The Gait Laboratory Force Plate at the Cleveland VA Medical Center

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INTRODUCTION

A key element in a gait laboratory is a force plate which may be used to measure the forces and moments applied by the foot onto the walking surface during a gait cycle. While many laboratories have relied solely upon motion data as obtained from using various camera techniques for analysis of gait, it is only with the inclusion of a force plate that the dynamic aspects of gait are appropriately considered.

A number of researchers have used a force plate to obtain a clinical evaluation of gait. Jacobs et al. (8) used the vertical component of the force exerted in walking for the diagnosis of hip joints: by analyzing this force as the sum of its harmonic components and by describing it by other mathematical parameters, different types of gait were classified. Yamashita and Katoh (13) used a specially designed force plate to analyze the moving pattern of the point of application of the vertical component of resultant force during level walking.

Suggested by Boccardi et al. (1) is a new technique of displaying force plate data, namely a "Butterfly Diagram" Force vectors are displayed on a storage screen where each vector represents the projection, onto the sagittal plane, of the ground reaction with its magnitude, inclination, and point of application clearly shown. Other investigators such as Bresler and Frankel (2), Cunningham (5), Endo and Kimura (6), and Iwai and Kozumi (7) have studied different characteristics of the vertical force obtained through the use of a force plate.

In much of the previous work as just outlined, the reduction of the data obtained from the force plate was accomplished manually, and was often considered separately from other data acquired. In order to circumvent some of the inherent difficulties associated with these approaches, the force plate at the Cleveland Veterans Administration Medical Center has been interfaced to a PDP 11/45 minicomputer so that the data-reduction step may be automated, and so that force data may be combined with motion and EMG information to provide a more complete evaluation of gait.

In this paper, the characteristics of force plates in general will first be discussed. Next, the construction of our force plate will be outlined—its physical construction, transducers used, and force components directly measured. After that the hardware interface to the computer will be discussed followed by a description of the software programs that have been written for calibration, data acquisition, and display. Finally, the mathematics of the force plate is detailed in the Appendix.

GENERAL CHARACTERISTICS OF FORCE PLATES

During the stance phase of each gait cycle, a varied mixture of rapidly changing vertical weight, horizontal shear, and rotational twisting moments are developed by the foot onto the walking surface. If a complete footstep "force signature" is to be obtained, then each of the force and moment components must be sampled regularly at a sufficiently high rate. Also, most applications require that the components measured include fore-aft, vertical, and lateral forces, as well as the moment about an axis normal to the walking surface and the coordinates of the center of pressure.

The center of pressure, as defined by Cavanagh (3), is the projection of the centroid of the vertical force distribution onto the ground plane, or in effect, the location where the resultant force vector would act if it could be considered to have a single point of application. The moments about the axes in the plane of the walking surface are usually assumed to be zero since the foot cannot pull upward on the plate (no "suction" action). The particular components measured in our implementation are shown in Figure 1 and will be further discussed in the next section.

To measure a force, it is necessary to obtain its magnitude in an indirect manner by observing the response of some device to the presence of the force. Regardless of the device used, virtually all force plates use the deflection of a sensing element as a measure of the force applied. Of the large number of sensing elements employed to transduce forces, four have been principally used in force plate applications:

1. Mechanical springs and pointers,
2. Piezoelectric crystals,
3. Linear variable differential transformers, and
4. Electrical resistance strain gages.

The Cleveland VA force plate employs the electrical resistance strain gage.

Finally, in order for the force plate to function adequately in gait studies, the following characteristics are required:

1. The force plate must be capable of resolving forces and moments within the range appropriate to the activity and subject being studied.
2. The force plate should have good static linearity and accuracy. Usually, the sensing element is chosen such that the force acting on the element is directly proportional to the displacement of the element, and the system can be calibrated by adjusting the offsets and gains of the supporting electronics.
3. The force plate should have a good dynamic response;

