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Measurements of Relative Lower Body Segment Positions in Gait Analysis

A thesis submitted in partial satisfaction of the requirements
for the degree Master of Science
in Engineering Sciences (Bioengineering)

by

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SYMBOLS

x_i — local (imbedded) rectangular reference axes

X_i — axes of a global rectangular Cartesian coordinate system

$\underline{x}_i^j$ — a displacement vector in the direction of the i-axis of the imbedded coordinate system for body j, with components referred to the global coordinate system

θ_i — orthopedic angles for lower body segments, to be defined

R — right - left alternation symbol, with the value +1 for the right side and -1 for the left side of the body

ω_i — i^{th} component of angular velocity

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ABSTRACT OF THE THESIS

Measurements of Relative Lower Body Segment Position

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Kinematic description of the lower body segments during locomotion is discussed in the context of clinical gait analysis. Precedents for the use of ordered sets of finite rotations to specify relative orientation of body segments are noted (Morrey and Chao, 1975, 1976; Lewis and Lew, 1977), and explicit definitions given for such rotations for lower body segments. It is proposed that such a description would serve as a solid convention for gait analysis from both the clinical and bioengineering points of view. The measurement of the angles via a particular, visual system of analysis is discussed. Accuracy is considered; it is concluded that the angles as measured by the system are reproducible to within 2°-5°. The question of how well the measurements reflect actual bone orientations needs to be addressed, but it is estimated that such discrepancies do not in most cases exceed the uncertainty mentioned. Some preliminary experimental results for normal adult gait are presented

I. THEORY AND ANALYTICAL TECHNIQUES

A. THEORY

The quantitative analysis of characteristics of human gait is becoming increasingly important as a clinical tool and a fundamental method in research concerning normal and pathological patterns of locomotion. Measurements of relative positions of the segments of the lower body are an important part of the description of human gait. Such measurements, along with other information such as cadence, step length, duration of swing and stance phases, and floor reaction data from force plates, are the typical data taken at existing gait analysis facilities.

However, the convention for describing lower body segment orientations is somewhat confused. To begin with, clinically defined joint angles such as flexion/extension and abduction/adduction are generally utilized. They are normally employed to describe a limited range of ideal motions, and used in this sense are unsatisfactory where complex composite motion is present. More rigorous or extended definitions must be specified. Much of the confusion also results from the fact that many researchers fail to stipulate exactly which angles are measured in their studies, and what the angles mean. This information may only be implicit in the way that the data was taken.

In visual systems of gait analysis, joint-angle measurements are often made from a plane view. The early work of Levens, Inman, and Blosser (1948) describing transverse rotations of lower body segments is an example. The authors state that a three-dimensional technique was originally employed, with motion picture cameras in several planes allowing a spatial analysis, but that measurement obtained from a single overhead camera gave results which they felt were not significantly different. The angles calculated in the three-dimensional analysis are not specified; the measurements made from the overhead view are presumeably the angular excursions of linear targets projected onto that plane. These targets, pins extending into the bones of the pelvis and lower extremities, were located in horizontal planes, roughly perpendicular to the direction of progression, with the subject in the anatomical position. Angular excursions between two adjacent segments were observed.

The studies of Murray, Drought and Kory (1964) and Murray (1967) are further examples wherein measurements were made directly from plane images. These authors in both cases used stroboscopic photography. In a side view, angular excursions between strips of reflective tape, placed on lower body segments, were measured from the film. In a transverse planar view, stick targets attached to the thorax and sacrum were used.

The gait analysis laboratories at Shriner's Hospital for Crippled Children in San Francisco and Children's Hospital and Health Center in San Diego are two examples of clinical gait analysis facilities that up to the present have made measurements from plane views of motion picture film of subjects walking. In all cases mentioned, the precise definitions of the angles measured are indicated only implicitly, and quantitative consideration has not been given the implications of the measuring techniques on the meaning or significance of the angles observed.

Another method for measuring relative positions of lower body segments in gait analysis involves the use of electrogoniometers. These are potentiometers attached to two body segments in such a way that they are rotated by angular excursions between the segments. In electrogoniometric studies, the angles to be measured are again seldom specified in a rigorous way; they are often only implicit in the mechanical linkage of the goniometer or goniometers to the two body segments. Examples include the work of Tipton and Karpovich (1965), who used uniaxial goniometers to measure sagittal rotations, and Johnston and Smidt (1969), who used triaxial goniometers (consisting of a triad of potentiometers) to measure hip joint angles. Johnston and Smidt do not specify the order of linkage of the potentiometers, which is all-important in determining the axes of rotation of the measured angles. This can be found only by examining a photograph of the device in place on a subject. (It should be noted that the order and orientation shown theoretically would measure angles in accord with those presented in this paper, discounting possible aberrations due to mechanical linkage.)

It seems clear that a concrete and rigorous system of description of relative lower body segment orientations is needed. In choosing such a system it was desired that the measurements be biomechanically useful, yet still correspond with the senses of the terms used clinically, since the work was being done for a clinical facility (Children's Hospital and Health Center, San Diego). Measurements made directly from a plane view were ruled out for two reasons: such measurements depend on the orientations with respect to the camera of both the proximal and distal segments, which was felt to be a biomechanical disadvantage; and the clinical senses of the angles would also be violated in some cases for much the same reason. An example is shown in Fig. 1.

It was desired that the measurements be made relative only to the proximal segment of each joint. In gait analysis, joint motion in the lower extremities is frequently treated as rigid-body motion about a point fixed with respect to the proximal segment, since the segments are generally constrained by the joint structure to prevent relative translation at articulation. In engineering, this type of motion is often described with the use of Euler angles, which are a mathematical decomposition of the orientation of the moving (distal) body into a unique set of three ordered, finite rotations initiated from some reference orientation. The rotations must be ordered since finite rotations cannot be construed to be vector quantities and their

