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A Method of Isolating Treadmill Shock and Vibration on Spacecraft

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A major problem is currently felt to exist in the implementation of materials processing on a spacecraft. Crystal growers and others have placed requirements of one micro-g or less on the vehicle. Simple math produces startling figures for such a restriction e.g., for each ton of vehicle mass with 10^{-6} g acceleration limit; Perturbing Force limit, F = .002 lb. For each 10^5 lbs F = 0.1 lb. For each 10^6 lbs F = 1.0 lb.

Forces generated by normal human movement on spacecraft of 5×10^5 pounds weight are on an order-of-magnitude greater than allowed by this specification and forces generated by locomotion on a treadmill are more than two orders-of-magnitude greater. Other exercises and normal onboard functions generate forces in between. See figure 1. To accommodate many essential functions it is obvious that even on a vehicle as large as Space Station, a reduction of more than two orders of magnitude in force is required. Commonly used passive shock and vibration isolation devices cannot meet such demands. Active isolation devices are complex, heavy and also would have difficulty meeting the requirements. However, by a new arrangement, adequate isolation can be obtained. Isolation of the treadmill will be treated here since it is considered the most significant disturbance at this time. There are many other mechanical events not treated here which must also be considered.

Treadmill shock and vibration characteristics

Forces generated by human locomotion, walking, jogging, running, and jumping, have been studied since the last century and are well known and reasonably constant between individuals and circumstances (1-6).

Biodynamics of locomotion

In walking on Earth, one foot is always in contact with the ground, but force is cyclically shifted from foot to foot. The movement of each foot is a *step* and a step by each foot completes a cycle or *stride* (7). In both walking and running step rate and stride increase with velocity (figure 2). In walking, magnitude of the vertical *foot ground forces* (FGF) vary about the individual's body weight (BW) as the center of mass is raised and lowered by acceleration/deceleration from muscle forces, producing the typical biphasic pattern for one foot shown in figure 3. Since ground contact of the steps overlap, a composite FGF pattern is produced as in figure 4. In jogging, running, and jumping the body is actually thrown clear of ground contact and as would be expected there is a sharp increase in vertical forces (figures 3 and 5). For walking, the basic vertical foot ground force patterns are cyclic, relatively complex waveforms which vary from approximately 1 to 1.5 BW with frequency variations from $<$1. to, say, 2.5 Hz. Jogging/running produces a series of zero based pulses which approximate a half sine waveform with amplitudes from 1.5 to 3.0 + BW and frequencies from 1 to 4 Hz and periods of $\sim$500 to $<$100 msec.

There are some individual variations including assymetries between right and left legs which can reach 25% difference. See figure 5. Chief of the individual variations are 'heel' and 'forefoot' runners with the heel runners producing a brief spike on each step (figure 6). Horizontal forces are much less with a typical example of fore aft forces shown in figure 7. These forces increase with increasing velocities. Lateral forces are smaller still as shown in figure 8. Again, note that the period of ground contact and step frequency are a function of speed. Figure 9 is a comparison of FGF in 3 axes at a slow walk and fast run.

There are *no* significant differences between ordinary FGF and those from treadmill locomotion in one-g.

Treadmill in weightlessness

The basic scheme of a treadmill for weightlessness is shown in figure 10 with the major difference from Earth treadmills being a force system which replaces gravity. While FGF have never been measured in weightlessness there is little reason to expect major waveform differences at one-g equivalent force levels. Conversely, there will be a difference of 1 BW constant force[2] transmitted to the spacecraft since the subject weight equivalent force system is attached to the treadmill frame and only inertial forces will be transmitted to ship's structure, e.g., the typical waveforms and amplitudes shown in figures 4 and 5 will have 1 BW as their zero reference.

[1]Only crew related activities are addressed here.

[2]This assumes that there is no change in bungee force with their slight extension on each step.

In summary, then, inflight treadmill locomotion will produce cyclic and pulsatile forces ranging from a fraction of BW to possibly three BW in the Z axis with lesser forces in other axes. The major, or Z axis force during jogging/running will be an almost half sinusoidal pulse with a base width of <0.1 to ~ 0.5 sec at a frequency of ~ 1 to 4 Hz.

Isolation means

Passive

A wide variety of shock and vibration isolation systems using springs and mechanical resistance are available. They all function in a manner equivalent to either a resonant circuit, whose frequency is below that of the vibration, or else as a low pass filter. In either case, a compliant connection is involved (figure 11); and in the case of the treadmill this would allow excessive motion without a counterpoise mass since the treadmill weighs less than 100 pounds and would undergo excessively large excursions under the force of walking and especially running. However, even adding counterpoise mass to the TM will not solve the problem with passive shock mounting for the force attenuation will still be inadequate to meet the requirements.

Active attenuation

A relatively recent development is the use of forces and displacements to offset those of shock and vibration. A single-axis schematic is shown in figure 12 for such a system. $\mathbf{M_1}$ is the mass to be stabilized, and is also the support mass. $\mathbf{G_1}$ is the disturbing force generator, and $\mathbf{M_2}$ the unbalanced mass driven by $\mathbf{G_1}$. Any accelerated motion along $\pm$X axis will transmit a force $\mathbf{F_1}$ to the mounting of $\mathbf{M_1}$, which also contains a sensitive force transducer $\mathbf{T_r}$ (alternatively, the mounting could be compliant and an accelerometer mounted on $\mathbf{M_1}$).

Any force sensed would generate an (almost) equal and opposite force $\mathbf{F_2}$ in $\mathbf{G_2}$, $\mathbf{M_3}$. The mass $\mathbf{M_3}$ could be smaller than $\mathbf{M_2}$ but larger accelerations and resulting displacements would be required.

While practical in many situations, in this case, six degrees of freedom would require compensation; the forces/displacements are large and compensating forces would consume large amounts of power. To achieve good compensation in such a system, extreme care would also have to be taken in amplifier and generator characteristics and even then compensation would never be perfect.

Proposed Solution

A practical alternative is shown for one axis in figure 13. Mass $\mathbf{M_2}$ is made large enough to be an effective counterpoise to $\mathbf{M_1}$, the moving mass (TM). This allows the subject to run on the TM and produce acceptably small oscillations of it.

In practical terms, this mass would not simply be ballast but relatively fixed portions of the vehicle (not primary structure) such as storage lockers, etc., which will provide the mass for free. This mass will be calculated to limit TM movement to say, a few tenths of an inch. The combined TM and counterpoise mass will be floated in the vehicle and provides an acceptable, totally isolated system; however, air currents and other small pertubations will cause it to ultimately drift into contact with structure. To avoid this, small appropriate counter forces must be applied. There are many ways to do this, ranging from non-contact sensors controlling airjets to magnetic or other fields. The simplest is a combined sensor/force generator (SFG) attached to a filament. In the example shown, two such SFGs ($G/S_{1,2}$) are used. They operate as follows. A small drift may be detected and a force $\mathbf{F_1}$ or $\mathbf{F_2}$ will be developed to offset it. This force will have two characteristics: it is constant regardless of short-term displacements of $\mathbf{M_2}$, and it is limited such that it can never exceed the allowable spacecraft shock and vibration g limits.

