SECTION TWO

Instrumented Gait Analysis Systems

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INTRODUCTION

The measurement of human gait has come a long way in the past 40 years. Modern gait analysis started with the work of Inman and Eberhart (1–3) in the 1950s and became a useful clinical tool through the pioneering efforts of Perry (4–7) and Sutherland (8,9). These pioneers were able to show the clinical value of relating muscle function to joint motion and phases of the gait cycle, which resulted in surgical procedures to improve the gait of those suffering from spastic paralysis and other neuromuscular disorders.

That these early researchers obtained clinically useful results is all the more amazing when one considers the basic instrumentation available to them. Most of the instruments were pieced together from various sources (10) and/or developed "in house." Joint motion was measured from custom-made electrogoniometers or laboriously digitized by hand from motion picture films (9). Raw electromyography (EMG) was recorded on analog tape recorders and displayed with footswitch timing information on "Visicorder" strip charts. Hand measurement of footswitch timing from these records was used to calculate temporal gait parameters. A roomfull of strip chart albums at the Pathokinesiology Laboratory of Rancho Los Amigos Medical Center testifies that, with proper dedication and effort, a lot can be done with less than optimal tools.

The computer age has brought with it a much brighter picture for today's clinician who wishes to perform clinical gait analyses. From relatively inexpensive devices to very costly systems, the necessary tools are readily available to equip a modern gait lab. The large number of vendors provides many options from which to choose when selecting gait instrumentation (**Table 1**). Unfortunately, with all these suppliers, confusion can arise as to how to spend gait instrumentation dollars.

The purpose of this article is to provide information on the types of gait instrumentation that are commercially available and give some criteria for selecting the appropriate instrumentation. Also included are unique and/or key features of each manufacturer's products. This will not be a "Consumer Report" type of article, as I have not used or tested all the instruments reported here. Instead, this report is based on my understanding of gait instrumentation in general, the material provided to me by the manufacturers, and personal communication with other engineers and users of these systems.

PICTURE VIDEO

Techniques have been developed to enable a trained observer to make critical judgments about an individual's gait, by viewing a video recording of the person walking (11). Hence, one of the simplest pieces of gait instrumentation also is one of the most useful. A picture video system allows the clinician to record a person's gait prior to applying any instrumentation (EMG electrodes, footswitches, motion markers, and so forth) that might alter the gait patterns. It provides visual documentation of what occurred during the instrumented tests and is the only way of resolving differences when the recorded footswitches or motion data do not correspond to the clinician's visual image of the subject.

Table 1.
Gait instrumentation manufacturers by type.

Manufacturer	Picture Video	Temporal Gait			Foot Pressure		Motion		Force		EMG				
											Electrodes		Acquisition		Analysis
		Foot Switch	Mats	Other	Mats	Insoles	Goni	Video	Plates	Load Cells	Surface	Wire	Wireless	Cable	
AMTI									X	X					
Ariel								X							
Bertec									X	X					
Biometrics Ltd.							X								
B & L Engineering	X	X		DL							A				X
Bortec											A			W, FO	
BTS	X	X		X				X			A		X	FO	X
Charnwood Dynamics				X				X							
CIR Systems			X												
Delsys											A				
EQ Inc.			X												
IOMED											A				
IVM											P				
Kistler									X	X					
Konigsberg													X	FO	
Market-USA				X			X			FS			DL		X
Motion Analysis				X				X							
Motion Lab Systems		X									A			W	X
Musgrave Systems					X										
Nicolet Biomedical											P	X			
Noraxon													X	W	X
Northern Digital								X							
Novel Electronics					X	X									
Oxford Metrics				X				X							
Peak Performance	X			X				X							
Qualisys				X				X							
Sensor Medics											P				
Tekscan				X	X	X									

FS = Force Sandals A = Active P = Passive DL = Data Logger W = Wire FO = Fiber Optic Goni = Goniometer

A basic video system consists of a VCR, one or two video cameras, a character generator, a video mixer, and a TV monitor. The video mixer combines the images from two cameras so that an anterior/posterior (A/P) and lateral view can be observed simultaneously. Some users find the two views confusing and prefer to combine a simultaneous record of EMG and/or footswitch data on oscilloscopes with a single view of the person walking. The character generator enables one to overlay text (e.g., name, date) on the video image. Three manufacturers provide picture video systems (**Table 2**) that were designed to be used with specific

Table 2.
Picture video system features.

Manufacturer	Recorder	Storage Media	Used With	Software Controlled?
B & L Engineering	VCR	Tape	Vicon Motion System	Yes (1)
BTS	VCR	Tape	BTS ELICLINIC	Yes
Peak Performance	DVR	Disk	Peak Motus Motion System	Yes

DVR = Digital Video Recorder
(1) VCR must be manually operated if used without the Vicon.

motion systems. The clinician should check with the manufacturer if he or she wants to use it with another system or as a stand-alone system.

TEMPORAL GAIT MEASUREMENTS

Since gait is repetitive in nature, temporal gait measurement systems provide the clinician with a valuable analytical tool in gait analysis by quantifying the timing of critical events in the cycle. Cadence, gait cycle duration, stance and swing times, single limb support, and initial and terminal double limb support are typical parameters measured. By making the measurements over a defined walking distance, average velocity and stride length also can be defined. Measuring only velocity and single limb support can reveal a great deal about an individual's functional ability to ambulate. As that person gets weaker, has painful joints, or feels unstable, velocity will decrease and less time will be spent in single limb support on the affected side.

Footswitches

Footswitches are a convenient and inexpensive way of obtaining temporal gait measurements. There are two basic types, compression closing and force sensitive resistor (FSR) switches, usually configured as thin insoles, which can be placed between the foot and shoe or taped to the bottom of a bare foot.

Compression closing switches consist of a sandwich of thin pieces of brass shim stock separated by a compressible (nonconducting) foam rubber insole (**Figure 1**). In the contact areas, conductive rubber cylinders are inserted into holes in the insole. When pressure is applied, the insole compresses and the conductive rubber cylinders contact the pieces of brass on each side of the insole, closing an electrical circuit. This sandwich is held together with duct tape and is typically about 4-mm thick.

The FSR switches consist of two thin layers of flexible plastic, with printed circuits on the inner surfaces, separated by a thin layer of double-sided adhesive. Holes in the adhesive create contact areas. As pressure is applied, carbon on one surface contacts a metal pattern on the other surface, creating a resistive electrical circuit (**Figure 2**). As more pressure is

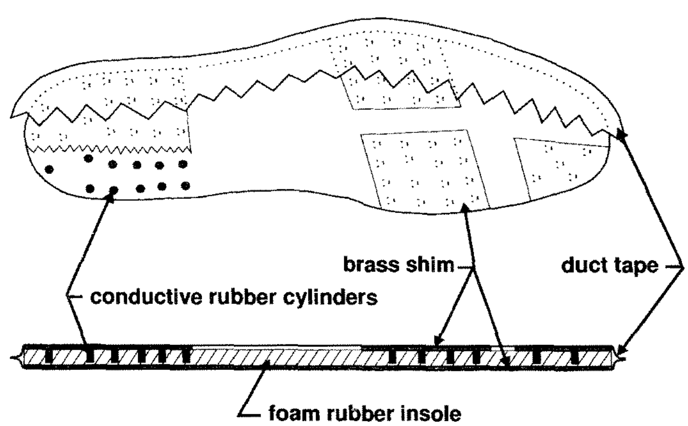

Figure 1.
A typical compression closing footswitch (not to scale). For clarity, the duct tape, which holds the "sandwich" together, is only shown along the lateral edge on the top view. The cross-section view shows the conductive rubber cylinders and brass shim, as well as the two duct tape layers.

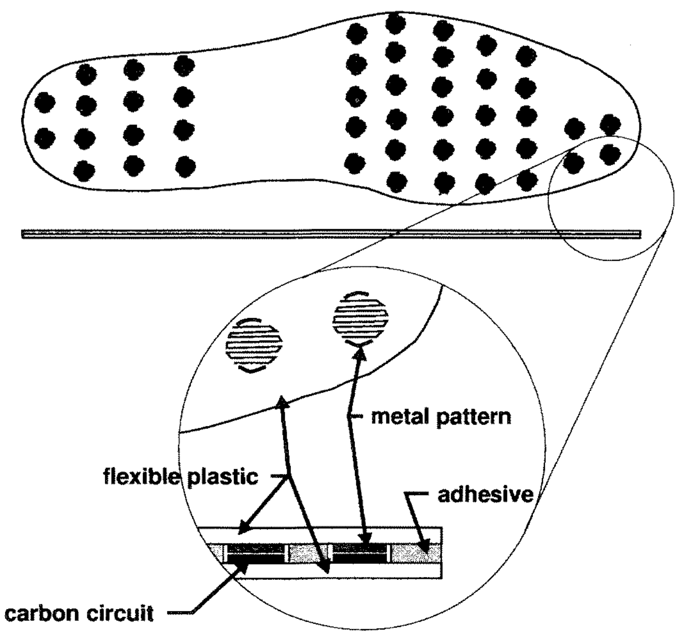

Figure 2.
A force sensitive resistor (FSR) footswitch (not to scale). An enlarged view of a portion of the toe section shows more detail of the flexible plastic layers with the printed circuit contact areas on the inner surfaces. Pressure causes carbon on one surface to contact a metal pattern on the other surface, creating a resistive electrical circuit. As more pressure is applied, the resistance drops to a level that is detected as a switch closure. The interconnecting printed circuit traces are not shown.