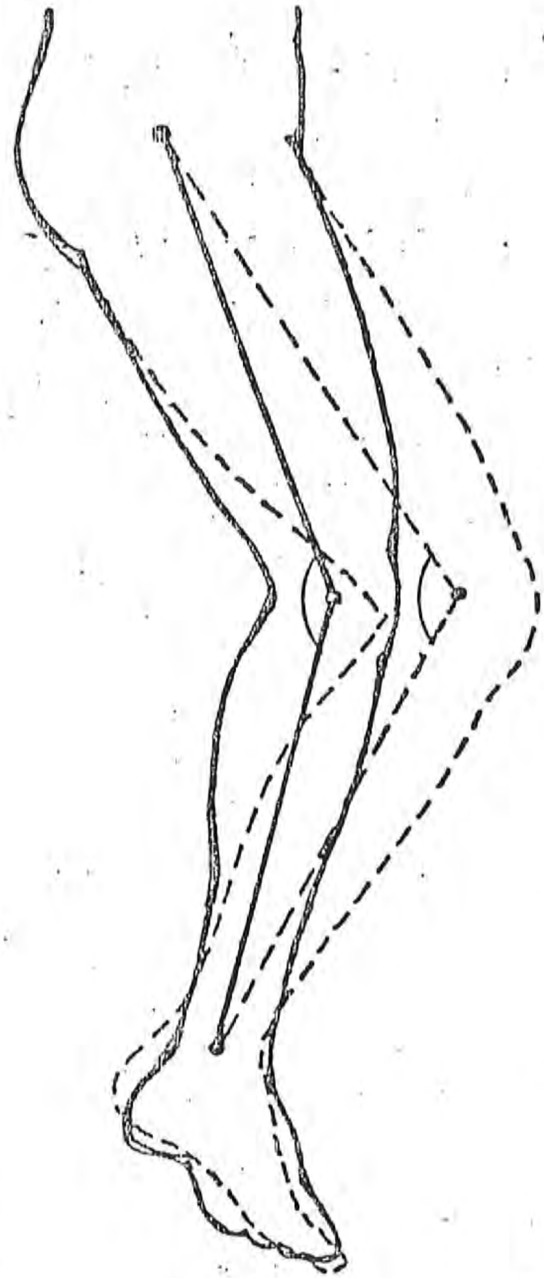

Fig. 1. Distortion of the angle of flexion at the knee by hip abduction/rotation. This type of problem occurs in gait analysis with plane images and is particularly important in pathological patterns of locomotion.

sums are not commutative. In the case of joint motion, the rotations may be taken about imbedded axes intersecting at the joint center. It was found that the conventional Euler Angles of precession, nutation and spin did not concur with the clinical notions of joint angles, but a different combination of ordered, finite rotations proved satisfactory. Morrey and Chao (1976) utilized this type of description in a study of passive motion of the human elbow joint. In this study, the humerus, and radius and ulna, are assigned rectangular Cartesian coordinate axes with specific orientations (using, for example, bony landmarks), and successive finite rotations about the imbedded radio-ulnar axes are used in the description of the orientation of the radius and ulna with respect to the humerus. The angles used are referred to as Euler angles.

Lewis and Lew (1977) point out that a better nomenclature would be "orthopedic angles". In their technical note, they generalize the theoretical notions discussed by Morrey and Chao by deriving an expression for the tensor of relative rotation between two body segments, which is independent of the orientation of the imbedded coordinate systems with respect to their segments and from which the orthopedic angles can be obtained.

Orthopedic angles for description of lower body segment orientations will be defined below. It was felt that the simplest approach for the purpose of gait analysis would be to utilize imbedded axes with specific orientations to aid in expressing the angles. Equivalent descriptions (except for sign convention) consisting of three orthopedic angles are used to specify thigh position with respect to the pelvis, and shank position with respect to the thigh. In addition an analogous system is used to characterize the orientation of the pelvis with respect to the walkway down which the subject progresses. However, since for the pelvis the rotations do not necessarily take place around some fixed point with respect to the walkway, the information derived concerns only pelvic orientation in space and does not completely specify position. Because of the complexity of foot motion, a set of only two ordered rotations are used, in this case to describe the orientation of the long axis of the foot with respect to the shank.

A set of orthogonal imbedded axes for each segment of the lower body may be easiest defined with the body in the following reference position: consider first the anatomical position. The plane roughly defined by the sacrum is normally tilted forward somewhat; it must be vertical in the new position. Line segments extending between the centers of the hip, knee, and ankle joints must be vertical. A line segment extending from the center of the calcaneum to the foot surface over the space between the second and third metatarsal heads of each foot must be perpendicular to the long axis of the shank and oriented directly anteriorly. Then the x_1 axis of each segment extends horizontally with positive sense to the subject's right. The x_2 axis of each segment extends horizontally with positive sense directly forward. The x_3 axis of each segment extends vertically with positive sense upward. If the subject is placed on the walkway facing the direction of progression, the orientation of the global coordinate axes, which form a spatial coordinate system for the walkway, would coincide with that just described for the axes of the lower body segments. The axes for each segment of the lower extremities may be considered to constitute a rectangular Cartesian coordinate system, with origin at the center of the most proximal joint of the segment. (See Fig. 2 below.)

The following set of orthopedic angles may be defined for the pelvis, thigh, and shank. For the pelvis, which does not necessarily rotate about a fixed point, no origin is assigned the axes and x_i denote imbedded axes somewhere in space with the orientation described above.

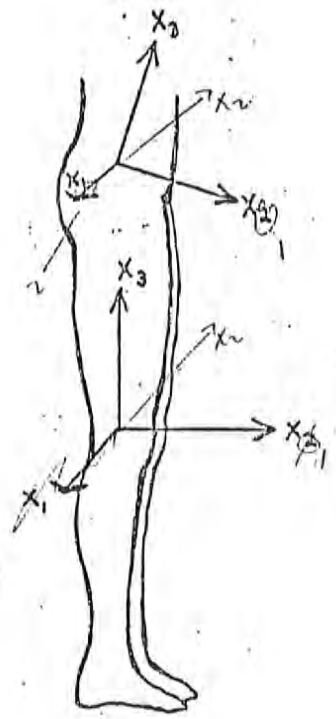

Fig. 2. Rectangular reference axes for the pelvis (upper frame) and segments of the lower extremities (lower frame). Pelvic axes reflect the fact that the pelvis is normally tilted forward somewhat in the standing position.

1.) With the axes of the segment aligned with those of the next most proximal segment (pelvic axes aligned with those of the walkway), the segment is first rotated through an angle θ_1 about the imbedded x_1 axis. This is the angle of:

Pelvic tilt (left-handed rotation is taken as positive);

Hip flexion/extension (right-handed rotation or flexion is positive);

Knee flexion/extension (left-handed rotation or flexion is positive).

2.) The segment is then rotated through an angle

θ_2 about the imbedded x_2 axis (it is important to note that the orientation of the imbedded axes change with the successive rotations.) This is the angle of:

Pelvic obliquity (upward rotation is positive for each side-this is left-handed rotation for the right side and right-handed rotation for the left);

Hip ab/adduction (abduction is positive-this is right-handed rotation for the right side and left-handed for the left);

Knee varus/valgus displacement (varus displacement of the shank is positive-this is right-handed rotation for the right side and left-handed for the left.)

3.) The segment is then rotated through and angle θ_3 about the imbedded x_3 axis to its actual position with respect to the next most proximal segment. This is the angle of:

Pelvic rotation (internal rotation is positive-this is right-handed rotation for the right side and left-handed for the left);

Hip rotation (internal rotation as described is positive);

Knee rotation (internal rotation as described is positive).

For the foot, the following set of two orthopedic angles may be defined which describe the orientation of the x_2 (long) axis of the foot with respect to the shank.

