JUSTIFICATION OF GONIOMETRIC METHOD AS A MEANS TO EVALUATE JOINT REPLACEMENT PATIENTS

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ABSTRACT

Accurate measurement of human joint motion is essential to the design and evaluation of internal joint prostheses and artificial limb replacements. triaxial electrogoniometer, instrumented by three miniature precision potentiometers, was developed to fulfill this task. Special linkage was used to attach this apparatus externally to the joint. Three-dimensional angular motion following the classical Eulerian angle definition was measured in real time. The error due to exoskeletal attachment was corrected by the method of 4 x 4 matrix. This technique is now being routinely used on the patients with abnormal hip, knee and ankle joints for objective functional evaluation.

INTRODUCTION

The chronic disease of arthritis and the traumatic inflicted degeneration of human articulating joints have caused severe functional disability for a very large population in this country (1). The loss of manpower and the medical care expenses are incalculable. Following in the wake of the dramatic breakthrough in total hip replacement introduced by Charnley (2)(3), internal joint prosthetic replacement has become the treatment of choice for severely diseased and deformed joints in the human body, particularly in the lower extremities, which includes the hip, knee and ankle joints. A selection of some of the most commonly used internal joint prostheses in the lower extremities is illustrated in Figure 1.

Anatomical and functional integrity of lower extremity joints is essential to human mobility. If any one of the related joints is affected by the disabling disease, the walking pattern will be abnormal, thereby creating substantial functional limitation. Artificial joint replacement is aimed at alleviating this functional impairment and at the same time controlling the pain and correcting the deformity caused by the disease process. Performing objective functional evaluation of these joints in normal subjects will help to establish the standard norm for the joint functions, which can provide the basic design requirements for the prostheses. Such evaluation, if carried out on patients before and after joint replacement, will obtain a quantitative assessment of this new surgical treatment modality. Subsequent design modifications and surgical technique improvements can be implemented to enhance better results.

Traumatic and pathological amputation of the lower leg at various levels requires artificial limb replacement so that the patient can accomplish ambulatory functions, needed in daily activities. The design of artificial limbs requires certain basic guidelines based on measured normal walking data. Evaluation of these artificial devices when they are applied to

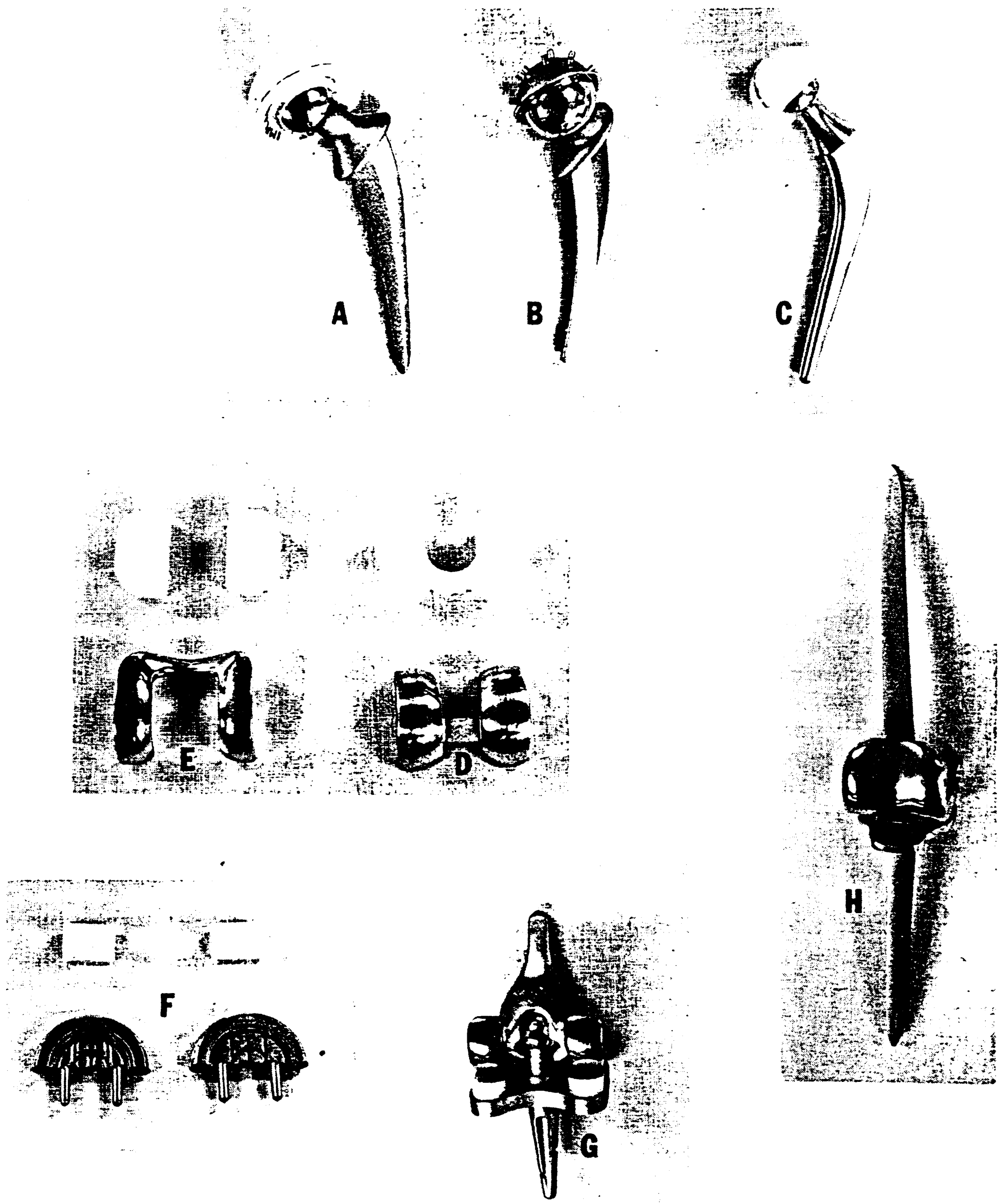


Fig. 1 - Commonly used joint prostheses for the hip and knee. (A) Müller-Charnley Total Hip. (B) McKee-Farrar Total Hip. (C) Charnley Total Hip. (D) Geometric Total Knee. (E) Dual Condylar Knee. (F) Polycentric Total Knee. (G) Spherocentric Knee. (H) Gepar Hinged Knee.

patients also demands certain quantitative means to record the joint motion magnitude and patterns. A reliable and easy-to-use instrument capable of providing accurate joint motion data is therefore warranted.

