SECTION FOUR

Future Directions in Gait Analysis

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INTRODUCTION

Gait analysis has advanced considerably over the past century. Since the pioneering work of Braune and Fisher (1), much effort has been put into developing the needed technology for human movement analysis. Automated movement tracking systems have replaced hand digitization. Advances in the aerospace industry have been utilized for the development of force plates for kinetic analysis. Computerized electromyography (EMG) systems have replaced hand palpitation. Currently, the technology and knowledge for gait analysis have advanced to a level that permits rapid analysis.

During the past decade, health care delivery systems have evolved at a pace that few expected. The most visible change is the development of managed care delivery systems. An increasing emphasis is being placed on determining the outcome of various clinical procedures. A number of approaches and methods are applied by doctors, nurses, therapists, and other specialists to prevent a particular condition, ameliorate its effects, or change a given state. A scientific basis for clinical practice is being requested. An increasing emphasis is being placed on obtaining accurate measures to determine the outcome of various clinical procedures.

Gait laboratories can play a key role in these managed care scenarios. The objective measurements provided by gait analysis techniques are central to measurement of the patient's progress. The future of gait analysis will depend upon advances made in experimental, analytical, and interpretation techniques for gait studies.

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HEALTH CARE REFORM

Health care costs have risen dramatically over the last 3 decades (**Figure 1**). In 1960, the national health expenditure for health care was 5.3 percent of the gross national product (2); by 1994, health care expenditure had risen to 13.7 percent. The United States currently spends almost three times more on health care than on education or defense, as can be seen in **Figure 2** (3). The U.S. health care system is the most expensive in the world (**Figure 3**). Health care expenditure in the United States was approximately \$950 billion in 1994 (2); this is one-third more than any other industrialized nation. In addition to being the most expensive system in the world, U.S. health care costs are growing more rapidly than those in any other industrialized nation. Personal expenditures from medical care have increased over three-fold in the past six decades (2). Initially, most of the payment for personal health care was from out-of-pocket payments (**Figure 4**), but this percentage has decreased and the contribution from health insurance has continued to increase throughout the decades.

Given these economic realities, much emphasis is placed on systems for delivery of health care. These delivery systems were set up to offer the potential for controlling cost by providing coherent networks to obtain discount pricing by integrating the financing and delivery of medical care. Managed care, and everything that it represents (cost containment, competition among providers, constraints on health services,

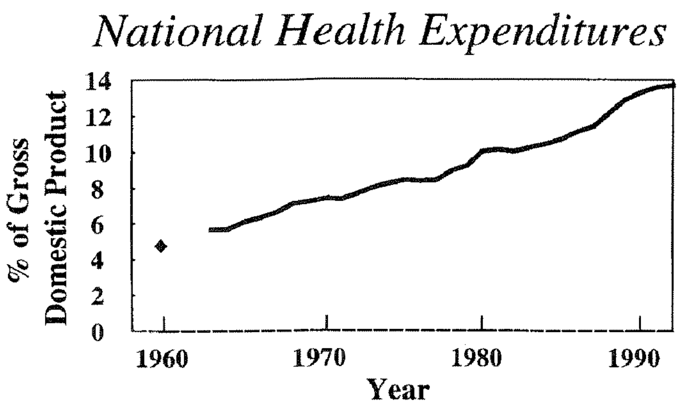

Figure 1.
National expenditures for health care over the last 3 decades, expressed as % of Gross Domestic Product (2).

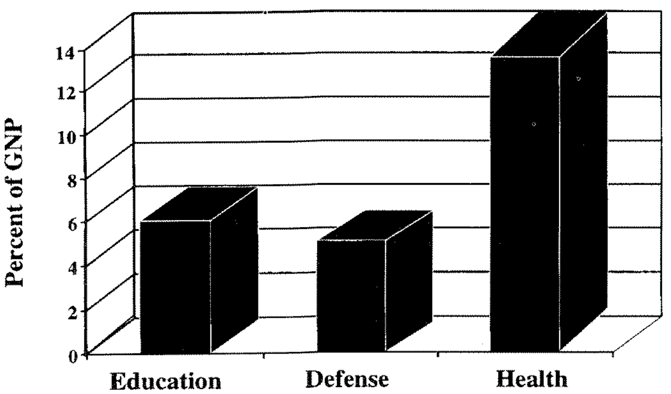

Figure 2.
National expenditures for education, defense, and health in 1994 (3).

reimbursement decreases, and utilization review) has forever changed the traditional fee-for-service model (4). Enrollment in managed health care plans has increased dramatically in the last decade (5). In 1984, 89 percent of patients were covered by an indemnity (fee-for-service) program while less than 10 percent were covered by a managed care program. In sharp contrast, in 1997, 10 percent were covered by an indemnity program while 80 percent were covered in a managed care program. Thus, it is clear that a paradigm shift in health care delivery is occurring.

In the U.S., the evolution of the health care environment varies by location, with the evolution of the market occurring most rapidly in the western states (6). Cost and quality vary widely. Proponents of managed care have shown that this new model for health care delivery has lowered costs, hospital-stays, and mortality rates. Markets with heavily managed care penetration demonstrated that the average hospital costs were reduced by 11.5 percent compared with the national average (5). This was a combined result of providers utilizing fewer resources due to financial incentives and HMOs driving payment rates down. In these highly competitive markets, the average length of stay was also 16.9 percent below the national expected level (5). In addition, hospitals in high managed care markets experienced actual death rates (adjusted for the clinical condition of the patient) that were 8 percent lower than expected on a national basis (5). Nevertheless, one cannot overlook the fact that rationing of "non-medically necessary care" is also being done for financial gain. The proliferation of "for-profit" HMOs has changed the face of health care. Instead of accumulating savings in order to provide better care, these savings go into the pockets of investors in for-profit HMOs. With each year, HMOs have continued to increase their profitability. In 1994, the annual pretaxed earnings of the HMO industry were $4.13 billion (7). Thus, while it is stated that the most significant change in health care has been the shift of risk from payers of health care to the providers, it is also important to note that this shifting of risk can also be related to the shifting of profitability of health care.

It is important that individuals involved in health care policy development, organization, and delivery understand that gait analysis can be used to eliminate unnecessary surgery. DeLuca and colleagues (8) have shown that frequently the number of surgical procedures are reduced after a three-dimensional (3-D) gait analysis, when compared to a clinical examination and videotaping alone. Further, gait analysis will maximize the return when surgery is indicated by providing recommendations for multilevel surgery (9). The use of an appropriately timed gait study should make it possible to develop a treatment plan for a person that can be completed in one operative setting. Objective gait analysis data can be used to quantify the person's functional status; depending on his or her functional status, bilateral multilevel surgery can be performed. When appropriately planned, no further surgery will be needed. This reduction in the number of surgeries will lower the overall long-term cost of treatment. One of the important features of the new health care system will be a greater emphasis on the prevention of disease and measurement of clinical outcome. Patient functional status before and after treatment will need to be studied.

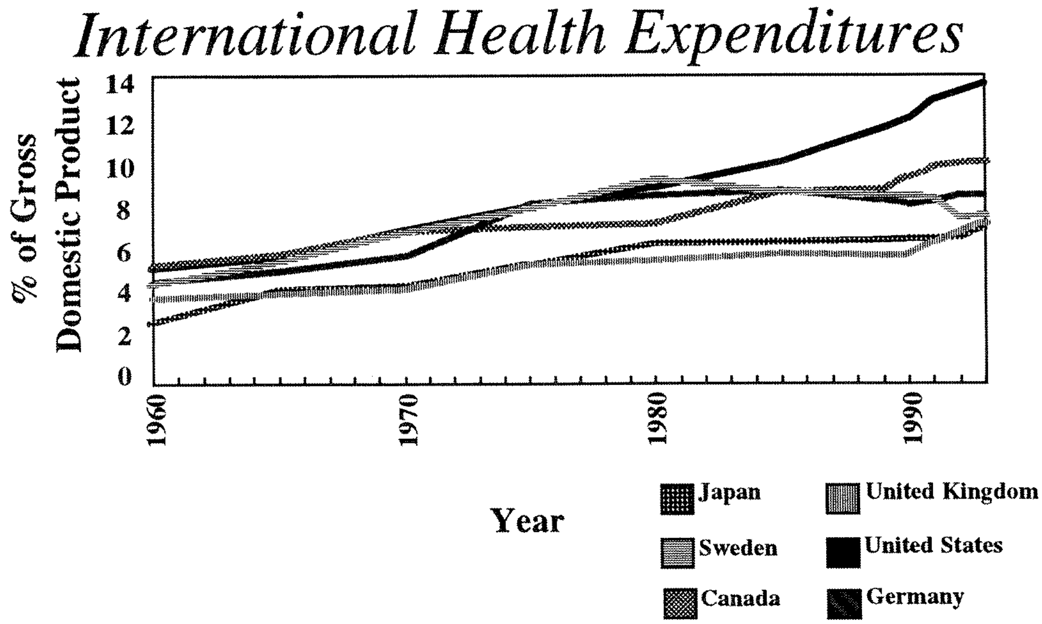

Figure 3.
International expenditures for health care over the last 3 decades, expressed as % of Gross Domestic Product (2).

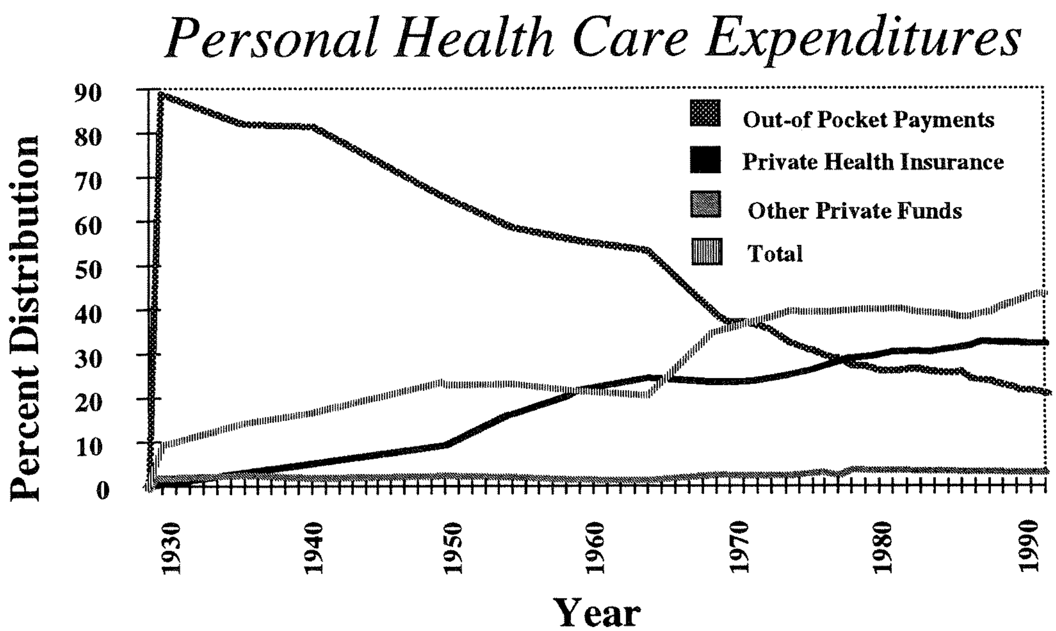

Figure 4.
Personal expenditures for health care over the past 6 decades. The distribution is subdivided into out-of-pocket payments, government payments, private health insurance, and other private funds (2).

Payors are turning their attention from short-term savings to long-term predictable improvement in both cost and quality.

Challenges exist to further evolve the science of clinical gait analysis to make it effective as an assessment tool. Currently, a clinical gait analysis study consists of five broad areas (**Figure 5**). Initially, a history and physical examination is performed on the patient. If it is determined that he or she could benefit from a gait analysis study, an evaluation is requested. The gait study consists of data collection, data reduction, analysis, and interpretation of the results of the study. This information is compiled in a clinical report and recommendation is given for treatment. The future of gait analysis will depend upon advances made in experimental, analytical, and interpretation techniques. Opportunities for future enhancements of gait studies are outlined in the following sections.

