion, adduction, and external rotation. (B) First diagonal arm extension components — shoulder extension, abduction, and internal rotation. (C) First diagonal leg flexion components — hip flexion, adduction, and external rotation. (D) First diagonal leg extension components — hip extension, abduction, and internal rotation.

boat, playing the piano or violin, walking, and even grasping and releasing objects. When reciprocal actions are not utilized in motor activities, movements are adversely affected in relation to power, skill, or coordination.

DIAGONAL PATTERNS IN DEVELOPMENTAL AND SPORT SKILLS

There are many illustrations of diagonal patterns occurring naturally in both develop-

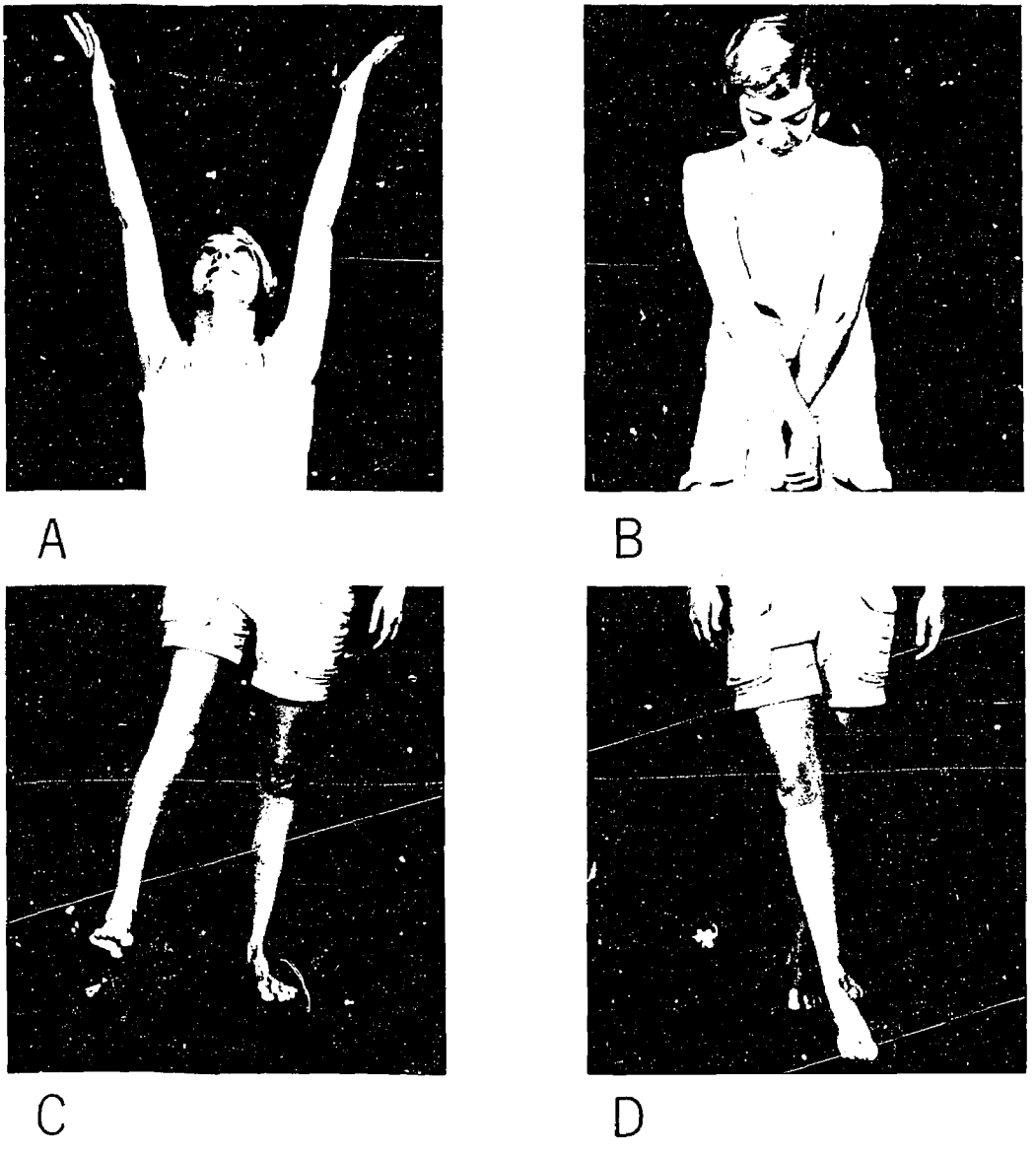


Figure 3. Second diagonal arm and leg patterns. (A) Second diagonal arm flexion components — shoulder flexion, abduction, and external rotation. (B) Second diagonal arm extension components — shoulder extension, adduction, and internal rotation. (C) Second diagonal leg flexion components — hip flexion, abduction, and internal rotation. (D) Second diagonal leg extension components — hip extension, adduction, and external rotation.

mental and sport skill activities. Similar diagonal components can be identified in the movements of infants, young children, and adults even though the spatial and temporal characteristics of the patterns may differ.

Developmental activities

During the course of neuromuscular maturation in the human infant, reflex actions containing components of the *first diagonal flexion* pattern appear to develop