1.) With the foot and shank coordinate axes aligned, the foot is first rotated through an angle θ_1 about the imbedded x_1 axis. This is the angle of plantar/dorsiflexion (dorsiflexion or right-handed rotation is positive.)

2.) The foot is then rotated through an angle θ_2

about the imbedded x_3 axis to bring the long axis to its actual position. . This is the angle of ankle rotation (internal rotation as described earlier is positive.) (See Figures 3 and 4 for illustration.)

The clinical and biomechanical advantages of such a system of description lie in the fact that the information is presented in a form which is familiar and useful to both clinicians and bioengineers. A clinician will recognize that the angles defined for the hip, knee, and ankle joints are in accord with the medical terms which are used to label them. In particular, the joint angles are measured with respect to the proximal segment only, and are thus independent of the orientation of that segment. An engineer will recognize that, while the angles do not correspond exactly to conventional Euler angles, they are formulated in a similar manner, and techniques which utilize Euler angles may be readily generalized to make use of the orthopedic angles as well. Specifically, rigid-body dynamics is an area in which Euler angles are frequently employed and in which the orthopedic angles could also be used. A few notions concerning such applications will be discussed below.

The relative orientation of the two rectangular Cartesian reference frames may be expressed as a direction cosine matrix which represents a rotation of coordinates. Since the orthopedic angles uniquely specify the relative orientation of distal and proximal (or pelvic and global) frames, the corresponding direction cosine matrices may be written in terms of the orthopedic angles. (1) below relates distal to next most proximal frames for all segments except the foot:

$$(1) \quad \begin{bmatrix} C\theta_2 \overset{C}{\cancel{S}}\theta_3 & -C\theta_2 S\theta_3 & S\theta_2 \\ C\theta_1 S\theta_3 + S\theta_1 S\theta_2 C\theta_3 & C\theta_1 C\theta_3 - S\theta_1 S\theta_2 S\theta_3 & -S\theta_1 C\theta_2 \\ S\theta_1 S\theta_3 - C\theta_1 S\theta_2 C\theta_3 & S\theta_1 C\theta_3 + C\theta_1 S\theta_2 S\theta_3 & C\theta_1 C\theta_2 \end{bmatrix}$$

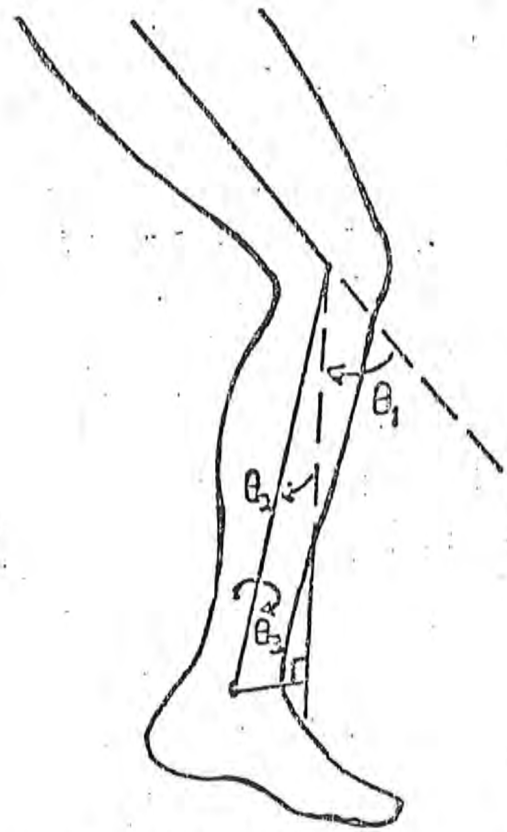

Fig. 3. Orthopedic angles fur the knee. Angles for the pelvis and hip are similar except for sign convention.

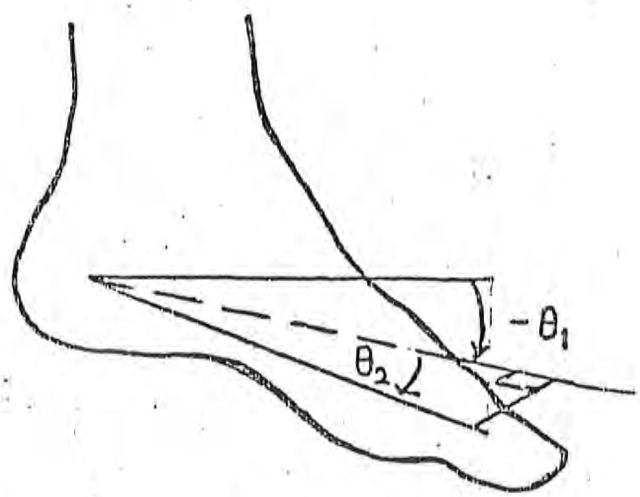

Fig. 4. Orthopedic angles for the foot

S and C are used to represent sine and cosine respectively. Right-handed rotations are assumed. In the cases where left-handed rotations are taken as positive, the arguments may be replaced by their negatives in the expression.

If the orthopedic angles for the foot are assumed to give a reasonable description of the overall position of the foot, i.e., if the foot is treated as a rigid body with the two degrees of freedom implied by the orthopedic angles, the direction cosine matrix relating the foot frame to the shank frame may be written:

$$(2) \qquad \begin{bmatrix} C\theta_2 & -S\theta_2 & 0 \\ C\theta_1 S\theta_2 & C\theta_1 C\theta_2 & -S\theta_1 \\ S\theta_1 S\theta_2 & S\theta_1 C\theta_2 & C\theta_1 \end{bmatrix}$$

Right-handed rotations are again assumed. The matrices are obtained by considering successive rotations of coordinates corresponding to the orthopedic angles taken in reverse order and direction of rotation (i.e., left-handed).

An important feature of Euler angles is that their time derivatives, each directed along its corresponding instant axis of rotation, represent components of the instantaneous angular velocity of the moving body with respect to the "fixed" frame. Similarly, the components of the angular velocity of a distal segment with respect to the proximal frame may be written in terms of the orthopedic angles and their time rates of change. For the pelvis, thigh, and shank:

$$(3) \qquad \begin{aligned} \omega_1 &= \dot{\theta}_1 + (\sin \theta_2)\dot{\theta}_3 \\ \omega_2 &= (\cos \theta_1)\dot{\theta}_2 - (\sin \theta_1)(\cos \theta_2)\dot{\theta}_3 \\ \omega_3 &= (\sin \theta_1)\dot{\theta}_2 + (\cos \theta_1)(\cos \theta_2)\dot{\theta}_3 \end{aligned}$$

For the foot, treated as a rigid body:

$$(4) \qquad \begin{aligned} \omega_1 &= \dot{\theta}_1 \\ \omega_2 &= (\cos\,\theta_1)\dot{\theta}_2 \\ \omega_3 &= (-\sin\,\theta_1)\dot{\theta}_2 \end{aligned}$$

Right-hand rotations are again assumed, and for left-hand rotations the argument may again be replaced by its negative.