In recent years, objective functional evaluation has played a significant role in orthopaedic management of patients with musculoskeletal joint diseases. (15)(16)(17). The methodology developed enables one to examine the anatomical integrity and functional status of affected joints in quantitative terms. The reliability of the experimental technique provides new dimension to correlate the exact functional and anatomical abnormalities with clinical examination results. Many important medical and rehabilitative decisions have been influenced by these findings. Such a unique capability offers an opportunity to introduce new disciplines into the field of medicine so that innovative concepts relating to patient care can be developed. This inter-disciplinary action would be extremely helpful to many medical problems confronted with unsatisfactory solutions.

Since the correction of joint deformity and restoration of normal function are important factors in judging the success or failure of the treatment of joint disease patients, an objective gait analysis of the hip, knee and ankle motion on a group of subjects before and after joint replacement surgery can accomplish the following objectives.

1. Correlate joint functional deficits and deformities with clinical and biochemical assessment of the disease.

2. Provide an objective means to evaluate the effectiveness of therapeutic and surgical treatments on arthritic patients.

3. Recommend better physical and occupational therapy for patients with systemic involvement so that undesirable usage of joints could be avoided to prevent further deterioration of disease status.

4. Identify critical timing for more aggressive (surgical) treatment for patients in the advanced disease stage to ensure best possible results.

EXPERIMENTAL METHOD AND INSTRUMENT DESIGN

Human lower extremity consists of three major joints; the hip, knee and ankle, as illustrated in Figure 2. The hip joint is basically a ball-and-socket joint possessing three degrees of freedom. The knee joint resembles a hinge joint with one degree of freedom in flexion-extension. However because of the laxity and irregular joint surface geometry, small motion in other planes is also important. The ankle is a more complex joint because of the subtalar structure. If the ankle can be regarded as an ensemble of bony elements providing relative motion between the foot and the tibia, it could be assumed as a modified ball-and-socket joint. As a result, all lower extremity joints could be treated as some sort of ball-and-socket joints capable of producing three-dimensional rotation. In designing the measuring device, this basic requirement is therefore essential.

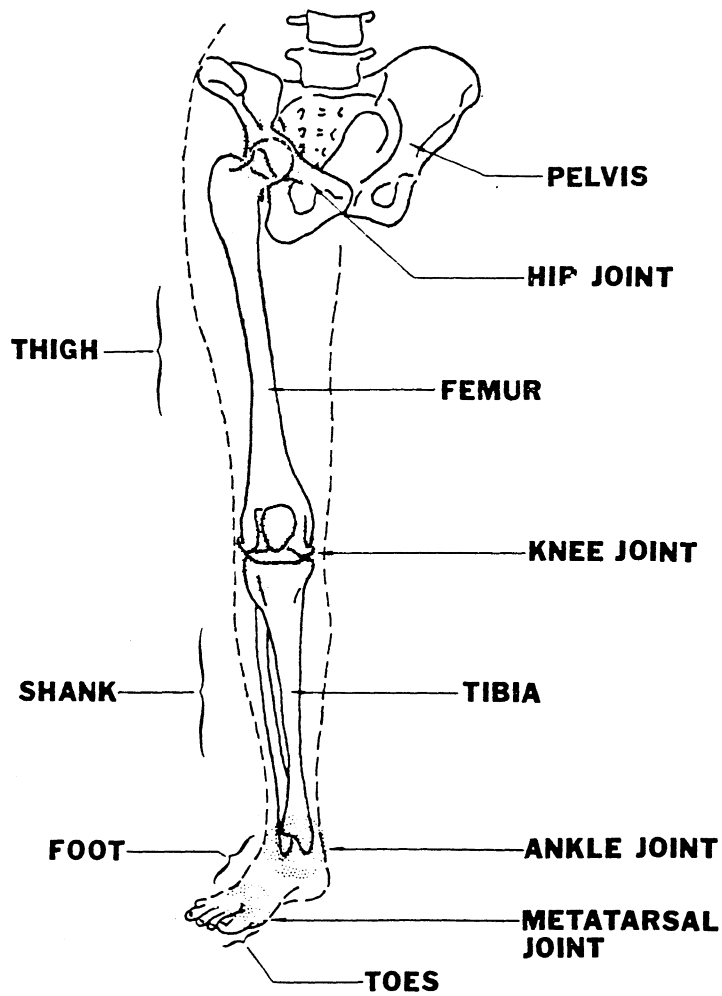


Fig. 2 - Skeletal joint system of human lower extremity.

For the convenience of specifying the direction and sense of joint motion in accordance with clinically acceptable terminology, the following table of definitions is used.

Joint	Angular Motion	Axis	Sense
	Flexion-Extension	Z_H	Ext. (+), Flex. (-)
Hip	Abduction-Adduction	Y_H	Add. (+), Abd. (-)
	Int-Ext. Rotation	Z_H	Int. (+), Ext. (-)
	Flexion-Extension	Z_K	Flex. (+), Ext. (-)
Knee	Abduction-Adduction	Y_K	Add. (+), Abd. (-)
	Int-Ext. Rotation	X_K	Int. (+), Ext. (-)
	Plantar-Dorsal Flex.	Z_A	Plan. (+), Dors. (-)
Ankle	Abduction-Adduction	Y_A	Add. (+), Abd. (-)
	Int-Ext. Rotation	X_A	Int. (+), Ext. (-)

The reference axes and joint motion definitions are depicted in Figure 3 for the hip, knee and ankle joints.

Several techniques have been described in the past to measure lower extremity joint motion in human walking. These include the interrupted light photography method, (4)(5) the TV monitoring method, (6)(7) the accelerometric method, (8)(9) and the electrogoniometric method (10)(11). The photometric and TV methods require tedious data reduction and analysis procedures, thus making them difficult to apply to large patient population. The accelerometric method provides limited information concerning joint kinematics. The use of the electrogoniometric concept presents many advantages, particularly for fast data reduction. It was, therefore, selected for the present application. However, it must be recognized that such an instrument cannot measure the translational components of joint motion, and the joint has to be assumed as a ball-and-socket joint in a gross sense. In reality, the translational motion of lower extremity joints is small, therefore the use of the triaxial goniometer is justified.