EXPERIMENTAL TECHNIQUES

Advances in experimental techniques have been made possible because of the advances in computer technology, which need to be applied toward enhancements of data collection, data presentation, and quantification of muscle function.

Advances in Computer Power

Decreasing costs and simultaneous increases in the computational capacity of computers have facilitated many technological advances in scientific fields. In 1937, Howard H. Aiken of Harvard University conceived the first large-scale automatic digital computer. In the late 1960s, computers operated at an internal speed about 20 to 100 times faster than their counterparts of 10 years earlier. By the 1980s, speeds were 1,000 times faster than in the 1960s. Over the same period, storage capacities and computer memory increased by comparable factors (10). Thus, since 1945 the speed of computers has approximately doubled every 2 years. The exponential increases in the computational power of computers makes development and visualization of biomechanical models of the musculoskeletal system possible. The evolution of performance of microcomputers has surpassed the evolution of conventional supercomputers (**Figure 6**)*. The supercomputer curve shows a steady gradual increase in performance over the last 15 years. In contrast, dramatic improvements in integrated circuit technology are allowing microprocessors to close the performance gap with conventional supercomputers.

Beyond the purely technological improvements in memory and speed, user interface improvements have had an equally large effect on increases in productivity. The interface between the human and the computer has become easier to use and much more efficient. Computer programs of today feature pull-down menus, mouse-driven applications, and graphical input and display capabilities. These changes have resulted in user friendly systems that aid in the visualization and understanding of complicated biomechanical models.

Data Acquisition Systems for Movement Analysis

The techniques for motion analysis have progressed from motion photography, (11,12) and electrogoniometry (13,14) to automated stereometric systems (15–18). Motion data provides the information necessary for calculation of the time/distance parameters of walking (velocity, cadence, stance and swing times, etc.) and the angular position of the person's joints (hips, knees, and ankles) during the different phases of gait. The derived measurements indicate the degree of normalcy (or abnormality) and the presence of compensatory patterns. Techniques that quantify deviation from normal walking during the gait cycle are of greatest clinical interest and treatment potential for people with movement disabilities.

A number of technologies are in use today for the capture of human motion. Each of the existing approaches has undesirable constraints that limit its applicability for real-time modeling of full body motion with the prerequisite for accuracy, scan rate, number of sensors, and range, and without impingement of the limited function of disabled individuals. The five existing technology categories include the

- electromechanical linkage method
- stereometric method
- roentgenographic method
- accelerometric method
- magnetic coupling method.

Each technique has disadvantages.

An exoskeleton apparatus is employed with the electromechanical linkage method to measure joint motion. The primary disadvantage for this technique is the cumbersome nature of the instrument and, to a lesser

*Personal Communication with Lawrence Livermore National Laboratory, Lovermore, CA, 1995.

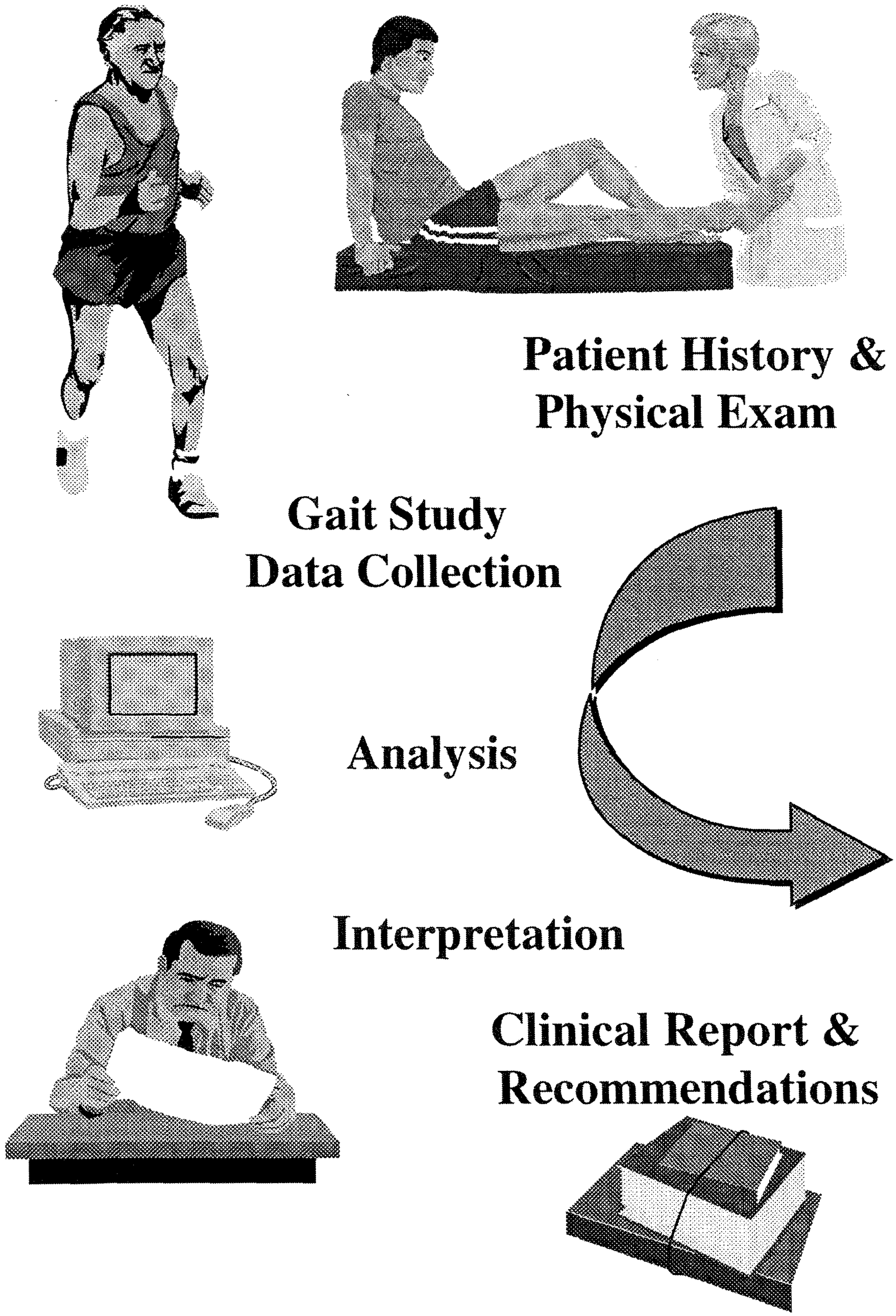

Figure 5.
Sequence of events for a clinical gait analysis study.

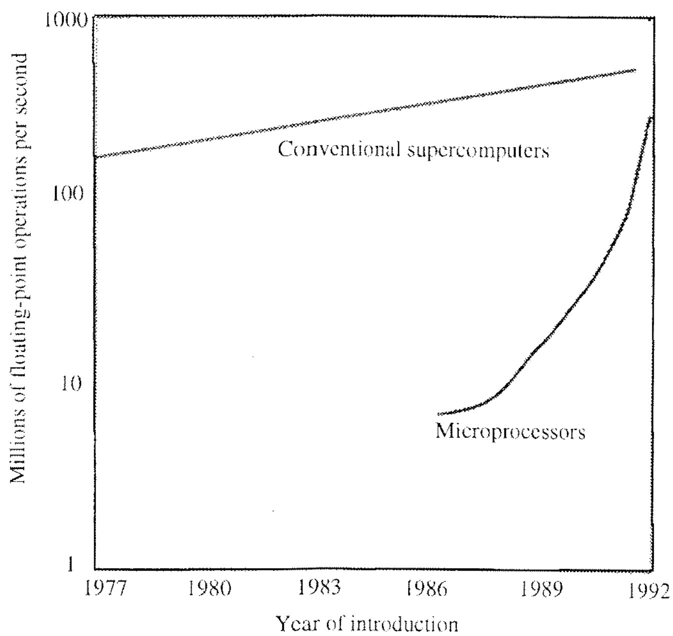

Figure 6.
Evolution of performance of supercomputers and microcomputers (11).

extent, cross coupling of the sensor inputs and joint motion. The requirement for the exoskeleton instrument affects the motion of young subjects making it unusable for clinical measurement.

The stereometric method is the most popular one currently used for clinical gait analysis. It employs visible markers attached to the skin on rigid segments of the body structure and tracks their motion using imaging equipment. This technique is implemented using charge coupled device (CCD) cameras and frame-grabber electronics to allow digital images to be captured as the subject moves within the field of view. Digital image analysis allows the physical location of each marker to be computed, using triangulation of the views from an array of camera systems. This technique has minimal impact on the natural motion of the subject and allows data capture without the need to tether the subject to the data acquisition hardware. However, a disadvantage of this approach is the increased image analysis complexity resulting from tracking the apparent position of the markers in a two-dimensional (2-D) image on a per camera frame-to-frame basis and correlating the position of each marker for the multiple camera positions. Occlusion of markers from the camera field of view and false readings caused by reflection phantoms pose non-trivial, unresolved complications in data capture. In addition, passive markers provide unlabeled trajectory segments that must be manually identified and resolved. This image analysis task requires a significant amount of time for the data gathering process. A second major disadvantage is the reduction in resolution as the camera system is altered to allow a larger field of view. The camera imaging sensors have a fixed number of pixel elements and a compromise must be reached between optical field of view and pixel element resolution size, limiting the clinical measurement volume to approximately a single stride. It is not feasible to measure gait patterns or variability with only one traversal of the instrument walkway. Thus, multiple walking trials need to be collected, which may fatigue the subject.

The biplanar roentgenographic method employs metal markers and x-ray films for the measurement of static positions of a body joint. This approach is not appropriate for the study of dynamic joint motion. Due to the use of ionizing radiation, it also represents a potential health hazard to the subject.

The accelerometric approach employs sensors attached to the rigid areas of the human subject that measure accelerations in three dimensions. Joint motion is then derived through integration of the accelerometer waveforms given appropriate initial conditions. Integration of the waveforms produces velocities for each of the sensor locations. A second integration step provides the displacement as a function of time. This technique can provide the kinematic motion measurement desired but has been implemented with a tether to the subject for the data acquisition; however, the tether affects the motion of the subject and represents an undesirable feature. In addition, this approach requires an accurate estimate of initial conditions, which is difficult to provide.

The magnetic coupling method employs a reference magnetic field source that surrounds the subject with an array of magnetic field sensing elements attached to the rigid segments of the subject. The position of each sensor is estimated through analysis of the magnetic field components passing through the sensor. This technique has the potential for providing complete six degree-of-freedom motion information, but has been implemented by using a tether to each of the sensors and the data collection system. The response of the system is limited to 30 Hz, which is below the required data acquisition rate for high fidelity measurements. Further, the sensing elements are sensitive to nearby ferromagnetic materials that may distort the field.

While the foregoing techniques have provided a means for the acquisition of joint motion, there are associated deficiencies for each. A system needs to be developed for real-time acquisition of human motion. The goal of this effort should be the development of a technique for precise measurement of human body motion. Suggested guidelines for the performance of the proposed system are given in **Table 1.** The unique characteristics specified request that the real-time system be able to function over a larger measurement area using high-scan rates and a large number of fiducial points. These system requirements will lead to greater accuracy than that which exists in current systems. These enhanced capabilities will eliminate clustering limitations and data reduction, reduce the cost of gait analysis as a clinical treatment planning service, and improve the turnaround and availability of information for clinical decision making. The advantages to be realized include a real-time motion acquisition and display, higher data sample rates, substantially increased work volumes, full body motion acquisition, reduced data loss from occlusion, and a significant time savings for data analysis. This development will open new windows of opportunity for the application of motion analysis to sports injuries and other domains requiring higher scan rates and larger measurement volumes. Successful development and commercialization of a real-time data acquisition system represents a new paradigm for human movement analysis.

Table 1.
Specifications for a real-time motion system.

