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KINEMATIC ANALYSIS OF HUMAN MOVEMENT

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Understanding the kinematics of human movement is of both a basic and an applied value in medicine and biology. Motion measurement can be used to evaluate functional performance of limbs under normal and abnormal conditions. Kinematic knowledge is also essential for proper diagnosis and surgical treatment of joint disease and the design of prosthetic devices to restore function.

In general, kinematic analysis of human movement can be categorized into two main areas: 1) Gross movement of the limb segments interconnected by joints, where the relative three-dimensional joint rotation is described by adopting the Eulerian angle system. With proper selection of axes of rotation between two bone segments, the associated finite rotation is sequence independent. This concept is particularly useful, since it matches precisely the clinical definition of joint motion. 2) Detailed analysis of joint articulating surface motion, where generalized three-dimensional, unconstrained rotation and translation are described utilizing the concept of the screw displacement axis. Knowing the surface geometry and soft-tissue constraints, the movement of an articulating joint can be analyzed to provide basic information for lubrication and wear studies. In addition, with appropriate numerical differentiation, velocity and acceleration can be obtained from the displacement information described by the above two methods.

Currently available measurement techniques of human movement can be classified into three categories: 1) electrical linkage methods; 2) stereometric methods and biplanar roentgenographic methods; and 3) accelerometric methods. Each system has its unique advantages and limitations in terms of the operational principle, instruments required, data reduction, and type of information produced. Representative analyses of human upper and lower extremity movement will be included as illustrative examples.

Keywords *— Joint, Kinematics, Motion.*

INTRODUCTION

Man's interest in the pattern of his movement goes back to prehistoric times and was depicted in cave drawings, paintings and statues. However, the first

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systematic investigation of human movement was not done until the fifteenth century by Leonardo da Vinci in his "Notes on the Human Body." Since then, many theoretical bases and experimental techniques have been developed for the kinematic analysis of sophisticated human movement. Since the main functions of the musculoskeletal system are to provide mobility and sustain load, it is reasonable to assume that mechanical factors play an important role in the function of this system. To determine these mechanical factors, motions and loads must be quantitated in precise mechanical terms. Kinematics is the study of body motion without reference to the forces causing this motion. This fundamental branch of dynamics finds a challenging application in the study of human movement.

In kinematic analysis, a complete and accurate quantitative description of even the simplest movement requires large volumes of data and variables. The complete kinematics of any body segment in a three-dimensional spatial system requires 15 data variables (21). These include the position vectors, linear velocity and acceleration of the segment's center of mass, angular orientation, angular velocity, and angular acceleration of the segment in two planes.

In order to describe these kinematic variables, a convention or coordinate system is required. Using a nonmoving inertial system, the absolute motion of the segment can be described. On the other hand, with the local coordinates attached to each segment, relative motion between segments can be calculated. Either an absolute or relative description of body movement has an important role in the kinematic analysis of human movement. This presentation will concentrate mainly on relative movement between human body segments, in other words, the kinematics of anatomical joints. First, various types of joint models and their associated motions will be discussed. Second, the theoretical basis for possible kinematic descriptions of these motions will be presented. Finally, currently available measurement techniques of human movement will be examined.

KINEMATIC MODELS OF HUMAN JOINTS

When motion of an anatomic joint, more specifically, a diarthrodial joint, is to be measured, a kinematic model of the joint should be established. Joint function is determined primarily by the shape and contour of the contact surfaces and constraints of the surrounding soft tissue. In reality, all anatomic joints have six degrees of freedom (DOF) in which six independent parameters must be measured and described if the relative positions of the attached body segments are to be defined. However, depending on analysis objectives and degree of accuracy requirements, simplified models are usually adopted. From the engineering kinematic point of view, the classification of models depends on the degrees of freedom of motion. On the other hand, medical classifications are usually based on the shape of the joint surface.

Hinge Joint

A hinge joint, or revolute joint, is the simplest but most common model used to simulate an anatomical joint in planar motion. Movement of the moving segment is confined to one plane about a single axis embedded in the fixed segment. In general, hinge motion includes both ginglymoid movement, such as in the elbow joint and the interphalangeal joints of the finger, as well as pivotal, or trochoid movement, such as the articulation between the radius and ulna where an arch-shaped surface rotates about a rounded, or peg-like pivot.