There are several simple approaches to such an arrangement, and two are shown in figures 14 and 15. Both methods use a filament and a reel which contains an optical position encoder to detect drift. When a drift[1] is detected by the **OE** (which could be analog instead of digital as shown) it will cause an increase in DC motor current **I** which produces a torque increase by the motor and reel and an applied force **F** in a direction to correct the drift and restore the mass to its usual neutral position. The small forces required are compatible with small available DC motors. An alternative is shown in figure 15 in which a small brushless AC motor runs continuously, and after torque multiplication by a gear train, is coupled to the reel and filament through a variable torque clutch. In the same way as above, errors in position produce changes in DC current to the clutch and corrective increases in torque and force **F**. The error detector/current generator will contain frequency selective components such that only slow drifts are responded to and short term position changes or oscillations ignored. If desired or necessary error rate damping may be incorporated. If multiple units are interconnected as below it may be desirable to coordinate their outputs through the computers shown. An alternative is shown in figure 15 where a small motor runs continuously and varying amounts of torque are applied through an electromagnetic clutch which transmits torque in proportion to the input current.

A member of these active tethers will be required to maintain position and the number and arrangement will be a function of the designer's ingenuity. My own minimum

[1]Drift is defined as a contained displacement of the mean distance X. Short term cyclic variations will be ignored by the system.

scheme, to date, which requires four and eight, would probably be more reasonable.

A conceptual arrangement of this system is shown in figures 16 and 17. In figure 16, the treadmill is attached to storage containers to provide adequate counterpoise mass. For launch or other activities, links will connect this assembly to secondary structure and during use these links may be easily removable. In figure 17, the subject is shown running on such a TM. Incidentally, such a unit can be self-powered through a battery and generator driven by the TM. In any event, power required will be a few watts.

Implementation

There are several approaches to solution of this problem. One could vigorously analyze all aspects of it, study in-flight TM forces, etc., and then try to extend the capabilities of existing resources, time and money.

A more efficient alternative is to mock up the proposed system in one axis on Earth using an air bearing. Next, a three-dimensional scale mock-up could (and should) be flown on the Orbiter. It is possible to do a full scale mock-up on Spacelab.

This effort could be started immediately with development of a key item, the dynamic tether, for a few thousand dollars. A brief review of hardware available shows that suitable components are readily available.

This technique may also be applicable to other problems which have not been considered here.

A patent application is in progress and details may be obtained from JSC Patent Counsel. The author will be happy to provide any additional details as desired and to continue to provide detailed recording of foot ground forces from a variety of locomotor activities and provide other sources for additional data.

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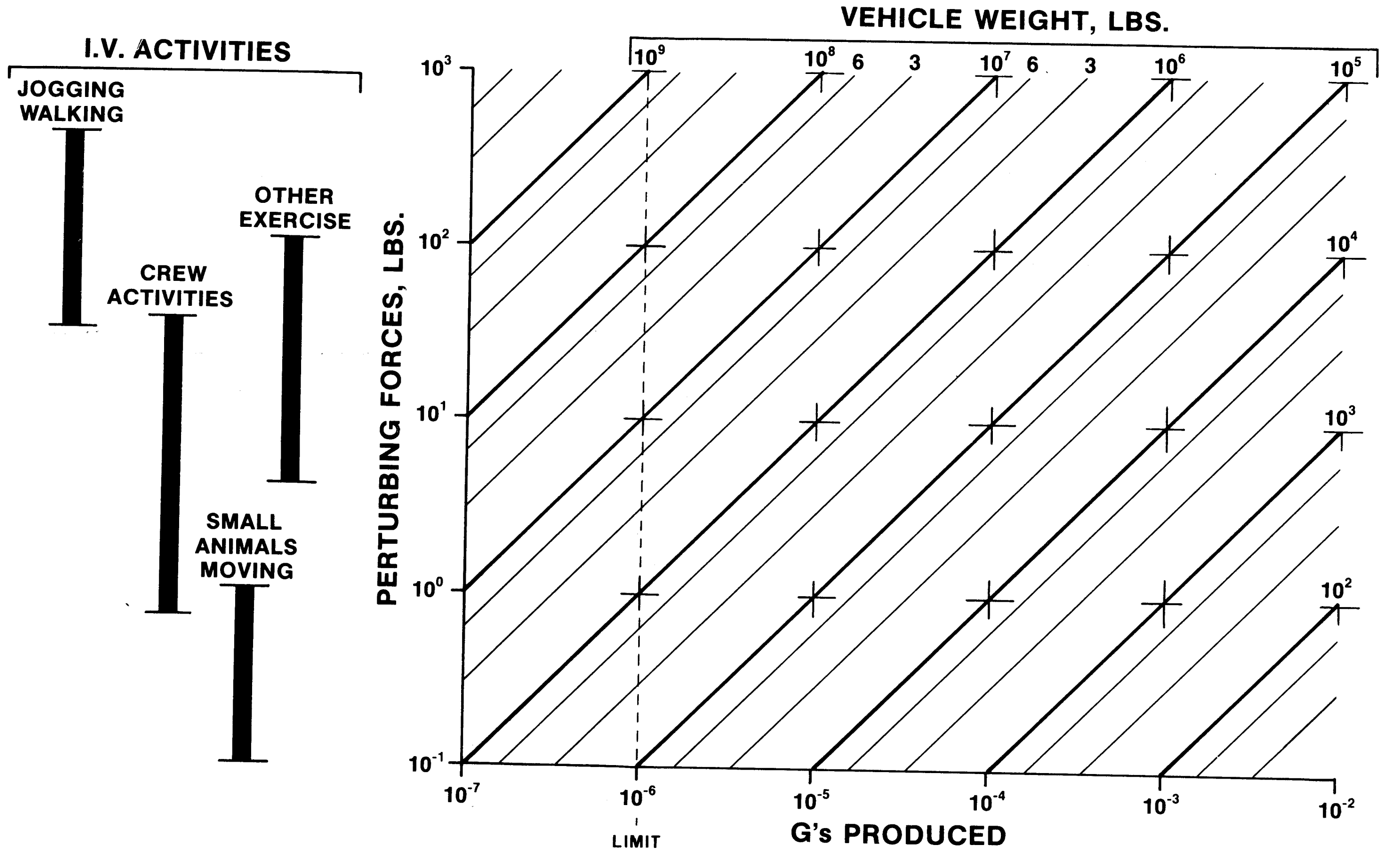

Figure 1.- Plot of relation between peak shock and vibration and disturbance produced for various vehicle weights. A single axis force on a solid mass was assumed. Values shown are typical for various activities.