Characteristic	Specification
Motion	Reported with respect to an absolute reference frame in real time
Sampling Rate	60 scans/s min, 200 scans/s desired
Resolution	1 mm
Latency	500 ms max
Limb Obstruction	None
Marker Numbers	30 min, 300 max
Marker Separation	1 cm max
Capture Range	0.5 m min, 50 m max
Subject Movement	Unaffected by instrumentation

min = minimum; max = maximum

Visualization of Human Motion

Gait analysis typically includes measurements of motion, force, and muscle activation patterns (electromyography). In recent years, dynamic measurements of foot pressure have been added to the armamentarium of diagnostic tools. The clinical interpretation of pathological gait requires holding in human memory a large number of graphs, numbers, and clinical tests from data presented on hard copy charts, x-rays, video, and computer-generated 3-D graphics from multiple trials of a subject (**Figure 7**). Further, comparisons must be made to data from a normal population in order to identify the potential movement problems for a given individual. The referring physician, who is not an expert in gait analysis, is overwhelmed by the magnitude of the number of measurements included in a typical clinical report. This information must be integrated into a cohesive plan for clinical intervention, which often includes multiple surgeries. While data collection techniques for gait analysis have continually evolved over the past 40 years, the method of data presentation has not changed over this same time. The data is still reported in 2-D charts with the abscissa usually defined as the percentage of the gait cycle and the ordinate displaying the gait parameter.

Recent developments in computer animation make it possible to apply advanced methods to visualize human movements. A highly dimensional space is needed to fully describe the complexities of human movement. The large volume of variables currently found in a typical clinical report should be replaced with a printout of a few graphic images that succinctly provide the needed information. It is difficult to fully appreciate and understand relationships between motion dynamics and physiologic or biomechanical variables without scientific graphic visualization.

Due to the complexity of gait-derived data, powerful visualization tools are needed. The ability to incorporate scientific visualization will provide unprecedented power to support the clinician's recommendations in a manner that the referring physician can intuitively understand and visualize. The popular scientific visualization techniques are 1) one-dimensional (1-D) plotting, 2) 2-D plotting, 3) 3-D volume visualization, 4) imaging processing, and 5) animation (19). Separate software packages are available to perform each of these techniques. However, as the need to solve

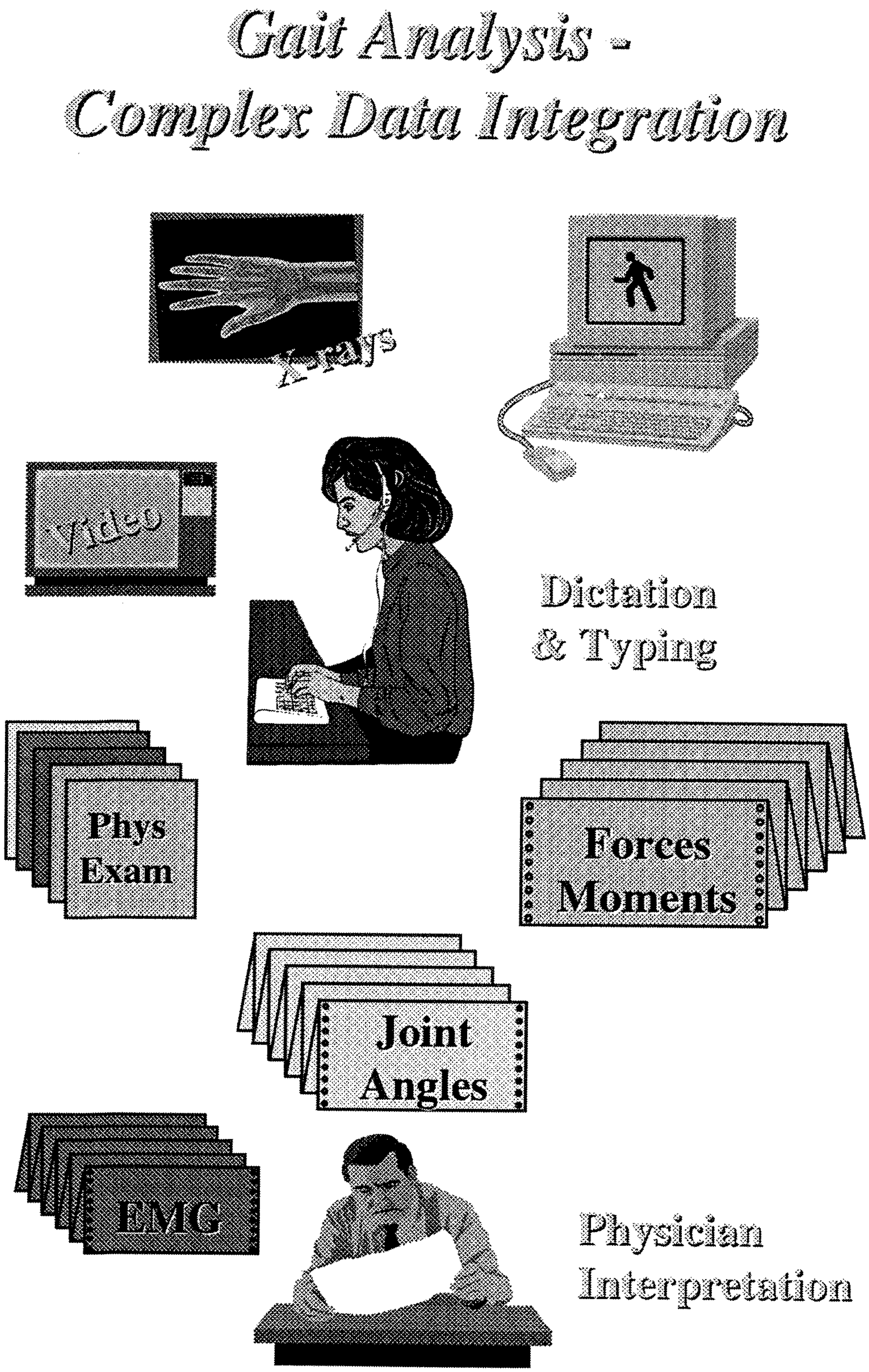

Figure 7.
Current situation for clinical interpretation of gait analysis reports. The large number of graphs, numbers, and clinical tests must be held in human memory in order for the appropriate comparisons to be made.

complex problems becomes more acute, one package is needed that provides all of these capabilities to enhance productivity.

A scientific computing environment is needed that will allow the rapid transmission, archival, retrieval, and manipulation of images within a system equipped with analytical tools useful for clinical and research purposes. Tools are needed for data collection, analysis, and visualization (**Figure 8**). A suitable database of normal gait patterns is needed for comparison. The ultimate goal of this scientific visualization workstation is to provide a user-friendly, menu-driven environment that will facilitate the reporting of biomechanical data and integrate real-time animation of fully 3-D realistic graphical depictions of articulated body segments. This system should provide clinicians with the ability to visualize the correlation between collected biomechanical data and the actual human motion. Furthermore, this system should provide the ability to simulate gait and compare the computer-generated simulation with experimentally collected data. The operator should be able to examine the data from any viewing angle, to zoom in or out, change the viewing perspective, or stop the motion. This system should have the ability to superimpose normal gait on a subject's gait in order to visualize differences. The system should also be able to align the bodies displayed to a common center of gravity or to a common point in the gait cycle (20). It should be capable of "removing" extremities in order to improve visualization of other body segments. The two most important goals are the realistic appearance of the human figure and the convenient specification of the biomechanical data. This application should be user-friendly so that it can be used by colleagues who are not necessarily programmers but have the expertise in their respective fields (e.g., medical doctors). The software environment should be capable of quick and easy customization to serve very specific needs.

Another key issue is the communication of the results. The clinician must be able to select only the most essential results for the communication to the referring physician and the patient. Otherwise, the individuals will be overwhelmed by the plethora of numbers while comprehending little. Practical display of data will provide an economical and efficient method of communicating information (21). When graphical portrayal of data is limited by dimensionality (i.e., three dimensions), other variations in the output such as color, sound, and shape can be used to help overcome this limitation. This application of technology should provide a mechanism to integrate all aspects of gait measurements and observations into a single tool for physician interpretation, diagnosis, and treatment recommendations (**Figure 9**).

Muscle Force Measurement

Muscle forces reflect the underlying neurocontrol processes responsible for observed movement patterns. In addition, muscle forces play a major role in determining stresses in bones and joints. Thus, a knowledge of muscle forces is fundamental for improving the diagnosis and treatment of individuals with movement disorders. Interpretation of muscle function has routinely been based on analyses of electromyographic data obtained during gait studies (22–24). More specific detailed knowledge of the muscle forces acting on the body will allow us to improve our ability to diagnose and treat persons with movement disabilities. It will also increase our understanding of muscle function during gait. Unfortunately, invasive techniques for measuring muscle forces are highly objectionable.

Techniques such as electromyography (EMG) do not provide the quantitative accuracy needed. A fundamental relationship exists between the tension that a muscle is capable of developing and the length of the muscle. The total muscle tension is composed of both active and passive components. This well-known phenomenon is described by Blix's curve, which demonstrates the relationship of total muscle force, passive stretch force, and muscle contractile force to the length of the muscle (25). Yet, the integrated electromyogram can only be proportional to the active component and will not account for the passive stretch of the muscle. Use of the integrated electromyogram as an indicator of the quantity of muscle contraction has another drawback. There is a significant delay between maximal electric activity in the muscle and maximal tension. The electromechanical delay has been estimated to be 30 to 90 ms (26–30), which would be approximately 3 to 9 percent of the gait cycle.

Measurement of intramuscular pressure is a conceivable solution. Intramuscular pressure is a mechanical variable that is proportional to muscle tension. Investigators have shown in studies on animals (31–33) and in humans (34–36) an approximately linear relationship between intramuscular pressure and muscle force during isometric muscle contraction. Further, estimation of muscle force from intramuscular pressure is not affected by changes in signal due to muscle fatigue

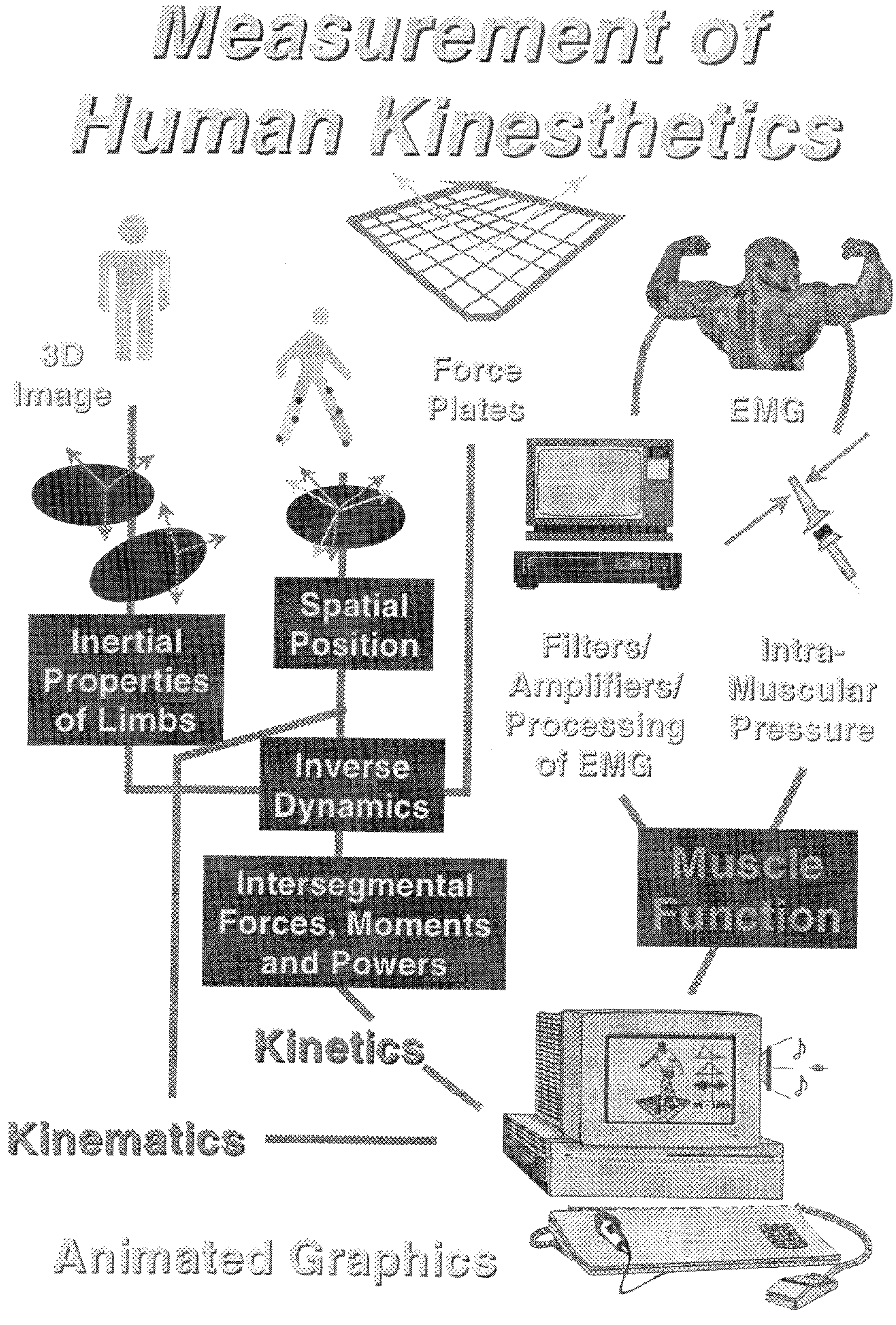

Figure 8.
Scientific computing environment needed for collection and visualization of human kinesthetics.