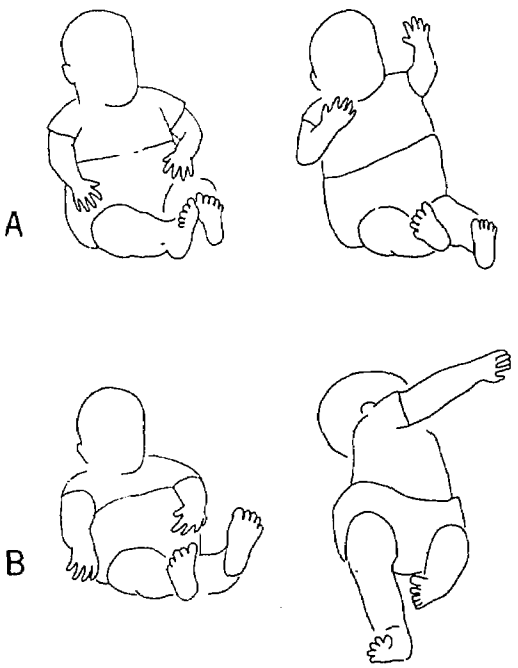


Figure 4. First diagonal arm patterns in developmental activities. The hand-to-mouth (A) and rolling patterns (B) of an infant.

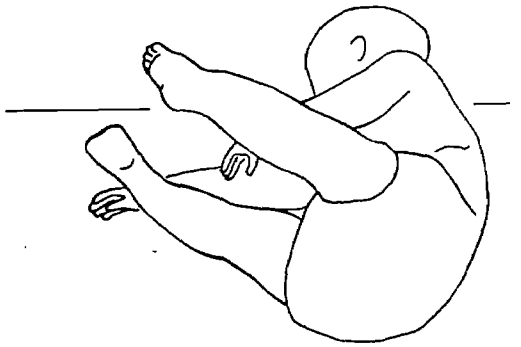


Figure 5. Rolling pattern of a five and a half month old infant using the second diagonal arm extension pattern.

first. This pattern is used during the first few months of life in hand-to-mouth patterns (Figure 4A) and in rolling from back-lying to side-lying positions. The early appearance of these flexion reflex patterns of the arms, legs, and trunk is associated with the predominance of generalized flexor tone in the young infant.

When rolling from a supine to a prone-lying position develops, the first diagonal flexion components of the arm pattern are then combined with extension and rotation of the head and trunk as seen in Figure 4B. Therefore, arm and leg movements are gradually integrated into motor synergies which exquisitely coordinate the head, limbs, and trunk to produce total movement patterns. As body righting reactions continue to mature, the infant is able to achieve a sitting position by flexing and rotating the trunk from a back-lying position. The flexion trunk pattern is combined with the *second diagonal extension* pattern of the arm (Figure 5). These synergies appear to be inherent in the developing organism and can also be demonstrated in lower primates such as the rhesus monkey (3).