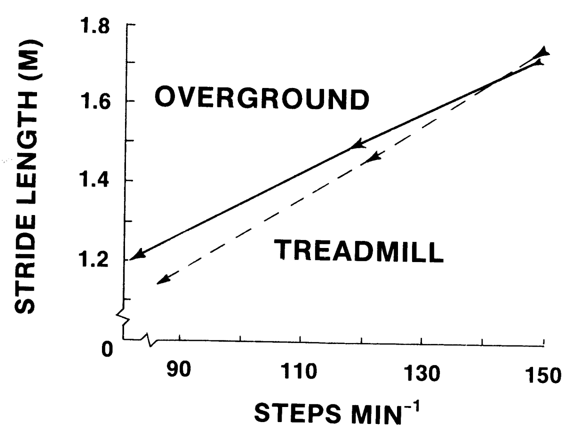

Figure 2.- Average variation of stride and step rate. Velocity is product of steps per min X stride length. The slight difference is found between ground and T.M. locomotion. From Taves, et al.

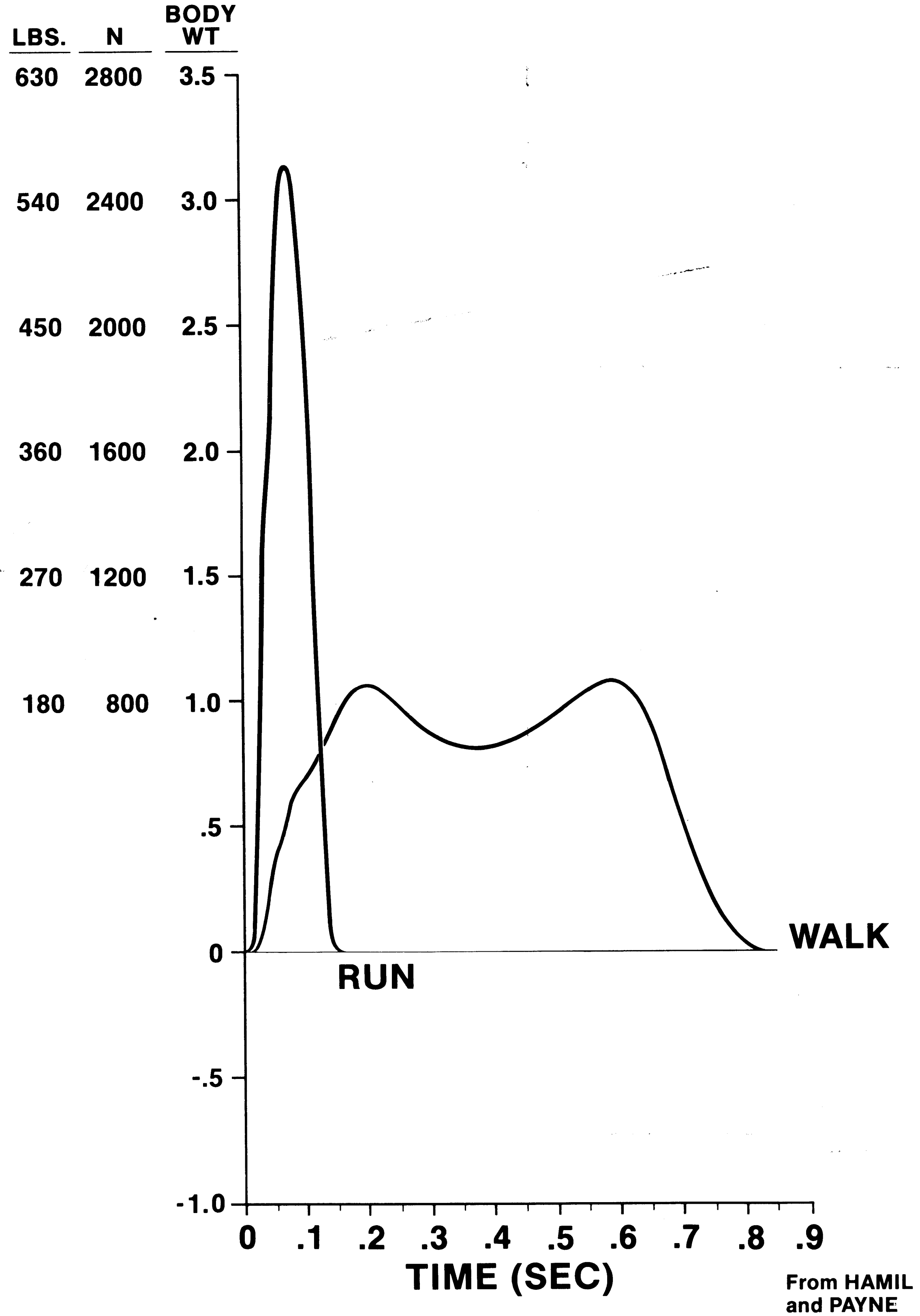

Figure 3.- Vertical foot-ground forces from one foot illustrating range from slow walk to rapid running. The waveforms of walking and running are each characteristic but change period and amplitude with velocity.