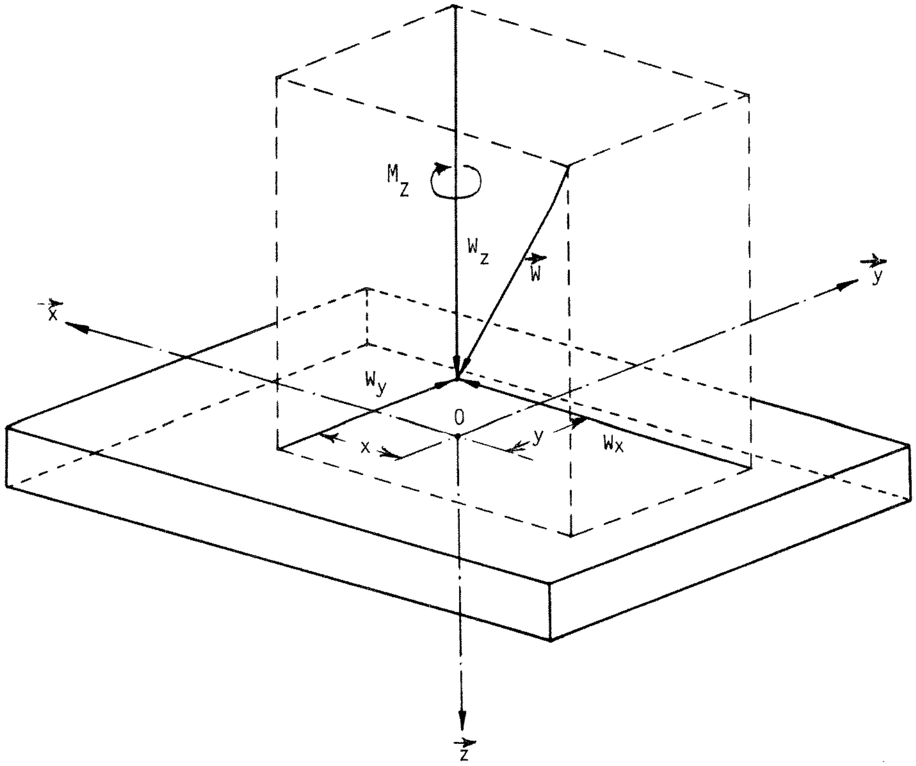


FIGURE 1.
Cartesian coordinate system attached to the force plate along with the quantities computed.

the framework must not be so heavy that the natural frequency of the whole assembly is too low. In normal level walking, the frequencies generated vary between 0–20 Hz., and in (9) it was found that a force plate with a natural frequency of 200 Hz. was suitably accurate. However, in (10) it was stated that for sufficient accuracy, the natural frequency should not be lower than approximately three to five times the desired highest frequency of the activity under study (i.e. 60–100 Hz. in normal level walking). The natural frequency of our force plate is approximately 70 Hz.

4. The force plate should have low hysteresis. That is, the maximum difference in output at any measurand value within the specified range, when the value is approached first with increasing and then with decreasing measurand, should be low.
5. The framework to which the sensing elements are connected must be sufficiently stiff that (to a good approximation) the sensing elements deflect and not the framework.
6. Minimal crosstalk between transducers measuring orthogonal force components is required. That is, either the member to which each transducer is mounted must be well isolated so that it can only deflect in a given direction, or each transducer must have unidirectional sensitivity only.
7. The walking surface must be rigid to avoid dynamic amplification, yet it should be sufficiently sensitive.
8. The supporting structure should be rigid and motionless with respect to the ground.
9. High noise immunity from floor vibration is required.

FORCE PLATE CONSTRUCTION

The Cleveland Veterans Administration Medical Center force plate is set in the middle of, and on the same level as, a wooden walkway. Force plate and walkway are elevated approximately two feet above the laboratory floor (Fig. 2). The walkway is covered by a metal screen which provides an electrical ground for a foot-switch system. The screen obscures any gap in the wooden surface of the walkway around the force plate so that the patient is not aware of the plate's existence. The walkway is designed so that gait analysis may be accomplished while the patient is walking in either direction. Also, if the patient does not place one and only one foot solidly on the surface of the force plate, then he may be instructed to repeat the motion — with one additional pass usually being sufficient.

As shown in Figure 3a, the force plate is composed of three major sections: a top plate (cover), an inner plate, and a support frame. The top plate provides the surface on which the foot must be placed and is shown as Plexiglass in Figure 3a. The present cover is made of ¾-inch plywood sandwiched between two ⅛-inch aluminum plates.

The top plate is rigidly attached to the inner plate which is further attached to the support frame through seven supports, each instrumented with strain gage elements. Three of these supports are vertical (one of these is shown in Fig. 3b), and four of them are horizontal (two of these are shown in Fig. 3c). Two of the horizontal supports are aligned with the $\vec{x}$ axis of the walkway and two are aligned with the $\vec{y}$ axis.

The x and y supports are paired, and each pair is positioned at diagonally opposite corners of the structure (Fig. 3). Stability is increased by positioning the three vertical supports well outside the perimeter of the walking surface. (See Figs. 1 and 4 and the Appendix for a more specific definition of the coordinate system and points of support).

Crosstalk is reduced at each support through the series combination of a strain gage member and a bending member, positioned at a right angle to each other. Thus the strain gage measures only forces in the required direction. Also, these members are preloaded to give a more linear relationship between force and gage resistance.