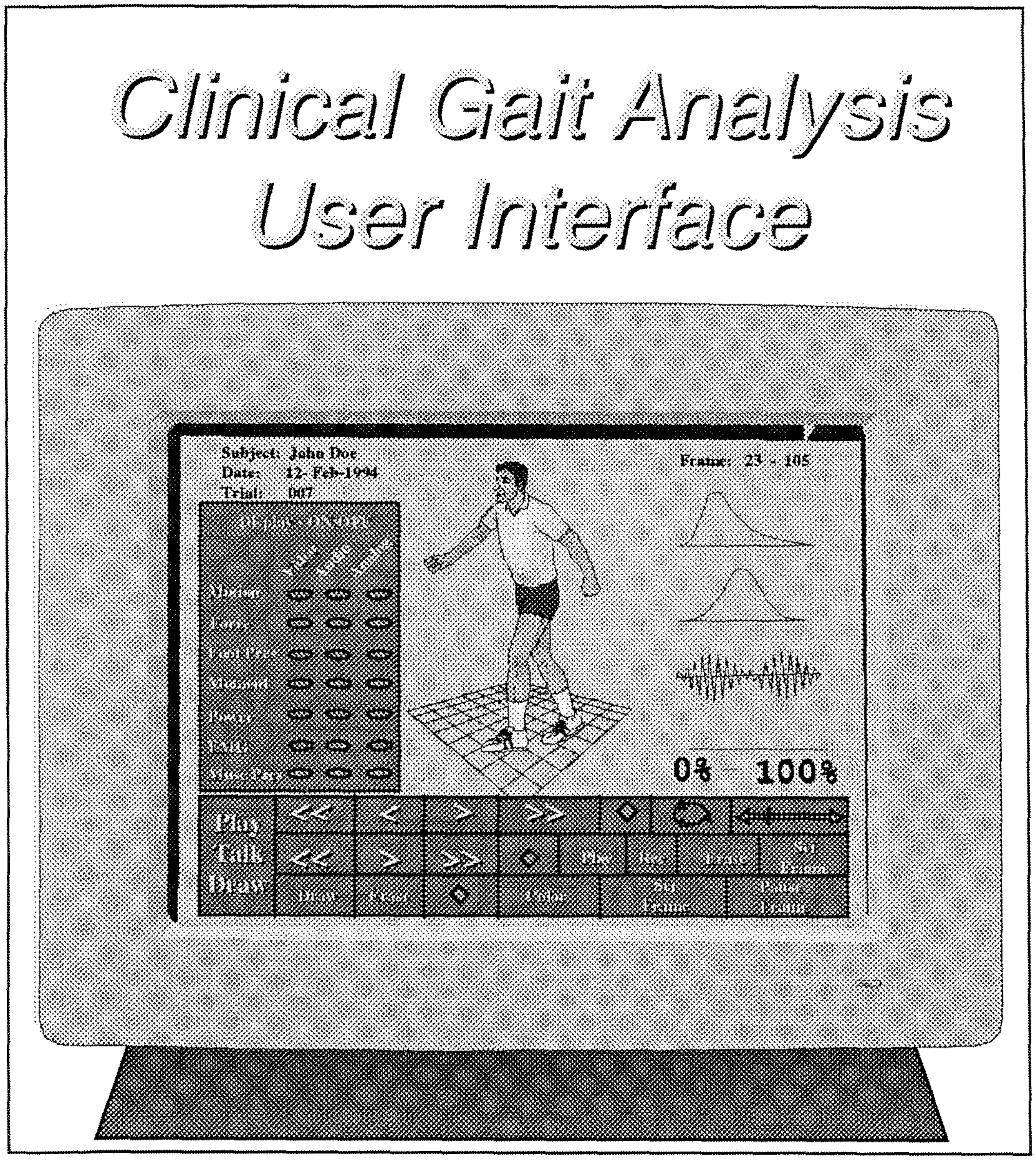

Figure 9.
User interface for graphical portrayal of gait analysis data.

(37,38). Nevertheless, the absolute intramuscular pressure depends on the depth of the recording catheter within the muscle (32,38), the shape of the muscle (39), and the compliance of the surrounding tissue (40). Baumann et al. (41) reported that intramuscular pressure is related to the active and passive components of muscle tension during gait. Kaufman and Sutherland (42) have also reported that the intramuscular pressure during walking parallels the electromyographic activity, but also accounts for passive stretch of the muscle (**Figure 10**). In the future, more work is needed in the use of intramuscular pressure to quantify muscle force. Improvements in microsensor technology can be used to facilitate these measurements.

ANALYTICAL TECHNIQUES

A fundamental concern in the study of human locomotion is a description of the kinematics and kinetics involved. During the study of gait, a large number of measurements are taken. The experimental data are entered into an analytical model to obtain the values of variables not directly measurable. The analytical model is a link segment model. The human body is modeled as a system of articulated, rigid links, which represent the lower limb segments and the upper body. By modeling the body as an ensemble of rigid-body segments, it is possible to calculate the movement and loads at any articulation.

Kinematics

In order to establish a mathematically workable model, Cartesian coordinate systems are established on each body segment (43–47). These anatomically based axis systems are fixed in each body segment and move with it. The coordinates of bony landmarks are used to build a right-handed orthogonal coordinate system. The unique specification of anatomical coordinate systems requires a minimum of three noncolinear points that are defined with respect to surface landmarks associated with each segment. In order to obtain the joint movement, expressions have to be obtained relating the position of each segment in the model with respect to adjacent segments. Joint motions are usually 3D. The anatomical description of the relative orientation of the two limb segments can be conveniently obtained by relating the two coordinate systems embedded in the proximal and distal body segments. The ability to describe joint orientation in 3-D space following traditional rigid-body motion theory is essential. For finite spatial rotation, the sequence of rotation is extremely important and must be specified for a unique description of joint motion. For the same amount of rotation, different final orientations will result from different sequences of rotation. 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. In the past 15 years, the concept of Eulerian angles has been adopted in the field of biomechanics to unify the definition of finite spatial rotation (48,49). If a unit vector triad (**I,J,K**) is attached to a fixed segment along the XYZ axes and another triad (**i,j,k**) is fixed to the moving segment along the xyz axes (**Figure 11**), the relationship between them after any arbitrary finite

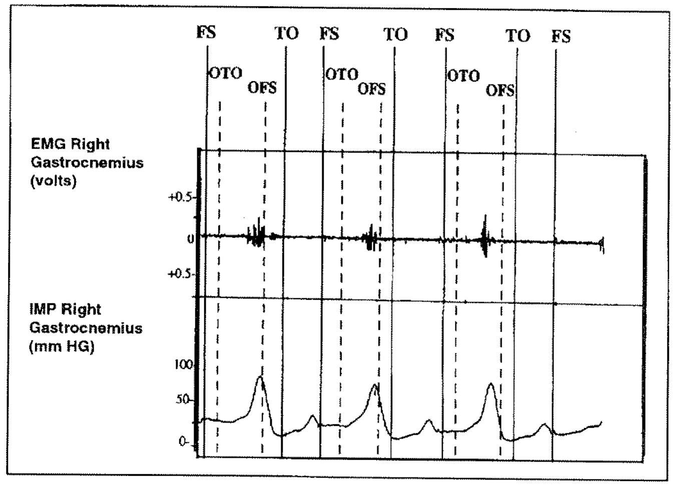

Figure 10.
Raw data for single subject during gait: EMG and intramuscular pressure are being recorded from the gastrocnemius muscle. Stance phase of gait occurs from FS to TO. Swing phase of gait occurs from TO to FS and single-limb stance from OTO to OFS. Peaks in intramuscular pressure during gait can be correlated with peaks of active contraction and passive stretch of the gastrocnemius (42).

rotation can be expressed by a rotational matrix in terms of three Eulerian angles, ϕ, θ, ψ as follows:

$$\begin{bmatrix} \mathbf{i} \\ \mathbf{j} \\ \mathbf{k} \end{bmatrix} = \begin{bmatrix} c\theta c\phi & c\theta c\phi & -s\theta \\ -c\psi s\phi + s\psi s\theta c\phi & c\psi c\phi + s\psi s\theta s\phi & s\psi c\theta \\ s\phi s\psi + c\psi s\theta c\phi & -s\psi c\phi + c\psi s\theta s\phi & c\psi c\theta \end{bmatrix} \begin{bmatrix} \mathbf{I} \\ \mathbf{J} \\ \mathbf{K} \end{bmatrix}$$

where s=sine and c=cosine. The Eulerian angles can be calculated based on the known orientation of these unit vector triads attached to the proximal and distal body segments.