Diagonal arm flexion patterns are therefore naturally combined with trunk and neck extension movements, and diagonal shoulder extension patterns are used with trunk and neck flexion. These total patterns can be readily observed in both primitive reflex movements and in more advanced balance and righting reactions of the infant. Natural synergies can also be demonstrated in normal adults performing bilateral first diagonal arm patterns without previous instructions regarding head and trunk positioning. Execution of bilateral arm flexion diagonal movements in adults unconsciously elicit some degree of trunk and neck extension, and bilateral arm extension diagonal patterns evoke concurrent neck and trunk flexion.

The sequential stages of motor development leading to locomotion in the upright position include pivoting in the prone position, crawling in prone, creeping on hands and knees, and finally in walking and running. Other stages may intervene, but these appear to be the most fundamental. Each stage demands greater development of equilibrium reactions and extensor muscle strength to resist the force of gravity. In the first few months of life, the infant "practices" resisting the force of gravity in the prone position by extending the head and trunk and by bilaterally flexing and extending the

arms and legs. When prone progression finally occurs, the first pattern is usually crawling in a circle or pivoting as shown in Figure 6A, with the arms and legs combined in alternating patterns.

Crawling and creeping patterns are extremely variable, perhaps the most variable of all the developmental motor patterns, but nonetheless, elements of spiral diagonal patterns can be identified. According to Milani-Comparetti and Gidoni (4), the *assumption* of the "static" hands-knees position is initially organized by the symmetrical tonic neck reflex in which the arms extend and the legs flex when the head is extended (Figure 6B) and vice versa. However, the symmetrical tonic neck reflex must be inhibited before *creeping* on the hands and knees begins, since creeping is a motor activity requiring reciprocal diagonal movements of the limbs. These observations can be appropriately generalized to other developmental patterns, such as sitting and walking, since these activities also seem to be organized symmetrically in the beginning stages of their development. Later these symmetrical patterns give way to spiral-diagonal sequencing as the more mature movements begin to appear.

The development of walking and running patterns is illustrative of the symmetrical-to-diagonal progression. The first few independent steps of the infant are usually taken with the arms raised in a protective symmetrical position and the legs advance in a primitive external rotation-abduction pattern (Figure 7A). The wide base of support in the early stages of walking demonstrates the unreliability of equilibrium reactions at this age. In contrast, the confident toddler demonstrates arm swings which are reciprocally patterned with leg movements, narrowed bases of support and leg patterns which are spiral and diagonal in direction as illustrated in Figure 7B. It is interesting to note from Figures 8 and 9 that the same symmetrical-to-diagonal progressions also appear in the arms during the initial stages of learning such motor skills as kicking and throwing a ball.

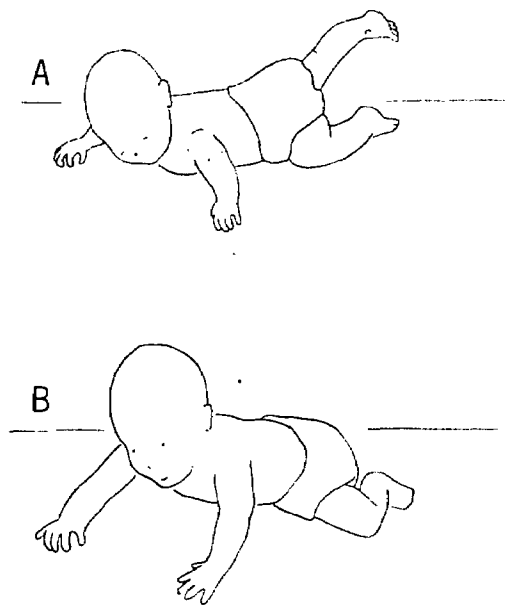
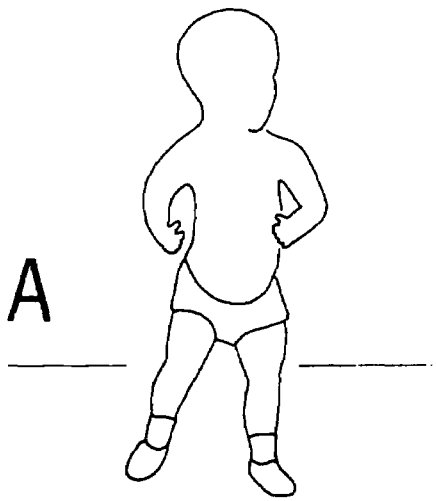


Figure 6. Prone progression activities in a five and a half month old child. (A) Crawling in a circle or pivoting combines diagonal arm and leg patterns. (B) Assumption of the hands-knees position using the symmetrical tonic neck reflex.