Normally, angular velocity is referred to an inertial frame, as in the LaGrangian treatment of rigid body dynamics. This would require transformation of components of the angular velocities of the segments distal to the pelvis, determined by (3) and (4) with respect to the accelerated proximal frames, to the global frame.

A variety of applications of such relations in examining the kinematics and dynamics of locomotion may be imagined. For example, in a study currently being undertaken by the author with preliminary orthopedic angle data from normal subjects, the generalized forces which must be applied at the joints to achieve normal leg motion during locomotion are being estimated numerically using a LaGrangian formulation of the problem.

B. ANALYTICAL TECHNIQUES

Analytical techniques were developed by the author for calculation of the orthopedic angles from raw data taken at the Gait Analysis Laboratory, Children's Hospital and Health Center, San Diego. Much of this work was eventually adapted for numerical analysis in the form of a computer program which was written to process raw data taken from film records of subjects walking. A brief description of the system used to take the data and the techniques used to analyze them will be given below.

Existing facilities include a premarked walkway down which subjects progress. High-speed motion picture cameras record the action from a front view and two lateral views. The optical axes of all three cameras project directly over the center of a force plate located in the walkway (the center of this force plate serves as the origin of the global coordinate system mentioned earlier). Gait analysis subjects are outfitted in small briefs and a number of markers and targets are placed on their lower bodies to aid in the determination of limb orientations. Some of these will be discussed in further detail subsequently.

The subjects normally take a number of walks on the walkway while the cameras record their progress. Data from the film taken is later recovered with use of a motion analyzer (Vanguard Mfg. Co., New York), a device equipped to measure locations of points of an image projected onto a rear-projection screen. The right and left sides of a walking subject are analyzed seperately, usually with data from two different walks.

Each view of a gait study includes a synchronized digital chronometer. Corresponding frames for the front view and the appropriate side view for whichever side is being analyzed are read on the motion analyzer; this process is repeated for small increments of walking time until an entire walking cycle, beginning and ending with heel strike on the side being analyzed, is read. (Reading a frame is used to mean recording the locations of all relevant points in the image.) The information is encoded onto magnetic tape as it is taken. This tape is used to transfer the information to a computer for processing.

This is the general gait analysis procedure for determining lower body segment orientations, which was followed originally and is used currently. For the implementation of orthopedic angle measurement, the part of the procedure which had to be altered involved the fundamental methods of data analysis. Spatial coordinates of various targets on the moving body had to be calculated (measurements were previously made almost entirely from single plane views), and a number of new or different targets had to be included to obtain the necessary information for calculation of the orthopedic angles. The algorithms on which such calculations are based had to be developed and employed in a computer program for data analysis.

The algorithm for calculating the location of a point visible from the front and side views is derived from the optical model illustrated in Figure 5. The coordinate system shown is the walkway system described earlier. The X_1 and X_2 coordinates of a point are obtained by considering the intersection of two lines which are constructed with information from each view. There is ambiguous information concerning the X_3-coordinate of the point; the values for this parameter calculated with data from the two views may disagree slightly, i.e., the lines illustrated may actually be skew lines. In this case, the X_3 value is taken as the average of those obtained from the different views.

Certain points which are used are consistently visible from only one view. Only two coordinates are calculated in these cases, using another set of equations which require an estimate of the missing coordinate value. The value for a nearby point is usually used for an estimate. The calculation of spatial coordinates represents the initial block of the computer program.

In the second part of the program, preliminary to the calculation of the orthopedic angles, vectors parallel to the sets of axes described for the lower body segments are constructed using the spatial data. (The components of these vectors are all referred to the global coordinate system.) Here the superscripts p, t, s, and

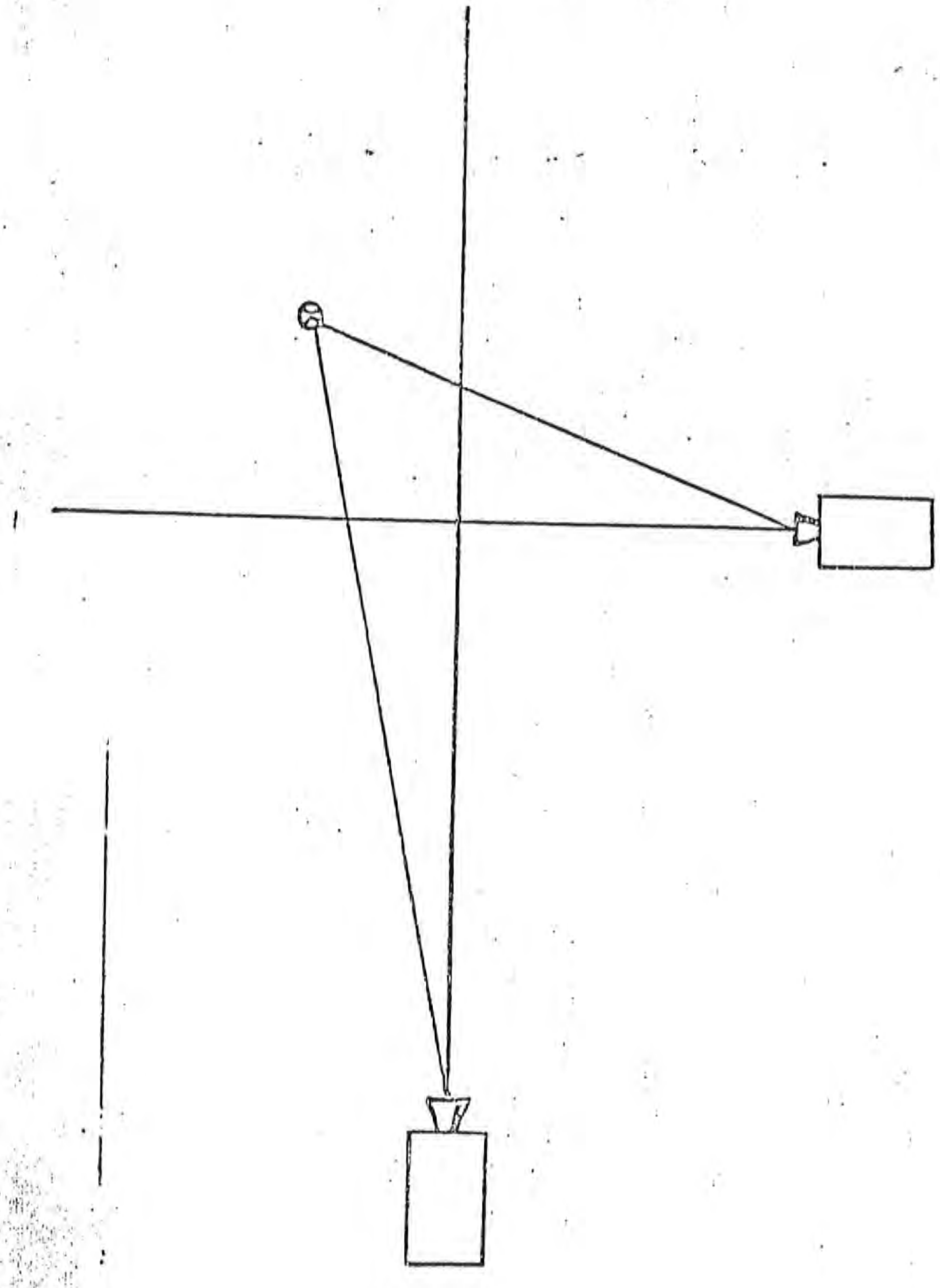

Fig. 5. Optical model for the determination of X_1 and X_2 coordinates of a point in space. The location is determined as the intersection of two projected lines.

f will be used to refer to the pelvis, thigh, shank, and foot, respectively. $\underline{x}_i^j$ are vectors as described in symbols.