General Planar Joint

This model is usually used to simulate more general planar joint movement in which relative motion between all points takes place in parallel planes without a single fixed axis or center of rotation. This joint has three DOF, namely, two translations and one rotation. Usually, this motion consists of gliding movement such as that between the carpal bones of the wrist. In addition, this general three degrees of freedom planar-joint model has also been used for the analysis of knee-joint motion.

Universal Joint

The universal joint allows rotation about two axes through the joint and has two degrees of freedom. Anatomically, the universal joint is associated with two types of articulating joints. In one type, a saddle-shaped bone fits onto a socket that is concave-convex in opposite directions such as the articulation of the first metacarpal and trapezium. The other type of articulation is the ellipsoidal or condyloid joint such as the wrist joint where movement takes place in two perpendicular planes.

Ball and Socket Joint

This joint consists of a ball-shaped head that fits into a concave socket where movement of the moving segment takes place through rotation about three axes that intersect at the joint center. The relative motion is characterized by all points of the moving segment traveling on concentric spheres about the single joint center on a fixed body. A ball and socket joint, or enarthrosis, has three DOF and is the joint most commonly used to model three-dimensional joint movement such as that of the shoulder and hip joints.

General Spatial Joint

For completeness, a general spatial joint is included which does not assume any limitation on the number of degrees of freedom between the moving and fixed segments. The moving body is allowed six DOF, namely, three translations and three rotations. This model is commonly used when only detailed relative movement of the articulating surfaces is examined. The measurement and description of the relative motion associated with the general spatial joint are usually more complicated than are those of the simplified models. Nevertheless, it has been widely used for study of the human knee and wrist joints.

ANALYTIC DESCRIPTION OF JOINT MOVEMENT

Planar Motion

In general planar motion, the moving segments can have both translation and rotation about the fixed segment. Because of the translational component of motion, the center of rotation or axis of rotation for the moving segment will change throughout the course of motion. At any point in time, an approximate center of rotation can be determined, which is defined as the instantaneous center of rotation (ICR). Since the velocity of a point on a rigid body experiencing rotation during a small period of time must be perpendicular to a line joining the point and the center of rotation, this specific property can thus be used to determine the ICR graphically. In experimental measurements, however, it is nearly impossible to determine the velocity of different points on a body in motion. An alternate method for approximating the ICR was described by Franz Reuleaux in 1876 (16). In this method, the instantaneous locations of two points on the moving segment are identified from two consecutive positions within a short period of time, and the intersection of the bisectors of the lines joining the same points at the two positions defines the ICR (Fig. 1). For a true hinged motion, the ICR will be a fixed point throughout the movement. Otherwise, loci of the ICR or centrodes will result. If the fixed segment is taken as the reference member and the motion of the moving segment is used to define the ICR, the resulting ICR will form a curve on the fixed segment called the fixed centrode. On the other hand, if the moving segment is used as the reference, the curve of the ICR determined by the relative motion of the fixed segment will form the moving centrode on the moving segment.

In practice, determination of the ICR by the above-described method is highly sensitive to error in the location of the points used to define the individual ICRs, and the ratio of these errors especially increases exponentially as the individual displacements or time increments are made smaller (15). Increasing the size of these incremented intervals will definitely decrease the error in determining the ICR. However, with larger intervals, the true kinematics will not be faithfully imitated.

For description of general planar or gliding motion of the articular surfaces, the terms sliding, spinning and rolling are commonly used. Sliding motion is defined as the pure translation of a moving segment against the

