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19. LOADCELL SUPPORTS FOR A DYNAMIC FORCE PLATE

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SUMMARY

An apparatus was developed to accurately measure components of force along three mutually perpendicular axes, torque, and the center of pressure imposed by the foot of a subject walking over its surface. The data obtained are used to supplement high-speed motion picture and electromyographic (EMG) data for in-depth studies of normal or abnormal human gait. Significant features of the design--in particular, the mechanisms used to support the loadcell transducers--are described. Results of the development program and typical data obtained with the device are presented and discussed.

INTRODUCTION

Since 1965, a group of orthopedic surgeons, medical researchers, and aerospace engineers have worked together* to develop and perfect the equipment and techniques needed to thoroughly characterize and quantitize human gait parameters. Early efforts by Sutherland and Hagy (Ref. 1) were focused on the use of high-speed motion picture cameras and a multi-channel EMG system to acquire data on angular motions and neuro-muscular activities of the lower extremities during walking. As these efforts progressed, the need for force, torque, and center of pressure measurements which were correlated in time with the motion picture and EMG data, became increasingly obvious. Consequently, in 1971, a device designated as the Dynamic Force Plate† was conceived and built. With this device, precise measurements of

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*The work described herein was sponsored by the Shriners Hospital for Crippled Children, San Francisco, California

†U. S. Patent pending. Development models are currently in operation at Shriners Hospital, San Francisco, California; the Mayo Clinic, Rochester, Minnesota; and Children's Health Center, San Diego, California

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vertical force, forward-aft shear force, medial-lateral shear force, torque, and center of pressure location are obtained as functions of the percent of walk cycle (time) while the subject's foot is in contact with the plate.

During the design and development of the force plate system, the most critical problem encountered was that of devising loadcell support mechanisms which were suitably rigid, yet which permitted the six degrees of freedom needed to obtain the desired measurements. These supports were required to provide relatively high load capability, minimum misalignment, and negligible friction. Three different support mechanism concepts were developed and evaluated during the program. In the chronological order of their development, these were: (1) sliding friction supports. (2) ball-joint/conical pivot supports, and (3) spherical segment rocker supports. The latter were found to be superior in terms of accuracy, repeatability, low-friction, low-noise, and high-load capabilities. Moreover, installation and calibration procedures were significantly simplified with this design.

SYSTEM DESCRIPTION

The Dynamic Force Plate is shown in the photograph and cut-away perspective drawing of Figs. 1 and 2, respectively. Application of current aerospace instrumentation technology to the design of the system resulted in selection of piezoelectric quartz crystal loadcell transducers to obtain the necessary measurements. Originally developed for the adverse environments and demanding requirements of unique aerospace applications, these rugged loadcells extend heretofore unavailable measurement capabilities to the medical community. Compared to more conventional strain gage loadcells, the piezoelectric devices offer the following advantages: (1) passive operation (i. e., no active excitation power supply is required), (2) a wider load range for a given load rating, (3) a higher sensitivity due to higher output voltage, (4) a higher frequency response, (5) a higher structural rigidity, (6) a wider operating temperature range, and (7) a smaller physical size envelope.

The particular loadcell transducers selected provide up to ± 10-volt output signals over a load range from approximately 0.09N to 2.2kN (0.02 to 500 lbf) with a frequency response from near DC (static force) to approximately 200 hz*. Once installed, they require little or no maintenance or recalibration. Output signals are generated only in response to changes in the applied load; consequently, they are summed electronically using a charge amplifier in order to determine the total net force applied at any particular instant in time.

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*The value given is representative of the total system and depends primarily upon the mass and rigidity of the plate; the upper limit of response for the transducer alone is 5000 hz.

Development models feature use of a transparent plexiglas plate in order to permit photographing of the footprint pressure patterns from beneath the walk-way surface as shown in Fig. 3. However, high-load, high-frequency-response models now being planned for use in large animal gait studies will require metal or composite plates in order to accommodate vertical forces of up to 17.8 kN (4000 lbf) and to provide system frequency responses of up to 1000 hz or higher.

The Dynamic Force Plate system, as demonstrated by the existing developmental models, is eminently suited to automatic data acquisition and modern, high-speed computer reduction, analysis, and display techniques. In the installation at Shriners Hospital, for example, force, torque, and center of pressure data are recorded, processed, and plotted in engineering units within approximately 7 minutes after any given walk cycle. This is accomplished using an Electronic Processors, Inc. general purpose EPI-118 minicomputer which is connected directly to the force plate system (Ref. 2).

LOADCELL SUPPORTS

Fig. 4 shows a closeup view of one corner of the force plate assembly. One of the two loadcells provided to measure forward-aft shear and torque, and the single loadcell used to determine medial-lateral shear, can be seen as installed within the load frame. This photograph, taken looking down on the device with the cover plate removed, actually shows the load cells assembled with the original sliding friction supports. However, it is also representative of the installation for the ball-joint/conical pivot supports and the spherical segment rocker supports developed later. Details of each of these support mechanism concepts are presented and discussed in the following paragraphs.

Sliding Friction Supports

Exploded views of the shear/torque force link assembly (on the left) and the compression spring assembly (on the right) are shown in Fig. 5 for the sliding friction support concept. The force link assembly shown is typical for any one of the three shear/torque loadcells and for any one of the four vertical loadcells, although detail dimensions do vary for the shear/torque and the vertical force applications. Each of the three shear/torque loadcell assemblies is pre-loaded in compression by one of the three spring assemblies provided. This permits measurement of load in both directions using a single loadcell transducer at each location. The output is zeroed electronically after the preload is adjusted to the desired value.

With this concept, all force link (loadcell) and compression spring assemblies are mounted rigidly to the load frame through the threaded mounting studs. In order to load any given transducer, the plate must be free to deflect in the direction of the applied load. This requires sliding of the microseal bearing surfaces normal to the loadcell axis (see detail shown in Fig. 5) for all of the system transducers mounted perpendicular to the applied load axis. A potential error in measuring the applied load is thus introduced due to the frictional reactions imposed by the transverse-axis loadcells. A secondary source of error also results from the side load imposed on any given loadcell transducer due to the sliding friction.