$\underline{x}_1^p$ is represented by a line segment between corresponding points on the iliac crests, directed from left to right. Markers are placed over the iliac crests, attached to a belt secured around the hips. Only the x_1 and x_3 components of the vector can be obtained directly, since the markers are readily visible from only the front view. The x_2 component is obtained by assuming the vector to be perpendicular to a stick target which is attached to the belt and projects forward from the pelvis in a sagittal plane. $\underline{x}_2^p$ is represented by a line segment extending from the tip to the base of a stick target secured over and perpendicular to the sacrum. This target is visible only from the side views, so only the x_2 and x_3 components of the vector are obtained directly. The x_1 component is obtained through the assumed orthogonality of $\underline{x}_1^p$ and $\underline{x}_2^p$. $\underline{x}_3^p$ is obtained as the vector product $\underline{x}_1^p \times \underline{x}_2^p$.

$\underline{x}_3^t$ is represented by a line segment directed from the center of the knee joint to the center of the hip joint. (The locations of the hip, knee and ankle joints are estimated by the film reader with the aid of attached targets and external landmarks.) A vector is also constructed which is directed from the center of the knee joint to a marker over the upper patella; the vector product of this vector and $\underline{x}_3^t$ is taken as $\underline{x}_1^t$. $\underline{x}_2^t$ is obtained as the vector product $\underline{x}_3^t \times \underline{x}_1^t$.

$\underline{x}_3^s$ is represented by a line segment directed from the center of the ankle joint to the center of the knee joint. A vector is also constructed which is directed from the base to the tip of a stick target attached with a belt perpendicular to and projecting forward from the tibia. $\underline{x}_1^s$ is taken as the vector product of this vector and $\underline{x}_3^s$. $\underline{x}_2^s$ is obtained as the vector product $\underline{x}_3^s \times \underline{x}_1^s$.

For the foot, only the vector $\underline{x}_2^f$ is constructed. It is represented by a line segment directed from the center of the calcaneum to a marker located over the space between the second and third metatarsal heads. (The location of the center of the calcaneum is estimated by the film reader with the aid of external landmarks.)

Expressions for the orthopedic angles for the pelvis and hip and knee joints will be given below. $\underline{e}_j^i$ are obtained as $\underline{x}_j^i/|\underline{x}_j^i|$. In this case, the superscripts p and d denote the proximal and distal segments being considered, respectively. (For the pelvis, $\underline{e}_j^p$ may be taken to be unit base vectors of the global coordinate system.)

(5)
$$\theta_2 = S\ \arcsin[\underline{e}_3^d \cdot \underline{e}_1^p] \quad 2$$
$$S = \begin{cases} +R \text{ for hip, knee} \\ -R \text{ for pelvis} \end{cases}$$

R = +1 R
-1 L

(6)
$$\theta_1 = S\ \arcsin[(\underline{e}_3^d \cdot \underline{e}_2^p) \sec(\theta_2)]$$
$$S = \begin{cases} +1 \text{ for pelvis and knee} \\ -1 \text{ for hip} \end{cases}$$

(7)
$$\theta_3 = -R\ \arcsin[(\underline{e}_2^d \cdot \underline{e}_1^p) \sec(\theta_2)]$$

The following expressions give the orthopedic angles defined for the foot:

(8)
$$\theta_2 = -R\ \arcsin[\underline{e}_2^f \cdot \underline{e}_1^s]$$

(9)
$$\theta_1 = \arcsin[(\underline{e}_2^f \cdot \underline{e}_1^s) \sec(\theta_2)] \quad 3$$

The calculation of the orthopedic angles, repeated for each frame of film read, represents the final phase of the gait analysis computer program.

II. ERROR AND DISCUSSION

There are a number of sources of uncertainty which are present when orthopedic angles are measured via a visual system of gait analysis. In this section, the physical error inherent in the particular system of data recovery used at Children's Hospital and Health Center will be discussed, as well as more general theoretical uncertainties and problems in gait analysis.

One of the first sources of uncertainty which must be dealt with lies in the definitions of the orthopedic angles themselves. In the text, the segments involved are assigned imbedded axes and simply treated as rigid bodies during subsequent rotations. Clearly soft-tissue motion may vary and this rigid-body assumption is not entirely correct. More rigorous definitions usually involve the relative orientations of the bones of the segments considered (Morrey and Chao, 1976). The visual means of measurement described in the text was chosen to try to reflect the orientation of the bones of the segments. The important question is: How accurately and reproducibly can the necessary reference frames for the body segments be assigned, theoretically, in different subjects? The factors under consideration involve inherent differences in bone shape and structure, and alignment. Of course, in practice, other differences in build may influence external appearances which are used to estimate limb orientations. The question of how reproducibly reference frames may be assigned in different individuals cannot be answered with empirical gait analysis data; study of anthropometric data may provide insight. However, all indications are that the more important component of error in a visual system is due to general estimation of bone orientation by the use of surface landmarks, and inaccuracies introduced by the data recovery process.

Another theoretical question involves shank and foot orientations. The reference frame for the shank is constructed so that rotation of the segment about its long axis is reflected in the knee rotation measurement. However, some rotation of the segment may occur along its length, as occurs in the forearm during pronation/supination, which would appear externally as a torsion. The tibia and fibula are much more constrained in this respect than the radius and ulna, but the effect may nevertheless be present and may not be negligible in magnitude in comparison to knee rotation. Foot measurements, particularly ankle rotation, would be affected.

The foot presents further questions in terms of describing motion. "Ankle" motion is normally a composite of motion at both the ankle and subtalar joints, the latter of which does not have an axis of rotation conveniently aligned with the bony landmarks used for analysis (Close, Inman, Poor, and Todd, 1967). Furthermore, small movements at the other joints of the foot continuously distort the segment under dynamic conditions. The importance in locomotion of supination and pronation, largely a result of subtalar motion and ignored in this paper, needs further investigation as relates to measurement in gait analysis.