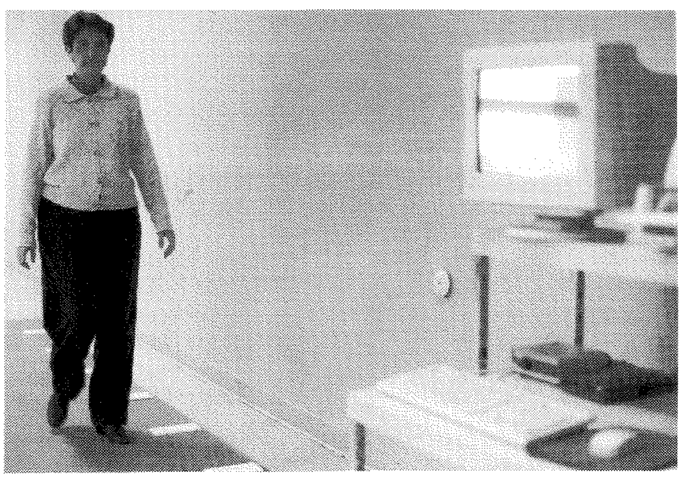

Figure 3.
A person walking down the "GaitRite" gait mat, free of any encumbering equipment. The computer at the right displays the foot/floor contact patterns as the switches in the mat close due to foot pressure. The temporal and spatial gait parameters are calculated and displayed for printing and storing in the database. (Photograph used with permission.)

applied, the resistance drops. The associated circuitry triggers, at a predefined resistance value, indicating a switch closure.

Footswitches typically have contact areas in the heel, first and fifth metatarsal, and great toe areas (**Table 3**). Some facilities use discrete switches taped to critical areas under the foot rather than an insole, which incorporates the switches into a single module. The advantage of discrete switches is that different sizes are not required to fit a large range of foot sizes. The disadvantage is in getting reliable data because of difficulty in consistently placing the switches at the proper locations under the foot.

Typical footswitch activation delay times, as compared with force plate data, are from about 1 to 2 percent of the gait cycle. For a nonimpaired person walking with a 1-second gait cycle, this is a delay of about 10 to 20 msec at both initial and terminal contact. Some footswitch software compensate for this delay.

Some facilities obtain temporal gait data from their video motion systems, identifying foot-floor contact from the motion marker trajectories. A disadvantage of this technique is that the temporal resolution is restricted to the frame rate of the video system (20 msec for a 50 Hz frame rate).

In addition to the footswitches, B & L Engineering (Tustin, CA) manufactures the Footswitch Stride Analyzer, a computer-based instrument that computes all of the temporal gait parameters based on footswitch data averaged over a measured distance. This system also provides a graphic representation of the foot-floor contact patterns (12). The user wears a small battery-powered microcomputer recorder unit (data logger), which stores up to four runs of data. An optical link is used to download the data to a PC for calculation and printing of the results. A light-sensitive switch worn on the user's upper arm triggers the recorder when he or she passes special triggering lights set up at the beginning and end of the measured walkway.

Gait Mats

Gait mats are relatively new systems that provide both temporal and spatial gait parameters. These mats consist of a long strip of walking surface, such as carpet, into which is embedded an array of switches running across and along the length of the mat (**Figure 3**). As a person walks down the mat, the switches close under the feet, enabling the computer to calculate the timing of each switch closure. Since the geometry of the mat is known, the spatial parameters of gait can be

Table 3.
Footswitch features.

Manufacturer	Type	Areas of Contact	Thickness (mm)	Size
B & L Engineering	Compression Closing (Insole)	Heel 5th Met 1st Met Great Toe	3	All Standard Male & Female Sizes (1)
BTS	FSR (Insole)	Heel Lat Foot Med Foot	2	140,191, 216 & 267 mm long
Motion Lab Systems	FSR (Discrete)	User Selected	0.5	18 & 28 mm dia.

FSR = Force Sensitive Resistor Met = Metatarsal Lat = Lateral Med = Medial (1) Can be custom made to user selected sizes.

calculated. Besides step length measurements, the advantages of these systems are the elimination of any gait encumbering attachments, low cost, and portability. The major disadvantages are the spatial resolution due to the finite size of the switches and the temporal resolution due to limitations in the scan rate. Both systems (**Table 4**) provide an extensive database and have provisions for editing the raw data file if desired.

FOOT PRESSURE

Capacitive and FSR transducers are the two basic types in use today for plantar pressure measurement. The capacitive transducers consist of two capacitor plates separated by a compressible rubber dielectric material. As pressure is applied, the capacitor plates are pushed closer together resulting in increased capacitance, which is calibrated in units of pressure. The FSR transducers are fabricated in a manner similar to that described for the FSR footswitches. As pressure is applied to the transducer, the electrical resistance decreases, indicating an increase in pressure. The accuracy of these systems is dependent on the ability to reliably calibrate them, as the transducers tend to be nonlinear. Pneumatic pressure bladder calibration systems generally are used. Since the area of the transducers is known, the applied force can be calculated by adding up the force computed from each active sensor at a given point in time. These systems are valuable, because they provide a method of quickly determining the areas of high pressure on the plantar surface of the foot, areas that may be subject to tissue breakdown. Two types of systems, mats and insole devices, are available commercially.

Pressure Mats

A pressure mat is placed in the center of the walkway and used much like a force plate, with the subject stepping on it as he or she walks down the walkway. It provides a quick and easy way of obtaining a plantar pressure picture, as nothing needs to be attached to the individual. However, if the effects of shoe insoles or various orthoses are to be evaluated, an insole pressure-measuring device must be used. All three pressure mat systems listed (**Table 5**) are factory calibrated and have software that includes color pressure pictures, gait lines, force and pressure versus time, force and pressure/time integrals, and masks for detailed analysis of selected areas of the foot.

Pressure Insoles

Pressure insoles were designed to provide the same kind of data available from pressure mats, with the added advantage of in-shoe measurement and multiple cycles. Dynamic measurement of footwear and orthoses is possible with these insoles. One can quickly and easily compare the plantar pressure distribution with different shoe inserts and/or orthoses. With special care, barefoot data can also be obtained by lightly taping the

Table 4.
Gait mat features.

Manufacturer	Type	Active Area	Thickness (mm)	Switch Spacing (mm)	Temporal Resolution (msec)	Special Features/Considerations
CIR Systems (GaitRite)	Portable (1)	61 cm x 3.66 m	4	12.7	11	Can handle walking aid patterns Computes FAP score (3)
EQ, Inc. (GaitMat)	Transportable (2)	61 cm x 4.17 m	32	15	10	Needs 32 mm thick runways at each end for pre & post walk area (4)

(1) Can be rolled up and carried in a convenient plastic golf case.
(2) Folds into four 99 x 41 x 1 cm pieces that fit in a storage case.
(3) The Functional Ambulation Performance (FAP) score is a single numerical representation of a person's gait, based upon temporal and spatial gait data as well as the person's physical measurements (10*, 13*).
(4) Manufacturer does not provide runways.
*Reference numbers.

Table 5.
Pressure mat features.

Manufacturer	Sensor Type	Size (mm)	No. of Sensors	Sensor Density (per cm^2)	Sample Rate (Hz)	Calibration	Special Features
Musgrave Systems (Musgrave Footprint)	FSR	194 x 394 x 38	2,048	2.7	55.6	Dynamic Force	Double Plate System Available
Novel Electronics (EMED)	Capacitive	225 x 445 x 20	2,016	2	70	Static Pressure Bladder	Podometry Software Provided
Tekscan (F-Mat)	FSR	320 x 470 x 6	2,128	1.4	120	Static Force	Real Time Display

FSR = Force Sensitive Resistor

transducer to the bottom of the foot. The insole must be protected from possible damage and the clinician must insure that the floor/insole interface does not create a slipping hazard for the wearer. Both the Pedar and F-Scan systems (**Table 6**) incorporate the software developed for the pressure mats manufactured by their respective companies.

MOTION

Since walking involves cyclical movement patterns at multiple joints, it is important to measure these kinematic patterns as a basis for interpreting other gait data (EMG, force, stride characteristics). The kinematic measurements (which also include limb segment velocities and accelerations) are necessary for the determination of joint moments and forces (kinetics).

Two basic types of motion measurement systems are in use today: electrogoniometers and video motion systems. Although other techniques exist—hand digitized film (9), strobe light photography (10,14,15), and electromagnetic—they have either been replaced by newer technologies or never caught on as a clinically useful tool.