There are seven analog outputs from the force plate and

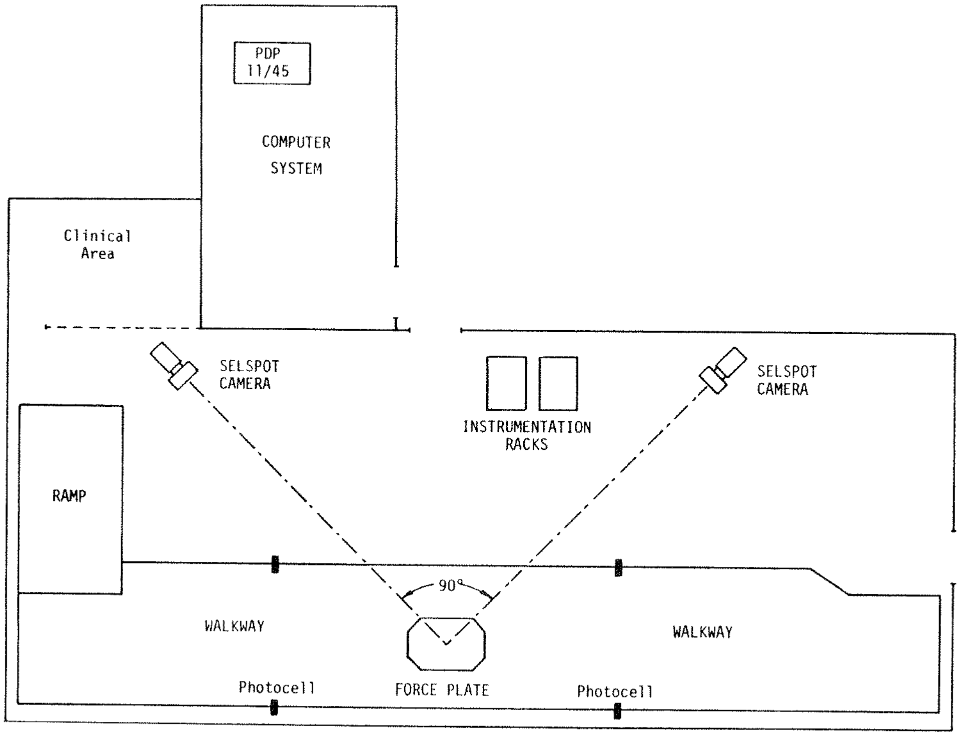
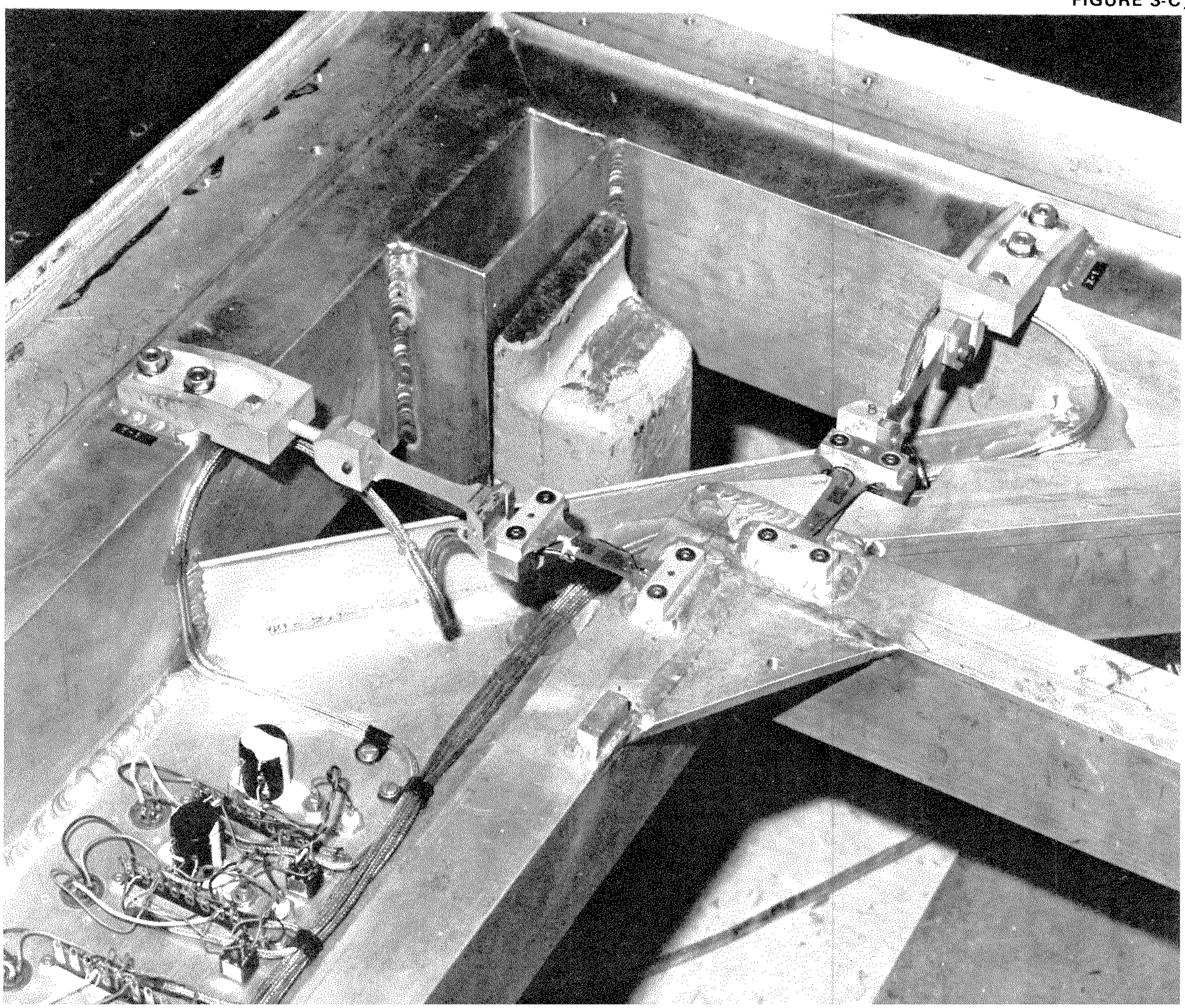


FIGURE 2.
Cleveland VA Medical Center gait laboratory layout. Subjects enter from the "clinical area", at left in drawing, and reach the walkway (which is two feet above floor level) by ascending the ramp.
The "positive" direction of the walkway starts with the ramp end (from left to right on this drawing), although gait analysis can be accomplished with the patient walking in either direction. In the paper and Appendix, the expressions "right", "left", "near" and "far" all apply in terms of an observer standing near the instrumentation racks, between the cameras.

FIGURE 3-C.