During the development program, an analysis was performed to predict the magnitude of potential errors due to friction. A coefficient of static friction of 0.02 was assumed in the analysis based on a data sheet supplied by the Microseal Corporation for the appropriate materials and surface finish. Results of the analysis indicated that an error in a measured shear load of approximately 17.8N (4.0 lbf) could occur due to frictional resistance of the vertical force loadcells with a 90.7-kg (200-lbm) subject on the plate. This magnitude of error was considered to be unacceptable, and the design of the loadcell supports was modified. Experimental results obtained with the sliding friction support concept showed that the errors in measured vertical force were not significant, but that those observed for shear loads were indeed high compared to the range of the expected loads.

Ball-Joint/Conical Pivot Supports

The loadcell support concept shown in Fig. 6 differs from the sliding friction support concept in that each loadcell assembly can rotate in order to achieve transverse-axis deflections. An adapter with a conical pivot is used in conjunction with a ball-joint swivel to provide the necessary rotational freedom.

Experimental results obtained with this system showed a marked improvement in accuracy. Errors due to internal friction within the mechanisms were reduced to negligible values. However, it was found that the initial calibration of the system was quite difficult due to a lack of axial rigidity within the neoprene washers used to align and cushion the swivel ball joint. Moreover, the maximum load capability of the system was limited by yielding of the conical pivot due to its extremely small contact area.

Spherical Segment Rocker Supports

The final loadcell support system concept that was evaluated during the development program is shown in Fig. 7. Using this concept, rotational freedom is provided by spherical segment rockers without sacrificing axial load capability. In addition, the difficulty encountered previously in calibrating the system due to the lack of axial rigidity was eliminated. In order to better provide the geometry envelope needed for the rocker segments, conical disc washer springs were used in lieu of the coiled compression springs.

TYPICAL FORCE PLATE DATA OUTPUTS

The data shown in Figs. 8 through 12 were obtained to illustrate the general capability of the Dynamic Force Plate system. Five walks with the right foot of one normal subject were recorded using the force plate system currently in operation at Shriners Hospital for Crippled Children, San Francisco. Since this force plate is connected directly on-line to an EPI-118 minicomputer, the data were recorded, processed, and machine-plotted automatically.

In Figs. 8 through 11, force and torque data obtained at a nominal cadence of 50 walk cycles per minute are presented as a function of percent of walk cycle (time). A walk cycle is defined as the period of time which elapses between consecutive heel strikes of a particular foot (in this case the right foot), and is, therefore, the reciprocal of cadence. As shown in the figures, the initial heel strike occurs at 0 percent of the walk cycle, toe off occurs (typically) at 62 percent, and the final heel strike occurs at 100 percent. Vertical force, fore-aft shear force, and medial-lateral shear force components are plotted in Figs. 8 through 10, respectively, in terms of the percent of body weight. Actual force values can be determined simply by multiplying the percent of body weight values by the actual body weight which [illegible] lb, for this particular subject. Torque values are [illegible] (in.-lb) in Fig. 11.

Inspection of the data presented in Figs. 8 through 11 reveals the remarkable repeatability of the force and torque components generated by the foot of a normal subject [illegible] the plate during successive walk cycles. Studies conducted [illegible] Shriners Hospital Gait Analysis Laboratory have shown that [illegible] are generally quite similar for different normal [illegible] gait characteristics can be distinguished by comparing [illegible] different subjects, and even by comparing those obtained for the left foot and for the right foot of a given subject. Moreover, significant deviations have been noted between normal average plots (i.e., composites of the data for a representative number of normal subjects) and the corresponding plots obtained for an abnormal subject. It is this capability to quickly and accurately distinguish and compare specific details of the normal and abnormal gait data, provided by the Dynamic Force Plate system, which illustrates its great value as a diagnostic and evaluative tool.

Another characteristic data output of the Dynamic Force Plate system is the center of pressure (CP)-time history. Fig. 12 shows CP-Time histories for the 5 normal-subject walk cycles discussed above. In this graph, the X and Y coordinate values refer to the position of the CP on the surface of the force plate with respect to a fixed reference point (X=0, Y=0) at one corner of the plate. Percent of walk cycle (time) values are shown in the circles for each walk cycle. Since the X and Y coordinates are computed from measured vertical force values, and since (by definition) the vertical force values are zero at 0 and 62 percent of the walk cycle, the CP-Time histories shown range from approximately 1 to approximately 59 percent of the walk cycle.

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CONCLUDING REMARKS

The application of aerospace instrumentation technology to the measurement of body forces imposed on a walk-way during normal or abnormal gait has resulted in the development of a unique medical research apparatus. Using the spherical segment rocker support mechanism concept developed during the program, the accuracy and repeatability of the data obtained are significantly enhanced. Similar force plate designs can be developed and used to obtain reliable gait data for other human or animal studies where force measurement capabilities of up to 17.8 kN (4000 lbf) are required.

REFERENCES

1. Sutherland, David H., M.D., and Hagy, John L.: Measurement of Gait Movements from Motion Picture Film. The Journal of Bone and Joint Surgery, Vol. 54-A, No. 4, pp. 787-797, June, 1972.