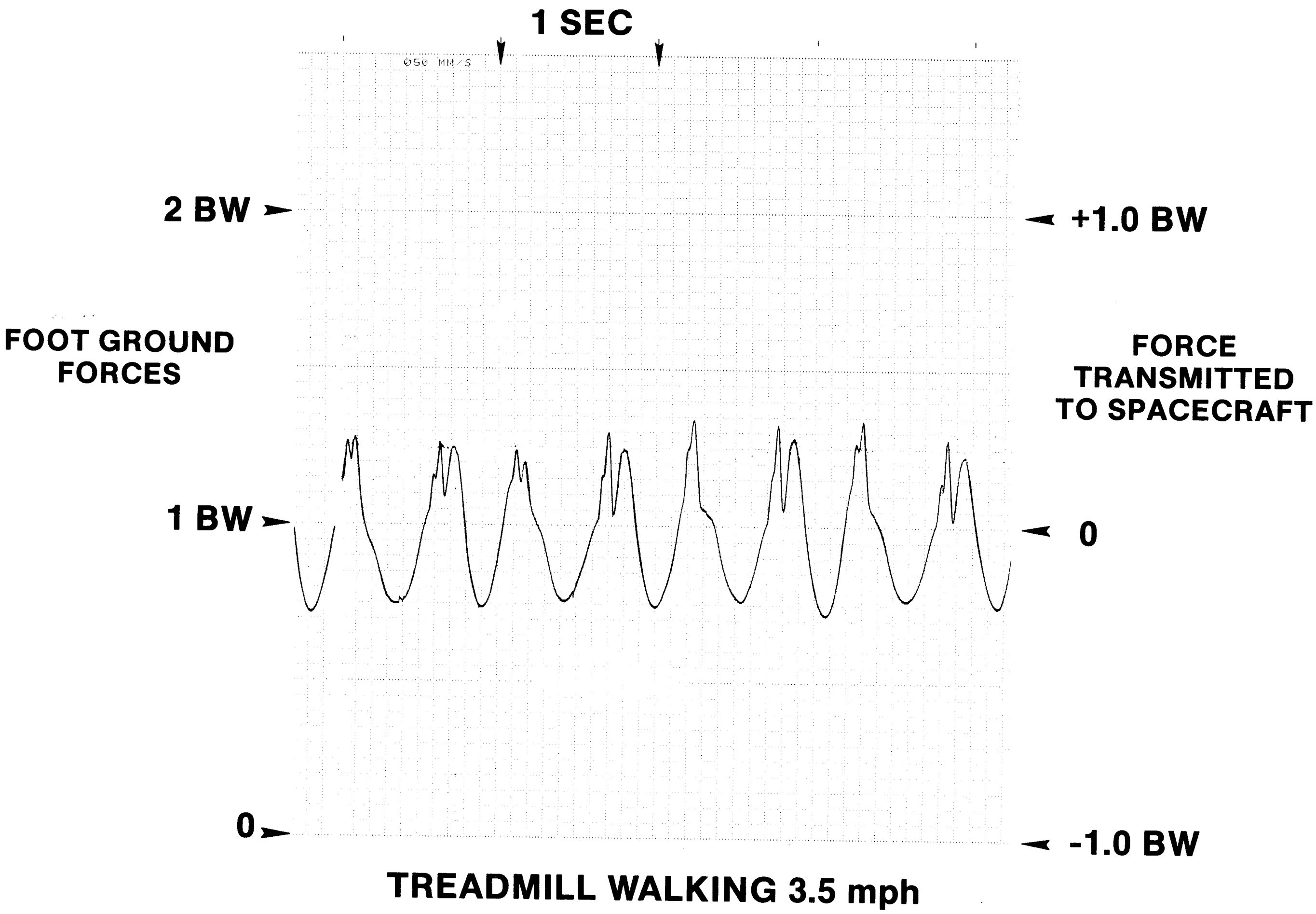

Figure 4.- Vertical foot-ground forces while walking at 3.5 mph. Overlap of foot ground contact produces the complex waveform. In weightlessness, with the treadmill arrangement shown in figure 10, forces transmitted to the spacecraft are given by the scale on the right.

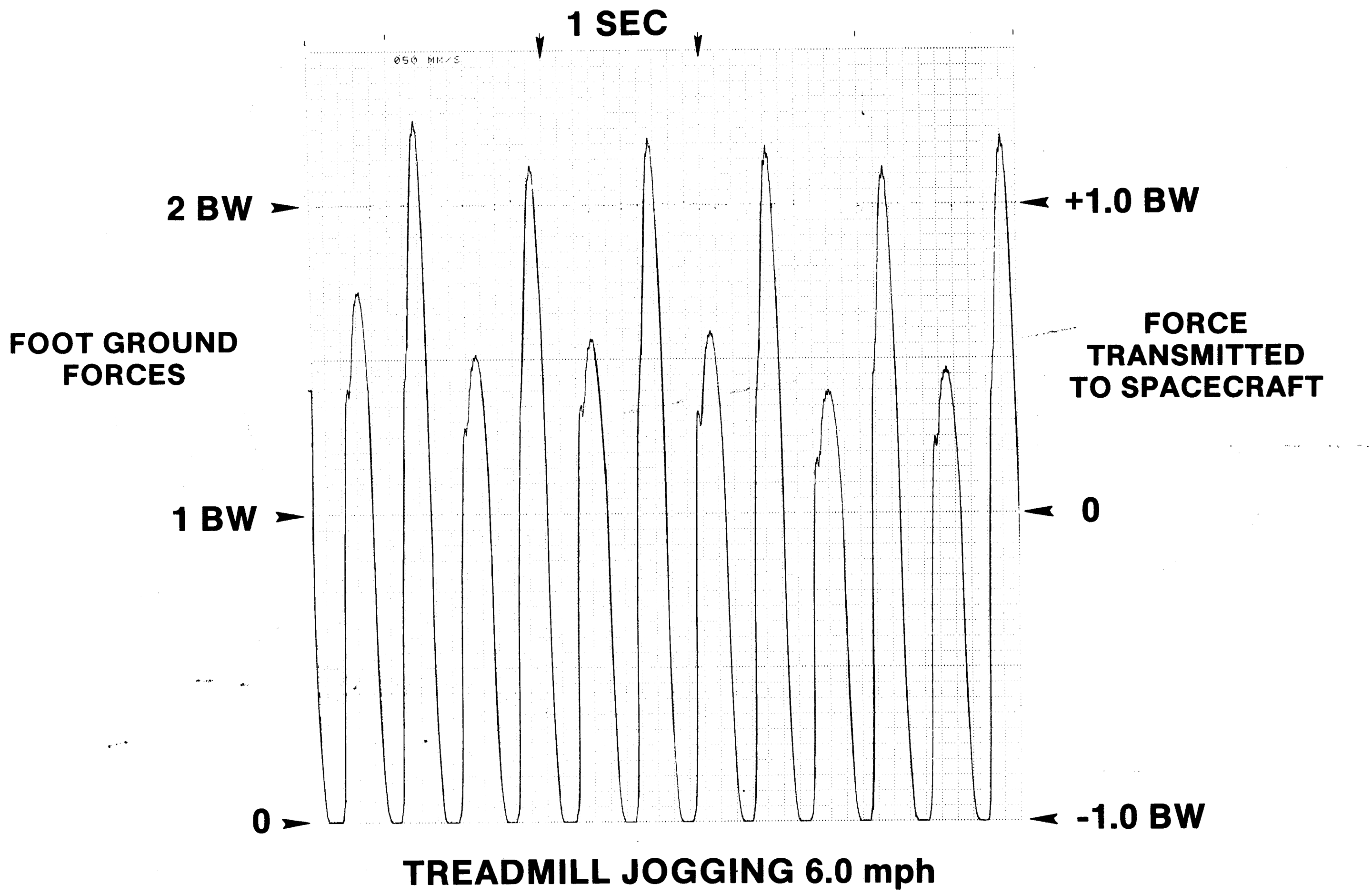

Figure 5.- Vertical foot-ground forces from jogging at 6 mph. Period of zero force occurs when both feet are clear of the ground. Note marked asymmetry between right and left legs. In weightlessness, using the treadmill in figure 10, the forces transmitted to the spacecraft correspond to the scale shown on the right.