For a more general unconstrained movement in space, three translations and three rotations are required to describe the joint motion. The displacement of a rigid body can take place along any one of an infinite number of paths. It is convenient to describe the displacement in terms of the simplest motion that can produce it. The most commonly used analytic method for the description of six-degree-of-freedom rigid-body displacement is the screw displacement axis (50–52). The motion of the moving segment from one position to another can be defined in terms of a simultaneous rotation, Φ, around and a translation, τ, along a unique axis, called a screw displacement axis, which is fixed in the fixed segment (**Figure 12**). The screw displacement axis is a true vector quantity. However, the amount of the finite screw rotation is not a vector quantity, and the

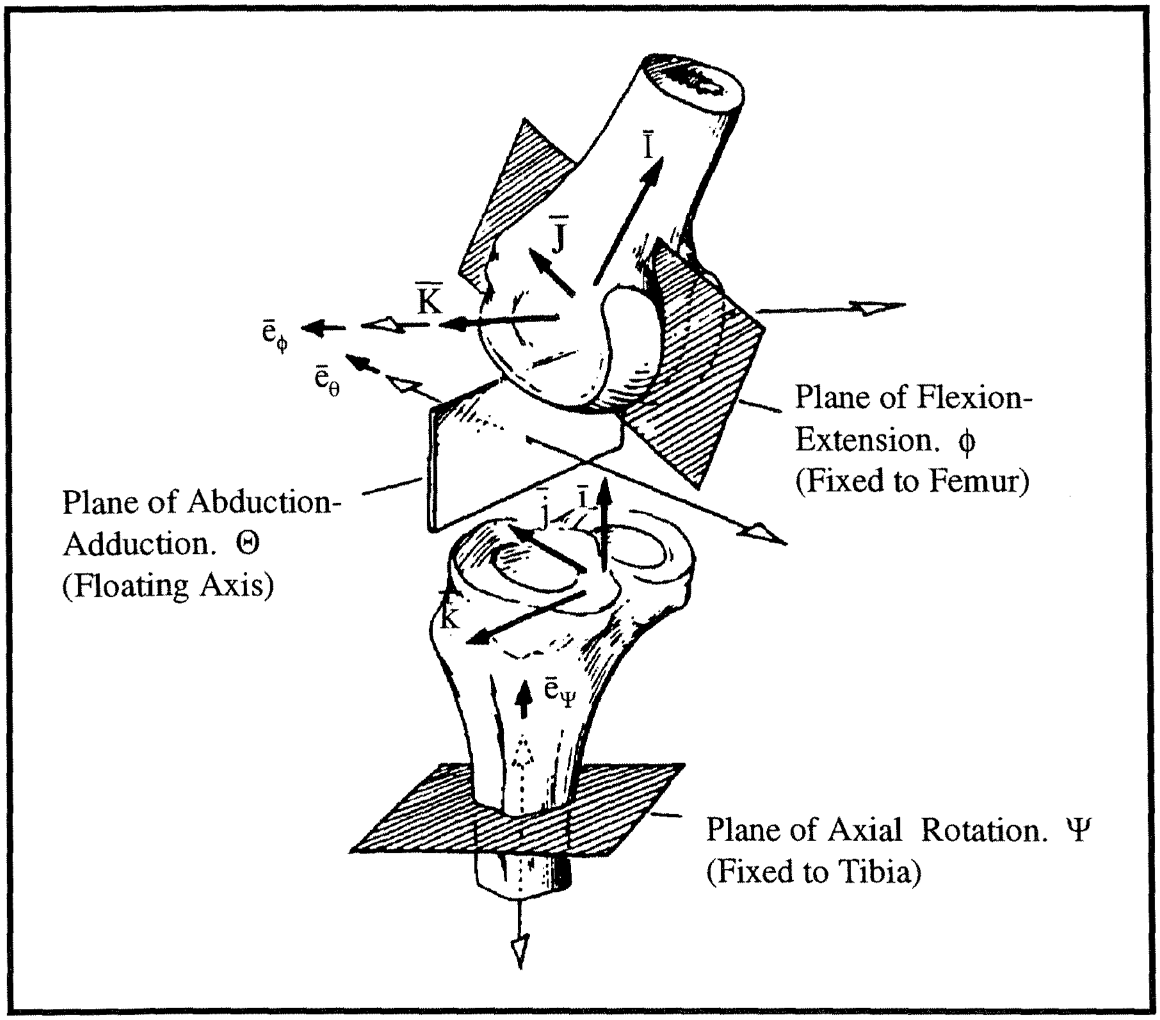

Figure 11.
Description of knee joint motion using Eulerian angle system. Axis fixed to distal femur defines flexion/extension motion, Φ. Axis fixed to proximal tibia along its anatomical axis defines internal-external rotation, ψ. Floating axis is orthogonal to other two axes and used to measure abduction-adduction, θ. (Reproduced with permission of Mayo Foundation.)

decomposition of it must be carefully interpreted because of the noncommutative nature of finite rotation. Woltring (53) recommended that the component rotations (flexion-extension, abduction-adduction, endo-exo-rotation) be defined as a component of the product $\mathbf{\Phi} = \mathbf{\Phi}\mathrm{n}$ where $\mathbf{n}$ is the unit direction vector of the screw axis.

Inverse Dynamics

Once the transformation matrices have been obtained, we can proceed to solve for the joint moments given the joint positions, velocities, and accelerations, and the ground reaction forces. Typically, these formulations are based on the inverse dynamics approach (54), proceeding from known kinematic data and external forces and moments to arrive at expressions of the resultant intersegmental forces and moments. If the exact motion history of the system, especially accelerations, is available, then this type of problem presents little mathematical challenge and can be solved by applying the equations of motion derived for the system (**Figure 13**). An unconstrained rigid body has six

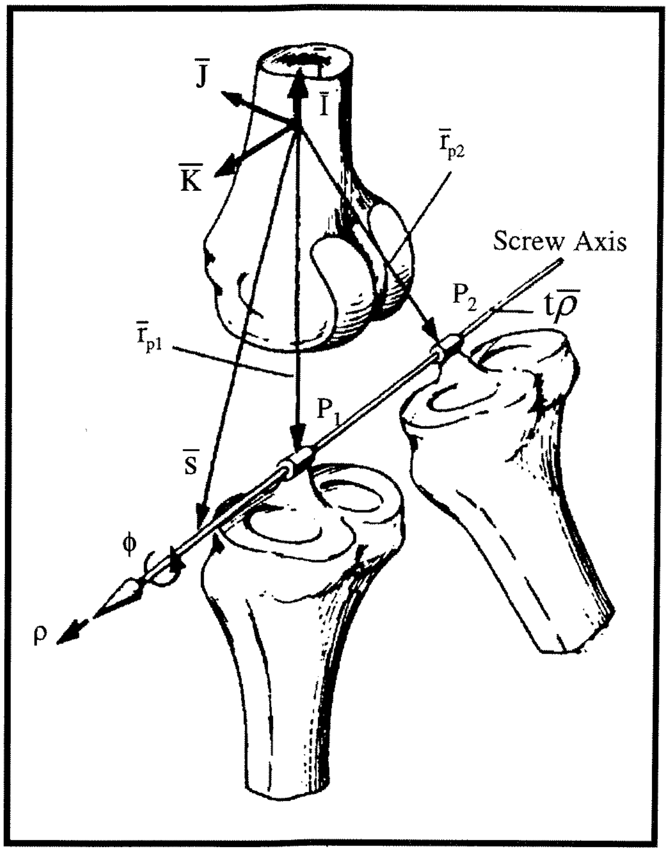

Figure 12.
Screw displacement axis can be used to describe general spatial motion. Tibia moves from position 1 to position 2 by rotation about screw axis by an amount Φ and by translating along the screw axis by an amount τ. (Reproduced with permission of Mayo Foundation.)

degrees of freedom. Hence, six equations of motion are needed to specify its configuration. Three equations can be chosen to represent the translation of the rigid-body center of mass and three equations to represent the rotation about any point, A. In the case of the motion of a rigid body in three dimensions, the fundamental equations are:

$$\Sigma F_A = md(\dot{\mathbf{r}}_c)/dt$$

$$\Sigma \mathbf{M}_A = \dot{\mathbf{H}}_A + m(\dot{\mathbf{r}}_A \times \dot{\mathbf{r}}_c)$$

These fundamental equations express that the system of external forces, $\Sigma \mathbf{F}_A$, and moments, $\Sigma \mathbf{M}_A$, acting at the limb segment are equipollent to the system consisting of the linear momentum vector, m $d(\dot{r}_c)/dt$, and the moment of momentum vector, $\dot{\mathbf{H}}_A + m(\dot{\mathbf{r}}_A \times \dot{\mathbf{r}}_c)$. Using measurements of the intersegmental load actions and the relevant kinematics, it is possible to compute the energy and power transmitted from one body segment to another. The joint powers are obtained from the scalar (dot) product of the intersegmental joint moment and the joint angular velocity as well as the intersegmental joint force and translational velocity. The rate of work done (power) can be calculated from:

$$\dot{W} = \mathbf{M} \cdot \boldsymbol{\omega} + \mathbf{F} \cdot \mathbf{v}$$

where $\dot{W}$ = mechanical power
$\mathbf{M}$ = intersegmental joint moment
$\mathbf{F}$ = intersegmental joint force
$\boldsymbol{\omega}$ = angular velocity and
$\mathbf{v}$ = translational velocity.

Frequently, the component due to translation is assumed to be small and the second term (F· v) is rarely included in joint power estimates for gait. This technique can be used to predict the transfer of energy from body segment to body segment through the muscles (55). The muscles can either generate or absorb mechanical energy by contracting concentrically or eccentrically, respectively.

Body Segment Mass Inertial Estimates

Estimates of body segment mass, center of mass, and moments of inertia are needed for these biomechanical models. These body segment parameters are used along with the segmental kinematics to compute the linear and angular momentum of the body segments. Estimates of these values are substituted into the Newton-Euler equations of motion to obtain an estimate of joint loads during physical activity. These body segment estimates are a big source of error in biomechanical models (56). Methods of obtaining inertial parameters of body segments can be classified into three groups:

- *regression equations*
- *geometric approximation*
- *direct measurement*

Regression equations have been developed based on cadaver studies (57–59) and living subjects (60–62). The equations have been developed through statistical analysis of the data. The regression equations based on cadaver studies typically lead to errors arising from differences in tissue composition and morphology between the cadaver samples and a given human subject (63). The study by Chandler et al. (59) was the first study to determine the segmental principal axes of

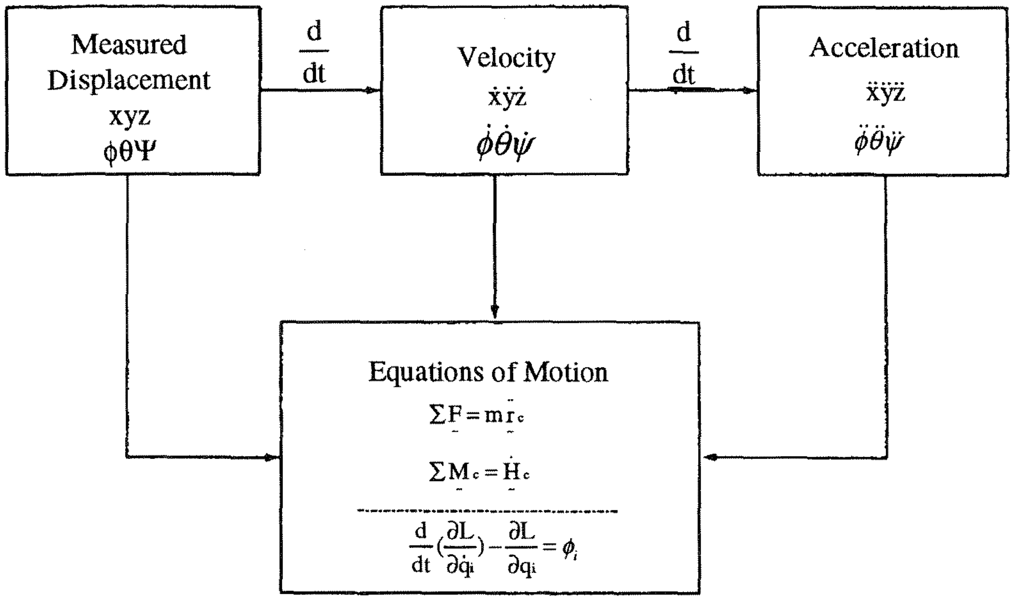

Figure 13.
Solution process for inverse dynamics problem. Displacement information must be differentiated twice to yield acceleration. Either Newtonian or Lagranian formulations can be used to formulate the equations of motion. (Reproduced with permission of Mayo Foundation.)

inertia and provided verifiable comparisons of derived photometric values and directly measured values. On the basis of these comparative relationships, a series of predicted regression equations were developed for adult males (61) and adult females (62). However, the sample sizes of these studies have been relatively small.

The *geometrical approximation* method represents the shape of different body segments with standard geometric forms that are capable of simple mathematical description (64–68) or magnetic resonance imaging (69,70). However, such techniques can involve high radiation levels (computed tomography) and require specialized, expensive instrumentation.

Future work should be aimed at obtaining inexpensive, fast, noninvasive, individualized estimates of the inertial properties of body segments based on *direct measurements.* One possibility is a video-based system (68). Error levels using this technique are on the order of 5 percent. Another possibility is the use of high-speed laser scanning. A 3-D laser scanner can obtain digitized images of a subject's limb in 10 seconds (71,72). Markers placed near anatomic landmarks can be used as reference points. These data can be used to compute subject-specific body segment parameters.