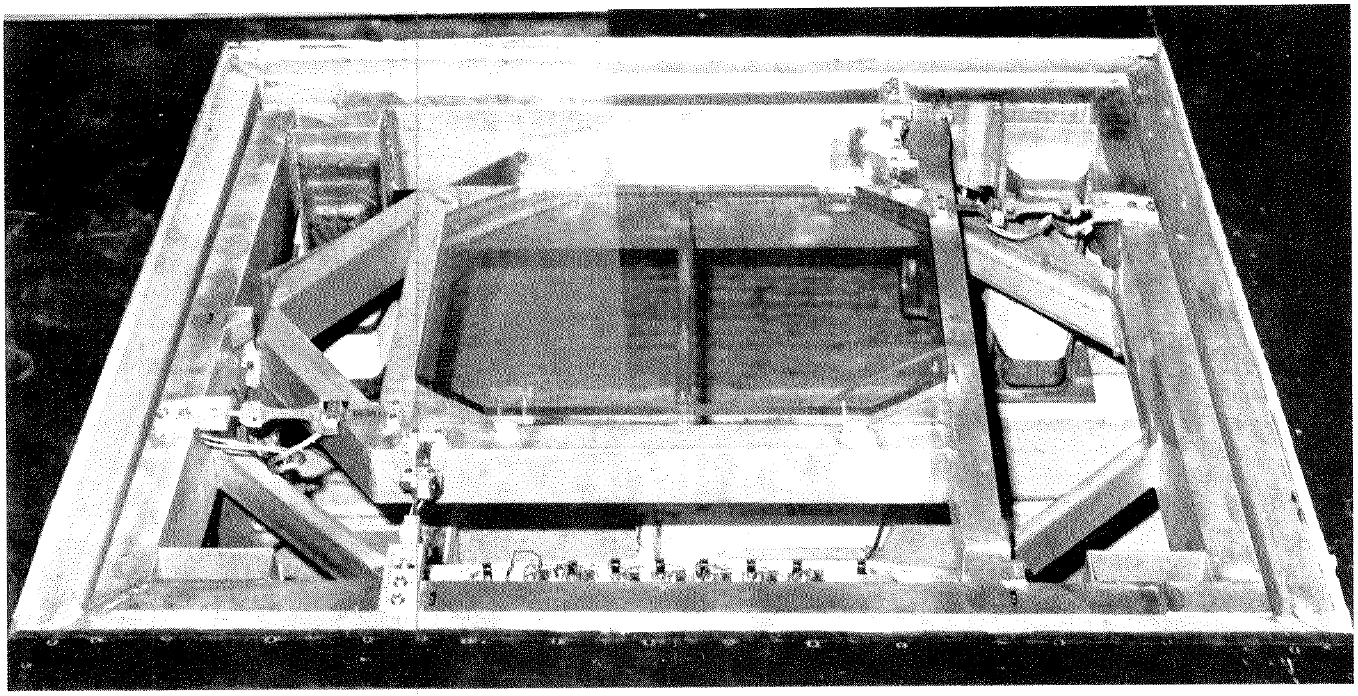


FIGURE 3-A.

Force plate, with flush cover plate removed, is seen in Figure 3-A above and in the engineering drawing (Fig. 4) below. Two of the four horizontal supports (labeled X 1 and Y 1 on drawing) appear in Figure 3-C at left. One of the three vertical supports (the one labeled Z 3 on drawing) appears in Figure 3-B, at right.

FIGURE 4

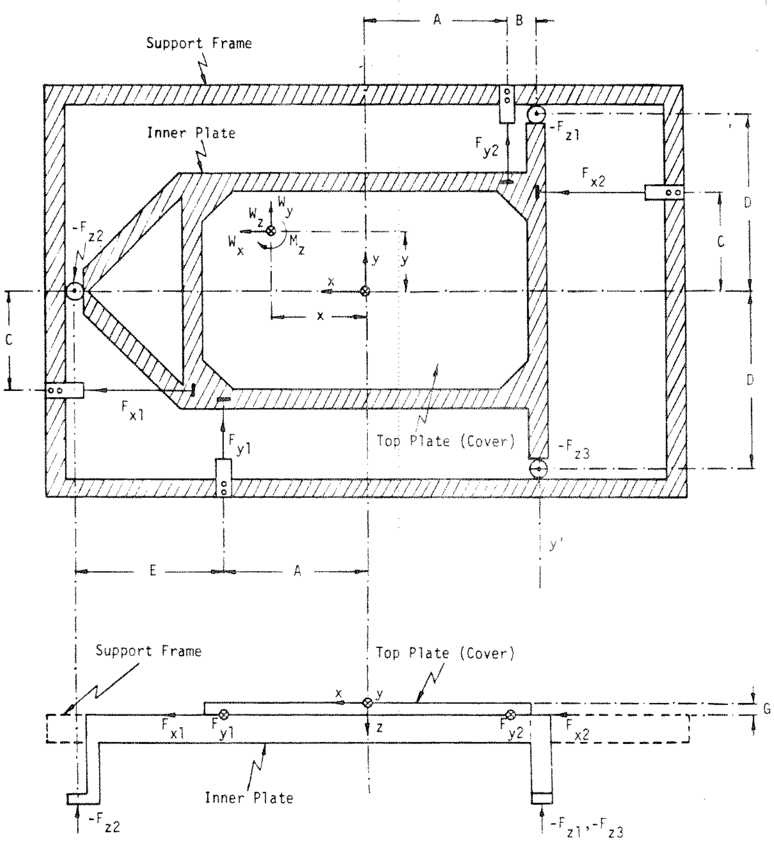
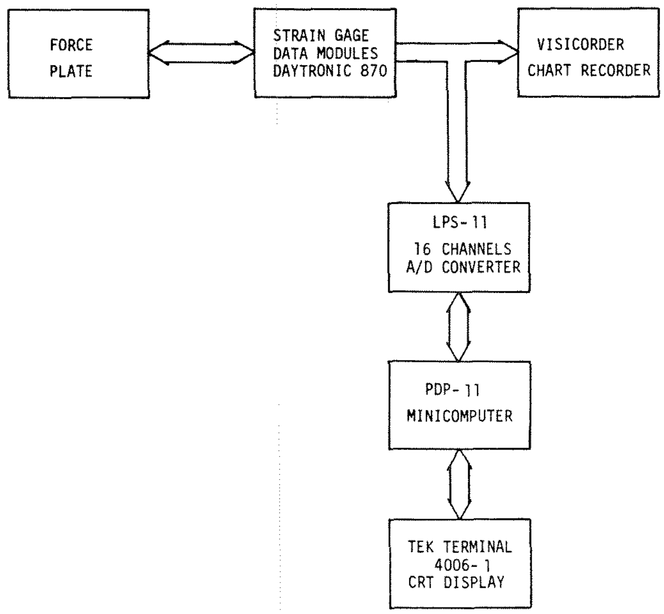