The error which may arise in the particular gait analysis procedure used at Children's Hospital and Health Center will be discussed next, beginning with the actual performance of the study. A source of error related to the construction of the lower body reference frames lies in the placement of the targets used with gait analysis subjects. Several targets are used by themselves to determine the vectors required to define the reference frames. The markers are all placed by trained technicians, but some slippage of belts can occur. In addition, in some cases the changes in momentum of stick targets may cause oscillation or displacement. In most subjects, with respect to the landmarks and other criteria used to place targets, the orientation of vectors determented by the targets may be determined to within about 3°, but target slippage and movement may reduce this to 4°-10° in some cases. An estimate of 3°-4° uncertainty in the determination of vector orientation, due to uncertainty in target placement, is reasonable to expect in a normal gait study. A concommittant uncertainty ranging up to the same magnitude can also be expected in the orthopedic angles measured.

It should be noted that pelvic measurements, made with respect to the global reference frame, are affected if the subject does not proceed directly along the walkway in the X_2 direction. This problem is usually negligible for adult subjects, but may be more important with younger patients. Since a number of walks are recorded, a film sequence can usually be found which minimizes this problem.

The error which may be incurred during the several stages of the data recovery process will next be considered. The first source of error can be classified as optical uncertainty. This represents the limits of resolution and total distortion of the images of subjects introduced by the optical systems of the high-speed cameras used to record them, and the cine projection device (Vanguard) used to measure them. The sources of distortion include lenses, prisms, and possible bending of the film. The resolution in views from the front and left side cameras is to less than 3mm., for an image point at the global origin. Because of a different optical system resulting in a grainer image, the right side view has a resolution of about 5mm. at the global origin. Some curvature is also introduced in the projected images such that a horizontal line experiences about 3% distortion over the total width of the field. The effect is less noticeable in the center of the field.

The effects of these uncertaintities on the determination of vector orientation may be considered. Because a straight line segment can experience 2%-3% distortion, an uncertainty of up to .02-.03 radians, or 1°-2°, can be expected in vector orientation. The effects of end-point uncertainty due to limits of resolution are negligible in terms of determining the orientations of larger vectors used in the program; an uncertainty of 2°-3° could be expected for the smallest vector determined. However, resolution is seldom a problem since specific point targets are only used in two cases, on the pelvic belt.

Two other possible mechanical sources of error are the sonic digitizer, the device which encodes the locations of points on the projected image, and the computer which processes the data. The digitizer includes a moveable unit with a cross-hair, which is placed over the points to be recorded by the technician reading the film. Its theoretical resolution is on the order of .1mm. or less, which corresponds to about 1 mm. in the image at the global origin. Thus the error introduced at this stage by the machine is small. The round-off error introduced by the computer is also negligible.

An important potential source of error in the data linkage is the reader recording the information from the Vanguard projection screen. A significant component of absolute reader error results from estimation of bone position using surface landmarks and targets. During the course of this research a study was attempted, utilizing a cadaver with pins driven into the bones of the segments and projecting from the surface, in an attempt to correlate estimated bone orientations as measured using the standard gait analysis procedure, and actual bone orientations as revealed by the pins. Relative orientations of pins and bones were measured following dissection. Unfortunately, due to technical difficulty, no useable results were obtained. However, some measure of the relative uncertainty in the reading process can be obtained by considering the scatter of measurements made from different readings of the same film sequences. Only preliminary results are available for the orthopedic angles as measured by the new system; some results are summarized below in Table 1.

A larger sample of additional information is available on reader scatter in plane image measurements. Some results are displayed below in Table 2 for two of the previously measured parameters (not orthopedic angles but projections), and should give some further indication of the scatter of angular measurements obtained with the type of data recovery system used.

For hip and knee measurements, preliminary results indicate a greater scatter for the three-dimensional orthopedic angle measurements than for comparable plane-projection angles. In addition, it should be noted that the incidence of values outside the general trend of the measurements is greater with the orthopedic angles as measured. Reader inexperience undoubtably played a role in the results and scatter will eventually decrease somewhat as the system becomes more familiar. But other factors may also have an effect. Since information must be drawn from two images to compute the orthopedic angles, the uncertainty is increased. In addition, as mentioned, the orientations of the smaller vectors constructed in the program are in greater doubt than those of longer ones, simply because of the length of the line segments and the effects of endpoint uncertainty. The most prominent example is the so-called "patellar vector", which is an important determinant of calculated femoral orientation.

As described in the text, this vector is taken as directed from the center of the knee joint to a marker over the center of the upper patella (with the subject in the standing position). Geometrically, this vector and the line segment extending between the centers of the hip and knee joints are taken to determine a "sagittal plane" for the femur. The marker over the patella was chosen because the center of the patella

Orthopedic Angle	no. of data	mean variation of measurements	st. deviation of variations
Pelvic Tilt	7	1.00	.65
Pelvic Obliquity	7	.67	.47
Pelvic Rotation	8	.94	.56
Hip Flexion/ Extension	7	2.43	.73
Hip Ab/ Adduction	8	2.50	1.60
Hip Rotation	8	4.56	3.22
Knee Flexion/ Extension	8	4.00	3.09
Knee Varus/ Valgus	8	3.38	1.85
Knee Rotation	8	3.69	3.02
Plantar/Dorsi-Flexion	7	1.93	1.13
Ankle Rotation	7	1.93	.67

Table 1. Scatter of Orthopedic Angles from preliminary readings of a single film sequence by different readers.

no. of data	mean variation of measurements (degrees)	st. deviation of variations (degrees)
	Same Reader Hip Flexion/Extension	
18	1.89	1.23
16	2.59	1.61
20	1.23	.95
	Knee Flexion/Extension	
15	1.77	1.07
20	1.13	1.02
15	1.53	.95
	Different Reader Hip Flexion/Extension	
16	2.18	1.40
16	1.88	.90
17	1.59	1.16
	Knee Flexion/Extension	
17	2.50	1.79
15	1.53	1.06

Table 2. Scatter of plane-image joint angles from assorted readings of film sequences.

was left to be a good indicator of an anterior direction for the femur, and as the patella moves along the inter-condylar groove in knee flexion, the marker appears to remain situated over the groove. Other markers for the femur or stick targets placed in the same area were felt to be unsatisfactory because of soft-tissue motion serving to obscure bone orientation.

However, the patellar vector is the smallest constructed and has the largest relative uncertainty of endpoint location. In addition to possible inaccuracy in estimation of the location of the center of the knee joint, the marker is not always clearly visible from the side view. Fortunately, the X_1 and X_2 components of the vector are the most accurately determined, and they are generally the most important as relates to the determination of the orthopedic angles. However, the uncertainty introduced may be considerable, as evidenced in the scatter of hip and knee orthopedic angles, and this may be particularly important in the angles of hip and knee rotation and knee varus/valgus displacement.