Sport skill activities

The classification of man's motor vocabulary into basic diagonal patterns is not only relevant in the areas of physical therapy, neurology, and motor development, but also in physical education since knowledge of the spiral diagonal components can be utilized in both the analysis and teaching of many sport skills. Underarm sport activities seem to use components of the *first diagonal* arm pattern. Similar joint actions are observed in the underarm throws of both children and adults, in running and in the standing broad jump. These activities are illustrated in Figures 10 and 11.

Second diagonal arm patterns are seen in both the backswing and the force producing phases of such sport activities as the overarm and sidearm throws, the tennis serve, the badminton smash, and the javelin throw (Figures 9B and 12). It is especially interesting to note that when the spiral-diagonal components are used to analyze sport activities, one finds that the tennis



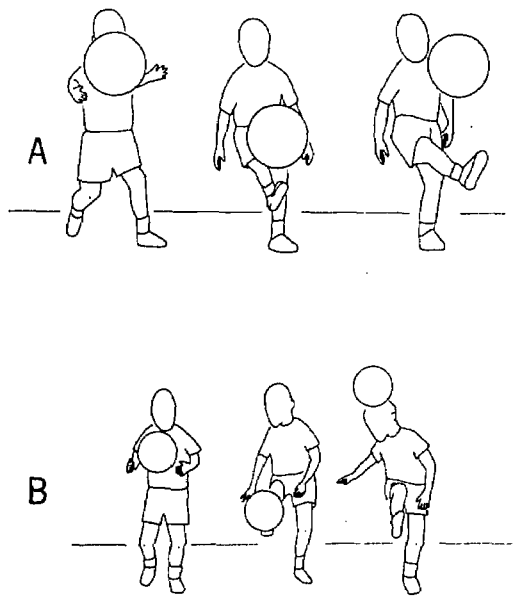


Figure 8. Symmetrical (A) to diagonal (B) progression of arm patterns in kicking of the same child at 2 years–9 months and at 3 years–9 months.

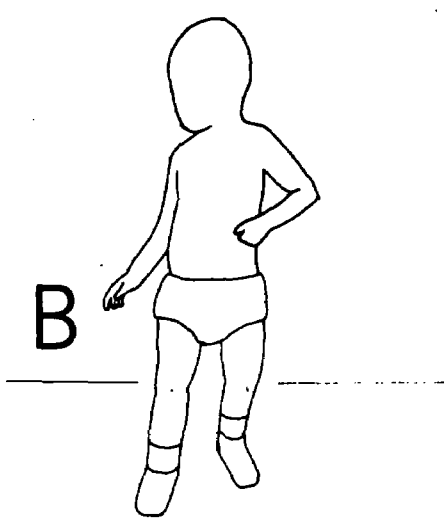


Figure 7. Developmental stages of erect locomotion. (A) Ten and a half month old child showing symmetrical arm movements and primitive leg external rotation — abduction patterns during early stages of walking. (B) Two year old child showing asymmetrical diagonal arm and leg patterns during later stages of walking.