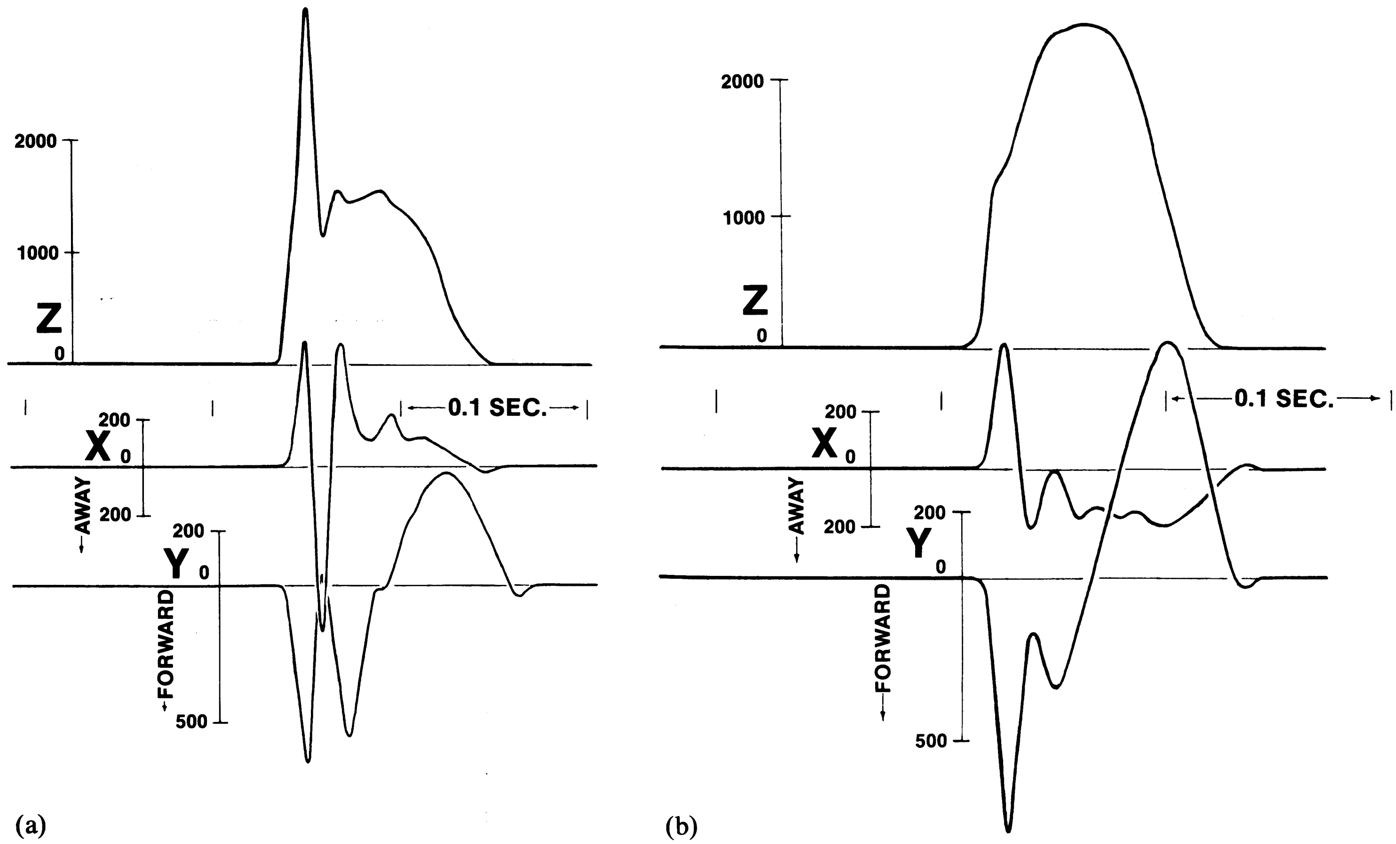

Figure 6.- Comparison of vertical foot-ground forces from 'heel', (a), and 'forefoot', (b), runners. Force scales are different for each axis.

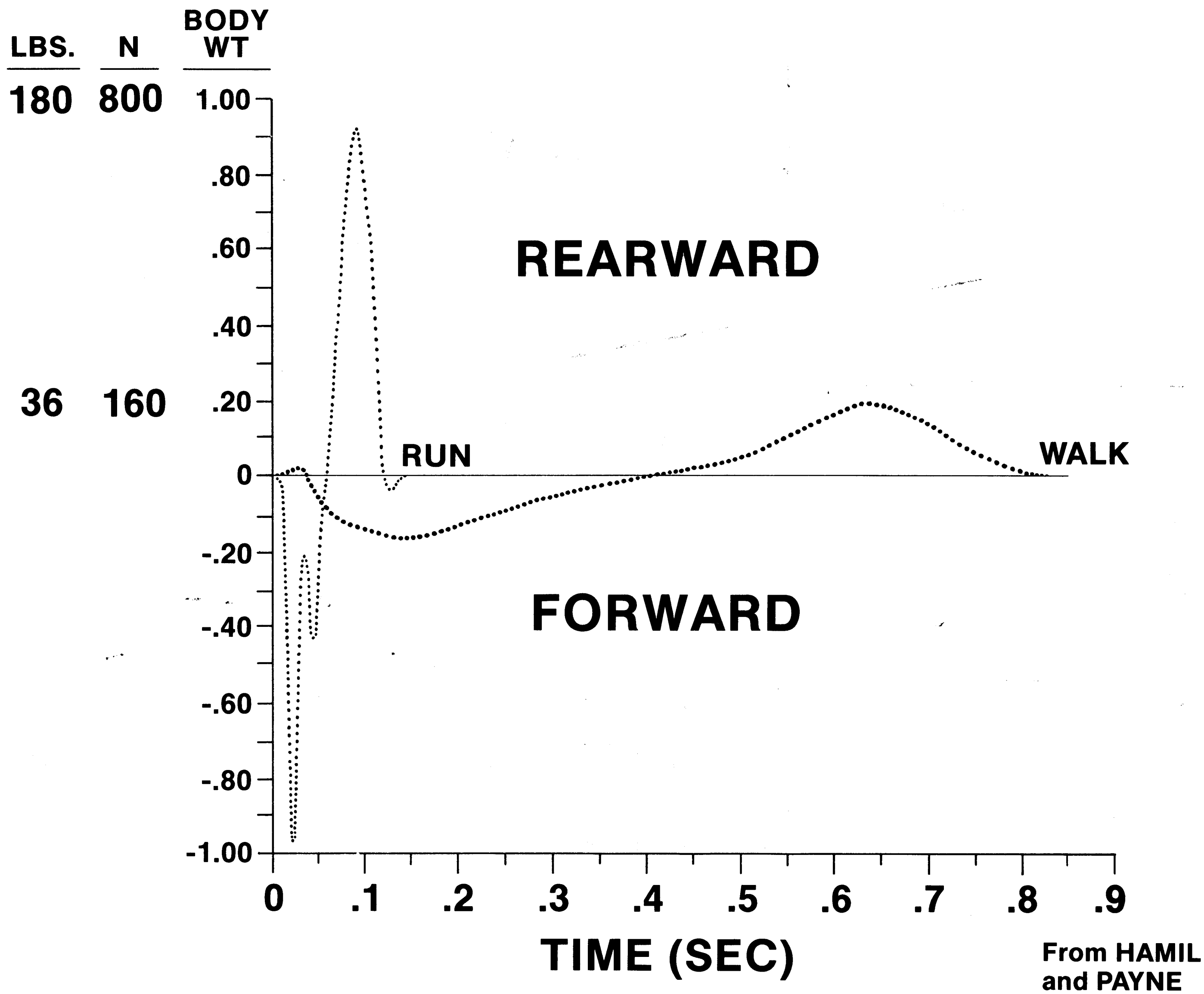

Figure 7.- Fore-aft horizontal, foot-ground forces in walking and running. During steady state conditions, the integral of these forces will be zero, except for wind and other resistance losses.