Varus/valgus displacement is probably the measurement most sensitive to the uncertainty. The expected, and usually measured, variation in this parameter throughout the walk cycle is frequently not significantly greater than the uncertainty present in the measurement, in normal gait analysis subjects. A trend in the pattern of varus/valgus displacement does seem apparent, however. Although the absolute values of the measurements are questionable in some cases, the general shape of the varus/valgus curve over the walk cycle may contain useful information. Of course, in pathological cases where constraints at the knee are weak and varus/valgus displacements much larger than normal in magnitude, the measurement may be a valuable clinical tool.

The reproducibility and accuracy of orthopedic angle measurements may improve as measuring methods and technology are refined. As an example, one suggestion for improving the reproducibility of hip and knee measurements is the use of the shank in place of the patellar vector to determine the femoral reference frame, with the assumption that the varus/valgus or carrying angle is always small. However, further investigation of changes in carrying angle of the shank when the knee is in flexion needs to be made, and the method is clearly of no use during most of the stance phase if floor reaction forces induce significant varus/valgus displacement, which would seem to be the case.

For goniometers, more effective mechanisms may be conceived, but mechanical linkages are normally beset by the same problems of soft-tissue motion that can affect visual systems of analysis. More detailed methods of measuring segment positions have been described (Kinzel, Hall, and Hillberry, 1972). Direct linkage with the bones of the segments, and analogously, implacement of bone pins in visual systems, provide a much more accurate means of joint angle measurement, but unfortunately such procedures are not clinically applicable in general.

Formulation of some elements of lower body kinematics and dynamics was presented earlier, based on a simple model of rigid-body motion. The effects of simplifying assumptions and uncertainties in measurement on locomotion dynamics will next be considered briefly. To begin with, the three degrees of freedom of motion at a joint (two at the ankle) which are implicit in the orthopedic angle description represent a somewhat arbitrary assumption. For example, while the hip may be reasonably assumed to allow three degrees of freedom of movement, the knee may be equally reasonably assumed to allow motion in only one direction. It is clear that in large part, knee rotation and varus/valgus displacement represent motion which takes place against passive forces of constraint, and thus these measurements are indicative of "virtual work" done against the constraints, which may be returned depending on the elastic nature of the constraints. This type of consideration would be important, for example, in study of the energetics of locomotion. To clarify, the orthopedic angles may be characterized as purely kinematical quantities with no consideration of the nature of the dynamic forces involved.

A basic assumption often made in gait analysis is that no significant translation occurs at the joints of the joints of the lower body under consideration, i.e., there exists a joint center which remains fixed with respect to both segments of a joint. A large number of studies exist which show that the instant centers of rotation of these joints are in reality not fixed but undergo small changes in position relative to the two segments (for example, Smidt, 1973). Changes in the instant centers of rotation are not generally considered significant, but they may have some practical implications for the function of dynamic components of the mechanical system. For example, Grant (1973) demonstrated that the location of the instant center of rotation of the temporomandibular joint has an important effect on the moment arms of muscles moving the jaw. Treatment of the segments of the lower body as affixed to each other at joint centers clearly provides a good approximation for many basic studies of locomotion. For some purposes, a more detailed analysis might be desired; techniques could presumably be developed in an improved visual system to permit such analyses.

In any study of locomotion dynamics, the actual uncertainty of the measurements will be important and have a predictable effect on the uncertainty of the results. A qualitative note might be made that some scatter in angular measurements between readings and different gait studies seems to be accounted for by "DC" shift in the valves of the measurements and that time rates of change of the angles may display somewhat less relative scatter.

III. CONCLUSION

In conclusion, orthopedic angles for clinical gait analysis have been explicitly defined, in the sense described by Morrey and Chao (1977) and Lewis and Lew (1977), as ordered sets of finite rotations specifying relative orientation of lower body segments. The advantages of the angles are that they correspond with accepted medical terminology and lend themselves to use in study of lower body kinematics and dynamics. The particular visual system of gait analysis used at the facility at which the author worked requires interpretation of data recovered from motion picture film of walking subjects. Interpretation involves construction of reference axes for lower body segments, which are used in explicit expressions for the orthopedic angles derived from their definitions. It is hoped that, even though techniques will undoubtably change to improve the accuracy and precision of the measurements, the use of orthopedic angles themselves in clinical research and diagnosis will become established and provide some sort of sound convention for gait analysis.

Problems of accuracy and precision were discussed in the second section, both general and specific to the particular system used. On the basis of the discussion, it is reasonable to expect an uncertainty of 2°-5° in the orthopedic angles as measured in this type of system, depending on the measurement, the walking pattern of the individual, and the position of the individual. Pelvic and ankle angles are generally more reproducible, hip and knee measurements less so. Unfortunately, the question of how well the segment orientation estimated with the aid of external landmarks reflects actual bone orientation was not answered due to the failure of the cadaver study. Thus additional error may be present, although there is reason to hope that its magnitude is not greater than the relative uncertainty already discussed. Theoretical uncertainties and problems were also discussed in the second section, with the hope that they will be considered by researchers in the field in the future studies of gait.

As suggested earlier, some preliminary work has been done analyzing walking patterns of normal adults participating in gait studies. The subjects chosen had plane-projection measurements matching established normal values as closely as possible. As a final note, the experimental results of these gait studies are presented below in Figures 6a and 6b. They represent the approximate ranges of orthopedic angle measurements from four to five adults. (If plane projection measurements were felt to deviate too far from the established values, the orthopedic angles roughly corresponding to the plane angles were discarded.) Workers in the field will note that, qualitatively, a number of the curves, particularly flexion/extension measurements, resemble those obtained from plane image (or electrogoniometric) methods, for normal adults. It is felt that an improtant application of orthopedic angles will be in the analysis of pathological gait, and that in such cases the results will show considerably greater difference from those obtained by plane image analysis, than is seen in the case of normal gait.