Electrogoniometers

Electrogoniometers are electro-mechanical devices that span a joint to be measured, with attachments to the proximal and distal limb segments (**Figure 4**). These devices provide an output voltage proportional to the angular change between the two attachment surfaces. They operate on the assumption that the attachment surfaces move with (track) the midline of the limb segment onto which they are attached and, thereby, measure the actual angular change at the joint.

The two major advantages of these devices are low cost and ease of use. As is the case with all gait instrumentation, care must be exercised in applying them to the individual. The tracking assumption is reasonable for lean individuals, but the more "fleshy" and/or muscular the person being tested, the less likely the true angular change will be recorded due to skin and muscle movement. When considering these devices for gait, their accuracy should be carefully evaluated by testing them on individuals of various statures. The person should move through a known range of motion (i.e., 90°) while the goniometer output is being recorded. This will give a general idea of the kinds of errors the clinician might encounter.

A number of different potentiometric goniometers have been developed for gait. They were designed to cause a potentiometer shaft to rotate proportionally to the joint angle being measured. Various designs were incorporated to allow for the polycentric joint axis at the knee. One of these designs, the double parallelogram goniometer, has been used with considerable success at the Pathokinesiology Laboratory, Rancho Los Amigos Medical Center. The double parallelogram linkage allowed translation of the attachment cuffs to occur without creating a change in the potentiometer output. This device is not commercially available.

Biometrics Limited (Penny & Giles, Inc., Santa Monica, CA) has developed strain gauge goniometers that are light, flexible, and easy to use. They consist of a small diameter, tightly coiled, flexible spring with plastic endblocks on each end (**Figure 4**). The strain gauge mechanism housed inside the spring, changes electrical resistance proportionally to the change in angle between the longitudinal axes of the endblocks. One endblock is telescopic, compensating for changes in the distance between the endblocks as the limb moves. The endblocks are attached to the limb segments with double-sided adhesive tape. These devices are biaxial, enabling one to simultaneously measure sagittal and frontal plane motions. They come in various sizes, to accommodate different joints, and have a very large functional measuring range (greater than 180°). This company also makes similarly designed "torsiometers" for measuring axial rotations. For instrumentation, they provide a data logger, which stores the data for later downloading to a PC via a serial port (software is available). They also manufacture a four-channel amplifier that consists of a small portable body-worn unit and a larger tabletop base unit, for connecting to a strip chart recorder or computer A/D converter.

Infotronic (Market-USA, Inc., Severna Park, MD) sells a goniometer system that incorporates the Penny & Giles transducers described above. Their system has a data logger that stores the angle data on memory cards (see EMG Acquisition Systems, below). The data can later be downloaded to a PC. The software enables the user to plot angle/time and angle/angle diagrams.

Video Motion

Video systems utilize one or more video cameras to track bright markers placed at various locations on the person being tested. The markers are either infrared (IR) light-emitting diodes (LEDs) for active marker systems or solid shapes covered with retroreflective tape for passive marker systems. The systems keep track of the horizontal and vertical coordinates of each marker from each camera. In three-dimensional (3D) systems, the computer software computes 3D coordinates for each marker based upon the 2D data from two or more

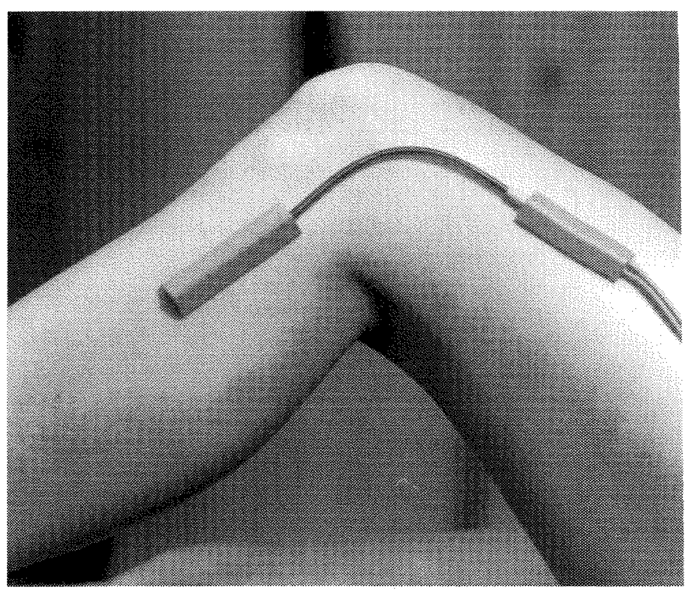

Figure 4.
A Penny & Giles strain gauge electrogoniometer applied at the knee. The strain gauge in the small spring measures the angle between the plastic endblocks that are attached to the leg with double-sided adhesive tape.

Table 6.
Pressure insole features.

Manufacturer	Sensor Type	Thickness (mm)	Sizes	No. of Sensors	Max. Sample Rate (frames/sec)	Calibration	Software
Novel Electronics (Pedar)	Capacitive	2.5	12 standard sizes (1)	99 - adult 84 - child	58	Static Pressure Bladder	Pedar Step Analysis (5) & EMED
Tekscan (F-Scan)	FSR	0.2	scissor trimmed (2)	960 max. (3)	100	Body Weight or Pressure Bladder (4)	F-Mat & Langer EDG for temporal gait

FSR = Force Sensitive Resistor
(1) Standard sizes range from 160 to 300 mm in length. Custom sizes available.
(2) Can be trimmed from men's 14 to child's size 3.
(3) Variable depending on trim size.
(4) Accuracy: Body Weight; 10%; Pressure Bladder, 3 to 5%.
(5) Step Analysis provides 2 & 3D pressure pictures, step timing and pressure and force as a % of the cycle.

cameras and the known location of all cameras. In practice, more than two cameras are needed, as markers become obscured from camera views because of arm swings, walking aids, and/or patient rotation.

If only one camera is used (2D), the assumption is that all motion is occurring in a plane perpendicular to the camera axis. This is seldom the case and any marker movement outside this plane will be distorted. As a result, 2D systems are not recommended for gait and should only be used in very controlled situations.

It should be pointed out that just because a system computes the 3D coordinates of each marker, it does not mean, *a priori,* that 3D kinematics will be produced. To obtain true 3D motions, each body segment must be defined by at least three markers (which create a plane passing through the segment), joint centers must be defined, and Euler angles computed. Knee and ankle joint centers are either determined from width measurements or medial markers used only during a calibration (''quiet standing'') test. Most commercially available systems provide software that attempts to determine true 3D kinematics (**Table 7**). Prior to purchasing a system, the buyer should ensure that he or she understands the assumptions in the kinematic modeling and their impact on the results. For example, most systems utilize a common marker on the lateral femoral epicondyle for both the thigh and shank segments. This hinge joint approximation at the knee may introduce errors with large flexion angles. The calculated hip joint center is often used in place of one of the thigh markers, a technique that can introduce errors in thigh motion. Some systems do not measure inversion/eversion at the foot due to the difficulty of placing three closely spaced markers on the foot.

Kinetics software computes the net joint moments, forces, and powers based upon the kinematics, ground reaction forces, and anthropometric data. Most provide kinetics in all three planes. As with the kinematics, one should be comfortable with the models used, and the way segment mass and moments of inertia are approximated.

All of the systems provide the capability of acquiring at least 16 channels of analog data simultaneously with the motion data (**Table 7**). Most compute temporal gait parameters measured from bilateral motion data if footswitches are not used. Most gait motion data are collected at a frame rate of 50 or 60 Hz, so temporal gait measurements utilizing the motion data will have a minimum time resolution of 20 and 16.7 msec, respectively, as compared with 2 msec or less for typical footswitch systems. The camera's field of view limits the number of strides available. Unlike footswitch systems, however, step length can be obtained from motion data.

Two important factors to consider for any clinical application are ease of use (which includes processing speed) and accuracy. Ehara et al., conducted a performance comparison (accuracy, marker noise, and processing speed) of nine video 3D motion systems (16). In addition to three systems available only in Japan and a

Table 7.
Video motion system features.