FIGURE 3-B.

FIGURE 5.
Block diagram of the force plate system.



associated electronics (one for each support), and from these, six quantities are determined: the three components of force (W_x, W_y, W_z), the coordinates of the point of force application (x,y), and the moment about an axis normal to the walking surface at the point of force application (M_z). (The complete mathematical relationships are derived and given in the Appendix.)

HARDWARE CONSIDERATIONS

Interfacing

A block diagram of the present set-up of the force plate system is given in Figure 5. The force plate has been interfaced to the PDP 11/45 minicomputer so that the three components of the foot reaction force, the point of application of the force (center of pressure), and the moment about the normal to the walking surface of the force plate (at the point of application) may all be computed digitally and the results appropriately stored and displayed.

The strain gages of the force plate are interfaced first through signal-conditioning amplifiers (a Daytronic model 870 unit). These modules supply regulated d.c. voltage to the strain gage transducers, provide balancing and calibration functions, and amplify the transducer's output-voltage signal. Seven channels of output are provided (see Equations A-13 to A-19) and may be directly displayed on the Visicorder high-speed chart recorder. These are further provided to the PDP 11/45 minicomputer through the LPS-11, 16-channel analog/digital converter. Finally, after the desired results have been computed, they may be displayed on a Tektronix 4006-1 CRT terminal which is interfaced to the PDP 11/45.

Calibration and Measurement

The calibration method used consists of applying known forces to the force plate and simultaneously measuring the voltage values as read by the computer, thus evaluating the transfer function for the entire system. Such an experimental calibration procedure was found necessary in (10). They found that any analytical approach to the determination of the transfer function from the dimensions of the force plate and sensitivity of the sensors is excessively idealized.

With the calibration method employed, the following assumptions were made:

1. No non-zero input exists which produces no output at all, and
2. Linearity and superposition apply.

Under these assumptions, the transfer function for the system may be described through the following matrix equation:

$$V = H \cdot F + B \quad [1]$$

where

V = Vector of voltage values read by the computer		(7x1)
H = Transfer matrix		(7x7)
F = Input force vector		(7x1)

Writing this out explicitly gives equation [2], shown below.

The offset voltage vector, B, is calibrated continually just prior to *any* force plate measurement. This is accomplished by reading the voltages within a short time interval (few seconds) before a load is applied to the plate and using the following equation:

$$V = B \quad \text{for } F = 0. \quad [3]$$

Periodically, the matrix H is calibrated by placing known loads on the force plate and measuring the resulting voltage vector. At present, it is assumed that the crosstalk between each of the seven force plate channels is minimal so that all off-diagonal components of the H matrix are assumed to be zero. It may be appropriate in the future to

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \\ V_7 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} & H_{13} & H_{14} & H_{15} & H_{16} & H_{17} \\ H_{21} & H_{22} & H_{23} & H_{24} & H_{25} & H_{26} & H_{27} \\ H_{31} & H_{32} & H_{33} & H_{34} & H_{35} & H_{36} & H_{37} \\ H_{41} & H_{42} & H_{43} & H_{44} & H_{45} & H_{46} & H_{47} \\ H_{51} & H_{52} & H_{53} & H_{54} & H_{55} & H_{56} & H_{57} \\ H_{61} & H_{62} & H_{63} & H_{64} & H_{65} & H_{66} & H_{67} \\ H_{71} & H_{72} & H_{73} & H_{74} & H_{75} & H_{76} & H_{77} \end{bmatrix} \begin{bmatrix} Z_T \\ Z_2 \\ Y_M \\ Z_M \\ Y_T \\ X_T \\ X_M \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \\ B_6 \\ B_7 \end{bmatrix} \quad [2]$$

have a more elaborate procedure, so that these terms may be included in the calibration.