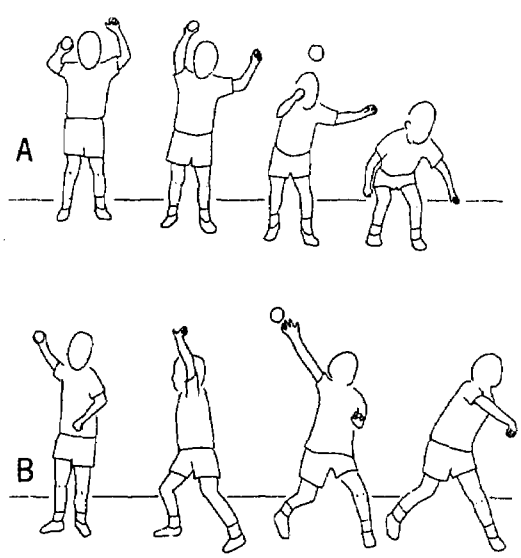


Figure 9. Symmetrical (A) to diagonal (B) progression of arm patterns in throwing of the same child at 2 years–9 months and at 3 years–9 months.

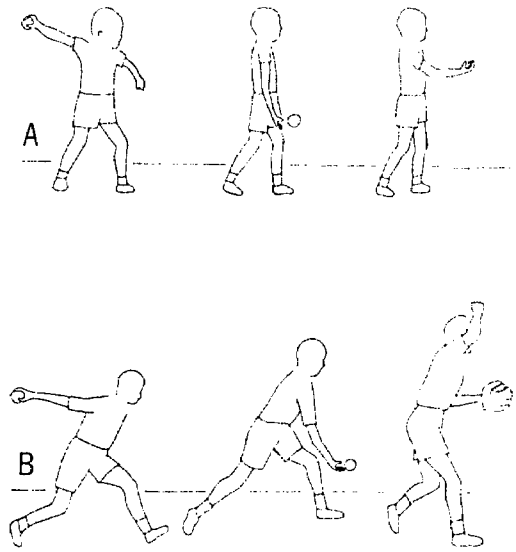


Figure 10. Similar first diagonal arm patterns of the force producing phase in the underarm throws of a 5 year–4 month old child (A) and an adult (B). The underarm throw pattern actually consists of reversals of muscle action. Thus, the backswing phase, which is not illustrated, is made up of the first diagonal extension pattern and the force producing phase uses the first diagonal flexion pattern.

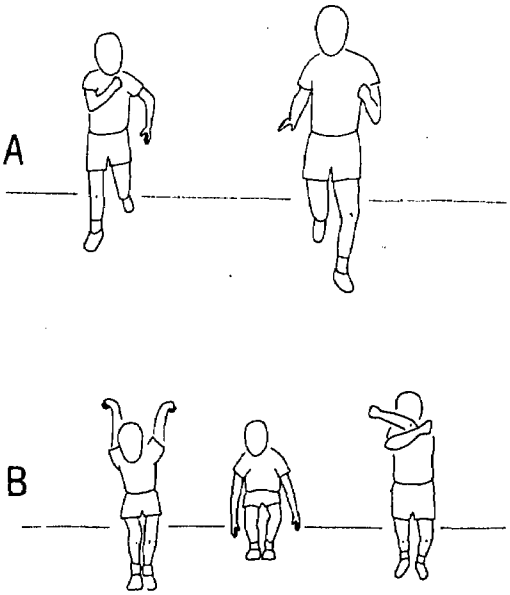


Figure 11. First diagonal arm components seen in running (A) and broad-jumping (B) activities. In running, the arms alternately perform the first diagonal patterns while in broad-jumping, both arms execute the same pattern simultaneously.