Manufacturer	System Type	Input Device	Comp. O.S.	Analog Channels No.	Analog Channels Rate (Hz)	Calib.?	Temporal Gait?	Marker ID	Kinematics 3D	Kinematics Foot Inv/Ev	Kinematics Knee & Ankle Joint Centers: Patient Calib.?	Kinematics Knee & Ankle Joint Centers: Measurements?	Kinetics Clinical Software
Ariel (APAS)	Passive	VCR's	W	32	2K	Yes	No	SA (2)	Yes	Yes	No	Yes	Sag, Fr Tr
BTS (Elite)	Passive	Video Camera	W, WNT DOS	64	1K	Yes	Yes	SA	Yes	(4)	Optional	Yes	Sag, Fr, Tr
Charnwood Dyn. (CODA mpx30)	Active	Scanner Camera	W, WNT	24	2K	No (1)	Yes	A	Yes	Yes	No	Yes	Sag, Fr Tr
Motion Analysis (ExpertVision)	Passive	Video Camera	WNT, Un, SG	64	5K	Yes	Yes	SA (3)	Yes	Yes (5)	Yes (6)	Yes	Sag, Fr, Tr
Northern Digital (Optotrak)	Active	Video Camera	DOS	16	4K	No (1)	No	A	Gait Software Not Provided				
Oxford Metrics (Vicon 370)	Passive	Video Camera	W	64	2.5K	Yes	Yes	SA (3)	Yes	No	Kn Axis Align	Yes	Sag, Fr, Tr
Peak Performance (Motus)	Passive	Video Camera	W	64	1K	Yes	Yes	SA	Yes	Yes	No	Yes	Sag, Fr, Tr
Qualisys (ProReflex)	Passive	Video Camera	W MAC	16	1.5K	Yes	Yes	SA	Yes	Yes	Optional	Yes	Sag (7)

W = Windows
WNT = Windows NT
Un = Unix
SG = Silicon Graphics
MAC = Macintosh
SA = Semi-Automatic
A = Automatic
Sag = Sagittal
Fr = Frontal
Tr = Transverse
(1) Yes, for 2 or more units.
(2) 2D ID for each camera.
(3) label 1 frame in 1 trial, remaining trials automatic.
(4) Inv/Ev available with CAST & SAFLOU options not in Anatomical option.
(5) No Inv/Ev if Helen Hayes marker set used.
(6) Required with OrthoTrak, optional with KinTrac.
(7) Frontal & Transverse with optional software.

system made in The Netherlands (a company I was unable to contact), the authors tested systems manufactured by five of the companies discussed in this paper (Ariel Dynamics, Inc., Trabuco Canyon, CA; Bioengineering Technology Systems [BTS], Milano, Italy; Motion Analysis Corporation, Santa Rosa, CA; Oxford Metrics Ltd., Oxford, UK; and Peak Performance Technologies, Inc., Englewood, CO). Due to their unavailability, the Japanese and Netherlands systems have not been included in this review.

Active marker systems have LED markers that are pulsed sequentially, so the system automatically knows (by virtue of the pulse timing) the identification of each marker. Marker tracking is not a problem, since the system can maintain the identification of markers temporarily lost from view or with crossed trajectories. Merging of markers can not occur with these systems, so the markers can be placed close together (**Figure 5**). These systems have the disadvantage of requiring that more equipment be placed on the user. A battery pack, pulsing circuitry, and the LEDs and cables must be attached to and carried by the user. For long duration tests, heat generated by the LEDs might be a problem.

Both commercially available systems (**Table 7**), CODA mpx30 (Charnwood Dynamics, Leicestershire, UK) and OptoTrak (Northern Digital, Inc., Waterloo, Ontario) have three cameras mounted in a rigid housing called a ''Scanner'' (CODA) or ''Position Sensor'' (OptoTrak). This enables them to be precalibrated at the factory, eliminating the need for the user to acquire calibration data (if only one Scanner or Position Sensor is used). Although the LED markers have a wide viewing angle, more than one unit may be needed in order to obtain adequate marker coverage for most cinical gait tests. Two units are required to collect bilateral data.

Rather than using conventional video cameras, the CODA mpx30 utilitzes specially designed cameras with a sensing array of photodiodes placed behind a shadow mask with a pseudo-random bar code pattern of black lines. When an LED, on the subject, flashes, a shadow of the mask is cast on the sensor array. The position of the shadow is related to the marker position by straight-line geometry (no lens is used). The averaging effect of signal contributions from all the sensing elements improves the resolving power of the system and provides a high signal-to-noise ratio. The field of view at 4 meters from the scanner is 5-m long × 5.6-m high. Each pair of LED markers is powered by a rechargeable button cell and is strobed by a tetherless IR telemetry system (**Figure 5**). The maximum number of markers—28— can be tracked at a 200 Hz sampling rate.

For the OptoTrak, the field of view at 6 meters from the Position Sensor is 2.6-m long × 3.5-m high.

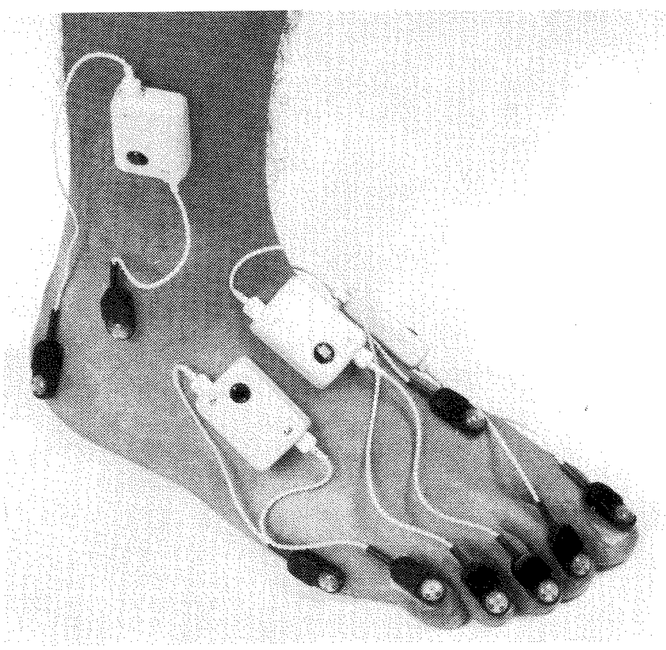

Figure 5.
CODA mpx30 active, light-emitting diode (LED) motion markers placed on the foot of a subject. The sequentially strobed markers enable them to be placed close together without merging in the cameras. Each battery pack provides the power for two markers and houses circuitry to receive an infrared (IR) strobe signal. Photograph is courtesy of Charnwood Dynamics and is used with permission.

An optional tetherless strober is available to eliminate the cable between the wearer and the control unit. The body-worn battery pack (required with the tetherless strober) weighs about one kg. Gait kinematic and kinetic software are not provided. Available software includes a data analysis package, real time rigid body, and application programmer's interface (API) programs. The API software (windows-based) allows clinicians to create their own application programs. The other software is DOS-based.

Passive marker systems have the advantage of using lightweight reflective markers without the need for electrical cables or batteries on the user. IR LEDs around each camera lens send out pulses of IR radiation that are reflected back into the lens from the markers (**Figure 6**). IR filters are used on the camera lenses and system thresholds are set to pick up the bright markers while less bright objects in the background are suppressed. Because of their passive nature, each marker trajectory must be identified with a marker label and tracked throughout the test. When markers are lost from view or their trajectories cross, they can lose their proper identification. Sophisticated tracking software exists that does a good job; however, user intervention is sometimes required. Potential merging of markers in various camera views places limitations on how close together markers may be placed with these systems. The six passive marker systems reported here require the collection of calibration data. Other features vary, but all provide kinematic and kinetic software (**Table 7**).

Laboratory Configuration

Lab configuration for video motion analysis usually ends up being a compromise between optimum camera placement and available space. Manufacturers provide good technical assistance in setting up their respective systems. In general, however, one should keep in mind a few "rules of thumb" to go by:

- Don't try to get by with only two cameras, as there is no way to position them to always have both cameras viewing all markers.
- Make sure the angle between any two cameras is greater than 45°. If two cameras that are separated by a small angle are the only cameras "seeing" a given marker, the determination of the marker's 3D coordinates is less accurate.
- Drape any exterior windows to eliminate outside light from the test area.

- Avoid locating cameras in high trafficked areas where one might be accidentally bumped after the calibration.
- Attempt to keep camera strobe lights from shining directly into cameras across the room.

The last two potential problems can be minimized by mounting the cameras to the walls or ceiling at an elevation of from 6 to 8 feet above the floor; they are then less likely to be bumped and the slight downward viewing angle will minimize strobe light glare from other cameras.

To determine the camera locations for a particular laboratory layout, one would draw a floor plan to scale, drawing a rectangle (around the force plate locations) the size of the desired motion test area. For each camera, a translucent, colored plastic, isosceles triangle should be cut out, with the acute angle equal to the lens-viewing angle. These triangles are laid on the scale drawing of the lab at the approximate desired camera location (**Figure 7**). The triangles are then moved around until each one covers the rectangle representing the motion test area. The camera locations are marked on the drawing and scaled off to obtain the actual camera laboratory coordinates. The system manufacturer should be able to provide the viewing angles for the camera lenses being used. If not, they are easy to measure by moving a marker horizontally in front of each camera and observing its location on the video monitor. One mark is made on the floor where the marker comes into view on one side and another mark where it leaves the other side of the monitor. The angle is measured between the two lines formed by these marks and the camera to obtain the viewing angle.