The development of the electrogoniometer was first introduced by Karpovich (12) and later used by other investigators. Many modifications have since been introduced for better results. The sophisticated design introduced by Lamoreux (13) is capable of measuring accurate joint motion, but the cumbersome attachments prevent it from being applied to patients. Following the old design used by Johnston, et al, (10) a new version of the electrogoniometer assembly was developed which can be conveniently applied to the hip, knee or ankle joint for on-line, real-time joint motion measurement. Figure 4 depicts this new design which is the most compact and easy-to-use triaxial electrogoniometer assembly available today.

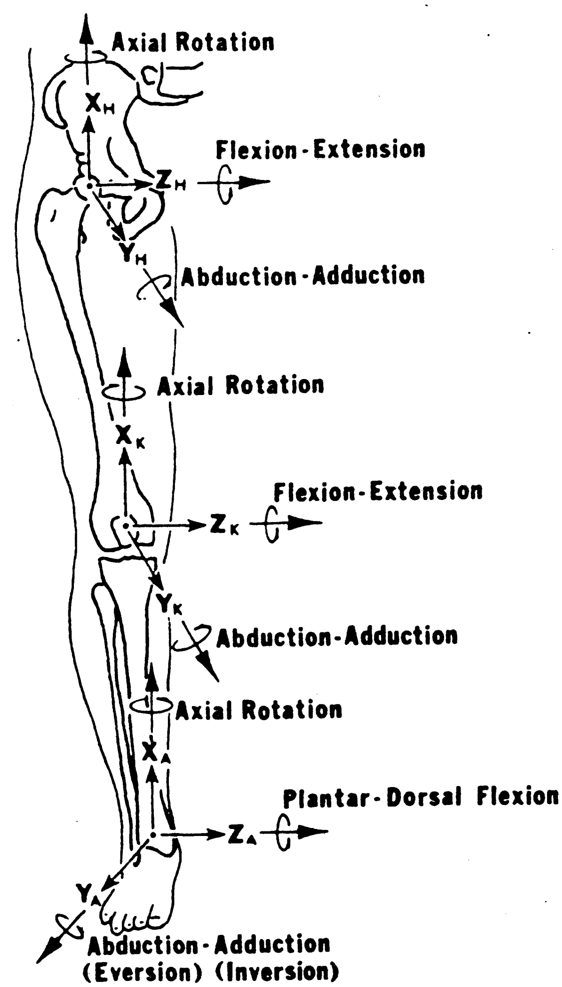


Fig. 3 - Definition of lower extremity joint angular rotation.

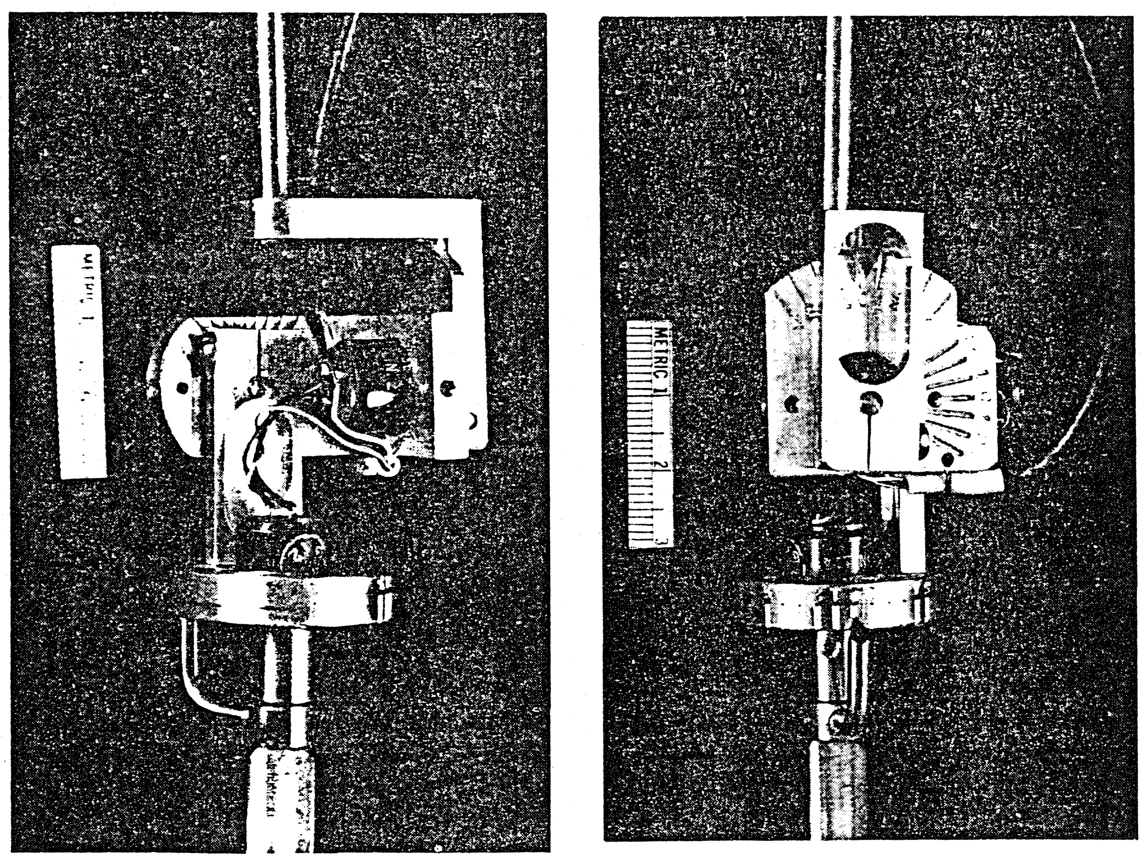


Fig. 4 - Triaxial electromechanical goniometer used to measure three-dimensional rotation of the hip, knee and ankle joints.

The goniometer is constructed by fixing three Duncan miniature potentiometers of the conductive-plastic type (Resolon Pot 1020-556) oriented orthogonally. Each pot has its own axis of rotation capable of measuring the three-dimensional angular motion following the definitions designated in the previous table. Beckman half-bridge pressure/force amplifiers are used for output signal conditioner. High resolution (0.1%) and linearity (1%) signals are plotted on a Beckman/Offener Chart Recorder and stored simultaneously in an Ampex FM 1300 Tape Recorder for later analysis.