2. Computer Applications; Medical Electronics and Equipment News, August, 1973.

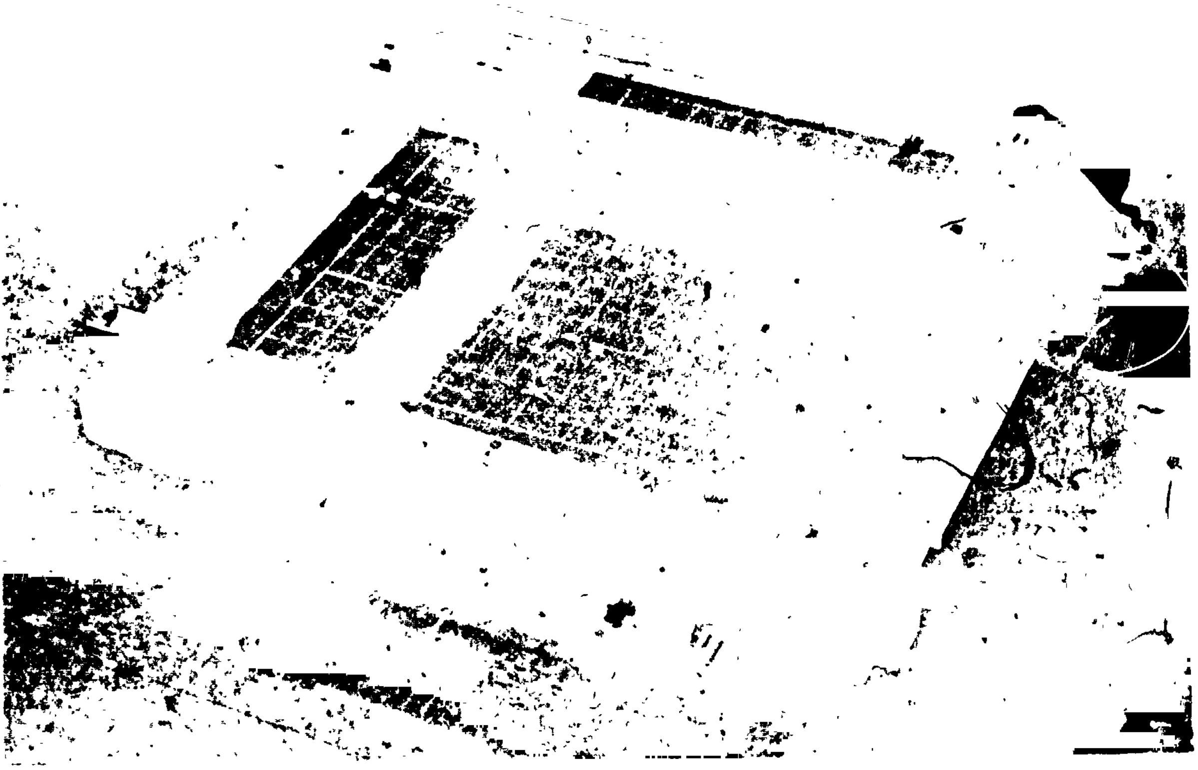

Figure 1. A Dynamic Force Plate Assembly

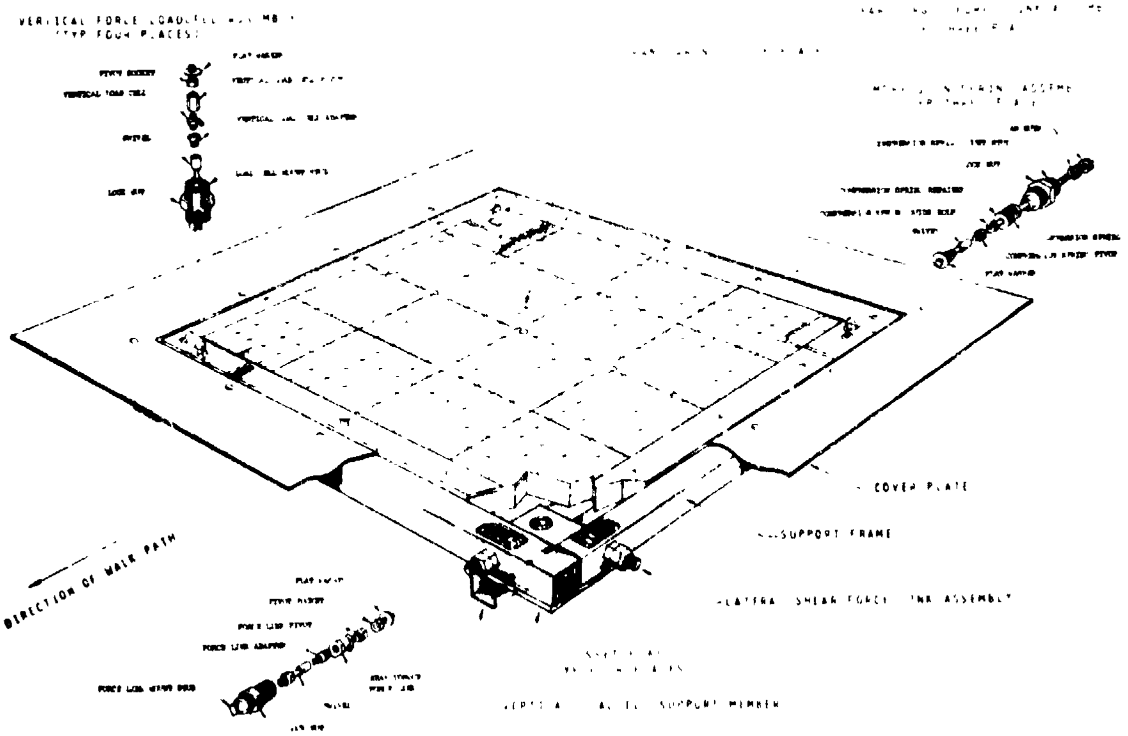

Figure 2. Cut-Away Perspective Drawing of the Dynamic Force Plate

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Figure 3. View of the Footprint Pressure Pattern