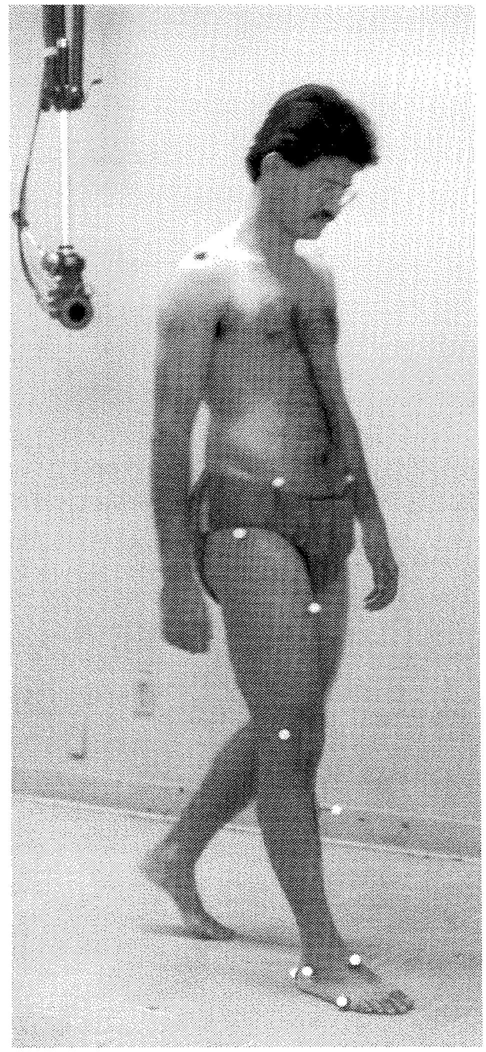

Figure 6.
A subject walking with light weight reflective (passive) motion markers positioned for a unilateral gait test in the Pathokinesiology Lab at Rancho Los Amigos Medical Center. One of six Vicon video cameras (hanging from the ceiling) is visible in the upper left of the photo. Note the ring of IR LEDs around the camera lens. (Photograph used with permission.)

FORCE

Gait is the result of muscle action exerting forces on the skeletal limb segments to produce motion and hence locomotion. It is not possible to measure these internal muscular forces; however, we can learn a lot about pathologic gait and joint loading by measuring external forces.

Force Plates

A force plate measures the ground reaction forces exerted by a person as he or she steps on it during gait. These devices consist of a top plate (mounted level with the surrounding floor) separated from a bottom frame by force transducers near each corner. Any force exerted on the top surface is transmitted through the force transducers. Force plates enable one to measure not only the vertical and shear forces, but also the "center of pressure" during gait. Modern video motion systems have made the determination of joint forces and moments possible through their kinetics software, which requires ground reaction forces.

Two types of force plates are commercially available: piezoelectric and strain gauge. For clinical gait applications, the type probably makes very little difference. Piezoelectric force plates utilize quartz transduc-

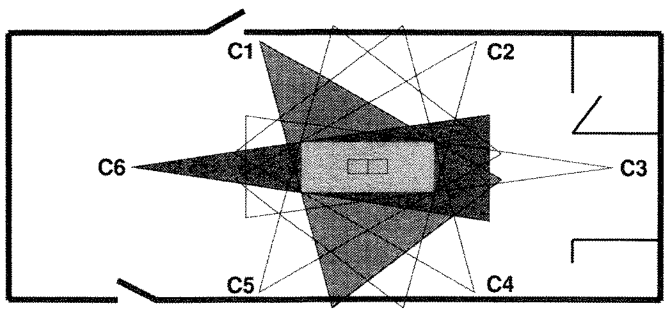

Figure 7.
Gait lab floor plan showing a method of determining camera locations to cover desired test area (light gray). Isosceles triangles represent the viewing angle of cameras labeled C1 through C6. Triangles for C1 and C6 are shown in different shades of gray for clarity. The triangles are moved until they just cover the desired test area. The point of the acute angle then represents the location of the respective camera. Two force plates are shown in the center of the test area.

ers, which generate an electric charge when stressed. They do not require a power supply to excite the transducers; however, special charge amplifiers and low noise coaxial cables are required to convert the charge to a voltage proportional to the applied load. The transducers are calibrated at the factory and no recalibration is necessary. In general, piezoelectric force plates are more sensitive and have a greater force range than strain gauge types. They do have some slow drift, which requires resetting of the charge amplifiers just prior to data acquisition. Strain gauge force plates utilize strain gauges to measure the stress in specially machined aluminum transducer bodies (load cells) when a load is applied. They do not require the special cabling and charge amplifiers of the piezoelectric type; however, they do require excitation of the strain gauge bridge circuit.

Three manufacturers (**Table 8**) produce a large variety of force plates for use in gait analysis. In addition to their own force plates, Kistler also sells the Bertec line.

Force Plate Installation

Considerable planning is required prior to installing the force plates, unless one intends to use unmounted force plates (a technique I do not recommend for gait testing). The top of the force plate(s) must be level with, yet not touch, the surrounding floor. In addition, the mounting structure (e.g., pylon, frames) should be as rigid as possible. Ideally, the force plate(s) should be mounted on a concrete pylon completely separate from the building. In most instances, however, basements or second and subsequent floor installations make this impossible. As a result, I am restricting my remarks to installations on an existing floor. This will require an elevated runway or floor for the gait testing so the force plate(s) can be mounted on the existing floor. An ideal method is to install a "computer access floor," such as the Tate ConCore 1250 access floor[1]. This floor has 610-mm square removable steel floor panels with a cementitous core material, which adds stiffness and minimizes the hollow sound when it is walked upon.

For fixed installations, the force plate mounting frame or frames (available from the manufacturer) should be anchored to the existing concrete floor with threaded anchors and nonshrinkable grout. Different manufacturers have slightly different recommendations and will provide assistance. For multiple force plates, the locations must be carefully planned to provide the widest range of testing. If set up for testing children, the configuration will probably be unsuitable for adults and vice versa. For this reason, many labs have gone to moveable force plate installations.

Movable installations require a large custom-made mounting plate with predrilled mounting holes at discrete locations (anchored similarly to that for fixed installations) or a large flat surface on which air bearing force plate carriers can operate to provide infinite adjustment of force plate locations (17). In this latter technique, Stanhope and Jarrett used an optical bench as the flat mounting surface.

We have adopted this optical bench method in our new gait lab installation (currently under construction). We are using a less expensive 1.07×1.68 m×102-mm thick, model CS-46-4, optical breadboard[2], which has slightly reduced flatness and stiffness specifications as opposed to an optical bench (**Figure 8**). The optical breadboard is being grouted to the concrete floor, with a non-shrinkable grout, to increase the rigidity and stiffness of the installation. Air bearings[3] (Flying Carpet Model "A" Floating Air Platform) are used to levitate the force plates for moving, and magnetic locks[2] (Newport Corp., model 150) lock them into place for testing[4] (**Figure 9**). A simple floor panel cutout scheme has been devised that allows two force plates to be located in multiple configurations (**Figure 10**). Corner

[1] Tate Access Floors, Inc., 7510 Montevideo Rd., Jessup, MD 20794.
[2] Newport Corporation, 1791 Deere Ave., Irvine, CA 92606.
[3] C&H Precision Tools, Inc., 194-20 Morris Ave., Holtsville, NY 11742.
[4] Personal communication with Steven J. Stanhope, PhD, January 27, 1997.

sections, with one dimension equal to the width of the force plates and the other dimension equal to half the length, are removed from four floor panels to accommodate these various configurations.

Advanced Mechanical Technology, Inc. (AMTI) of Watertown, MA, has developed a variation of the infinite adjustment mounting technique, sometimes called the "epoxy lake" method (**Figure 11**). They replace the optical bench or breadboard with a concrete pedestal onto which is flowed a thin layer (approximately 0.635-cm thick) of liquid epoxy. The liquid epoxy is self-leveling and cures to a hard, smooth surface. Air bearing force plate carriers (provided by AMTI) position the force plates to the desired locations (**Figure 12**). Since the epoxy surface is not Ferro-magnetic, magnetic locks can not be used to hold the force plates in place. Due to the weight of each force plate and its carrier (approximately 112.5 kg), it is unlikely that the shear forces developed during walking would cause them to move. Some installations use inflatable bladders resting against the force-plate carriers and the floor substructure to hold the force plates in place. Clinicians contemplating this technique should consult with the force-plate manufacturer to see if that is a viable option for use with the clinicians' force plates.

Force Measuring Sandals

Force measuring sandals record vertical force data from portable transducers attached to the bottom of the feet. They have the advantage of providing multiple strides of data for both feet as the person walks. As in pressure insoles, they do not provide shear forces.

The *Infotronic* (Market-USA, Inc., Severna Park, MD) Computer Dyno Graphy (CDG) system measures the vertical force at eight discrete locations in each of a pair of sandals strapped to the outside of a person's shoes. Factory calibrated capacitive force transducers are fabricated inside 3-mm thick soles. The typical life of a pair of sandals is about 3,000 uses. The wireless system stores the data on small computer memory cards in a data logger (see EMG Acquisition Systems, below). The sandals come in three sizes, small, medium, and large. When walking on a hard surface, the total force is reported to be within 3 to 5 percent of the actual force. There can be a loss of up to 25 percent when the person walks on a carpeted surface. The software provides force time curves, histograms of the force at each transducer, the gaitline (center of force), cyclogram (center of force for both feet), and a listing of the temporal gait parameters.