Specifically designed attachment devices were used at the hip, knee and ankle area to fasten the goniometer assembly, as seen in Figure 5. The attachment to the proximal segment of the joint forms a set of fixed coordinate systems and the distal attachment constitutes the moving referenc The relative angular motion between the fixed and the moving system provides the three-dimensional joint motion based on Eulerian angle definition.

Overhanging track above the walkway, as seen in Figure 6, carries the cables to transmit the signals to the recorders. Foot switches attached to the soles of the shoes (also shown in Figure 5) provide timing marks to identify the important periods of walking during patient experiments. A specially designed walkway is utilized to obtain other pertinent information concerning patient walking characteristics.

The patient is asked to walk back and forth along the walkway for eight to ten times. Two optical switches located at the midsection of the walkway (Figure 7) are used to identify the reliable sector of the gait for subsequent analysis. Step length is recorded by a specially designed apparatus, as shown in Figure 8. Similar tests will be performed for other activities of the lower extremity. All data will be recorded by a Beckman Strip Chart Recorder for verification purposes and transmitted directly to a PDP-1134 Computer for analysis.

Data analysis methods include: (1) statistical correlation, (2) harmon spectrum analysis, and (3) phase-diagram analysis. All clinical and biomech ical data are graded so that a performance index and symmetry index can be obtained to describe the functional performance of the patient studied. The entire experiment requires approximately 45 minutes. Within two hours after the examination, a complete analysis with all pertinent data will be compile for final evaluation on this patient. Such data can then be summarized and presented to the physician in charge. Proper evaluation on the functional status of the patient can then be made.

<u>ERROR ANALYSIS AND CORRECTION</u>

Since the goniometer assembly is attached externally to the joint, the potentiometers may not record the true joint motion. The error between the goniometer readings and the actual joint motion is defined as the cross talk, which has to be quantitated and corrected subsequently, if necessary. If the relative motion between the attachments and the bone beneath the soft

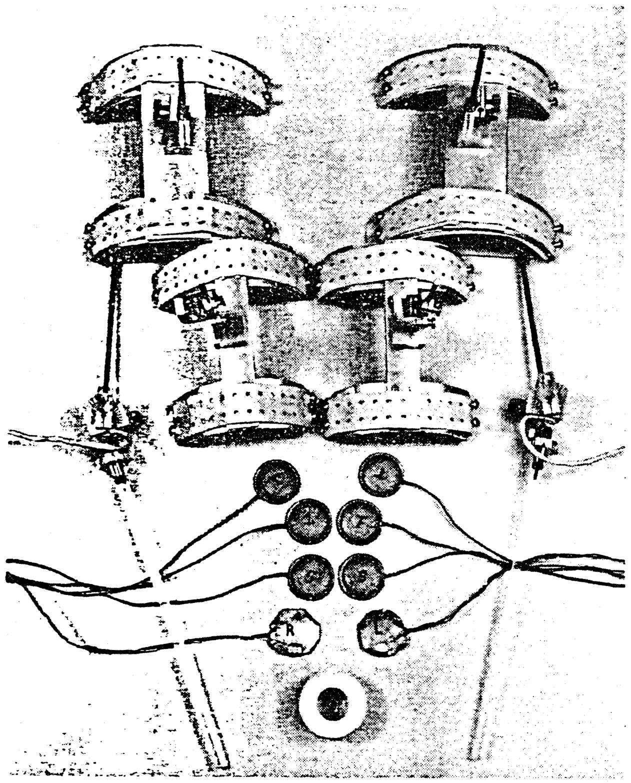
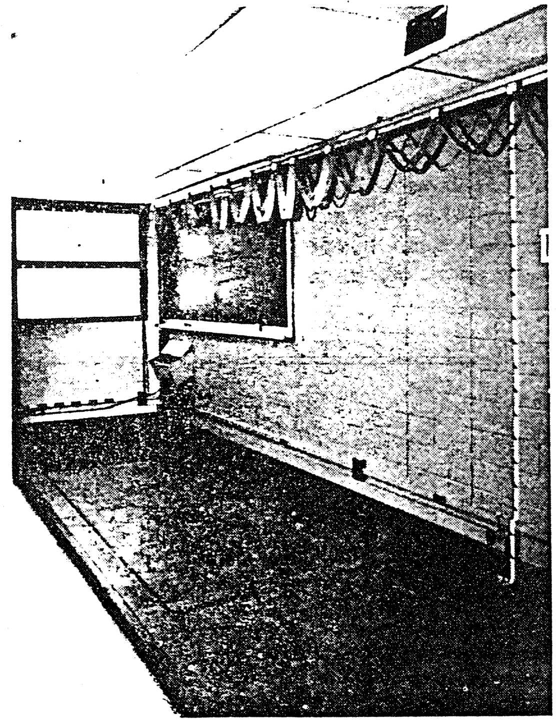
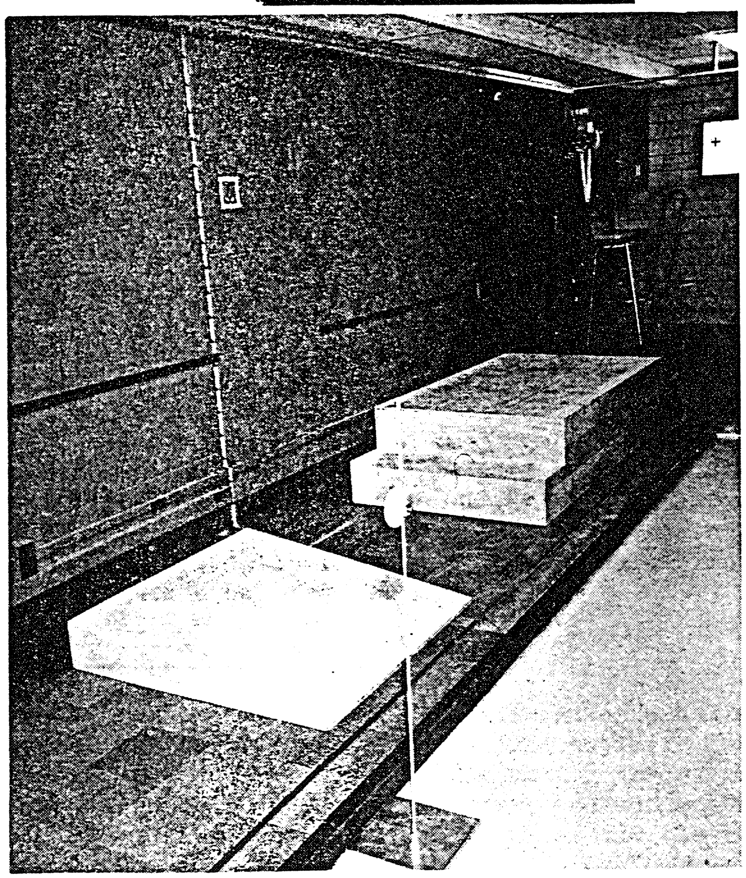


Fig. 5 - Triaxial goniometers, attachment apparatus and foot switch system used for human gait analysis.