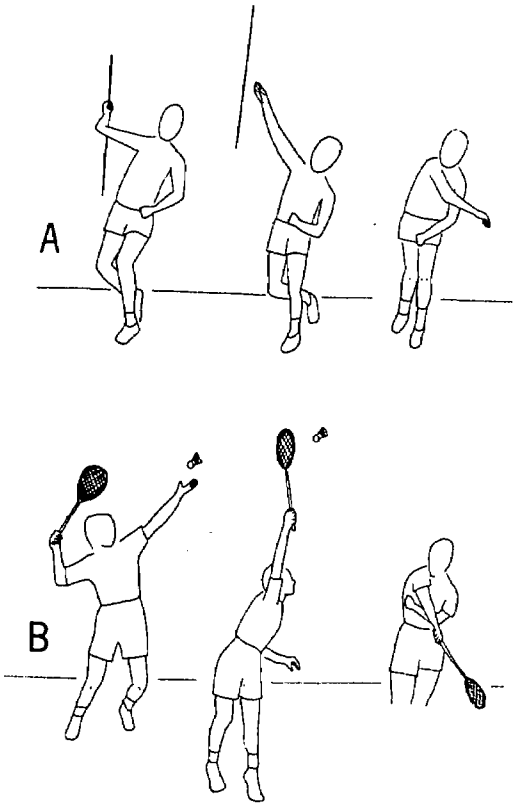


Figure 12. Second diagonal arm components observed in the force producing phases of the javelin throw (A) and of the badminton smash (B).

forehand and backhand drives are actually reciprocals of the same movement patterns as illustrated in Figure 13.

Various spiral-diagonal patterns may also be combined in sport skills or in activities of everyday living. For instance, combinations of the first and second diagonal arm patterns are used in batting as seen in Figure 14. Moreover, the two leg patterns are combined in such activities as walking, running, kicking, and speedskating, except that the timing and ranges of motion are different in each activity.

In teaching various sport activities, many of the so-called faults observed may be nothing more than manifestations of inherent patterns appearing when specific movement goals are introduced to the learner. For ex-

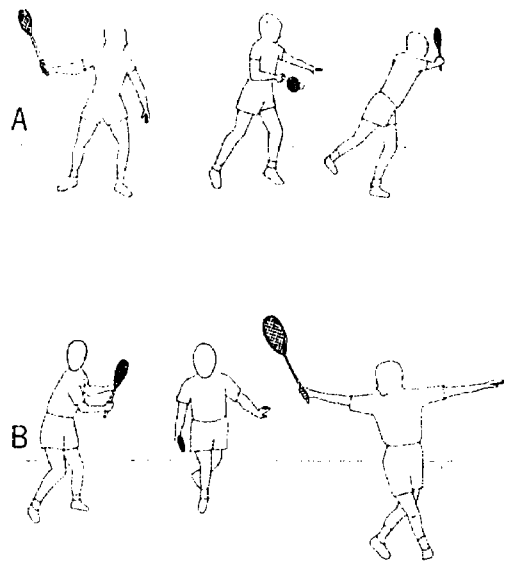


Figure 13. The force producing phase of the tennis forehand drive utilizes the first diagonal arm flexion pattern (A) while the backhand drive uses the first diagonal extension pattern, (B).

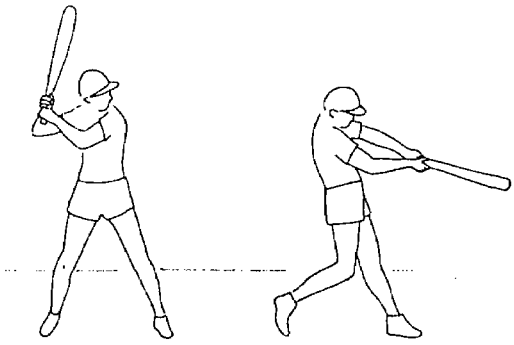


Figure 14. Batting combines the first and second diagonal arm patterns. The left arm uses the first diagonal extension pattern while the right arm utilizes the second diagonal extension pattern.

ample, beginning tennis players invariably pronate the forearm during the force-producing phase of the forehand drive rather than keeping the racket face open until after ball contact. Teachers of tennis should realize that forearm pronation is actually part of the arm second diagonal extension pattern and therefore not a "mistake" on the part of the student. Corrections should therefore be made from the standpoint of delaying the timing of the forearm pronation phase of the pattern and practice of this modification should continue until the whole movement feels natural to the beginner.

Thus, it seems that cross-diagonal movement patterns form the basic substrates upon which coordinated movements are built. Weiss (6) stated in 1941 that fundamental patterns of movement are genetically or inherently conceived within the nervous system. Since the four diagonal patterns of Kabat, Knott and Voss are so universally observed in reflex, developmental, sport, and motor activities of everyday living, it would seem that these fundamental patterns form the basis of man's motor inheritance.

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