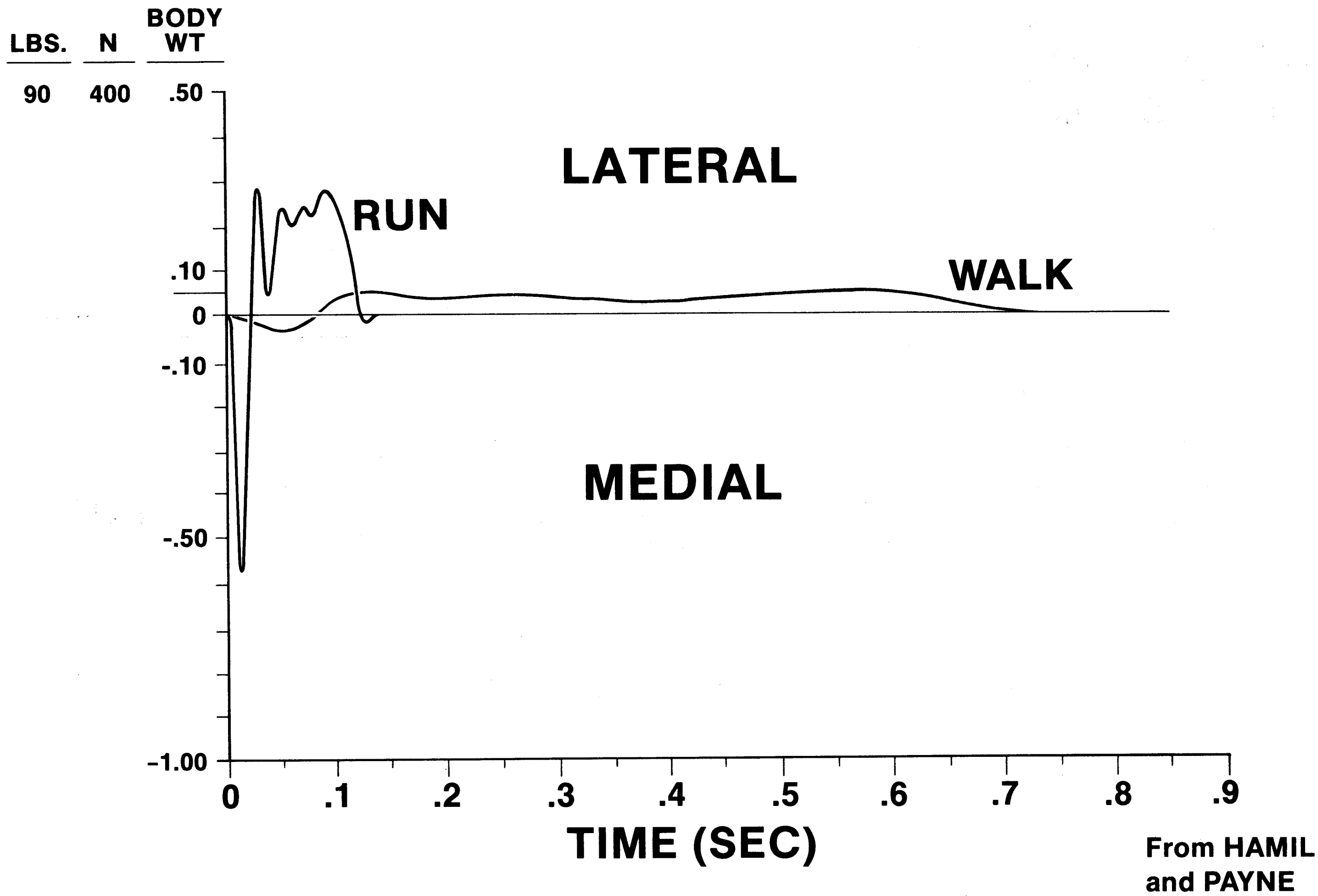

Figure 8.- Lateral horizontal foot-ground forces in walking and running. Note change from a slow walk to a rapid run.