Once H and B are experimentally determined, force measurement is accomplished simply by applying the following matrix equation:

$$F = H^{-1} (V-B). \quad [4]$$

It should be noted that the calibration procedure as just described is useful for determining the transfer function from the force plate into the computer in order to have an accurate measurement of the components of the force vector, F. However, as is noted in the Appendix, six other quantities are further computed from these components (Equations A-20 to A-25). They depend upon the dimensions of the force plate, and yet these parameters are not included in the calibration procedure. In the future in order to obtain a more comprehensive calibration, it may be appropriate to include them.

SOFTWARE CONSIDERATIONS

Calibration Program

As was discussed in the previous section, due to variations in the gains of the force plate's support electronics, it is necessary to calibrate the transfer matrix for the system periodically. A computer program has been written in FORTRAN to facilitate this task.

The program as written is interactive in that the user is prompted to apply a force to the plate in a specific direction (and sometimes at a specific point). After the user has finished the calibration step, the computer is directed to read the value and compute one of the diagonal elements of the H matrix and store it away. When all steps are completed the H matrix has been determined (off-diagonal terms are forced to zero).

It is very tedious and often unnecessary to apply actual loads to the plate when a calibration is to be performed. Because of this, shunt calibration resistors are used to replace the actual load. These are just fixed resistors that may be switched in across one arm of a strain gage bridge. They present an unbalance in the circuit which is equivalent to a particular mechanical input. The calibration program as written may be used equally well for these "equivalent loads". In this case the user simply activates the appropriate switches as prompted.

Data Acquisition Program

A FORTRAN program which collects seven channels of analog data through the LPS-11 A/D converter has been written. The data are collected at a required rate as defined by the user through an interactive operation. The algorithm accounts for offset (bias) of the channels sampled. The data are then multiplied by the inverse of the force plate's transfer matrix, H, which is stored on a disc file, and is converted into force units.

A file named after the subject is established. The file contains a four-record header which contains the following information:

Record 1: Subject's name
Record 2: Date of run
Record 3: Time of run
Record 4: File length, sampling rate, and number of samples between first photocell trigger and first force plate contact.

Two photocells are located at the beginning and the end of the walkway. See Figure 2.) The rest of the file contains the stance-phase data. Each record is composed of six types of data and is associated with one sampling point. The data in the record are arranged in the following order: W_x, W_y, W_z, x, y, M_z. (See Figure 1 and the Appendix for their definition.)

The program is composed of a main program and four subroutines, and it checks for collection errors. In the case of an error, a message is typed out on the terminal and the program is terminated.

Butterfly Diagram Program

As mentioned previously, a method of force plate data representation was suggested by Boccardi et al. (1) and by Pedotti (12). Upon initial evaluation, the diagram seems to be repeatable for the same subject at different times. Also, patients with similar disorders present similar variations in their vector diagrams. This method was further investigated by Cook et al. (4), and results indicate that the procedure holds promise for improved management of patients with locomotion problems.

With the FORTRAN program developed for our system, one can obtain the Butterfly Diagram in a perspective view (Fig. 6). Moreover, the program provides the capability of obtaining the diagram in any position and orientation defined by the user through an interactive process. Also, three standard options are installed: sagittal view (Fig. 7), frontal view, and a top view.

The method of assemblage of surface points as described by Paul (11) for three-dimensional space representation is employed in the graphics display program. Furthermore, the algorithm uses homogeneous transformations (4x4 transformations) for the computation of coordinate transformations (11).

SUMMARY AND CONCLUSIONS

The gait laboratory force plate at the Cleveland VA Medical Center has been described in this paper. It has been interfaced to the PDP 11/45 minicomputer in the laboratory so that the data obtained may be automatically processed, stored, and displayed all in real-time. Also, this allows the data to be easily combined with motion data from two Selspot cameras and EMG data so that more comprehensive gait analysis may be accomplished.

Concurrent work is addressing the question of estimating the forces in the muscles, ligaments, and joints during normal level walking. At some point in the future, it is expected that these forces along with all of the information directly acquired (force plate, EMG, and camera data) will