Forward Dynamics

These biomechanical models of the musculoskeletal system have improved our understanding of the complex processes underlying movement. Traditional gait studies have typically been conducted to collect experimental data and analyze movement and forces. In the future, the forward dynamics model can be used more extensively to study how the body actually produces movement. The forward dynamics problem provides the motion of a multibody system over a given time period as a consequence of the applied forces and given initial conditions. Solution of the forward dynamics problem makes it possible to simulate and predict the body segment's motion. The resultant motion is a result of the forces that produce it. Numerical computation of movements produced by applied forces can lead to an improved understanding of the locomotor system.

Using models to synthesize gait can provide insight into the relationship between muscle forces or joint moments and the body segment motions that result. The equations that govern the motion of the body can be expressed as:

$$[\mathbf{H}(\theta)]\ddot{\theta} = \mathbf{C}(\theta,\dot{\theta}) + \mathbf{G}(\theta) + \mathbf{F}_{\mathbf{m}}(\theta)$$

where $[H(\theta)]$ is an n x n inertia matrix for an n degree of freedom model

C $(\theta,\dot{\theta})$ is an n x 1 vector of coriolis and centrifugal terms

G (θ) is an n x 1 vector of gravitational terms

$\mathbf{F}_{\mathbf{m}}$ is an n x 1 vector of applied moments

$\theta,\dot{\theta},\ddot{\theta}$ are all n x 1 vectors of angular displacement, velocity, and acceleration.

Solving directly for the vector of angular acceleration gives:

$$\ddot{\theta}=[\mathbf{H}(\theta)]^{-1}\{\mathbf{C}(\theta,\dot{\theta}) + \mathbf{G}(\theta) + \mathbf{F}_{\mathbf{m}}(\theta)\}$$

Dynamic simulations of movement integrate this equation forward in time to obtain motion trajectories in response to neuromuscular inputs (**Figure 14**). The inputs can be either joint moments or muscle forces that act on the skeletal system to result in joint moments. Experimentally collected kinesiological data (i.e., body segment motion, ground reaction forces, and electromyographic data), can be used to compute the forward dynamics model inputs that give the measured motion trajectories. The simulated gait pattern can be studied to gain insight into the muscle coordination of the task.

Currently available models for simulating human locomotion have tended to be simple (73–83). State-of-the-art mathematical models of the musculoskeletal system need to be developed to predict gait patterns. The forward dynamics problem seeks the solution to a system of nonlinear ordinary differential equations (initial value problem). These differential equations are numerically integrated starting from the initial conditions. An important characteristic of this mathematical problem is that it is computationally intense. Because of this characteristic, it is very important to choose the most efficient method for solving this problem. Mathematical models have not been fully developed for several reasons:

1. The development of a dynamic model of the body that is sufficiently complex to encompass the multijoint, multibody, multimuscle characteristics of the human body requires considerable effort (84). The problem is to develop a model that is phenomenologically correct without being overwhelmingly complex for practical applications.
2. The muscle excitation patterns required as input to such a model are not fully defined (85). An improperly designed neural excitation pattern will simply result in inadequately coordinated body segment displacements.
3. The dynamic optimization algorithms to find iteratively an acceptable muscle excitation pattern are few and lack robustness (86).
4. The computational time required to find an adequate muscle excitation pattern is long (87).
5. The coordination principles provided by the neurological control systems in unimpaired individuals are poorly understood. The additional challenges of understanding pathological neuromuscular control systems have yet to be addressed.

When fully developed, these models need to include representations of the muscle tendon complex (87–91), skeletal geometry (92,93), kinematic models of the anatomic joints (94), and inertial characteristics of the body segments (95). Realistically developed theoretical models of the neuromusculoskeletal system will play a significant role in understanding locomotion.

Computer-based models are needed to study the biomechanical consequences of surgical reconstructions of the lower extremity. Upon review of data from a gait analysis study, surgical reconstruction is frequently

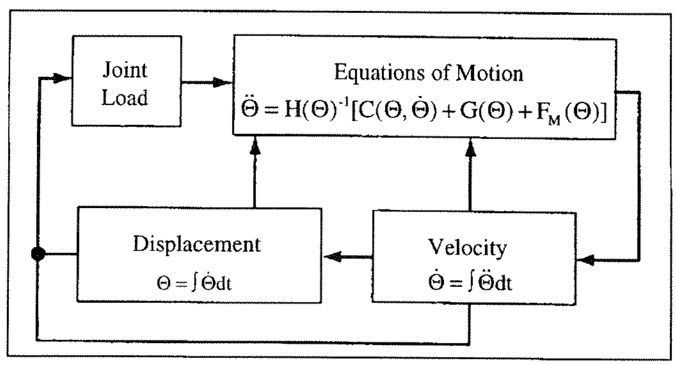

Figure 14.
Solution process for the forward dynamics problem. Joint load can be taken directly from joint moments or can be calculated from a muscle-tendon model and a joint moment arm model that yield joint moments. Joint loads cause angular accelerations, $\ddot{\Theta}$. Equations of motion are integrated to yield joint velocities, $\dot{\Theta}$, and displacements, Θ.

recommended. Sometimes the reconstructive procedure compromises the capacity of muscles to generate forces and moments about the joints. Computer models are needed to predict the anticipated effects that surgical alterations to the musculoskeletal system will have on a person's gait pattern. Relatively few researchers have developed computerized musculoskeletal models to plan orthopedic reconstructive surgeries for correcting pathological gait. Johnson et al. (95) developed a computer model of the hip to evaluate effects of surgical alterations. Dul et al. (96) developed a biomechanical computer model to simulate tendon transfer surgeries to correct equinovarus. Lindgren and Seireg (97) studied the effects of mediolateral deformity, tibial torsion, and different centers of foot support during gait in persons with varus deformity of the knee. Delp et al. (93) developed a graphical model of the lower limb to visualize the musculoskeletal geometry and manipulate model parameters to study the biomechanical consequences of orthopedic surgical procedures. Mann (98) developed a surgical simulation model to determine the effect of skeletal system alterations on subjects' specific gait patterns. Typically these surgical models compute static changes to isometric conditions but do not extend to dynamic movements such as gait. Future work is required to enhance these models.

Future models should include the 3-D characteristics of the musculoskeletal geometry, as well as subjects' specific parameters. The musculo-tendinous aspects of the model need to be scaled to the individual being studied. The numerical ability to predict ambulation following changes to the musculoskeletal system is imminently feasible. However, it has not currently been implemented.

INTERPRETATION OF GAIT STUDIES

Despite the growing availability of technology, gait analysis has not yet become a common tool for the physician. Gait laboratories have been started when individuals and institutions were willing to make the investment in time, effort, and money to assemble and operate gait laboratory systems. Gait laboratories have flourished when a combination of physician input and referral was coupled with day-to-day expertise in the form of physical therapists or other health care specialists and with technical expertise in the form of engineers and other technical staff (99). Several commercial gait systems are on the market. Increasing interest in gait analysis is emerging. Sixty-eight percent of the clinical gait analysis laboratories in the United States have been developed in the last 10 years (100). This trend demonstrates that gait laboratories are becoming recognized as an important clinical tool in the assessment of gait abnormalities.

When new gait laboratories are started, they frequently make a sizable investment in equipment. Nevertheless, instrumentation alone cannot make gait analysis clinically relevant. Clinical gait analysis includes the correlation and interpretation of the data. Taking care of patients in a gait laboratory requires turning data into information. The problem-solving process requires questioning the patient; performing a physical examination; obtaining kinematic, kinetic, and electromyographic data; and linking the symptoms (complaints), signs (physical exam), and test results (gait data) to obtain a treatment plan (**Figure 5**). In this process, it is important to distinguish between functional deficits that contribute to the individual's problem and compensations that the patient adopts in an attempt to walk more normally. The future of gait analysis lies in the ability to process data quickly and identify the patient's functional deficits. Classification methods are needed to characterize a person's gait and direct the clinician reading the gait study to the movement abnormalities. The ability to develop computerized classification techniques will make gait analysis accessible to a wider audience with limited experience. The initial step is to develop standards for collection, reduction, and reporting of clinical gait data.

STANDARDIZATION OF GAIT ANALYSIS TECHNIQUES

Standardization of gait analysis techniques must be established so that data can be shared between laboratories for expert consultation. Several national organizations are undertaking these endeavors. Standardized techniques are being defined for appropriate studies in various clinical settings. Measurement of normal and pathological movement for the purpose of providing recommendations for therapeutic treatment has been successfully achieved by practitioners and laboratories. However, approaches to data collection, reduction, presentation, and interpretation have varied considerably because of differences in equipment, facilities, personnel, and philosophy. The result is clusters of methodology without specific guidelines for comparison and communication.

The North American Society for Gait and Clinical Movement Analysis recognizes the need to facilitate communication and encourage the interchange of information among the many professionals who assess the problems of human movement. As a means for reducing confusion, this society has established a Standards Committee to define standards that can be adopted to achieve uniformity in clinical movement analysis. The Standards Committee was formed to achieve standardization of

1. nomenclature use in the collection, reduction, and presentation of data
2. approaches and techniques for data acquisition and reduction
3. quality assurance techniques
4. the form for presentation of results
5. methods for interpretation and reporting clinical findings
6. a format for sharing data between laboratories.

The Standards Committee intends to make contact with and work in concert with any and all parallel bodies that may exist in other specialty societies.

Accreditation is needed to assure quality and achieve continuous improvement of clinical gait and movement analysis. Accreditation attempts to assure that laboratories provide patient care that is effective in contemporary practice. Accreditation will publicly recognize those laboratories demonstrating a higher level of performance, integrity, and quality, which entitles them to complete confidence of the movement analysis profession. Accreditation efforts are occurring at two levels in North America.

The North American Society of Gait and Clinical Movement Analysis has established an Accreditation and Guidelines Committee. The Accreditation and Guidelines Committee will

1. serve as a liaison to nationally recognized accreditation boards pertaining to gait and clinical movement analysis
2. develop and recommend criteria for accreditation that may be used to evaluate the quality of patient care provided by laboratories involved in gait and movement analysis
3. bring together practitioners, evaluators, and administrators in an activity directed toward the continuous development and improvement in the quality of clinical movement analysis throughout North America
4. establish a process for continuous self-study and improvement of movement analysis professionals and laboratories.

The Commission for Motion Laboratory Accreditation has been formed as a non-profit organization. It was developed to enhance the clinical care of persons with disorders of human motion. These goals will be achieved by

1. developing measurement standards to improve the utilization of gait and human motion laboratories for clinical diagnostic purposes
2. evaluating and requiring human motion laboratories to meet a set of standard criteria that will include clinical indication, measurement precision, measurement accuracy, and uniformity of terminology.

The Commission contains representatives from the American Academy of Cerebral Palsy and Developmental Medicine, Pediatric Orthopedic Society of North America, American Society of Biomechanics, American Academy of Orthopedic Surgery, American Academy of Physical Medicine and Rehabilitation, North American Society of Gait and Clinical Movement Analysis, American Orthopedic Foot and Ankle Society, and the American Physical Therapy Association. The Commission will start to accredit laboratories in 1998.

Similar efforts are underway in Europe. The Computer-Aided Movement Analysis in a Rehabilitation Context (CAMARC) project is being undertaken under the Advanced Informatics in Medicine Action of the Commission of the European Communities with academic, industrial, public health, and independent partners from Italy, France, the United Kingdom, and The Netherlands.

The aims of the project are the

1. assessment of existing biomedical knowledge of movement analysis
2. standardization of test protocols
3. assessment and implementation of relevant digital signal processing algorithms
4. analysis of marketing potential of new instrumentation
5. development of design criteria for new devices.

It is the hope of this group to develop standards in the appropriate interface between the instrumentation and a suitable neuromusculoskeletal model. Accommodation of movement data and an appropriate model of human movement are expected to provide meaningful information for assessment of unimpaired and pathological movement for diagnosis, treatment planning, pre- and post-treatment comparison, and long-term follow-up.