Figure 4. Closeup View of the Loadcell Support **Installation**

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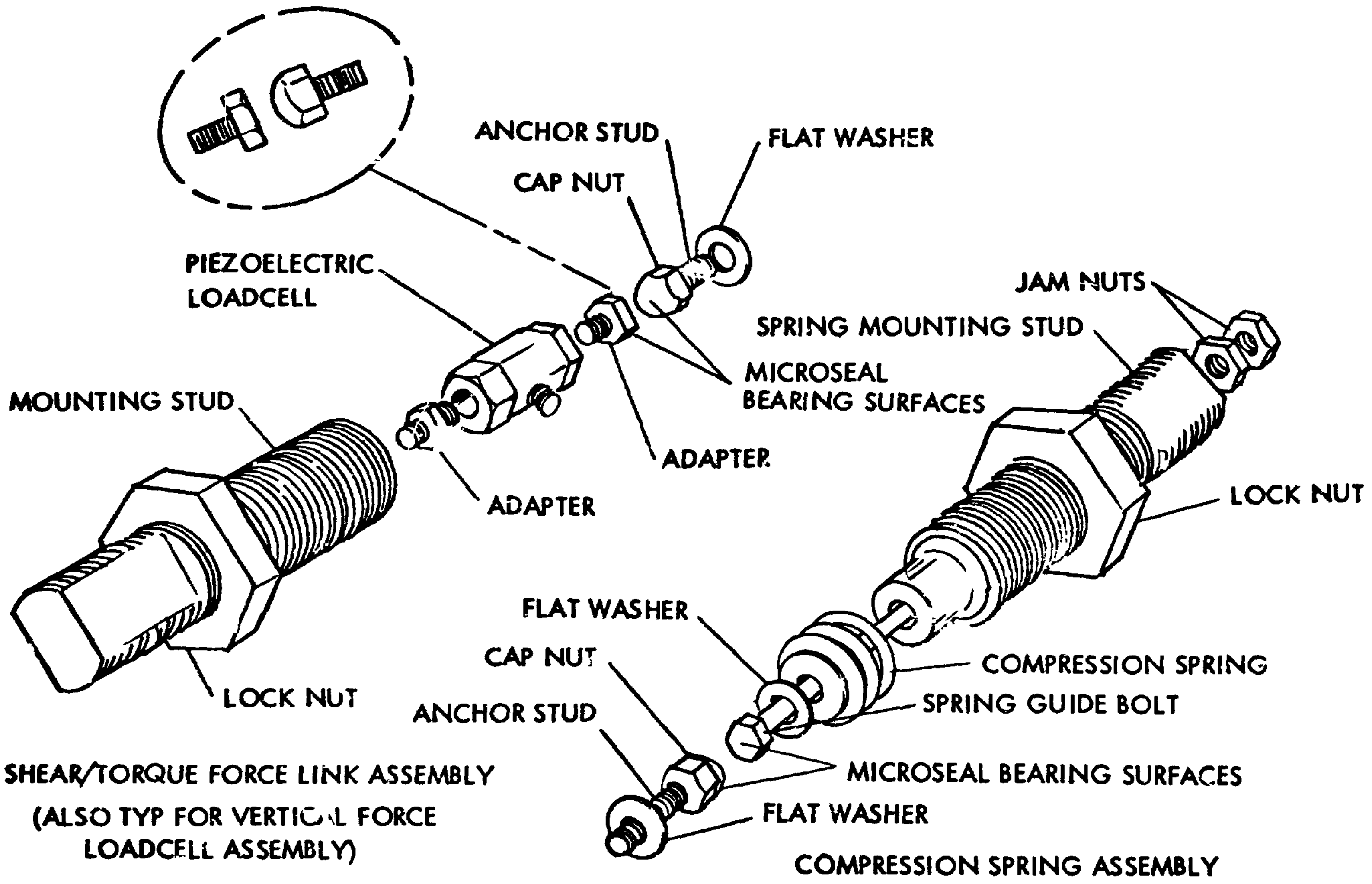