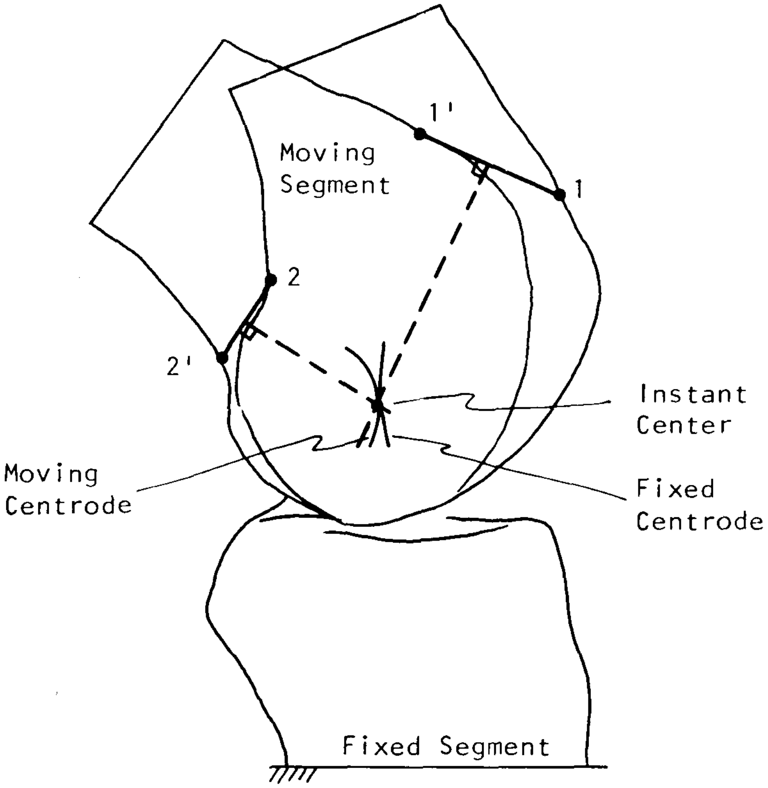

FIGURE 1. Determination of the instant center of rotation by Reuleaux's method. The points 1 and 2 displaced to 1' and 2', respectively, during the rotation of the moving segment. Perpendicular bisectors of these displacement lines intersect at the instant center for the displacement.

surface of a fixed segment. The contact point of the moving segment does not change, while its mating surface has a constantly changing contact point. If the surface of the fixed segment is flat, the ICR is located at infinity; otherwise it will be located at the center of the curvature of the fixed surface. Spinning motion is the exact opposite of sliding motion, where the moving segment rotates and the contact point on the fixed surface does not change. The ICR is, in this case, located at the center of the spinning body that is undergoing pure rotation. Rolling motion is motion between moving and fixed segments where the contact points on each surface are constantly changing. However, the arc length of the moving surface matches the path on the fixed surface so that the two surfaces have point-to-point contact without slippage. The relative motion of rolling is a combination of translation and rotation. The ICR is located at the contact point. Most of the planar motion of anatomical joints can be described using a combination of any two of the above three basic types of motion.

Eulerian Angle System

The spherical joint model is commonly used for analyzing anatomical joints. This type of joint allows three DOF of rotation; in other words, three angles are required in order to specify the relative position between the moving and fixed segments. It should be noted that for finite spatial rotation, the sequence of rotation is extremely important and must be specified for a unique description of joint motion. However, with proper selection and definition of the axes of rotation between two bony segments, it is possible to make the finite rotation sequence independent or commutative (4,19). In this selection of axes, one is fixed to the fixed segment and another is fixed to the moving segment. In the knee joint, for example, the flexion-extension angle (ϕ) occurs about a mediolaterally directed axis fixed to the femoral condyle, and axial rotation (ψ) is measured about an axis along the shaft of the tibia (Fig. 2). The third axis (also defined as the floating axis) is orthogonal to them and defines abduction-adduction (θ). These rotations match Eulerian angle description.

If a unit vector triad (I, J, K) is fixed to the fixed segment along X, Y, Z axes and another triad (i, j, k) is fixed to the moving segment, along x, y, z axes (Fig. 2), the relationship between them after any arbitrary finite rotation can be expressed by a rotational matrix in terms of the Eulerian angles (ϕ, ψ, θ).

$$\begin{bmatrix} \underset{\sim}{i} \\ \underset{\sim}{j} \\ \underset{\sim}{k} \end{bmatrix} = \begin{bmatrix} \mathrm{c}\phi\mathrm{c}\theta & \mathrm{s}\phi\mathrm{c}\theta & -\mathrm{s}\theta \\ -\mathrm{s}\phi\mathrm{c}\psi + \mathrm{c}\phi\mathrm{s}\theta\mathrm{s}\psi & \mathrm{c}\phi\mathrm{c}\psi + \mathrm{s}\phi\mathrm{s}\theta\mathrm{s}\psi & \mathrm{c}\theta\mathrm{s}\psi \\ \mathrm{s}\phi\mathrm{s}\psi + \mathrm{c}\psi\mathrm{s}\theta\mathrm{c}\psi & -\mathrm{c}\phi\mathrm{s}\psi + \mathrm{s}\psi\mathrm{s}\theta\mathrm{c}\psi & \mathrm{c}\theta\mathrm{c}\psi \end{bmatrix} \begin{bmatrix} \underset{\sim}{I} \\ \underset{\sim}{J} \\ \underset{\sim}{K} \end{bmatrix} \tag{1}$$

where s and c stand for sine and cosine, respectively. The Eulerian angles can be calculated based on the known orientation of these unit vector triads attached to the segments.