(A)



(B)

Fig. 6 - Gait laboratory walkway. (A) Overhanging track and force plate used to transmit goniometer data and record foot-floor reactions. (B) Wooden blocks used to simulate various ground slopes and stair conditions.

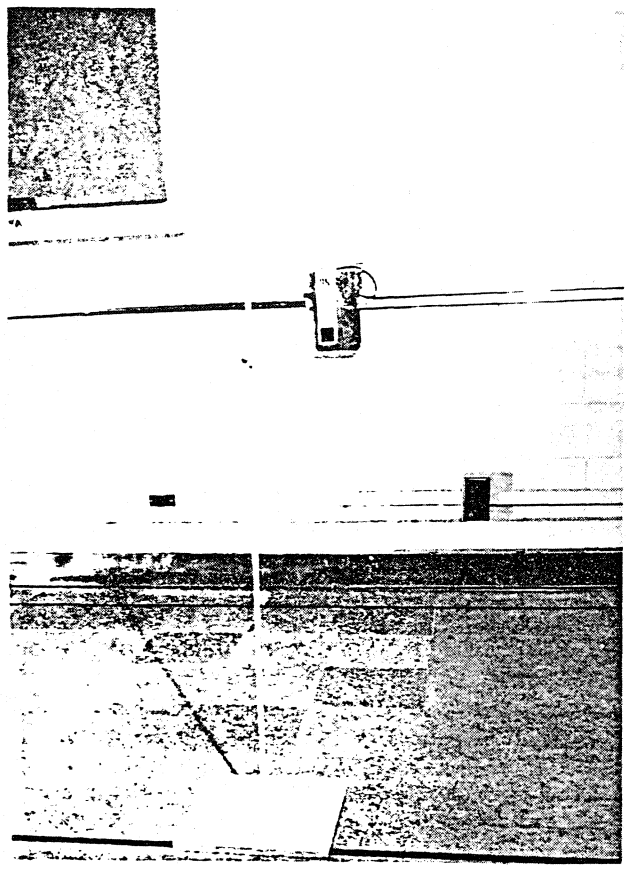


Fig. 7 - Optical switches used to determine gait temporal-distance factors.

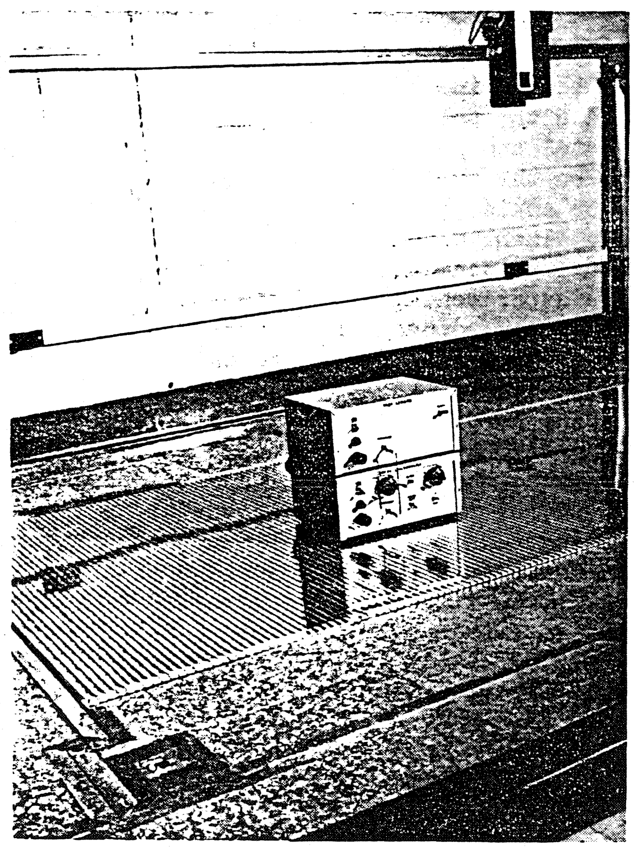


Fig. 8 - Foot conductive strips used to measure step length during gait.

tissue can be neglected, the goniometer linkage and the skeletal joint system can be modeled as a seven-bar spatial mechanism, as seen in Figure 9. Since two of the seven links are connected by a spherical joint (ball-and-socket), the mechanism has only three degrees of freedom. With the three angular motions recorded by the goniometer pots, the remaining motion of the entire linkage system is uniquely defined. Using the method of 4 x 4 matrix, the ball-and-socket joint (hip, knee or ankle) motion can be determined analytically.

The 4 x 4 matrix method and the way it is applied to correct the goniometer readings has been presented in a previous publication (14). It is, therefore, omitted here. In essence, it applies a linkage loop equation based on the 4 x 4 displacement matrix to determine the spherical joint motion through an iterative process. The true joint motion is first estimated and the error between the calculated and estimated results is minimized until the final results satisfy the linkage loop equation under certain convergence criteria. The differences between the final joint motion data and the potentiometer readings are defined as the cross talk, which will be used to assess the reliability of the measurement device.

Corrections were obtained for the hip, knee and ankle joints on subjects undergoing normal walking experiments. Figure 10 illustrates the difference between the goniometer reading and the corrected hip joint flexion-extension during normal walking. Small cross talks were also observed in other components of hip motion. Similar results were found for the knee and ankle joints. However, when motions in planes other than the flexion-extension were large, cross talks became significant and therefore required correction. In order to further verify this correction technique and to develop certain closed-form formula, a special experiment was conducted.

In normal correction process, the actual joint motion cannot be recorded directly since the joint is embedded inside the soft tissue. A special model was thus constructed to simulate the actual set up where two plastic cylinders were used to represent the distal and proximal joint segments. A triaxial goniometer was placed in between the cylinders to make up a ball-and-socket joint similar to a hip, knee or ankle joint, but its angular motion could be measured and recorded exactly. Then, a second electrogoniometer system was attached to the distal and proximal segments in an identical manner as that applied to humans. The entire experimental device is shown in Figure 11. Various experimental tests were then conducted to observe the effect of cross talks. The 4 x 4 matrix method was applied to examine the effectiveness of the correction procedure implemented.