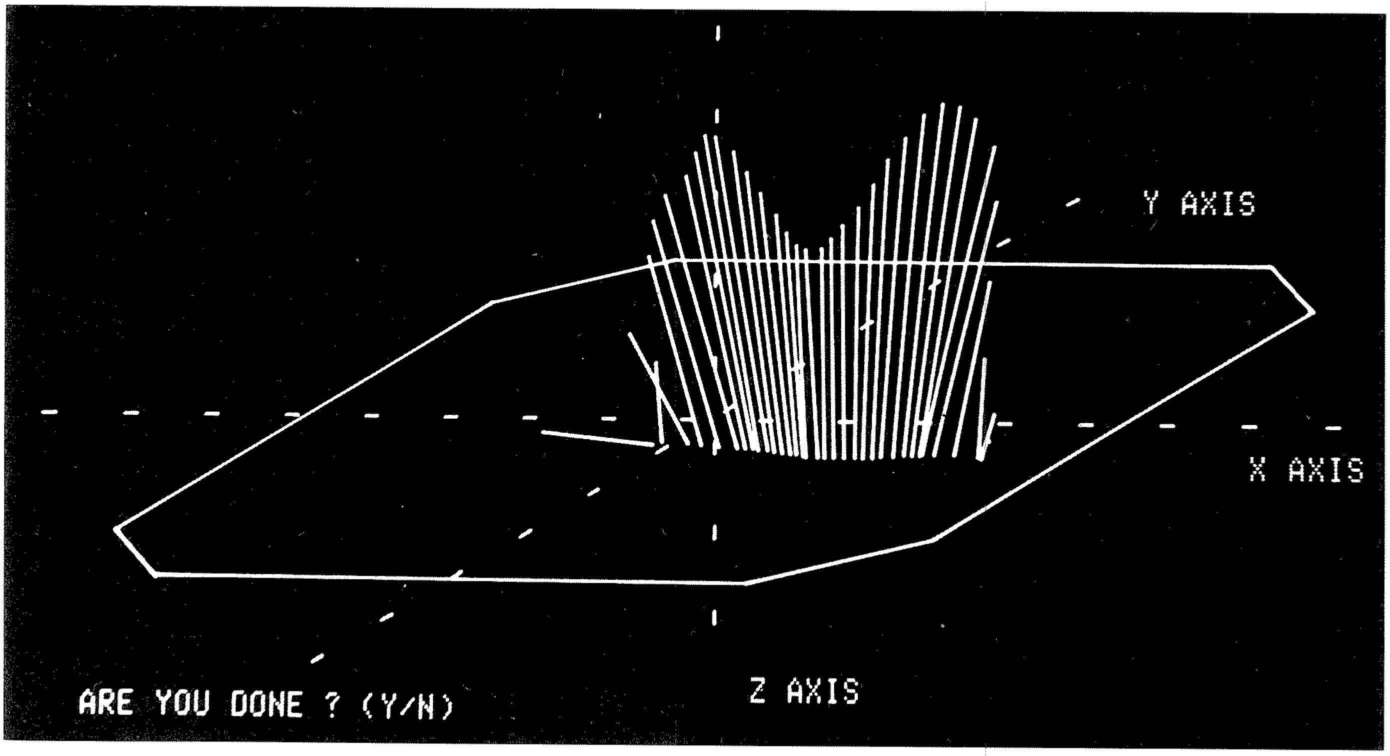


FIGURE 6.
Perspective view of a Butterfly Diagram.

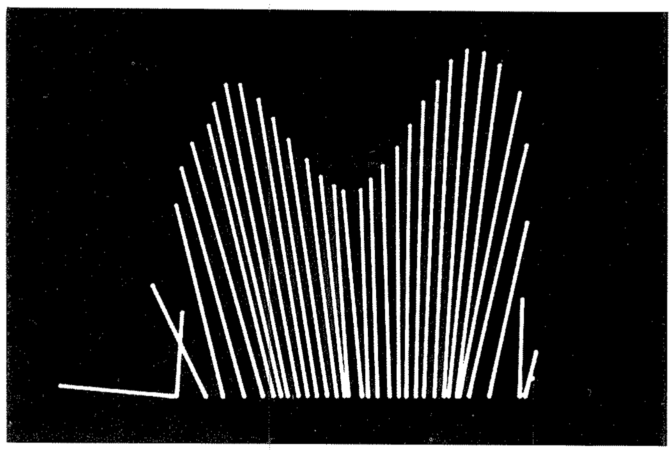


FIGURE 7.
Sagittal plane view of a Butterfly Diagram.

be combined and presented on a color graphics display showing the full dynamics of human gait for evaluation by a clinician. The force plate as described will be an important element in this system.

APPENDIX

The force plate as constructed has strain gages that directly measure seven different force components that are applied to the inner plate (and cover) by the support frame: F_{x1}, F_{y1}, F_{x2}, F_{y2}, F_{z1}, F_{z2}, F_{z3}. (See Figure 4.) From these, six quantities are to be derived: the three components of the reaction force applied by the foot to the cover (W_x, W_y, W_z), the coordinates of the point of force application (x,y), and the moment about an axis normal to the walking surface at the point of force application (M_z).

A right-handed cartesian coordinate system is attached to the force plate and all of the quantities described above are with respect to this system. The positive $\vec{x}$ axis points along the walkway from right to left. The $\vec{z}$ axis points downward into the plate while y satisfies the following equation:

$$\vec{y} = \vec{z} \times \vec{x}. \qquad \text{[A-1]}$$

The forces W_x, W_y, W_z may be related to the measured strain gage forces by writing a force-balance equation on the components as applied to the cover and inner plate assembly. This results in the following sets of equations:

$$W_x + F_{x1} + F_{x2} = 0 \qquad \text{[A-2]}$$
$$W_y + F_{y1} + F_{y2} = 0 \qquad \text{[A-3]}$$
$$W_z + F_{z1} + F_{z2} + F_{z3} = 0 \qquad \text{[A-4]}$$

where all components are defined as positive in the direction of the unit vectors of the coordinate system.

The above equations may be rewritten explicitly for the desired foot reaction forces:

$$W_x = -F_{x1} - F_{x2} \qquad \text{[A-4]}$$
$$W_y = -F_{y1} - F_{y2} \qquad \text{[A-5]}$$
$$W_z = -F_{z1} - F_{z2} - F_{z3}. \qquad \text{[A-6]}$$

In order to compute the coordinates of the point of application (x,y) and moment about the normal to the force plate at the point of application (M_z), moment balance equations may be written. First, considering moments about the x axis, the following equation is obtained:

$$F_{z1}D - F_{z3}D + W_z y - F_{y2} \ldots y_1 G = 0. \quad [A\text{-}7]$$

Solving explicitly for y and substituting the value of W_z from Equation [A-6], the following is obtained:

$$y = \frac{D\,(F_{z3} - F_{z1}) + G\,(F_{y2} + F_{y1})}{-(F_{z1} + F_{z2} + F_{z3})} \quad [A\text{-}8]$$