The advantage of using this system for description of spatial rotation of anatomical joints is that the angular rotations do not have to refer back to the neutral position of the joint because the rotational sequence can be totally independent and the measurement can be easily related to anatomical structures. However, it is important to recognize that two of the rotational axes in this system are nonorthogonal when the joint departs from its neutral position. Consequently, the system is difficult to use in kinetic analysis. Angular velocity and acceleration have to be transformed into a set of inertial axes in terms of the Eulerian angles defined.

Generalized Six-DOF Joint Motion

The most commonly used analytic method for the description of six DOF spatial motion is the use of a screw displacement axis (SDA) (11,13,18,22).

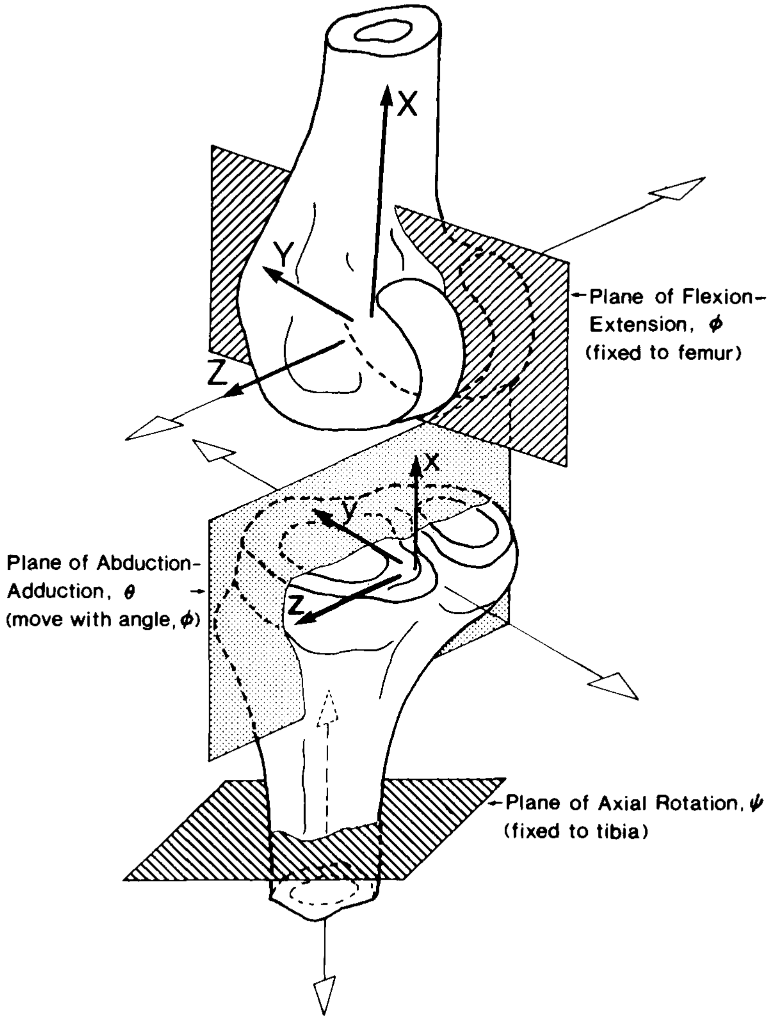

FIGURE 2. Description of the knee joint motion by Eulerian angle system.

The relative displacement of a moving segment from one position to another can be defined in terms of a rotation (ϕ) about and a translation (t) along a unique axis called the screw displacement axis which is fixed in the fixed segment (Fig. 3). The advantage of using a screw axis is that the orientation of the SDA remains invariant, regardless of the reference coordinate axes used. The screw displacement axis is a true vector quantity; its magnitude can be decomposed along any coordinate axes used for analysis. However, the amount of the finite screw rotation that is not a vector quantity and the decomposition of it must be carefully interpreted because of the noncommutative nature of finite rotation.