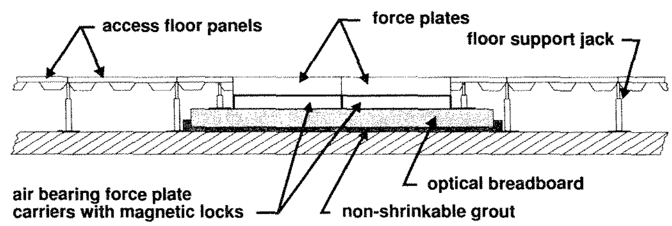

Figure 8.
Movable dual force plate installation on an existing concrete floor (crosshatch), utilizing an optical breadboard as the mounting surface. Force plate carriers with air bearings and magnetic locks position the force plates to the desired locations on the flat smooth surface of the optical breadboard.

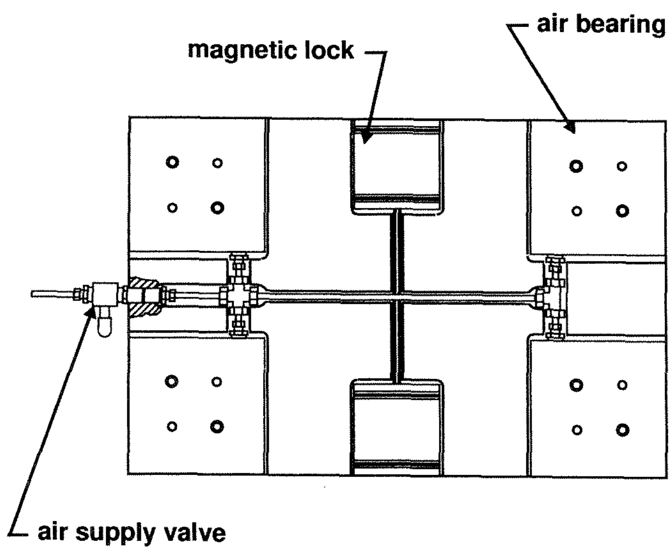

Figure 9.
Bottom surface of a force plate carrier with two magnetic locks and four air bearings. When moving the force plate, the magnetic locks are unlocked and pressurized air is supplied to the air bearings via the air supply valve and tubing. The heavy carrier and force plate can then be easily moved on a thin layer of air.

Force Measuring Walking Aids

Force walking aids are a very valuable tool in determining the amount of load being accepted by the upper limbs during device-assisted gait. Unfortunately, no manufacturer makes force measuring walking aids or load cells designed specifically for insertion in the shafts of canes, crutches, or walkers. However, all three force plate manufacturers sell load cells and both Bertec and AMTI have indicated that they would design and fabricate special load cells if specifications are provided.

Table 8.
Force plate features.

Manufacturer	Type	Sizes	Built in Amplifiers	Software	Special Types
AMTI	Strain Gauge	464 x 508 mm to 610 x 1220 mm	No	Yes	Will custom-make to customer specified dimensions
Bertec	Strain Gauge	464 x 508 mm to 900 x 900 mm	Yes	Yes	All can be used without rigid mounting (1)
Kistler	Piezoelectric	500 x 500 mm to 600 x 900 mm	Yes (1 model)	Yes	Portable system Transparent unit (2) Force Treadmill (3)

(1) As long as shear forces are low enough to prevent slipping of the force plate on the surface.
(2) Allows for photographing through the top of the plate.
(3) Vertical force only, for both feet.

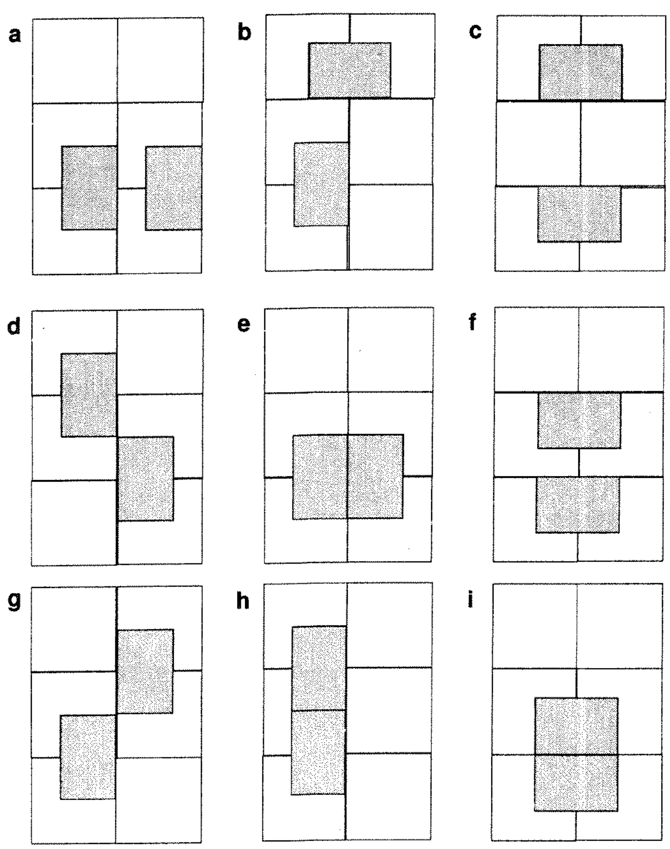

Figure 10.
Floor panel cutout scheme, which allows two force plates to be arranged within a 4-ft wide by 6-ft long area, in 9 configurations (a through i). Four of the 2-ft square floor panels must have one corner removed to accommodate the force plates (shown in gray). One configuration (h) requires two corner notched floor panels and one additional narrow floor panel strip along the left side.

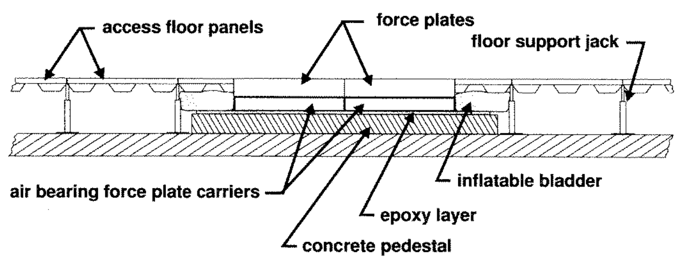

Figure 11.
Movable dual force plate installation on an existing concrete floor with a thin layer of epoxy as the mounting surface. Force plate carriers with air bearings position the force plates to the desired locations on the flat smooth epoxy surface (per AMTI). Although slipping is unlikely because of the weight of the force plates and carriers, inflatable bladders are sometimes used to insure that the force plates will not move.

ELECTROMYOGRAPHY (EMG)

EMG is a valuable tool in clinical gait analysis, as it can give the clinician an accurate representation of what the muscles are doing to contribute to the gait deviations observed and measured by the other instrumentation (i.e., motion, footswitches). Many surgical decisions are made based on the EMG records; therefore, it is extremely important to have instrumentation and techniques that provide high quality EMG signals. Surface electrodes have gained widespread use due to their ease of application and because skin penetration is not required. However, deep muscles can be reliably obtained only with intramuscular wire electrodes, since

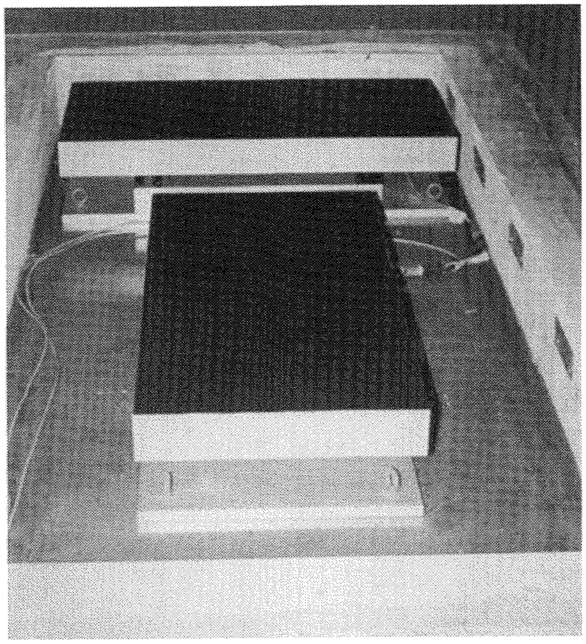

Figure 12.
Two AMTI force plates on their air bearing carriers, resting on a hardened epoxy surface. Floor panels (not shown) are positioned around the force plates for actual gait testing. Photograph is courtesy of Advanced Mechanical Technology, Inc. (AMTI) and is used with permission.

"cross talk" from more superficial muscles will render a surface EMG useless.