Figure 5. Details of the Sliding Friction Support Concept

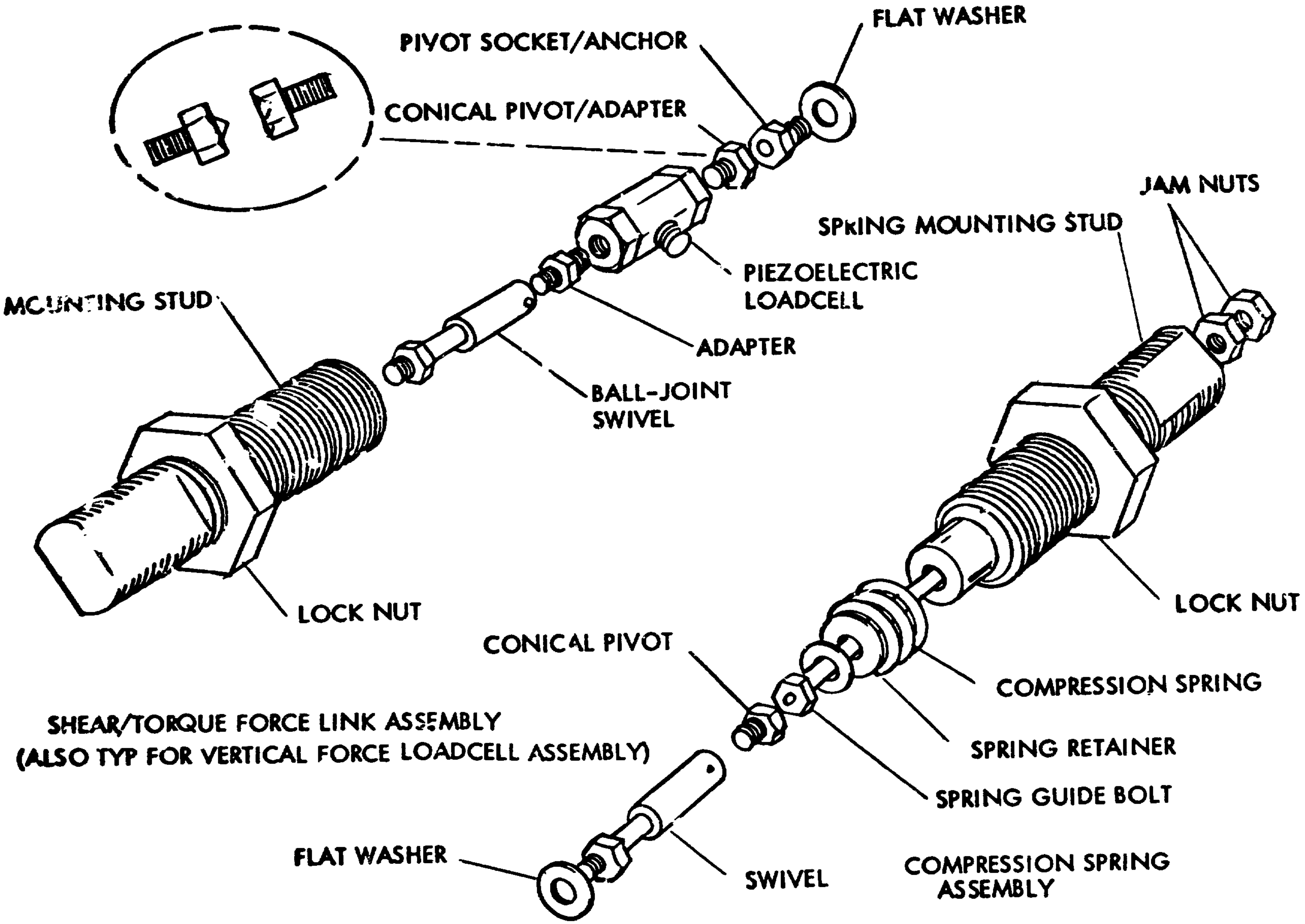

Figure 6. Details of the Ball-Joint/Conical Pivot Support Concept

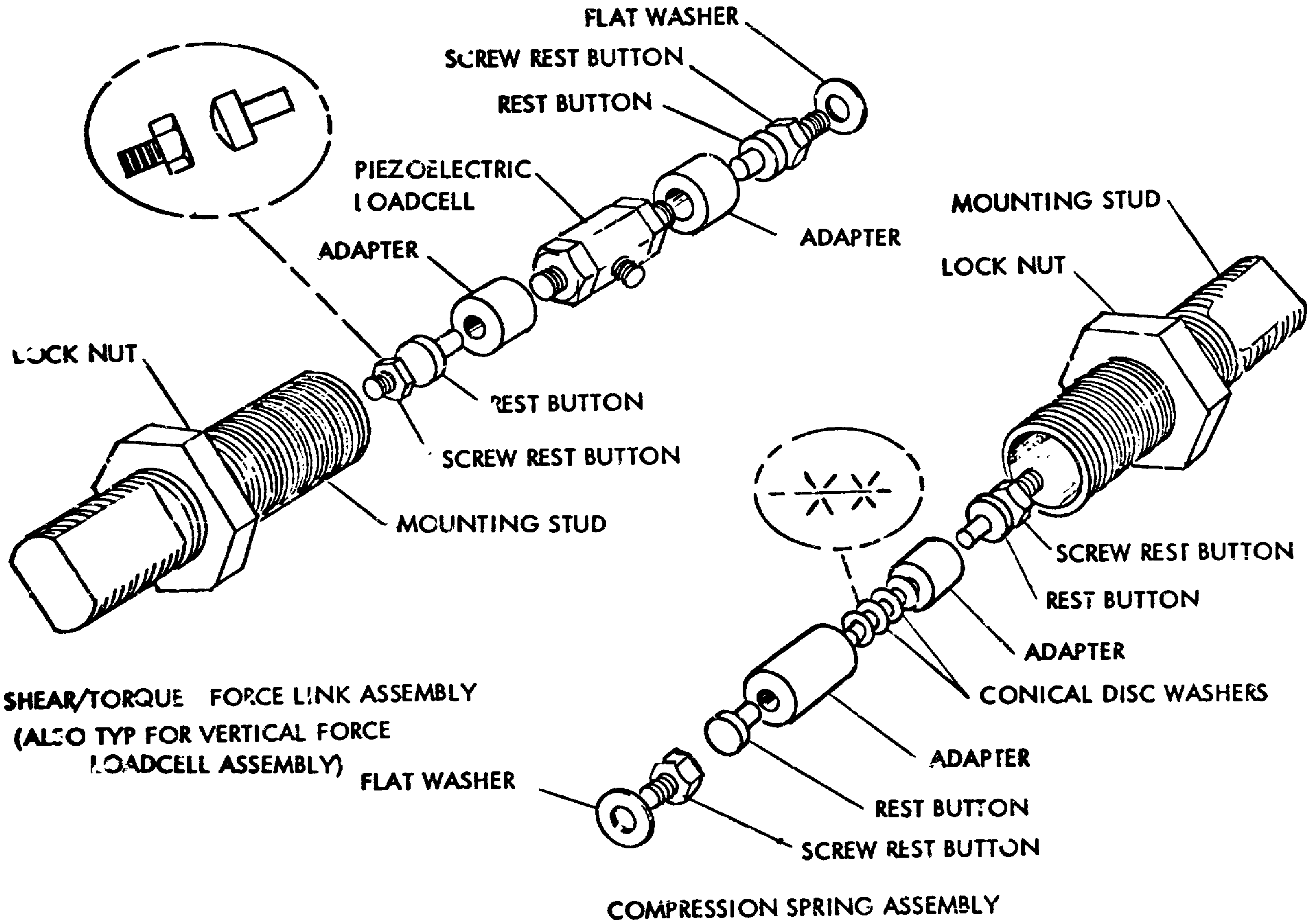