Similar results were found in that the amount of correction was small if flexion-extension remained to be the dominating mode of joint motion. However, if other motions (abduction-adduction and rotation) were significant (greater than 10 degrees), cross talks became significant and thus required correction. An example of the cross talk and the subsequent correction results are shown in Figure 12. The difference between the goniometer reading and joint reading reflects the magnitude of cross talk. After correction, the true joint motion was nearly duplicated, which demonstrates the reliability of the analytical correction technique used. The small variation

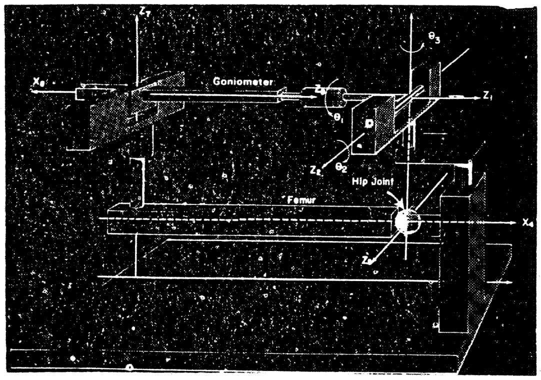


Fig. 9 - The 7-bar, 9 degrees of freedom spatial linkage system used to model the goniometer and lower extremity joints for error (cross talk) correction.

Fig. 10 - Comparison of the goniometer measured and mathematically corrected joint motion in hip flexion-extension.

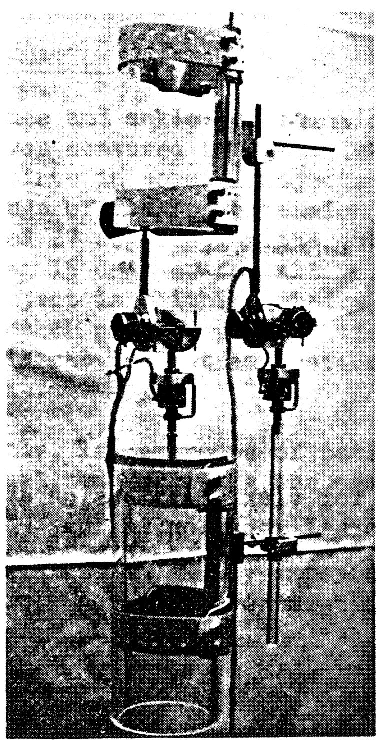


Fig. 11 - The experimental set up used to verify the analytical method of correcting the cross-talk error. The center goniometer system is used to simulate the actual anatomical joint to be measured.

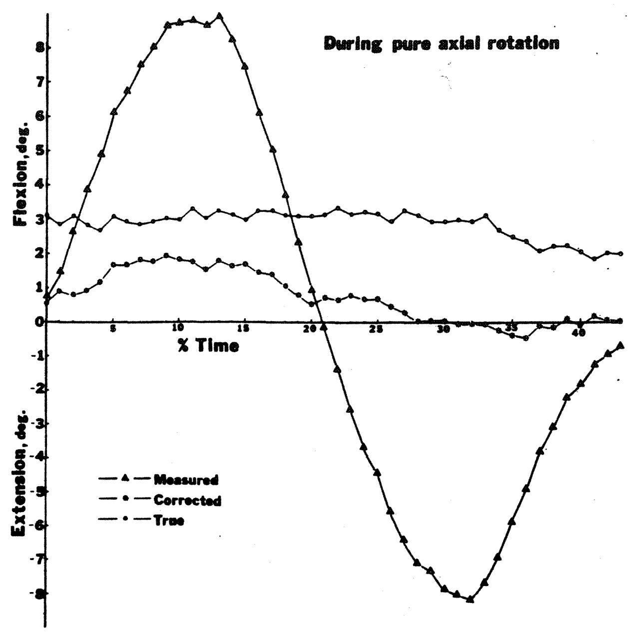


Fig. 12 - Cross talk in flexion-extension due to large axial rotation in the goniometer measurements. The corrected motion closely matches (the difference in magnitude was due to initial off set) the true joint motion measured by the goniometer situated at the joint center of the experimental model shown in Fig. 11.

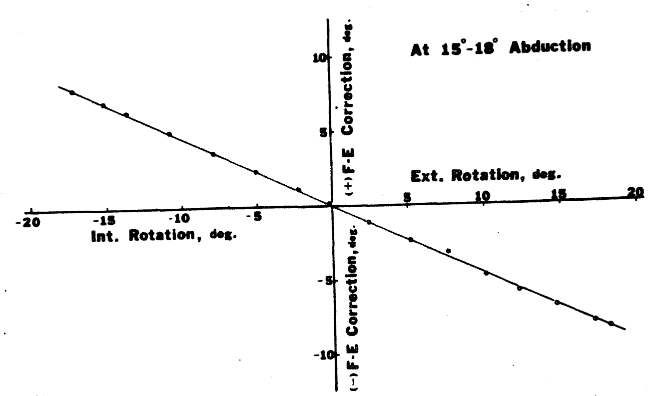


Fig. 13 - Correction relationship for flexion-extension as related to internal-external rotation in the goniometer measurements.

between the true and corrected values was due to the residual placement error. The important feature is to observe the nearly identical patterns exhibited.

The most significant correction is required for the flexion-extension component with large magnitude of internal-external rotation. The magnitude of correction (or the cross talk) on flexion-extension as a function of rotation is plotted in Figure 13, which fits the following linear equation nicely.

$$\phi_{jt} = \phi_{gon} \pm 0.48\ \phi_{gon}$$

where

ϕ_{jt} = flexion-extension occurring at the joint,

ϕ_{gon} = flexion-extension measured by the goniometer, and

ϕ_{gon} = internal-external rotation measured by the goniometer.