Next, consider moments about an axis y′ parallel to $\vec{y}$ and directed from the front to the back of the force plate. (See Figure 4.) The following equation results:

$$-F_{z2}\,(2A+E+B) - W_z\,(x+A+B) - W_x\,G = 0. \quad [A\text{-}9]$$

Solving explicitly for x and substituting the values of W_x and W_z from Equations [A-4] and [A-6], the following is obtained:

$$x = \frac{(F_{z1} + F_{z3})(A+B) - F_{z2}(A+E) + (F_{x1} + F_{x2})G}{-(F_{z1} + F_{z2} + F_{z3})}. \quad [A\text{-}10]$$

Last, consider moments about an axis parallel to $\vec{z}$ through the point of force application. The following equation results:

$$M_z + F_{x1}\,(y+C) - F_{x2}\,(C-y) + F_{y1}\,(A-x) - F_{y2}\,(A+x) = 0. \quad [A\text{-}11]$$

Solving explicitly for M_z and rearranging the equation somewhat, the following is obtained:

$$M_z = x(F_{y1}+F_{y2}) - y(F_{x1}+F_{x2}) + A(F_{y2}-F_{y1}) + C(F_{x2}-F_{x1}) \quad [A\text{-}12]$$

The present force plate was originally designed to function without being interfaced to a digital computer. Certain intermediate functions are computed in analog hardware through the appropriate use of Wheatstone Bridges. These functions are defined as:

$$X_T = -(F_{x1}+F_{x2}) \quad [A\text{-}13]$$
$$Y_T = -(F_{y1}+F_{y2}) \quad [A\text{-}14]$$
$$Z_T = -(F_{z1}+F_{z2}+F_{z3}) \quad [A\text{-}15]$$
$$Z_M = F_{z3}-F_{z1} \quad [A\text{-}16]$$
$$Z_2 = -F_{z2} \quad [A\text{-}17]$$
$$X_M = F_{x1}-F_{x2} \quad [A\text{-}18]$$
$$Y_M = F_{y2}-F_{y1}. \quad [A\text{-}19]$$

Using these functions, Equations [A-4], [A-5], [A-6], [A-8], [A-10], and [A-12] may be rewritten as follows:

$$W_x = X_T \quad [A\text{-}20]$$
$$W_y = Y_T \quad [A\text{-}21]$$
$$W_z = Z_T \quad [A\text{-}22]$$

$$x = \frac{Z_2\,(A+E) - G\,X_T - (Z_T - Z_2)\,(A+B)}{Z_T} \quad [A\text{-}23]$$

$$y = \frac{Z_M\,D - Y_T\,G}{Z_T} \quad [A\text{-}24]$$

$$M_z = Y_M\,A - X_M\,C + y\,X_T - x\,Y_T. \quad [A\text{-}25]$$

Equations [A-20] to [A-25] are implemented in the PDP 11/45 digital computer.

REFERENCES

1. Boccardi, Silvano, Gigliola Chiesa, and Antonio Pedotti: New Procedure for Evaluation of Normal and Abnormal Gait. Amer. J. Phys. Med., 56(4):163-182, 1977.
2. Bresler, B., and J. P. Frankel: The Forces and Moments in the Leg during Level Walking. Trans. Am. Soc. Mech. Engrs., 72:27-36, 1950.
3. Cavanagh, P. R.: A Technique for Averaging Center of Pressure Paths from a Force Platform. J. Biomech., 11:487-491, 1978.
4. Cook, T.M., B. A. Cozzens, and H. Kenosian: A Technique for Force-Line Visualization. Rehabilitation Engineering Center, Moss Rehabilitation Hospital, Philadelphia, Pa. Publ. #RR1-79, 1979.
5. Cunningham, D. M., and G. W. Brown: Two Devices for Measuring the Forces Acting on the Human Body during Walking. Proc. Soc. Exp. Stress Anal., 9:75-90, 1952.
6. Endo, B., and T. Kimura: Dynamic Analysis of Human Walking. Proc. 8th Int. Cong. Anthrop. and Ethn. Sci., pp. 335-339, 1969.
7. Iwai, R., and K. Kozumi: Force Plate Studies on the Kinetics of Human Locomotion. Bull. Miyagi Univ. Educ., 7:45-67 (In Japanese with English abstract.) 1972.
8. Jacobs, N.A., J. Skorecki, and J. Charnley: Analysis of the Vertical Component of Force in Normal and Pathological Gait. J. Biomech., 5:11-34, 1972.
9. Marsden, J. P., and S. R. Montgomery: An Analysis of the Dynamic Characteristics of a Force Plate. Measurement and Control, 5:102-106, 1972.
10. Nevins, J.: Exploratory Research in Industrial Modular Assembly. The Charles Stark Draper Laboratory Report, R-350, pp. 145-174, 1974.
11. Paul, R.: The Mathematics of Computer Controlled Manipulators. Proc. 18th Joint Auto. Cont. Conf., San Francisco, Calif., 1977.
12. Pedotti, Antonio: Simple Equipment Used in Clinical Practice for Evaluation of Locomotion. IEEE Trans. Biomed. Engng., BME-24(5):456-461, 1977.
13. Yamashita, T., and R. Katoh: Moving Pattern of Point of Application of Vertical Resultant Force during Level Walking. J. Biomech., 9:93-99, 1976.