Figure 7. Details of the Spherical Segment Rocker Support Concept

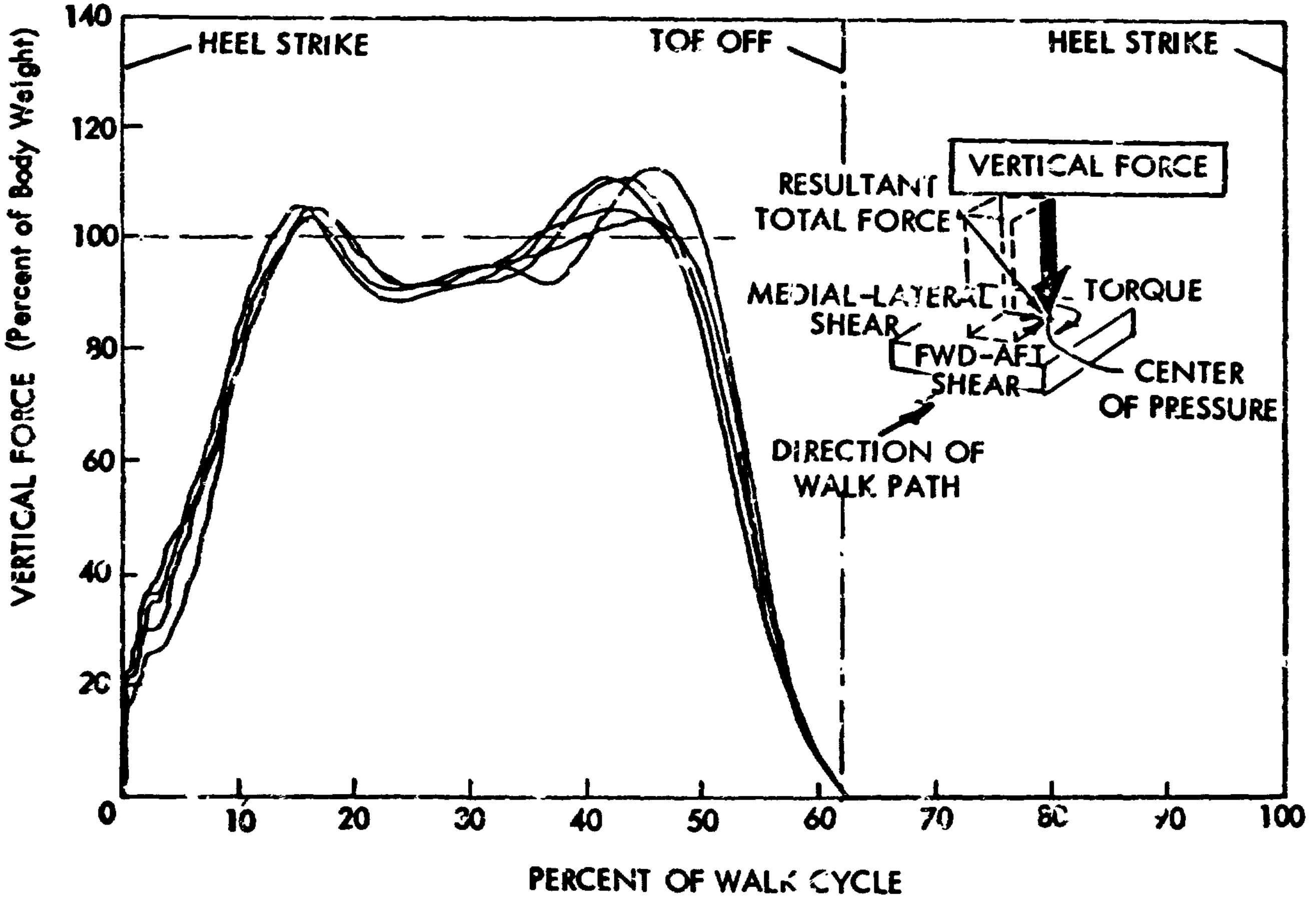

Figure 8. Variation of Vertical Force With Percent of Walk Cycle