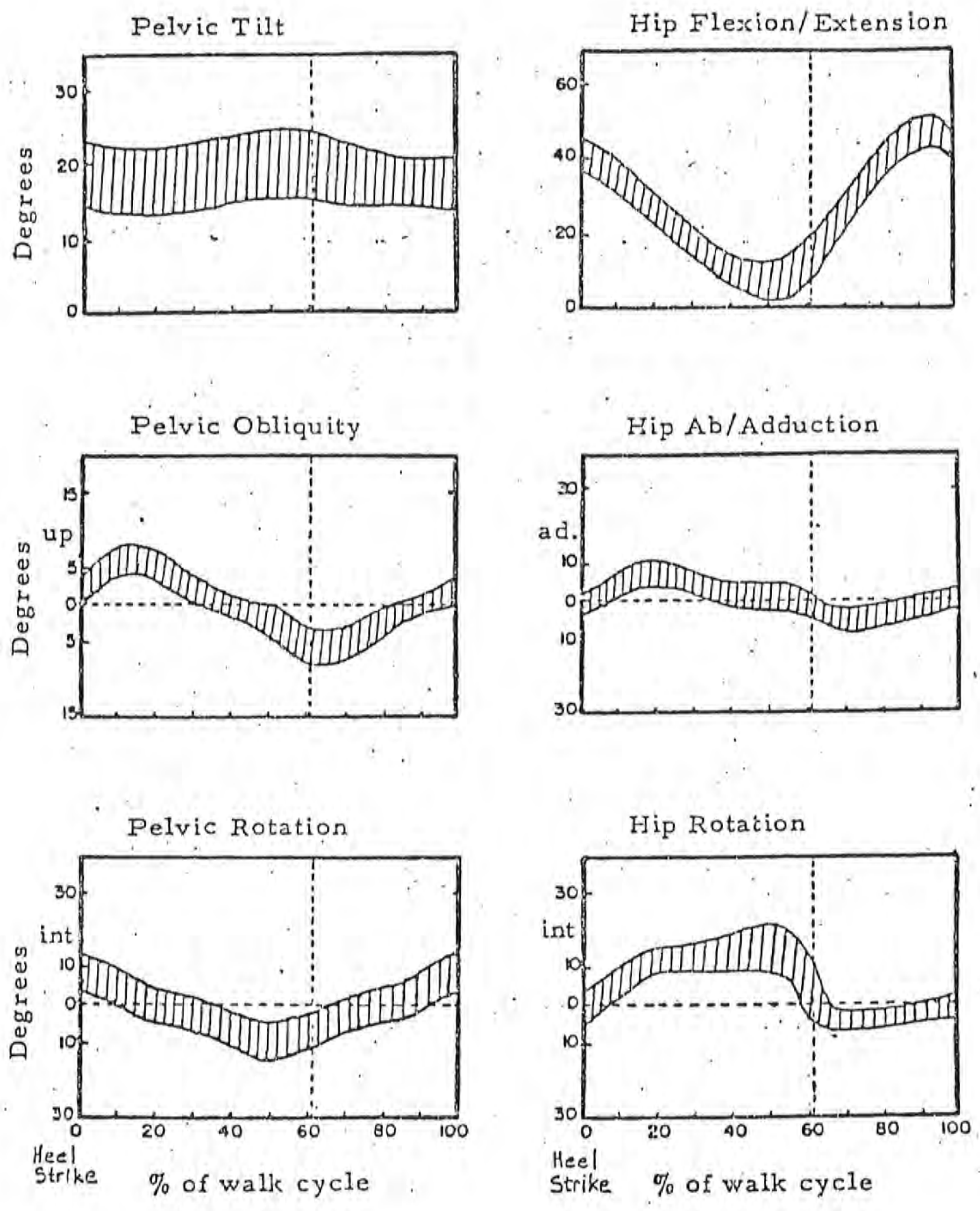

Fig. 6a. Preliminary range of orthopedic angle measurements for normal adult subjects, pelvis and hip

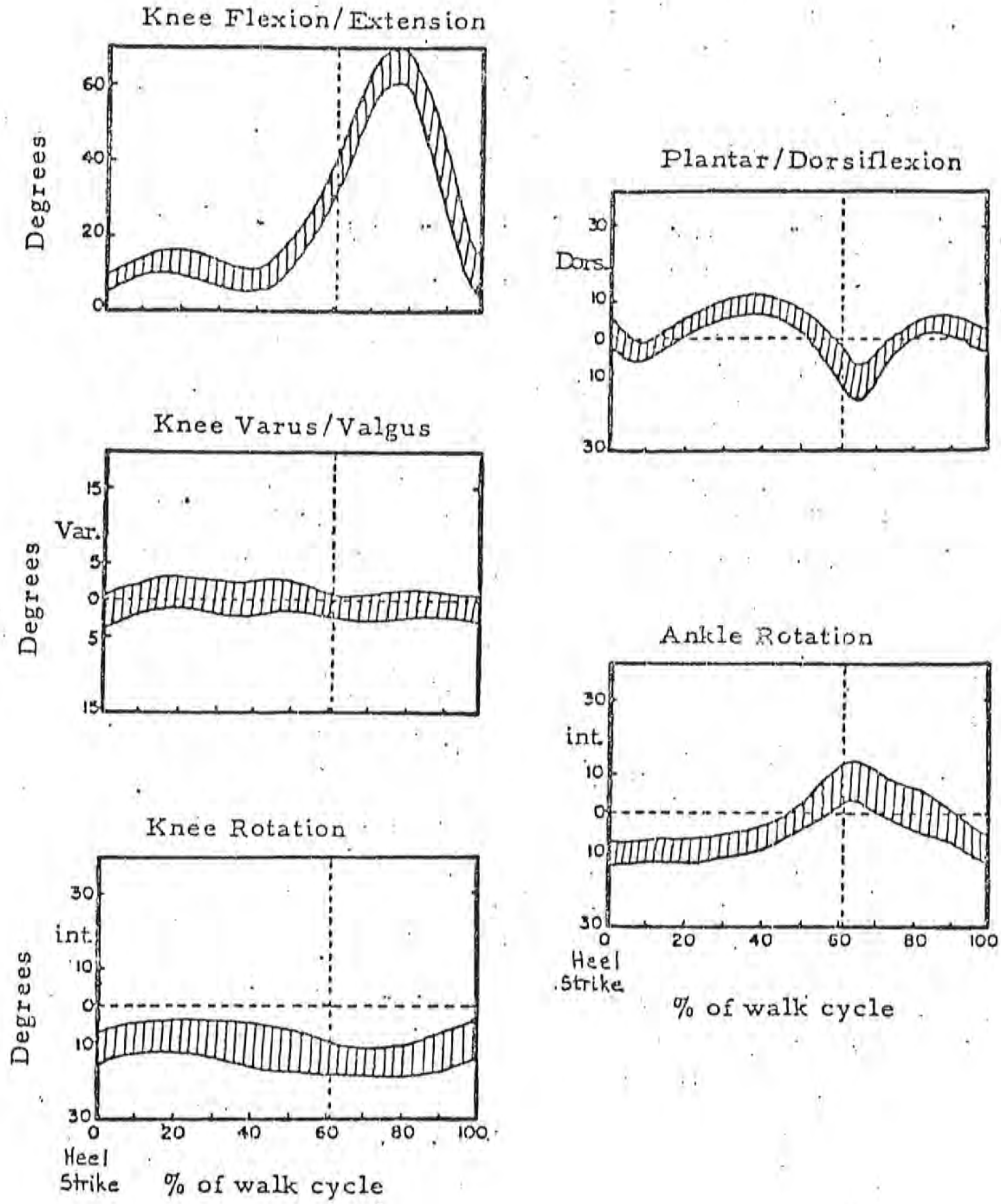

Fig. 6b. Preliminary range of orthopedic angle measurements for normal adult subjects, knee and foot

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