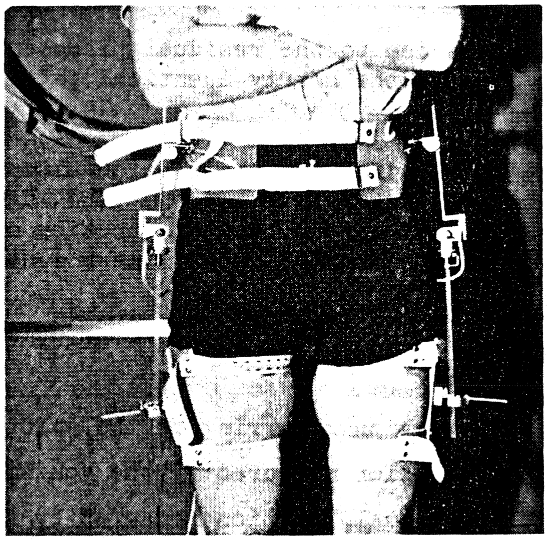
When the rotation is external, positive sign should be used in the above equation and when the rotation is internal, negative sign if applied. From the results of this experiment, the electrogoniometer is proven to be adequate and reliable to measure human joint motion data for functional evaluation purpose.

In normal walking, flexion-extension for all lower extremity joints is always dominant, which implies that the correction procedure may be avoided so that the goniometer pots provide the joint motion data directly. However, in abnormal subjects and in other activities of daily living where leg joints would require an excessive amount of rotation, analytical correction, as presented previously, has to be applied in order to produce accurate results.

PATIENT EVALUATION

Hip, knee and ankle joint motion during walking for a large normal population was measured to establish a data norm. Typical motion patterns for these joints in normal subjects are illustrated in Figures 14,15,16. The mean range of flexion-extension is 55 degrees for the hip, 62 degree for the knee, and 37 degrees for the ankle. The other two components of motion are less than 15 degrees for all joints. These motion components would vary when the subject is climbing stairs, walking on a ramp or side slope and performing other necessary activities. Under these circumstances, analytical correction is carried out automatically within the computer program during data analysis.

Currently, large groups of patients with abnormal lower extremity joints are being analyzed following the same experimental protocol. Those patients who are candidates for total joint replacement will be analyzed postoperatively. These results will be compared with that of the normals for objective functional evaluation. Many important clinical implications concerning the results of such surgical treatment can then be drawn.



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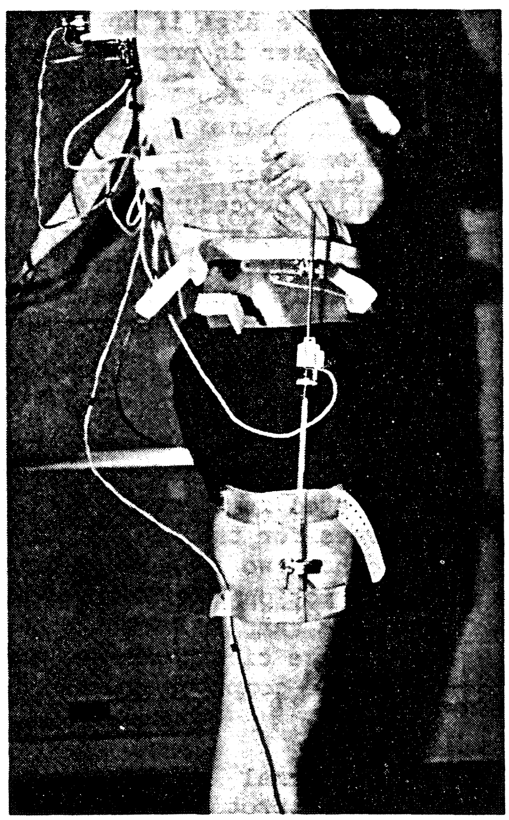

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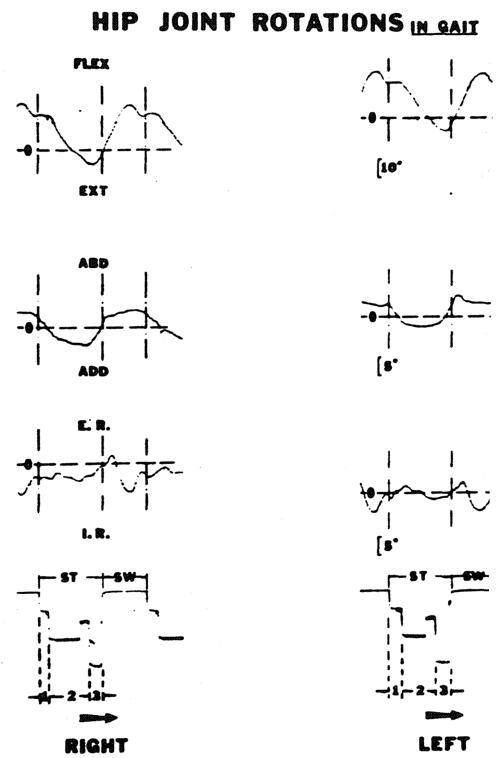
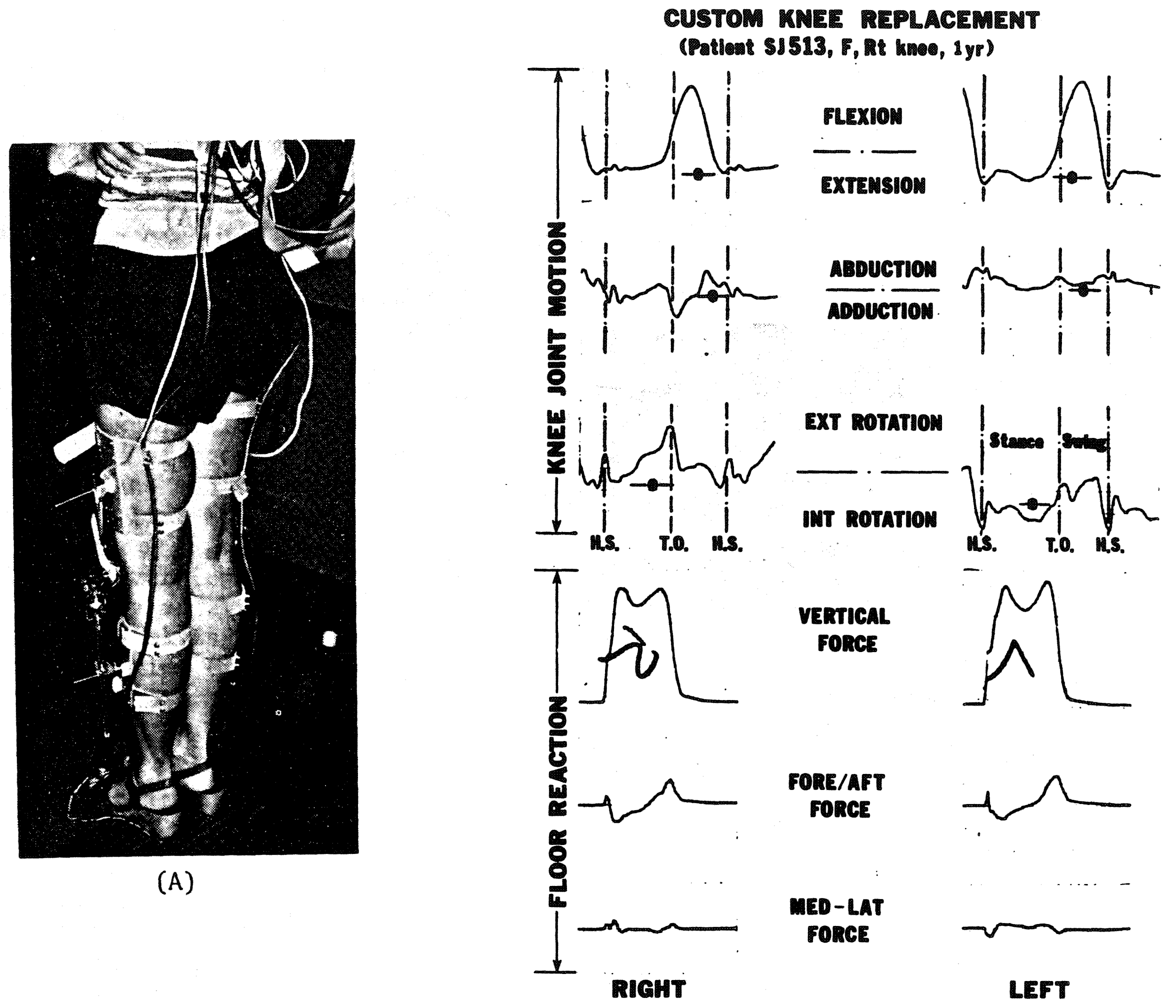