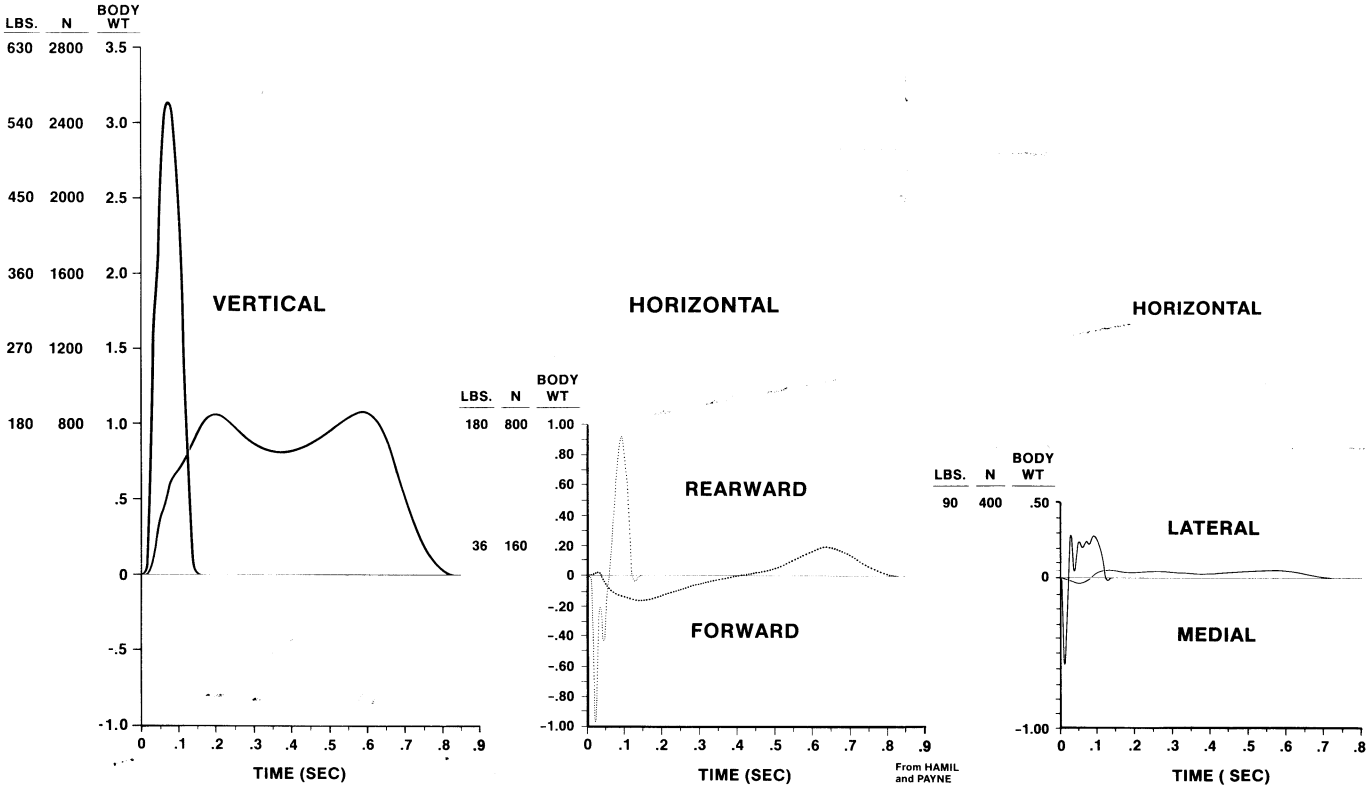

Figure 9.- Horizontal, lateral, foot-ground forces in walking and running plotted to a common scale. This was simultaneous measurement shown individually in figures 3, 7, and 8.

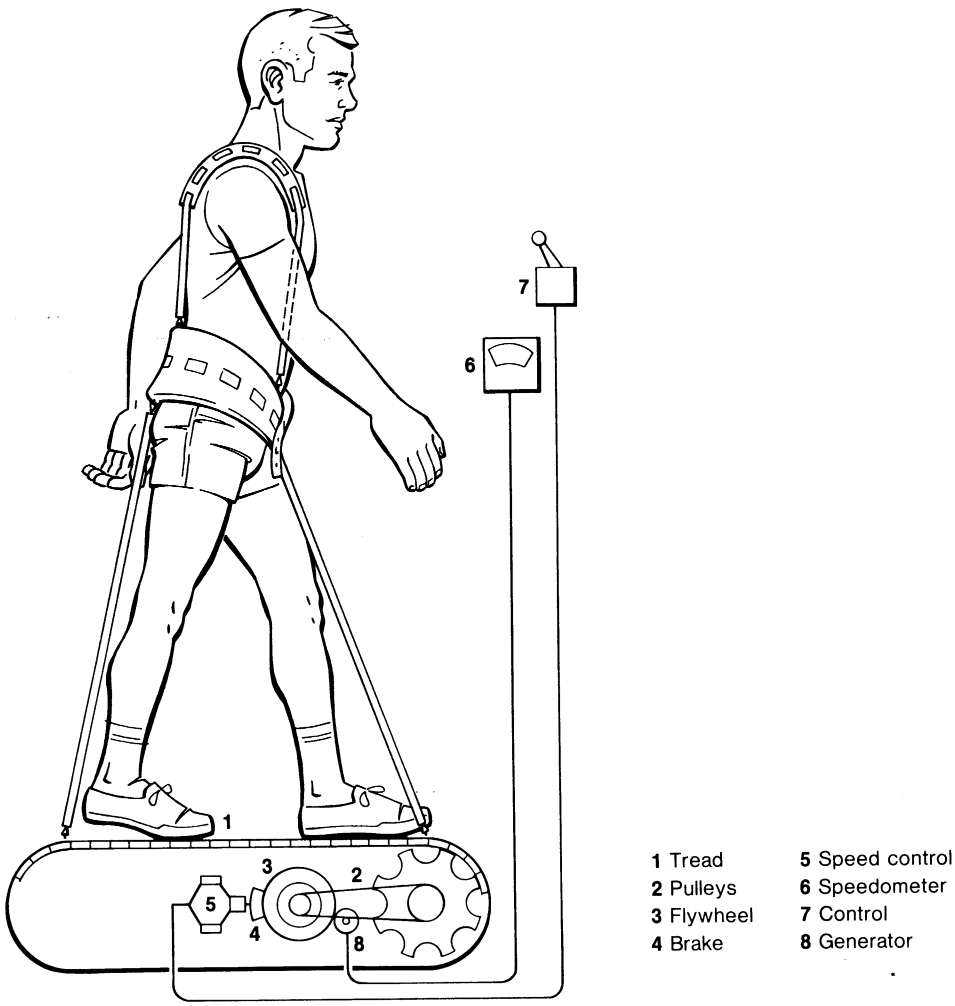

Figure 10.- Diagram of a passive treadmill for space flight. Bungees and harness replace weight on Earth.

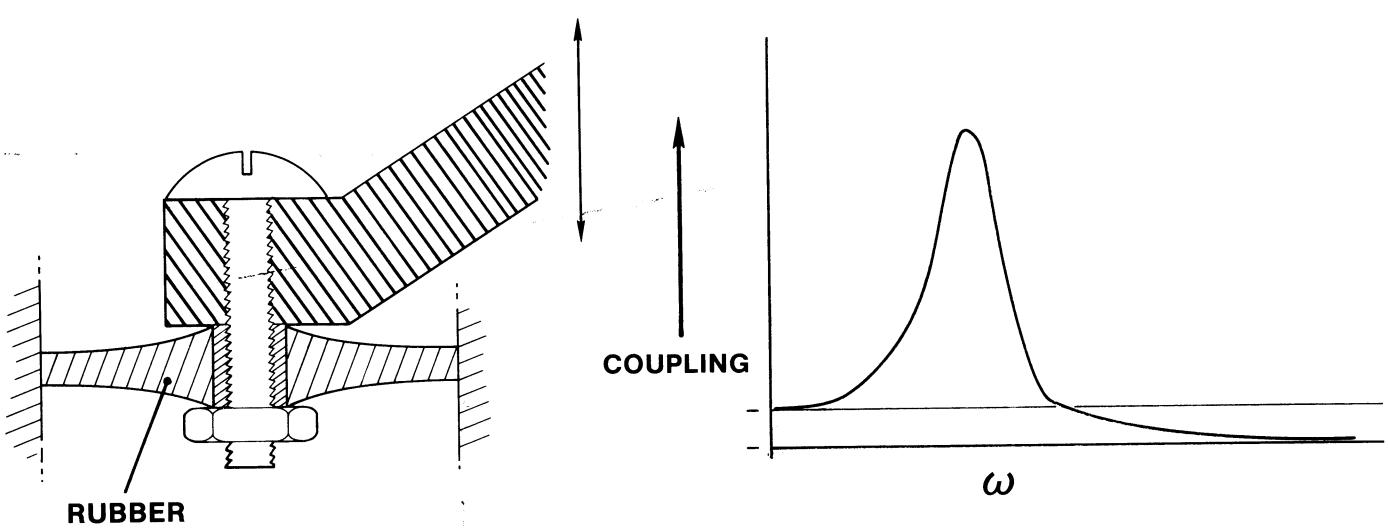

Figure 11.- Cross section of traditional passive shock mounting and its response curve. Modern devices are more sophisticated and efficient but suffer the same basic limitations.