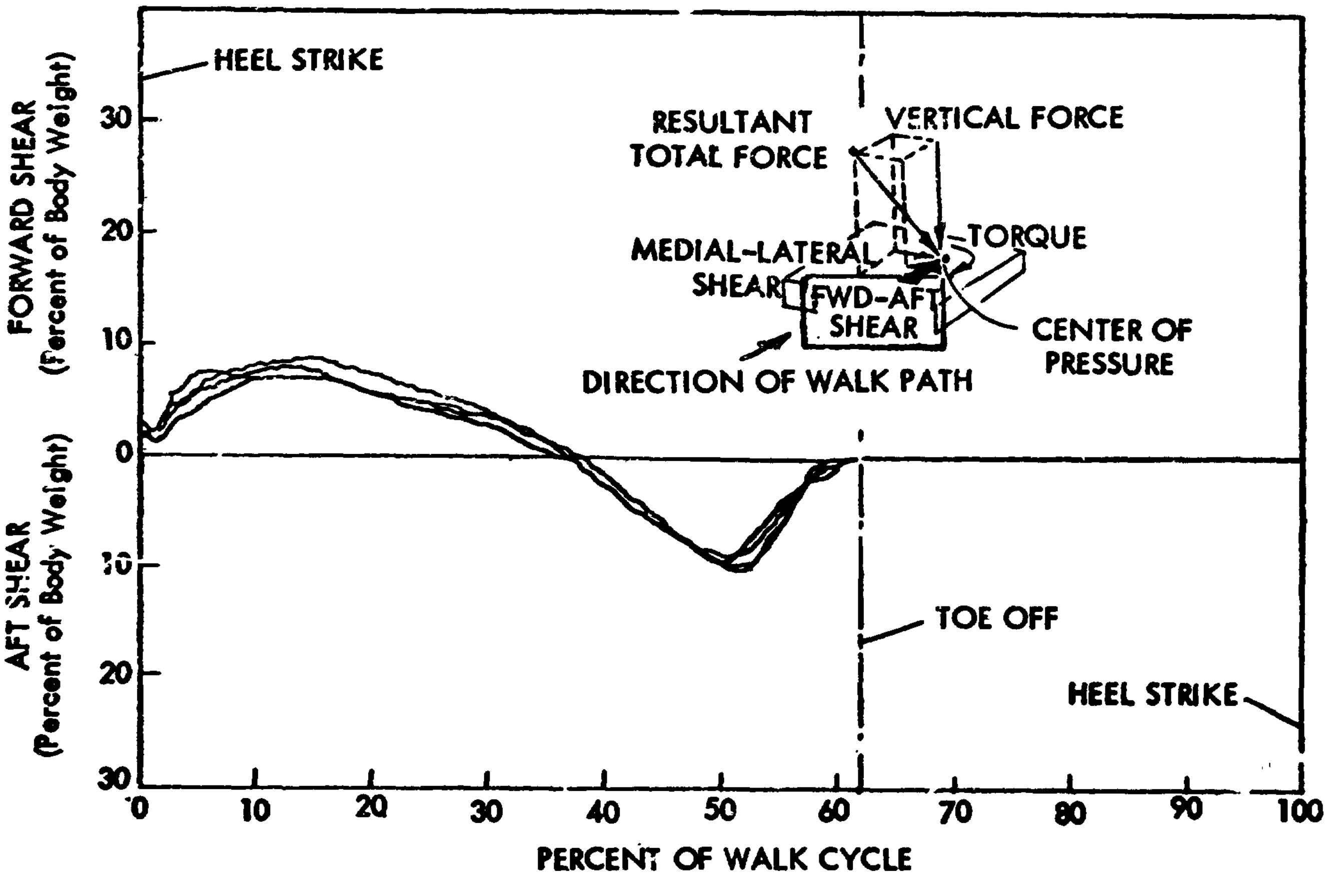

Figure 9. Variation of Forward-Aft Shear With Percent of Walk Cycle

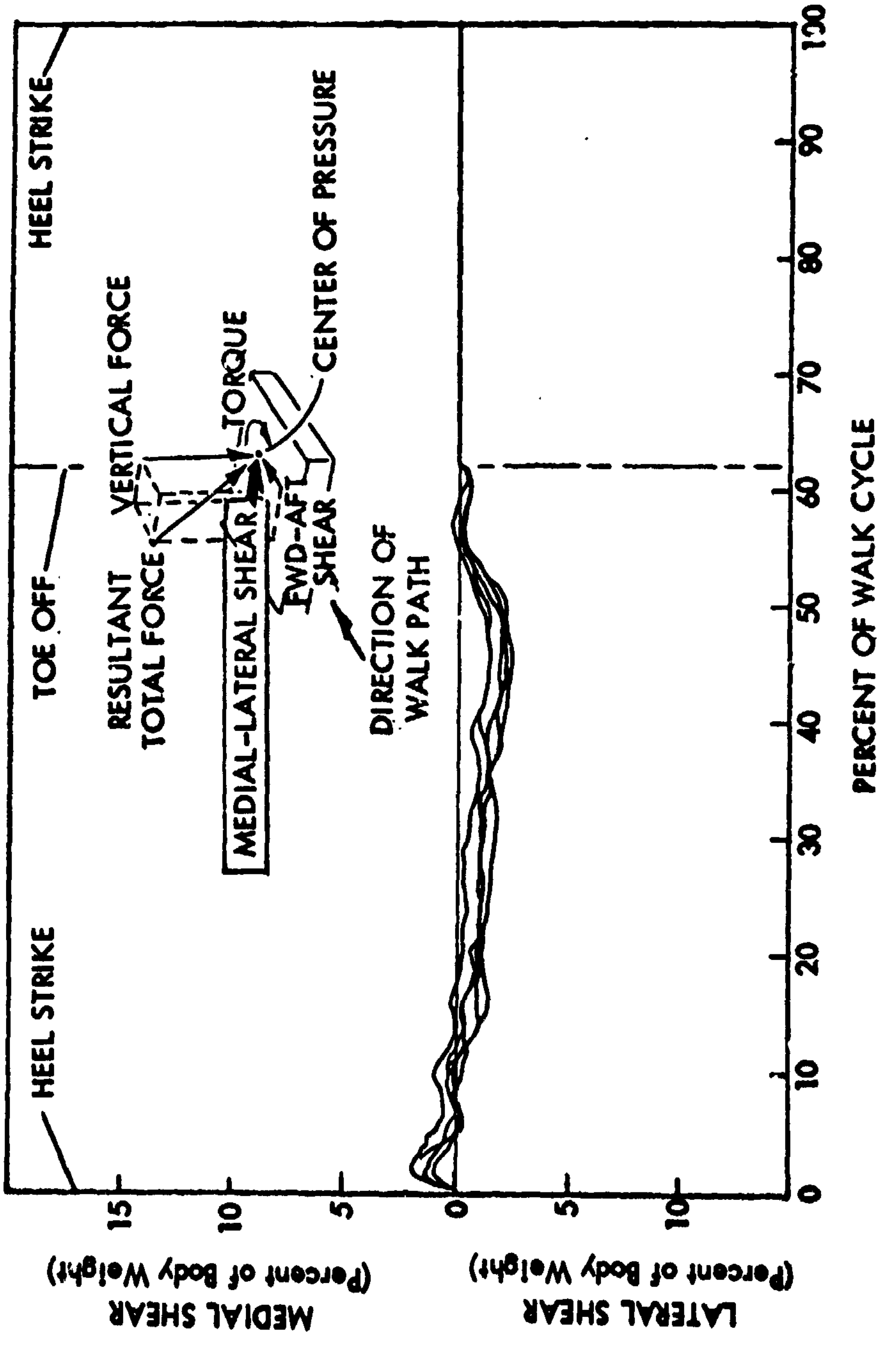

Figure 10. Variation of Medial-Lateral Shear With Percent of Walk Cycle