Wire EMG Electrodes

EMG Paired Hook Wire Electrodes (Nicolet Biomedical Inc., Madison, WI) are made of insulated nickel alloy wire. The two wires are bent approximately 180° where they exit the tip of a hypodermic needle. The bent end of one wire is 5-mm long and the other 2 mm. Both have 2 mm at the end stripped of insulation. They are available in 25 gauge, 50-mm long and 27 gauge, 30-mm long needles.

Clinicians who choose to fabricate their own intramuscular wire electrodes, can follow the method originally described by Basmajian and Stecko (18) or the modified technique detailed by Kerrigan, et al. (19). We have used the method described by Kerrigan for many years with good results (**Figures 13** and **14**). We use the wire with green insulation, in order to visually tell the difference between stripped and unstripped sections of wire[5] (0.002 Stablohm 800 B Annealed, HPN Insulation, Green). When using the thermal stripper to remove the insulation from the loop of wire extending from the tip of the needle, one must burn all the way up to the needle, as the needle acts as a heat sink, keeping the insulation on the wire inside the needle from charring. This creates a smoother transition between insulated and uninsulated wire at the active end of the electrode. After trimming the two bent ends, the ends must not touch each other under any circumstance.

Surface EMG Electrodes

Surface electrodes come in two basic types: passive and active.

Passive electrodes are of the "Beckman silver/silver chloride" type and come as individual electrodes, so that a pair can be spaced over the muscle as desired. They are available in various sizes ranging from about 7 mm to 20 mm in diameter (**Table 9**). Conductive electrode gel is required with these electrodes, as well as double-sided tape washers (collars), for attachment to the skin.

Active electrodes have become quite popular, as they provide signal amplification at the electrode site (**Figure 15**). This reduces the electrical "noise," which can be picked up by passive electrode lead wires. A number of electrodes are available, all having high impedance differential amplifier inputs with high common mode rejection ratios. They differ in gain, size, and special features. Two of these electrodes consist of an amplifier package only; therefore, the user must attach separate passive surface or fine wire electrodes to them (**Table 9**). Delsys now manufactures a double differential active surface electrode that is reported to reduce cross talk (20).

EMG Acquisition Systems

EMG data acquisition systems come in two types: cable and wireless. Wireless systems are either radio telemetry or data loggers (**Table 10**). Cable systems eliminate the need for a battery on the wearer (power can be obtained through the cable) and signals are free from any radio frequency (RF) interference or dropout. The disadvantage is the need for a cable connecting the wearer to the instrumentation. Telemetry systems eliminate the cable, but suffer from problems with signal dropout and RF interference. They also require the use of a body-worn battery. Data loggers eliminate the cable and RF problems, but require a body-worn battery and are limited in the amount of data that can be acquired before being downloaded to the computer.

[5] California Fine Wire Company, 338 South Fourth St., Grover Beach, CA 93433.

Table 9.
Surface EMG electrode features.

Manufacturer	Type	Electrode Contacts: Shape	Electrode Contacts: Size	Electrode Contacts: Spacing	Ground Reference Electrode	Gain	Bandwidth (Hz)	Can be used with fine wire electrodes?
B & L Engineering	Active	Round	11 mm dia.	20 & 30 mm	Separate	330	12 to >1K	Yes
Bortec	Active (1)	NA	NA	User selectable	Separate	500	10 to 1K	Yes
BTS	Active (1)	NA	NA	User selectable	Separate	(4)	(5)	Yes
Delsys	Active (2)	Rectangle	1 x 10 mm	10 mm	Separate	10	DC to 200K	No
In Vivo Metric (IVM)	Passive	Round	7.2 mm dia. to 19 mm dia.	User selectable	Separate	NA	NA	NA
Iomed	Active	Round	10 mm dia.	18 mm	Centered	340	9 to 32K	No
Motion Lab Systems	Active (1)	NA	NA	User selectable	Not required	380	2 to 19K	Yes
Nicolet Biomedical	Passive (3)	Round	20 mm dia.	User selectable	Separate	NA	NA	NA
Sensor Medics	Passive	Round	11 mm dia. & 16 mm dia.	User selectable	Separate	NA	NA	NA

NA = Not Applicable
(1) Amplifier package, only. Used with separate electrodes.
(2) Double differential model available.
(3) Disposable, pre-gelled silver/silver chloride electrode.
(4) Not specified.
(5) See Table 10 for EMG system bandwidth.

EMG Analysis Systems

Much can be learned about a person's gait by a trained clinician viewing the raw gait EMG record; however, computerized analysis systems (**Table 11**) can provide valuable assistance and make the task less tedious and time consuming (21–23). One should keep in mind, however, that computers can only work with the instructions given and the data provided. With patient data, strides can be irregular, and if the software utilizes footswitches to define the gait cycle, problems can occur. For example, a scuff of the foot during swing may appear to the computer analysis software as another stance period. How the software handles these problems is very important. There is no substitute for a trained clinician viewing the raw record to make sure the computer analysis makes sense.

SAFETY (ELECTRICAL ISOLATION)

Electrical safety has always been an important consideration; but with the proliferation of gait labs, it has become an even more critical issue. Any electrical equipment that comes in contact with an individual must be either battery-powered or electrically isolated from the power mains. Electrical isolation is achieved by either transformer or optical isolators. An isolated instrument that is attached to a person should have leakage current of less than 10 micro amps—20 micro amps at the wearer end of a cable connecting the apparatus to that person (24). Not all battery-powered instruments are automatically safe. Consider a battery-powered instrument (on an individual) having data that must be downloaded to a computer. If the interface is

Table 10.
EMG acquisition system features.

Manufacturer	Data Transmission: Wireless	Data Transmission: Cable	Number of Channels	Bandwidth/ {sample rate} (Hz)	Filters: Highpass (Hz)	Filters: Lowpass (Hz)
Bortec		4 mm dia. wire or Fiber Optic cable	8 EMG 2 FSws	10 to 1K	None	None
BTS	FM Telemetry (diversity receiver)	Optional Fiber Optic cable	8 EMG 2 FSws	{5K}	1, 5 & 10	600, 400, 200, none
Konigsberg	PCM FM Telemetry	Optional Fiber Optic cable	8 (any mix of EMG, FSws & other)	{3K}	DC & 2 user defined settings	1K, 500, 250, 125, 62, 32, 16, 8
Market-USA	Data Logger		16 each of EMG, Gonis & FS	{EMG-5K, 200 for Gonis & FS}	None	None
Motion Lab Systems		3 mm dia. wire cable	10 EMG 2 FSws	20 to 2.3K	20 to 170	5, 10, 40, 150, 300, 600, 1.3K, 2.5K
Noraxon	Digitally Encoded FM Telemetry	Optional 10 mm dia. wire cable	8 EMG or 4 EMG & 2 FSws or 4 EMG & 4 Gonis	16 to 500	(1)	500

FSws = Footswitches PCM = Pulse Code Modulated Gonis = Electrogoniometers FS = Force Sandals
(1) A micro chip in the transmitter package implements a specially designed analog, adaptive high pass filter for noise removal. This filter design enables the low cutoff frequency to be very sharp, without ringing.

Table 11.
EMG analysis sytem features.

Manufacturer	Real time Oscilloscope Monitoring?	Normalize EMG?	Display Raw EMG?	Linear Envelopes?	Define GC with FSws?	Onsets & Cessations: As %GC?	Onsets & Cessations: Compare to Normal?	Spectral Analysis?	Other
B & L Engineering	No	To MMT or max EMG	Yes	Yes	Yes	Yes	Yes (1)	No	(2)
BTS	Yes	To MMT	Yes	Yes	Yes	Yes	Not in US	No	(3)
Market-USA	No	No	Yes	Yes	No	No	No	Yes	(4)
Motion Lab Systems	No	To max EMG	Yes	Yes	Yes	No	No	Yes	(5)
Noraxon	Yes	No	Yes	Yes	Yes	No	No	Optional	

GC = Gait Cycle FSws = Footswitches MMT = Manual Muscle Test
(1) You can incorporate your own data in the normal database.
(2) Report defines whether onset & cessation of EMG was normal, premature, prolonged, or delayed and in which gait phase it occurred.
(3) Database allows tracking of subject groups.
(4) Histogram gives amplitude distribution.
(5) Allows editing of footswitch on and off times.

Figure 13.
An intramuscular wire EMG electrode being inserted (with a 25-gauge hypodermic needle) in a muscle of a subject.

not electrically isolated, the package must be removed from that individual before it is connected to the computer. Electrical instruments in the lab, whether they come in contact with the person or not, must be solidly grounded and the ground integrity should be checked on a regular basis. The resistance from the ground prong on the power plug to the chassis should be less than 0.15 ohms. Similarly, the resistance from the ground lead in the power receptacle to a known ground should be less than 0.15 ohms.