Numerous methods can be used to determine the orientation and location

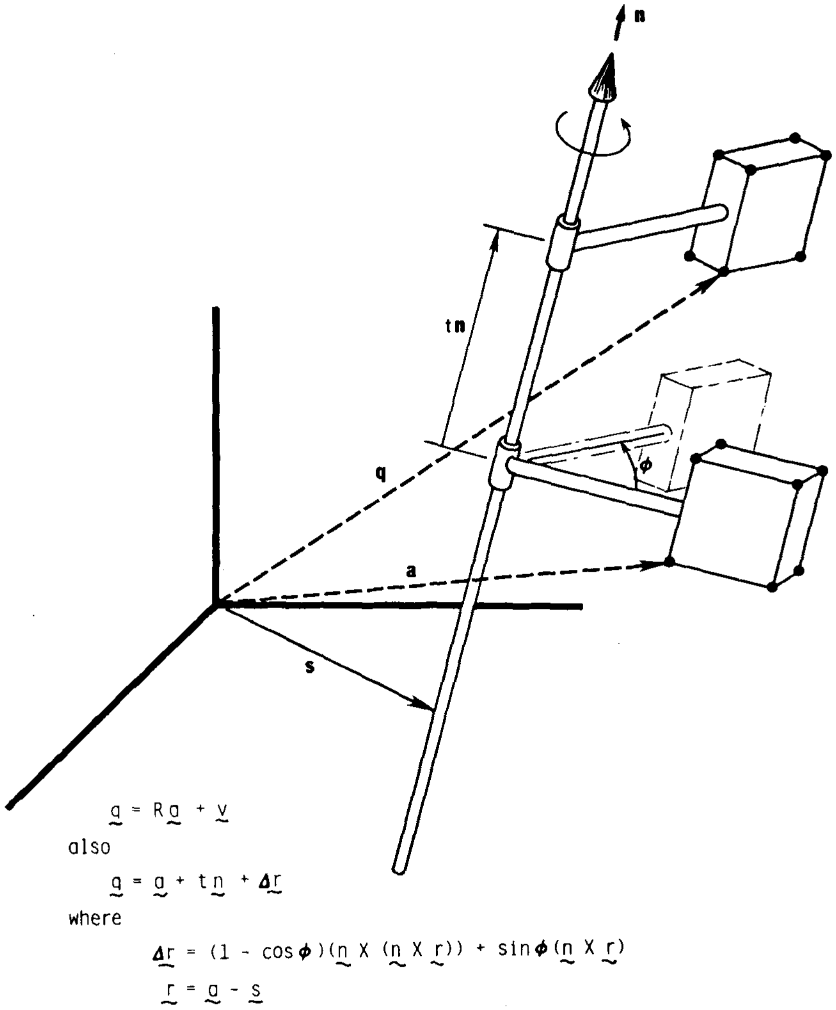

FIGURE 3. Description of the generalized 6-DOF joint motion by using screw displacement axis. The relative displacement of a moving segment from one position to another can be defined in terms of a rotation (ϕ) about and a translation (t) along a unique screw displacement axis.

of the SDA (11,13,18,22). The SDA is parallel to the angular velocity vector; therefore, the orientation of the SDA can easily be defined if the angular velocity of the moving segment is available. However, since the velocity is expressed instantaneously, the precise location of the SDA can be difficult to locate within the displacement of a finite time period. In addition, determination of linear and angular velocities represents a significant experimental problem.

An alternate method to determine the orientation of the SDA and screw rotation is based on a rotational matrix used to define the location of reference points with respect to a coordinate system after finite rotation. This rotational matrix can be expressed in terms of directional cosines between the coordinate axes before and after rotation or in terms of Eulerian angles as shown in Eq. 1. For the SDA, if the directional angles for the SDA are Ax, Ay, Az, letting ϕ be the screw rotation, the rotational matrix $[R]$ can also be derived (9).

$$[R] = \begin{bmatrix} \mathrm{C}\phi + \mathrm{V}\phi \mathrm{C}^2 A_x & -\mathrm{S}\phi \mathrm{C}A_z + \mathrm{V}\phi \mathrm{C}A_x \mathrm{C}A_y & \mathrm{S}\phi \mathrm{C}A_z + \mathrm{V}\phi \mathrm{C}A_x \mathrm{C}A_z \\ \mathrm{S}\phi \mathrm{C}A_z + \mathrm{V}\phi \mathrm{C}A_x \mathrm{C}A_y & \mathrm{C}\phi + \mathrm{V}\phi \mathrm{C}^2 A_y & -\mathrm{S}\phi \mathrm{C}A_x + \mathrm{V}\phi \mathrm{C}A_y \mathrm{C}A_z \\ -\mathrm{S}\phi \mathrm{C}A_y + \mathrm{V}\phi \mathrm{C}A_x \mathrm{C}A_z & \mathrm{S}\phi \mathrm{C}A_x + \mathrm{V}\phi \mathrm{C}A_y \mathrm{C}A_z & \mathrm{C}\phi + \mathrm{V}\phi \mathrm{C}^2 A_z \end{bmatrix} \tag{2}$$