CLASSIFICATION TECHNIQUES

One of the main obstacles to automated gait analysis is the difficulty of distinguishing between normal and abnormal movements. A person's gait is classified as abnormal when the person's gait parameters deviate excessively from normal. The clinical application of gait analysis is aimed at identifying these inappropriate deviations. In its simplest form, the problem of classifying gait disorders is a problem of mapping a multivariate temporal pattern to the most likely known disorder. Robust analysis of these data requires consideration of interactions among a large number of highly coupled variables, and the time dependence of these variables. Two approaches have been utilized: statistical techniques and artificial intelligence techniques.

Statistical Techniques

Several statistical techniques have been applied to the analysis of gait data. These include the "bootstrap" method (99,101), the linear discriminant method (102–104), principal component analysis (105), and cluster analysis (106). The *bootstrap technique* (107) was used to establish boundaries about the mean curve for unimpaired subjects (controls) to mark the limits of normal variability (99,101). These boundaries were designated as prediction regions. This technique was undertaken after initial attempts at setting boundaries for the variability within normal subjects using ensemble averages of one or two standard deviations failed. Kelly and Biden (108) compared the results of classification of knee motion by ensemble averaging versus bootstrapping. The motion curves of 39 unimpaired 5-year-old children were classified using both techniques. The ensemble-averaging method utilizing ± 2 standard deviations misclassified 16 of 39 normal subjects as abnormal. In contrast, the bootstrapping method classified all subjects as "normal." Bootstrap estimates of the prediction regions are of the form:

$$\hat{F}_h(\Theta) - m\hat{\sigma}_f(\Theta) \leq \tilde{F}_h(\Theta) \leq \hat{F}_h(\Theta) + m\hat{\sigma}_f(\Theta)$$

where $\hat{F}_h(\Theta)$ = the latest squares estimate of the subject's sum of harmonic coefficients

$\hat{\sigma}_f(\Theta)$ = the standard deviation of the harmonics, and

m = a positive number.

This technique has been applied clinically and has been shown to have a high sensitivity (109).

Methods of *discriminant analysis* have been shown to be effective in recognizing gait patterns of sound subjects and persons with gait deviation following total knee replacement surgery with a classification error rate of about 2 percent (102). This technique has also been used to develop knee and hip performance indices with well-demonstrated utility (103,104).

Principal component analysis and *cluster analysis* techniques have been used as a stepwise pattern-recognition approach to identify patterns of gait deviations. *Principal component analysis* is used to reduce the enormous quantity of data obtained in a gait study to a parsimonious set of features that describes gait patterns accurately (105) and results in a reduction in dimensionality of the original set of waveforms. Individual waveforms can be reconstructed using a linear combination of basis vectors modulated by weighting coefficients. Numerical representation using principal component analysis is important for two reasons (105): first, it is a parsimonious representation of cyclic subgroups within a larger patient population, and second, it may be very useful in identifying and classifying homogeneous subgroups within a larger patient population. *Cluster analysis* is used to place objects into groups or clusters suggested by the data, not defined *a priori.* Subjects in a given cluster tend to be similar to each other in some sense and subjects in different clusters tend to be dissimilar. These techniques have been used for classifying unimpaired subjects (110), persons with spastic paralysis (111), and persons with anterior cruciate ligament (ACL) deficiency (112).

Methods based on statistical analysis will continue to play a role in the processing of gait data. The strengths of statistical methods are that they provide a mathematical foundation for the analysis, accept experimental noise in the measurements, and offer robust time-series analysis. The weaknesses of statistical methods are that they ignore the physical meaning of the measurements and treat each variable in isolation.

Artificial Intelligence

An alternative approach to the analysis of gait dynamics is to use artificial intelligence (AI) techniques to diagnose gait disorders. Two categories of AI that have been used successfully are knowledge-based systems and neural networks.

Knowledge-based systems are most commonly referred to as ''expert systems'' and are characterized by large amounts of domain-specific knowledge and methods that embody the clinician's problem-solving strategy (113–115). Expert systems organize a knowledge base of facts that can be used to explain the logical connection between gait parameters and gait functional deficits. The facts in the knowledge base are arranged in premise-conclusion pairs called rules. The rules serve the purpose of causally relating gait parameters and functional deficits. The rules are probabilistic in nature, so inferences made by the program are seldom ''all or nothing.'' The strength of expert systems is that they encapsulate high-level knowledge from ''experts,'' and they model interactions among variables. However, the drawback of expert systems is that they assume that abnormal gait has been classified, and they only weakly model time.

A second method of AI is the *neural network*. Neural network designs are based on the structure of the human brain and try to emulate the way intelligent information processing occurs. The basic structure of a neural network is very simple. It consists of an array of elements usually called nodes, interconnections between these nodes, and some input/output scheme (**Figure 15**). The intelligent information properties of the network arise from the formation of the topology of the network, the learning rules of the nodes, and the particular type of nodes. Neural networks, despite their simplification of natural behavior, process information in novel ways. These networks have collective computational properties, such as association, generalization, differentiation, preferential learning, optimization, and fault tolerance. The use of these properties appears to have promise for the development of solutions to problems that have intractable or unknown algorithms and/or are too computationally intense. Neural networks follow an adaptive information-processing method well-suited for modeling dynamic processes.

Neural networks, which are capable of performing pattern-recognition tasks useful in the analysis of gait dynamics (116,117), have been shown to be capable of performing difficult temporal pattern processing tasks of gait kinematic data (118). The specific type of neural network used was a modification of standard back propagation as described by Elman (119). The network consisted of 12 input units, 10 hidden units, and 12 output units (**Figure 15**). It was trained using a set of 25 simulated unimpaired 7-year-old individuals. The simulated individuals were generated from the mean and variance data for the ''normal'' population (99). For each time increment, 12 motion variables, which contained the sagittal, coronal, and transverse plane motions of the pelvis, hip, knee, and ankle, were input to the neural network. The output of the network was the 12-tuple of motion variables at time increment, t+1. In this way, the network was trained to learn the temporal pattern of gait motion. The data set was subdivided into 50 time steps of each variable over a single gait cycle. After training was completed, the neural network was presented with gait patterns for 25 children at each age increment from 1 to 7 years of age. The difference between the new gait pattern (y′) and the learned gait pattern (y) was analyzed where the output error was calculated as follows:

$$SS_{Error} = \Sigma_i \Sigma_j \, (y - y')^2$$

where i = number of individual data sets (25) at each age increment, and
j = number of gait cycle divisions (50).

This total sum-squared error measures the deviation of each age group from 7-year-old gait (**Figure 16**). The results provide evidence that gait stabilizes between the ages of 3.5 and 4.0 years. This characteristic of gait development is supported by both expert physicians (99) and previous statistical analysis (101). This example demonstrates that neural networks are capable of performing pattern-recognition techniques useful in the analysis of gait dynamics.

In the future, neural networks can be used to differentiate normal and pathological gait. A person's gait data will be analyzed to yield a total sum-squared error. If the value exceeds a threshold, the person's gait will be further analyzed to pinpoint the areas of gait deviations, based on the difference between the individual's gait pattern and the learned normal gait pattern. Additional networks can be developed to differentiate subcategories of gait abnormalities. Once the individual's gait has been identified as abnormal, it can be analyzed by subsequent neural networks that are trained to recognize predefined functional gait deficits. Thus, it

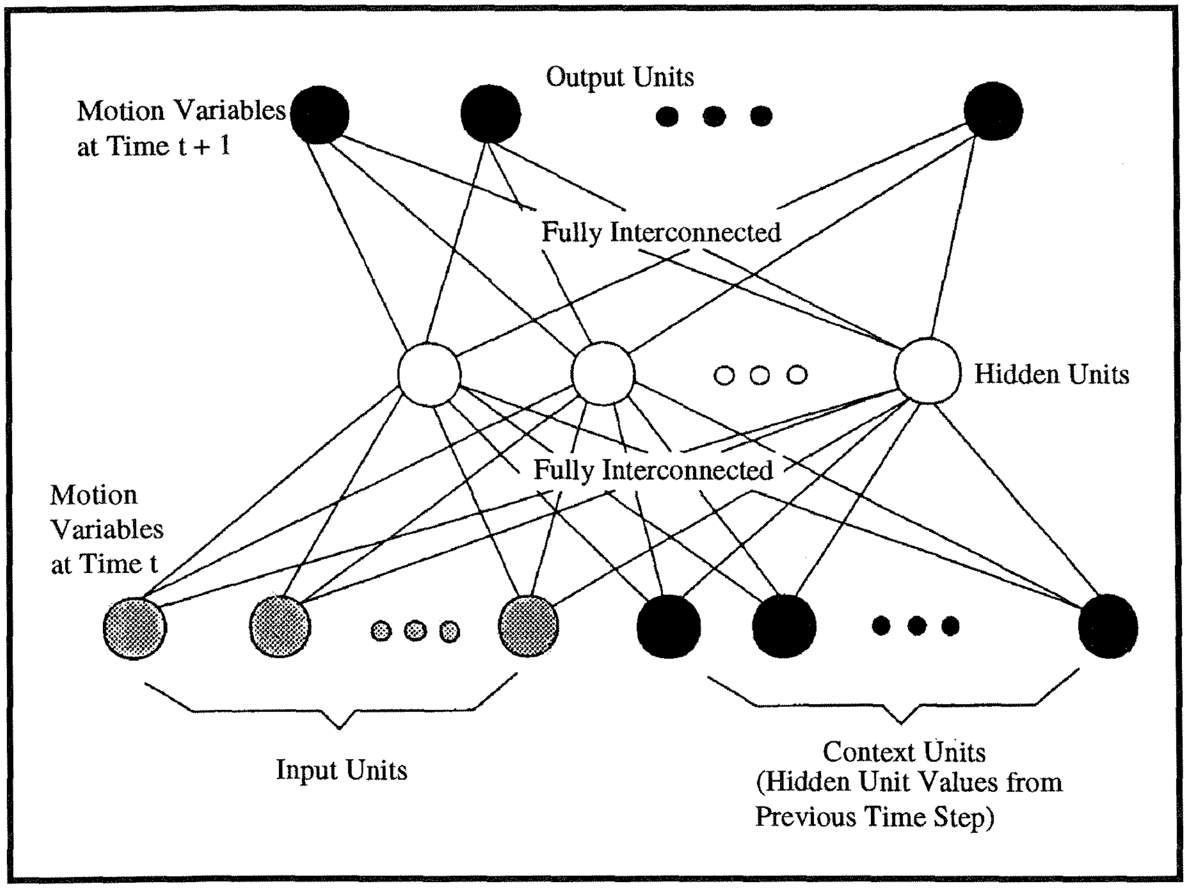

Figure 15.
Basic structure of a neural network (consisting of elements called nodes, interconnections between nodes, and an input/output scheme). This particular network is called a back propagation network and has a set of hidden nodes. It was used for temporal-pattern processing of gait kinematic data, which consisted of 12 motion parameters (118).

will be possible to identify the gait abnormalities of a subject.

Similar to the other techniques for classification of gait data, the strengths and weaknesses of neural networks must be recognized. The advantages of neural networks are that they capture the temporal structure of the gait variables, model the interconnection among these variables, and contain nonlinear processing elements. These advantages must be weighed against several disadvantages. First, neural networks require a large amount of data on which to be trained. Aside from unimpaired subjects, this amount of data on select pathologies might not be available. Further, neural networks require extensive training time in order to assure stable operation. Finally, neural networks do not distinguish between signal and noise (120).

Experienced specialists are needed to ensure that techniques used for pathological gait classification are reasonable. Each of the methods (statistical techniques, expert systems, and neural networks) offers advantages and disadvantages. The relative merits of each approach have not been fully investigated. In the end, it will be important to draw upon the strengths of all techniques in a productive and mutually supportive relationship in order to maximize the outcome.