All accredited medical institutions have policies and procedures relating to the purchase and safety testing of instruments used in their facilities. Often, Underwriters Laboratory (UL) or Canadian Standards Association (CSA) testing and certification are required. Obviously, small companies manufacturing instruments for a very limited gait analysis market can not absorb the costs of UL or CSA testing. Because of this, many institutions have policies that allow other (less costly) third-party testing. The facility policy manual should be checked to determine what is and is not allowed at that institution.

ACKNOWLEDGMENTS

The author would like to thank Sreesha Rao (for his special help with the motion section) and other staff members of the Pathokinesiology Service, Rancho Los Amigos Medical Center for their helpful suggestions and comments. Bob Manuel and Ron Clark of the Rancho Medical Equipment Repair Shop were very helpful with the safety issues. Thanks, also to the vendors who provided technical information and answered many questions about their respective systems.

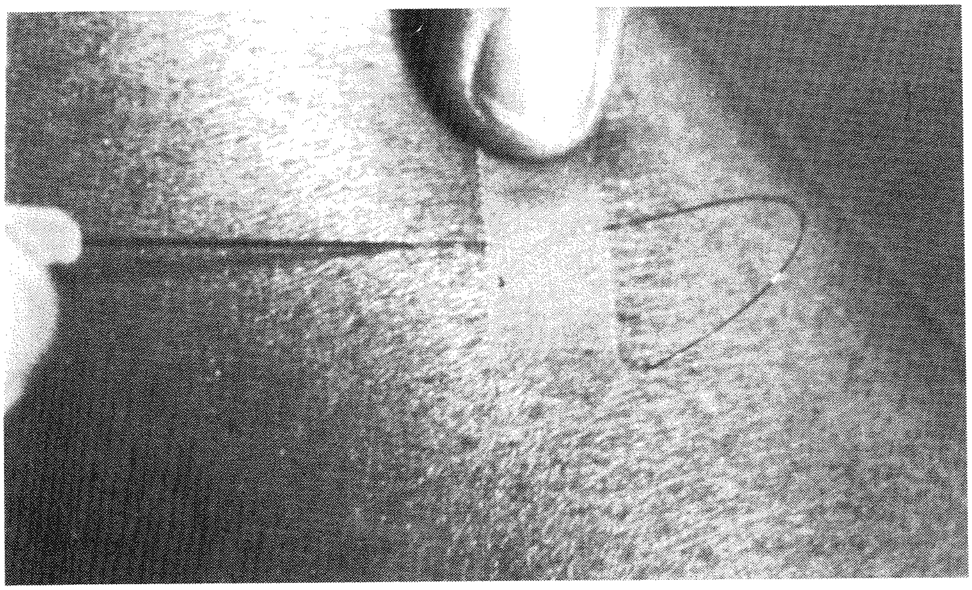

Figure 14.
Hypodermic needle being removed from intramuscular wire EMG electrode following insertion in the muscle. Note the loop of wire, which allows the wire to move as the muscle contracts. Used with permission: Craig J. Newsam. Quantification of aquatic therapy water-based methods: Part II: Fine wire electromyography. *The Journal of Aquatic Physical Therapy* 1996; 4(3):13–7.

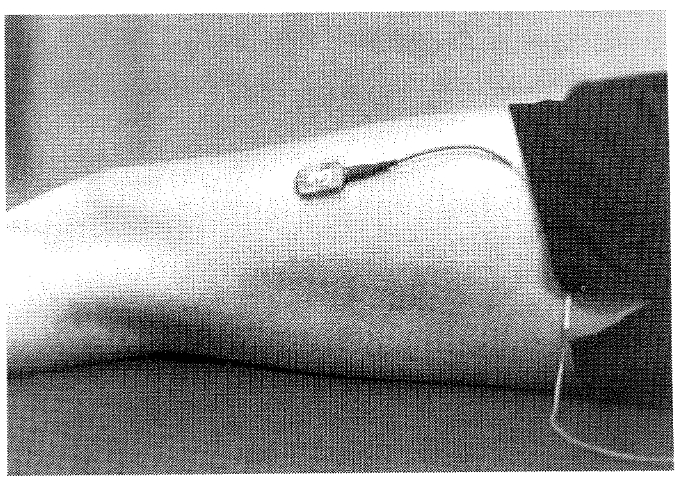

Figure 15.
A Delsys active surface EMG electrode placed over the quadriceps muscle of a subject.

APPENDIX
List of Manufacturers

Advanced Mechanical Technology, Inc. (AMTI)
176 Waltham St.
Watertown, MA 02172 (USA)
TEL: (617)926-6700 (800)422-AMTI
FAX: (617)926-5045
E-mail: lit@amtimail.com
Web: www.amtiweb.com

Ariel Dynamics, Inc.
6 Alicante St.
Trabuco Canyon, CA 92679 (USA)
TEL: (619)874-2547 (714)858-4216
FAX: (619)874-2549 (714)858-5022
E-mail: ariel1@ix.netcom.com
Web: www.arielnet.com

Bertec Corporation
1483 Delashmut Ave.
Columbus, OH 43212 (USA)
TEL: (614)421-2803
FAX: (614)421-2811
E-mail: Bertec@cris.com

Bioengineering Technology & Systems (BTS)
Via Cristoforo Colombo, 1A
20094 Corsico (Milano) ITALY
TEL: +39-2-458751
FAX: +39-2-45867074
E-mail: bts@bts.it
Web: www.bts.it/BTS
US Sales & Support:
TEL: (562)497-1797
FAX: (562)497-1797
E-mail: Fredcei@aol.com

Biometrics Limited (Penny & Giles)
Nine Mile Point Industrial Estate, Unit 25
Cwmfelinfach, Newport
Gwent S. Wales NP1 7HZ (UK)
TEL: +44 (0) 1495 200800
FAX: +44 (0) 1495 200806
E-mail: biometrics_ltd@compuserve.com
Web: www.biometricsltd.com
US Sales & Support:
Penny & Giles Inc.
2716 Ocean Park Blvd. #1005
Santa Monica, CA 90405-5209 (USA)
TEL: (310)393-0014 (310)452-4995
FAX: (310)450-9860
E-mail: nhandler@compuserv.com

B & L Engineering
3002 Dow Ave., Suite 416
Tustin, CA 92780 (USA)
TEL: (714)505-9492
FAX: (714)505-9493
E-mail: sales@bleng.com
Web: www.bleng.com

Bortec Electronics Inc.
7172 Sierra Morena Blvd.
Calgary, Alberta T3H 3G6, Canada
TEL: (403)686-1904
FAX: (403)249-7778
E-mail: bortec@cadvision.com
Web: www.cadvision.com/bortec/bortec.html

Charnwood Dynamics
17 South St., Barrow on Soar
Leicestershire LE12 8LY, England
TEL: +44 1509 620388
FAX: +44 1509 416791
E-mail: support@charndyn.com
Web: www.charndyn.com

CIR Systems, Inc.
790 Bloomfield Ave., Suite 2-10
Clifton, NJ 07012 (USA)
TEL: (973)473-7555
FAX: (973)473-7552
E-mail: sales@gaitrite.com
Web: www.gaitrite.com

Delsys Inc.
P.O. Box 15734
Boston, MA 02215 (USA)
TEL: (617)236-0599
FAX: (617)236-0549
E-mail: delsys@delsys.com
Web: www.delsys.com/~delsys

EQ, Inc.
600 Galahad Rd.
Plymouth Meeting, PA 19462 (USA)
TEL: (215)997-1765
FAX: (215)997-1282
E-mail: jimwalsh@fast.net

IOMED, Inc.
1290 West 2320 South
Salt Lake City, UT 84119 (USA)
TEL: (800)621-3347 (801)975-1191
FAX: (801)975-7366

E-mail: lduffin@iomed.com
Web: www.iomed.com

In Vivo Metric (IVM)
P.O. Box 249
Healdsburg, CA 95448 (USA)
TEL: (707)433-4819
FAX: (707)433-2407

Kistler Instrument Corp., USA
75 John Glenn Drive
Amherst, NY 14228-2171 (USA)
TEL: (716)691-5100
FAX: (716)691-5226
E-mail: biomech@kistler.com
Web: www.kistler.com

Konigsberg Instruments, Inc.
2000 Foothill Blvd.
Pasadena, CA 91107-3294 (USA)
TEL: (626)449-0016
FAX: (626)449-1086

Market-USA (Infotronic)
523 Benfield Rd.
Severna Park, MD 21146 (USA)
TEL: (410)647-2782
FAX: (410)647-5327
E-mail: marketusa1@aol.com

Motion Analysis Corp.
3617 Westwind Blvd.
Santa Rosa, CA 95403-1067 (USA)
TEL: (707)579-6500 (847)945-1411
FAX: (707)526-0629
E-mail: dan.india@motionanalysis.com
Web: www.motionanalysis.com

Motion Lab Systems, Inc.
4326 Pine Park
Baton Rouge, LA 70809 (USA)
TEL: (504)928-GAIT
FAX: (504)928-0261
E-mail: sales@emgsrus.com
Web: www.emgsrus.com

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