where C denotes cosine, S denotes sine, and V denotes versine = 1- cosine. The screw rotation ϕ may be found from the trace of the rotational matrix:

$$\phi = \cos^{-1}\{(tr[R] - 1)/2\} \ . \tag{3}$$

With ϕ known, the components for the orientation of the screw axis can be calculated. From the translation vector, which can be obtained by comparing the position vectors of the reference points on the moving body, the amount of translation along the SDA and the position vector of a point on the SDA can be calculated.

Unfortunately, like determination of the center of rotation for planar motion, determination of the screw displacement axis is highly sensitive to measurement error as well. The ratio of error increases exponentially with decreasing displacement (8,10). In practice, use of more than three reference points on the moving segment helps to minimize experimental error. Implementation of these procedures for determining a screw displacement axis description of human body movement has been explored extensively in the literature (11,18).

MEASUREMENT SYSTEM

In general, kinematic measurement of human joint movement can be divided into three categories: relative angular motion of limb segments interconnected by a joint, detailed joint articulating surface motion, and angular orientation of joints. The relative angular movement between limb segments provides a description of gross three-dimensional joint motion without concern for the detailed articulating surface motion. Such information is very useful clinically, since it describes the functional usage of the joint. The articulating surface motion is a refined description of joint kinematics. Such information is a prerequisite for accurate assessment of joint and soft-tissue forces.

There are many experimental methods to measure the kinematics of human movement (3). In nearly all methods, basic assumptions have been made in order to facilitate analytic description because of the complexity of the system involved. Although the precise instruments and techniques involved are different, they generally follow similar principles, and each has its unique advantages and disadvantages. The currently used methods can be generally classified into three categories: electromechanical linkage methods, stereometric methods, and accelerometric methods.

Electromechanical Linkage Methods

These methods use exoskeletal linkage systems containing rotatory potentiometers, called electrogoniometers. The linkages are fastened to both the proximal and distal limb segments which constitute the moving and fixed bodies between which the relative motion is measured (Fig. 4). Depending upon the sophistication of the mechanism design, the electromechanical linkage system can be used to measure simple hinge joint motion, three-dimensional angular rotation, or generalized 6-DOF rigid body relative motion (4,5,12,20).

There are several advantages to using the linkage system. It is easy to use and can instantaneously provide direct measurement of joint relative motion, without a tedious data reduction process. It is reliable and reproducible, and the accuracy is generally acceptable, particularly for clinical application. However, there are several inherent limitations. First of all, the linkage system usually provides relative motion which cannot be used directly for kinetic analysis. Instantaneous monitoring of the motion of one segment with respect to the inertial reference frame is necessary in order to achieve this purpose. Secondly, application of the linkage system is usually not located within the joint, so any misalignment will cause significant cross talk among the potentiometer readings and will make the instantaneous reading associated with the anatomical description difficult. However, such cross-talk error can be theoretically corrected (4,7).

Stereometric Methods

When three noncolinear points fixed to a rigid body are defined within an inertial reference frame, the position and orientation of that rigid body can be specified, and the relative rotation and translation occurring at a joint can be determined. The general principle of the stereometric method used for kinematic measurement is, basically, to monitor the locations of these reference points.

The reference points on the body can be conveniently represented by markers in the form of miniature light bulbs, reflecting dots, light emitting diodes (LED), and ultrasonic transducers. There are several systems used to monitor and define these reference points. The stereophotographic system is the simplest and uses two or three still cameras or high-speed movie cameras located at various orientations. The spatial locations of these reference mar-