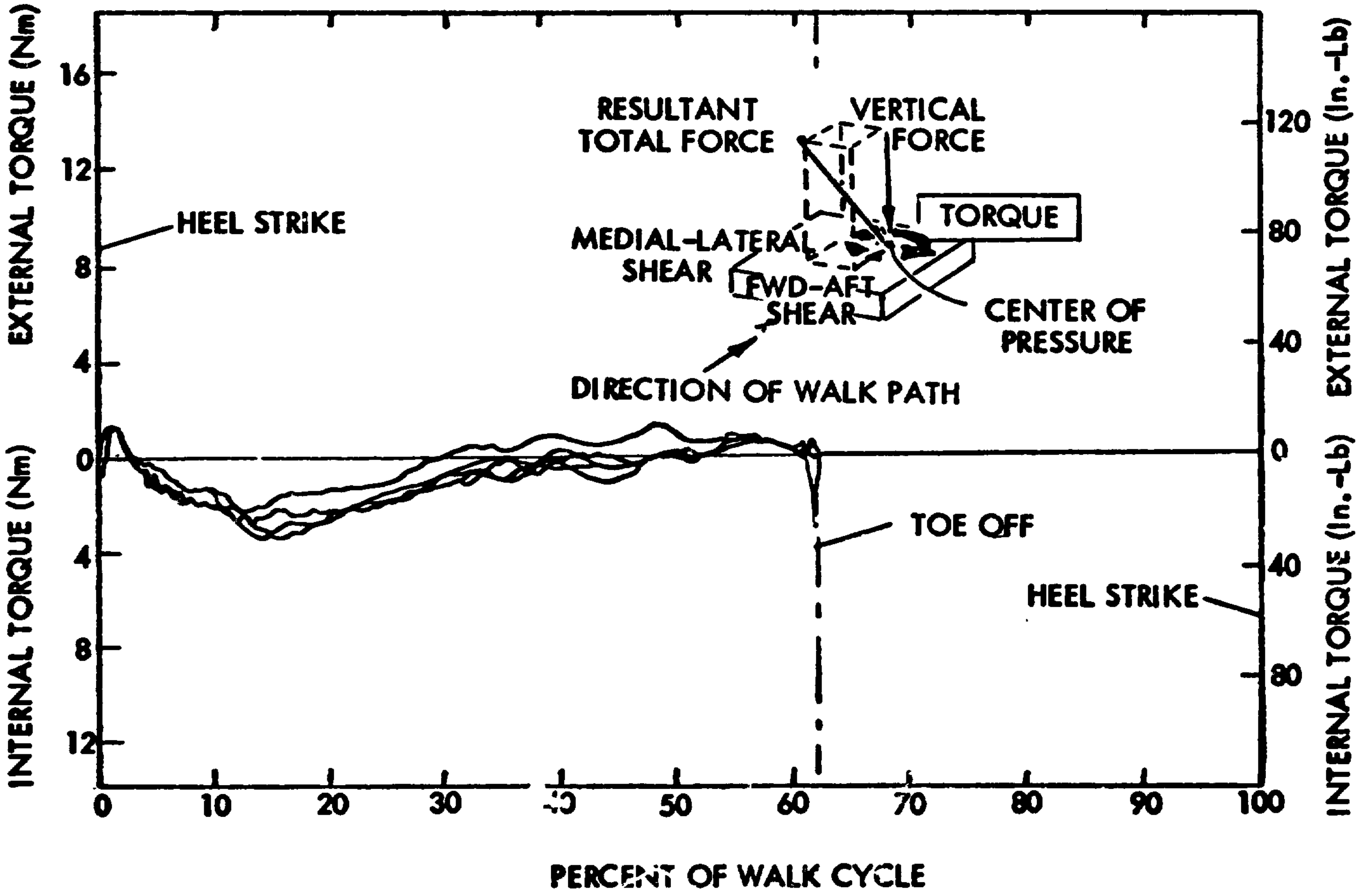

Figure 11. Variation of Torque With Percent of Walk Cycle

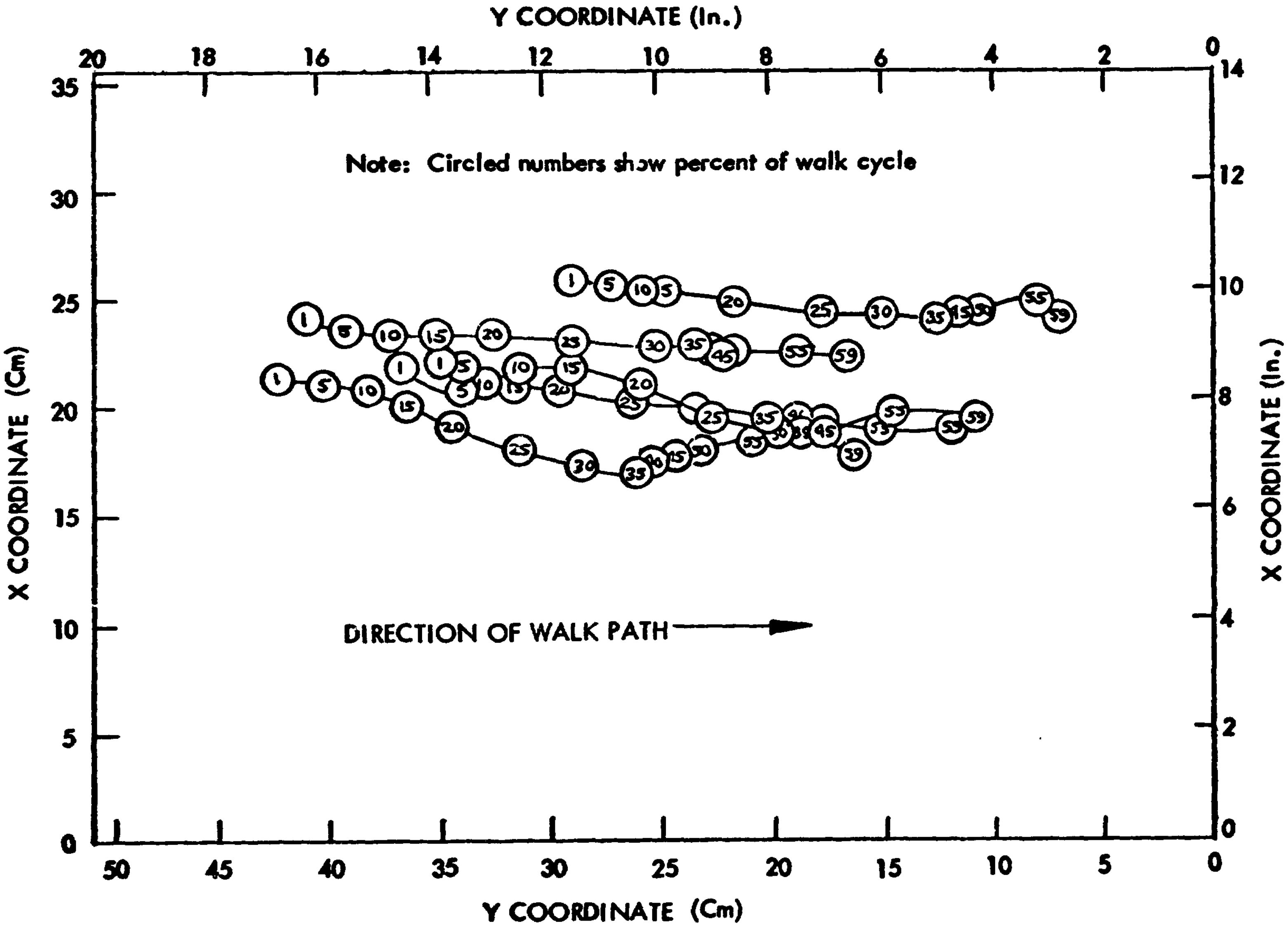

Figure 12. Center of Pressure - Time History