TELECOMMUNICATION

Distributed data and computing resources need to be incorporated in the scientific computing environment of every motion analysis laboratory. Users must be able to gain transparent access to data and computing resources located anywhere in the world. Clinicians and researchers scattered around the globe should be connected via a network. Individuals operating computer software environments residing on their desktops should be able to communicate with leading centers in gait analysis.

Once standards have been established, it will be possible to share information among medical centers in order to obtain additional expert opinions on difficult cases. Currently, efforts are being made to create a national information infrastructure—the so-called electronic superhighway. This electronic network will carry voice, data, and video in digital form. At present, an electronic network, the Internet, already exists. The Internet was established in 1969 as an experimental computer network organized and financed by the Department of Defense and the National Science Foundation. The network was created to facilitate the research of a small number of scientists, engineers, and researchers. No commercial usage was permitted at first. Over time, the number of users of the Internet has increased. Currently, it is estimated that there are over 15 million users (121). Most of these users are in the United States but there are users in 134 other countries as well (121). The number of commercial users is also increasing. In early 1993, more than half of the registered networks were private businesses (121).

A nationwide communication system can be used in health care. High-performance computing and networking can be used to speed development of gait interpretation techniques, facilitate diagnoses from remote locations, and achieve enormous improvements in efficiency by aiding multicenter studies on treatment techniques. Major medical centers are obtaining state-of-the-art telecommunication capabilities (122); this includes the transmission of data, audio, and visual information. Telecommunication networks have made people throughout the world accessible within a matter of minutes or hours. It is no longer necessary for collaborators to be near one another. Current telecommunication systems provide two-way video and two-way audio. The image must be high-resolution and obtained in real time so that medical examinations can be performed. This connection will enable the transmission of information over high-bandwidth networks for immediate physician-physician consultation on particular cases. The security of all transmissions must be assured by scrambling the signal to maintain the confidentiality of all patient information.

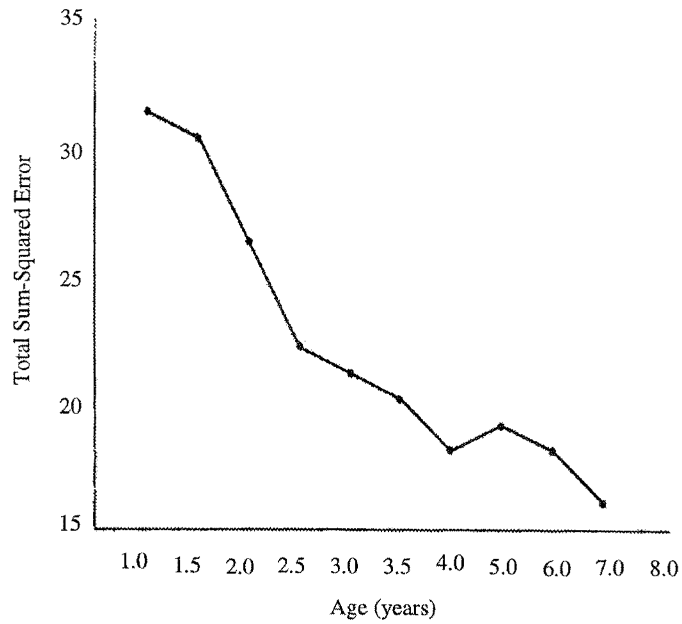

Figure 16.
Deviations of age group kinematic data from normal 7-year-old gait. Deviations expressed as a sum-squared error. Differences determined using a back propagation neural network. Results provide evidence that gait kinematics stabilize between 3.5 and 4.0 years of age (118).

In the years ahead, fiber-optic transmission and high-definition television will be among the advancements that will strengthen the interchange of information. Telecommunication will also enable the sharing of digital data with large bandwidth requirements for research purposes. The ability to share information will facilitate the development of databases that will enable clinicians to obtain knowledge for the treatment of specific gait disorders.

A national database for motion analysis data must be created. This national data repository can be used to pool gait assessments from participating centers throughout the United States. The database system should be based upon commercially available database software that can be used to maintain the data repository. Interaction with the database from participating centers would be through a web interface. The transmission of data would be protected through the secure sockets layer (SSL) protocol. This provides both encryption of the data and authentication of each participating center. An Internet accessible web server that supports the SSL protocol should be used. This web server would offer hypertext pages, software applications and connectivity to the database server. Access to this web server would be permitted only for participating centers.

Each center would collect information on patients who have undergone biomechanical, neurological, and radiological evaluation relevant to clinical treatment for neuromuscular disorders (**Figure 17**). The data would be reduced to a standard data format, through the use of an application existing on each center's local workstation, and submitted to the repository website over the Internet (**Figure 18**) using an encrypted file. An online submission form would be completed. Subsequently, a completed report file would be returned to the center via electronic mail upon a successful load of the data into the data repository. Sensitive information, such as identifying information related to patients and surgeons, would be identified as such upon submission and recoded to ensure confidentiality. Similarly, each center would be able to extract information for its own use, including data submitted by other centers. In this case, an interactive form would assist in the search criteria used to extract the data sets, which would then be bundled together as a set of standard format files and made available for transfer from the multi-center web server in a location accessible only to each individual center. Notification of the completion of the query would be via electronic mail, which would include a retrieval summary of the resulting data set. The bundled data set selected by the center would be encrypted and transferred via the Internet to the center's workstation. This data could then be used to make outcome comparisons of patients who had been treated for similar physical conditions.

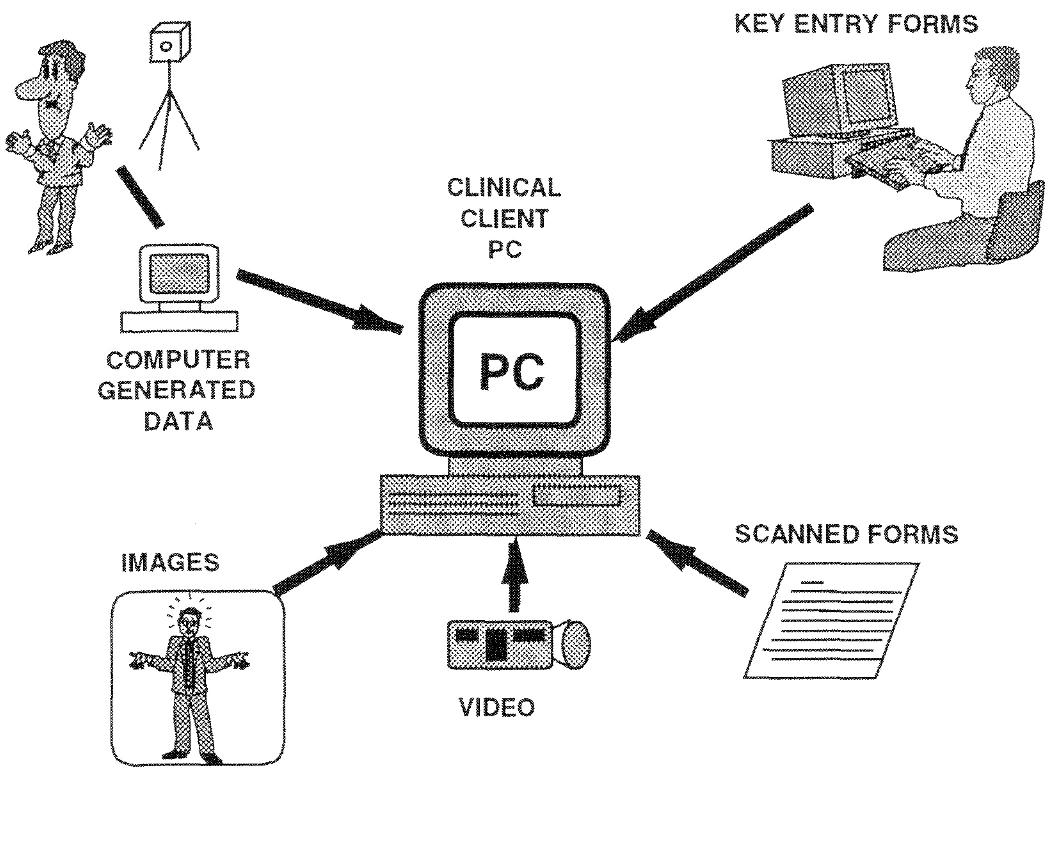

Figure 17.
Multimedia entry of patient data into a database.

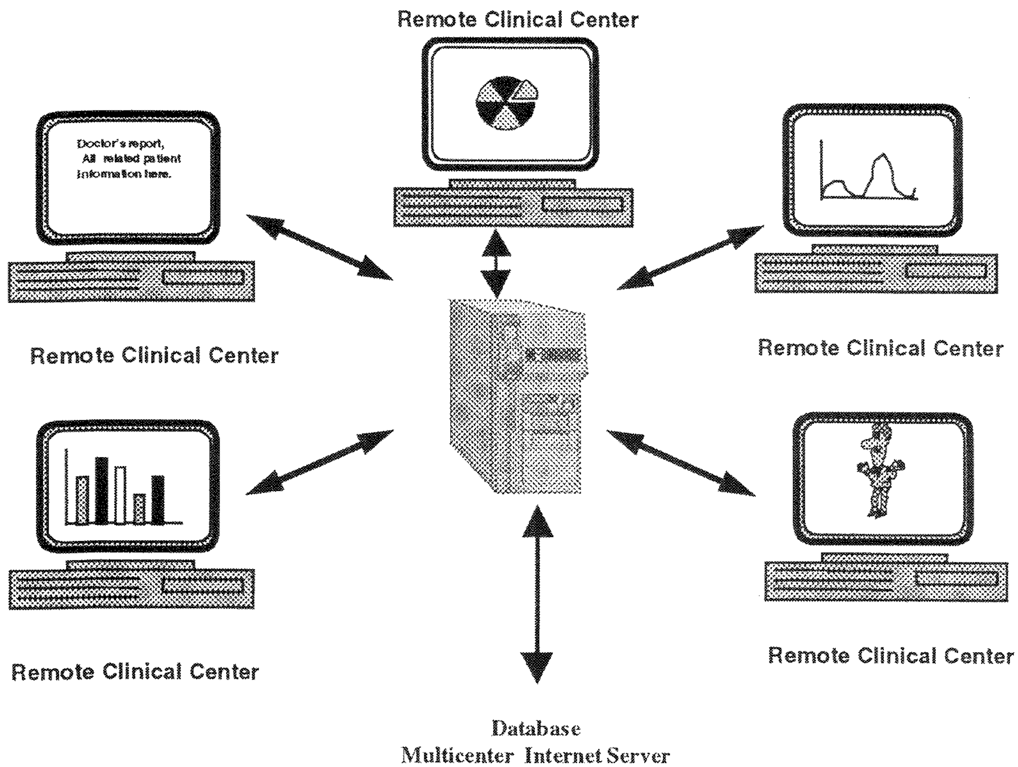

Figure 18. Remote storage/retrieval gait analysis data into a database repository.

SUMMARY

The ultimate goal of gait analysis is to provide reliable, objective data on which to base clinical decisions. A gait analysis laboratory requires an interdisciplinary team of individuals with various educational backgrounds who contribute their skills and who need to understand the underlying principles utilized to identify and correct neuromuscular deficiencies. The computer revolution will aid in developing new paradigms for computerized human movement analysis. New experimental techniques will be developed that will allow us to obtain real-time motion measurements. Computer animation techniques will become available to visualize gait data in an intuitive manner. Improvements will be made in our ability to obtain *in vivo* measurements of muscle function. Advances in both forward and inverse biomechanical models will continue. The future of gait analysis will require the ability to identify the critical tests, interpret data more quickly, predict the outcome of various clinical procedures, and quantify the outcome. Gait classification techniques will allow this to happen. Regional and national computer telecommunication networks need to be established whereby data can be exchanged to assimilate the knowledge necessary to predict the outcome of various surgical procedures. Efforts are underway to standardize techniques in order to facilitate the exchange of data. Reforms in health care will require that we be able to manage costs while providing an important clinical service. It is increasingly important that we consider the effectiveness of gait analysis and the role it will play in shaping the outcome of medical care.

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