(C)

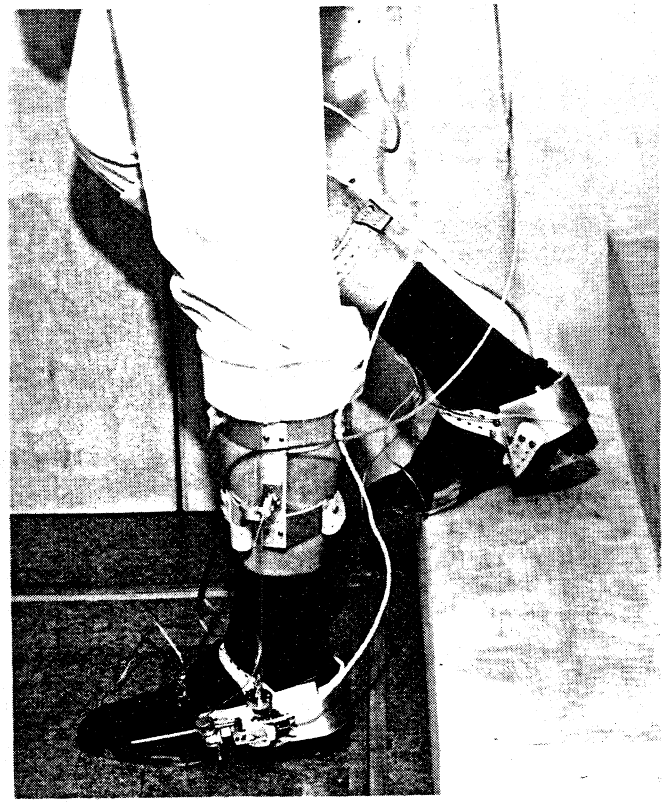
Fig. 14 - (A) Triaxial goniometer installation in the AP view for hip joint motion measurement during gait. (B) Lateral view. (C) Typical tracings of the three-dimensional hip motion measured by the goniometer system.



(A)

(B)

Fig. 15 - Knee joint motion measurement of a patient after segmental and total joint replacement of the right knee due to bone tumor resection. (A) Patient being instrumented to perform gait evaluation. (B) Tracings of the patient's right (replaced) and left (normal) knee motion in normal level walking. The bottom curves represent the foot-floor reaction forces measured by the force plate.



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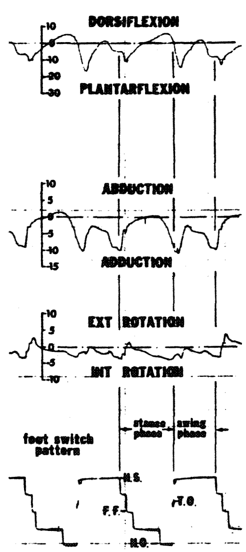

(B)

Fig. 16 - Triaxial goniometer system used for ankle joint motion evaluation. (A) Subject performing stair walking. (B) Tracing of the ankle joint motion during level walking.

This technique is also being used to analyze the walking patterns of amputees fitted with different artificial limbs. Quantitative assessments of the patients and the prosthetic devices are being used to establish the basis for artificial limb selection and rehabilitation training guidelines.

Modification of the current electrogoniometer is underway so that the data can be transmitted via telemetry to eliminate cables. Simultaneous measurement of multiple joints on the same extremity is also being investigated. Finally, this design concept has now been adopted to measure upper extremity joints such as the elbow and wrist.

SUMMARY AND CONCLUSIONS

An instrumented device, the electrogoniometer, capable of measuring hip, knee and ankle joint motion during normal walking, has been developed. This instrument is easy to use and reliable. In a large series of normal subjects, the magnitude and pattern of lower extremity joint motion during walking and other activities were established. Patient application is underway for the purpose of providing objective evaluation of the functional effect of joint disease and the results obtained from total joint replacement or artificial limb application.

The error (cross talk) introduced because of the linkage design was corrected by modeling the entire system as a seven-bar spatial linkage system and solving it, based on the method of 4 x 4 matrix. It was found that if flexion-extension of the joint is the principal model of motion, with other components remaining small, such correction is unnecessary since the magnitude of cross talk would be small. However, when axial rotation became large (greater than 10 degrees) analytical correction is necessary, particularly to the magnitude of flexion. This correction was found to be linearly related to the axial rotation; thus making the correction easily implemented.

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Chao cont.

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