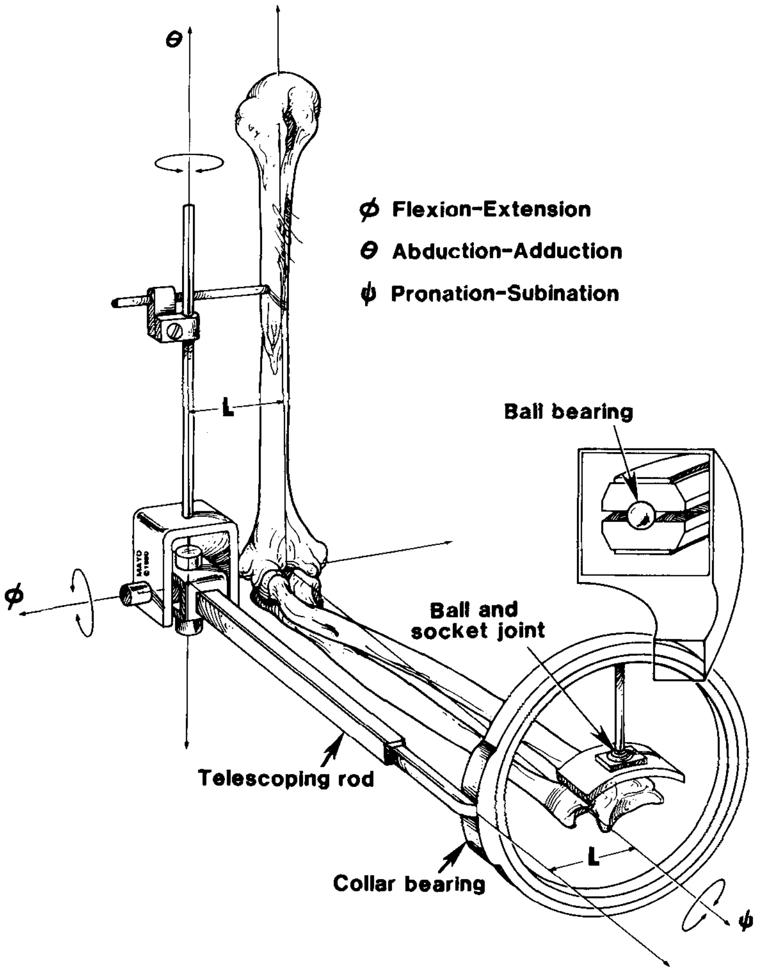

FIGURE 4. Triaxial electrogoniometer for elbow-joint motion measurement. Flexion-extension, abduction-adduction motion, as well as the forearm supination-pronation motion can be monitored simultaneously.

kers can then be constructed based on the film data viewed from oblique angles. Based on the same principle, TV cameras have also been used. The data on these reference locations can be used for not only the calculation of relative motion of the limbs at the joint but also the absolute motion within the inertial reference frame. The major disadvantage, of course, is the tedious procedures involved in data reduction and analysis. Parallax and magnification errors should be noted and compensated for analytically based on the optical principle (17,21).

More recently, with the development of analog photodetectors or image detectors in sensing units of standard TV camera lenses, location of the reference points by using either light reflectors or an LED can be automatically monitored and scanned by computer. These devices make the data reduction process much easier.

Based on a similar principle, a technique utilizing hypersonic impulses to represent the reference points was developed. Instead of using a camera, the spatial positions of the sonic transducers are directly monitored by microphone sensors and a microprocessor device (22).

Finally, in the same category as the stereometric method, the biplanar roentgenographic method has long been used to identify bony reference points for more accurate movement analysis of the skeletal system. Knowing the X-ray tube focal point, the spatial locations of the marker points are uniquely defined (2,6). This method can also be used to measure dynamic motion if cineradiography is applied.

Accelerometric Methods

Euler's theorem states that the general displacement of a rigid body, with one point fixed, can be obtained by a rotation about a unique axis. Since two directional angles can fix this axis, the addition of a third rotation about the axis completely defines the motion. Three independent measurements of acceleration can provide such data. If the rigid body also translates, then three additional accelerometers are required (14). The data obtained are the accelerations of the limb segments where the accelerometers are attached. Complete kinematic information can then be obtained through integration. However, the complex computation involved and instrument-related problems often make such a method difficult to use in practical applications.

SUMMARY

Kinematic analysis of human movement has both basic and applied value in medicine and biology. Gross measurement of motion can be used as a tool for evaluation of functional performance of limbs under various surgical or therapeutic treatments. Kinematic knowledge of precise articular surface movement is essential in the design of prosthetic devices for the restoration of joint function. Various levels of sophistication in terms of theoretical modeling and experimental measurement techniques are available. The selection of each of these techniques depends on the objective of the study. Above all, the advantages, disadvantages, and limitations associated with each of these techniques should be understood.

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