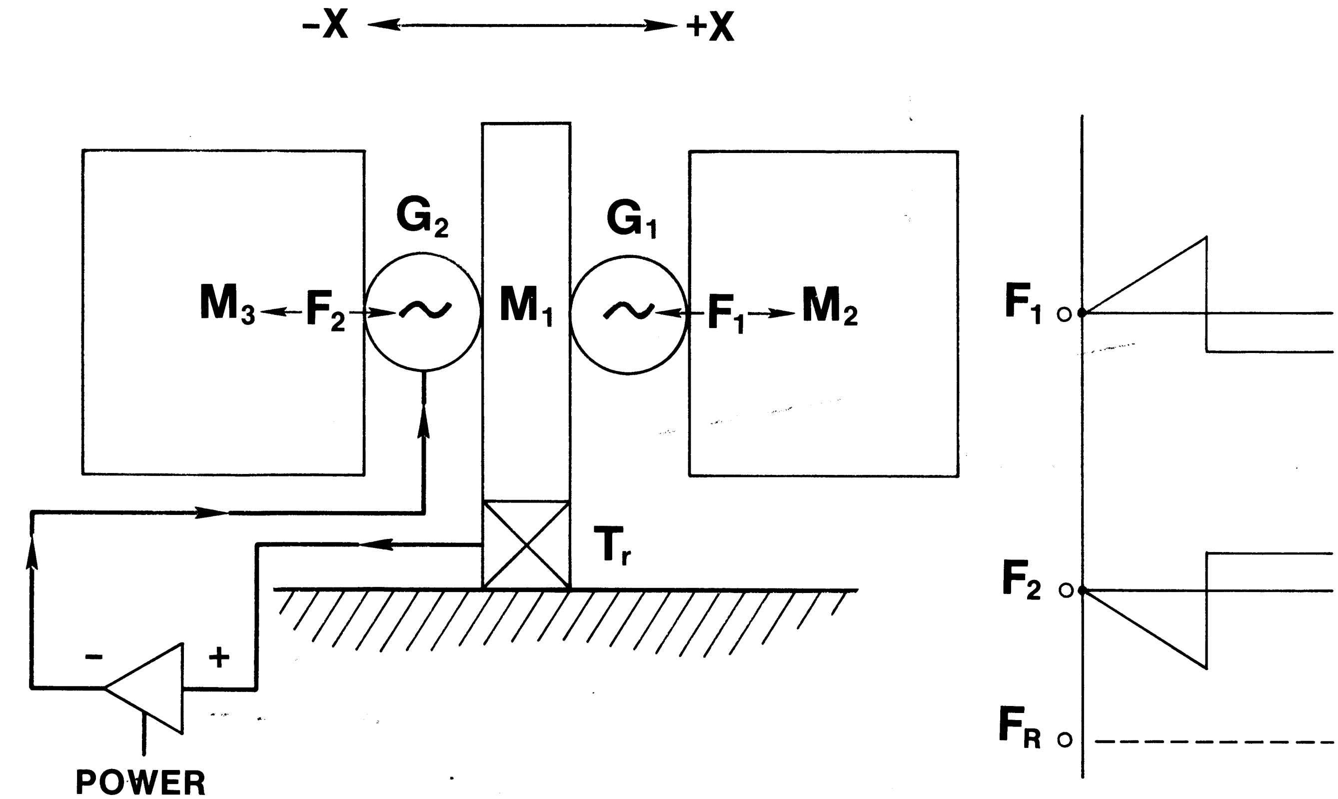

Figure 12.- Schematic of active compensation system for a single axis and response curves. See text.

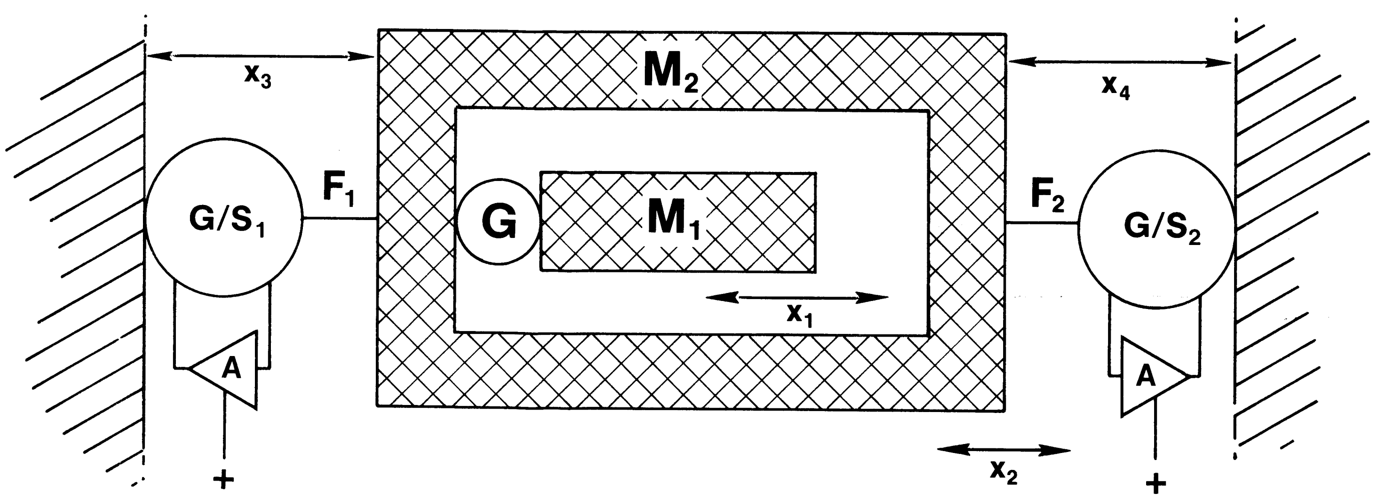

Figure 13.- Schematic of improved isolation system for one axis. $\mathbf{M_1}$ is subject equivalent mass, **G** is the equivalent force generator, $\mathbf{X_2}$ is motion of center of mass, $\mathbf{M_2}$ is treadmill mass plus counterpoise, $\mathbf{X_2}$ is motion of $\mathbf{M_2}$, $\mathbf{G/S_{1,2}}$ are tether force generators which sense changes in distances of treadmill assembly from structure $\mathbf{X_{3,4}}$ which are processed by computer elements **A** to produce constant limited correcting forces $\mathbf{F_{1,2}}$.

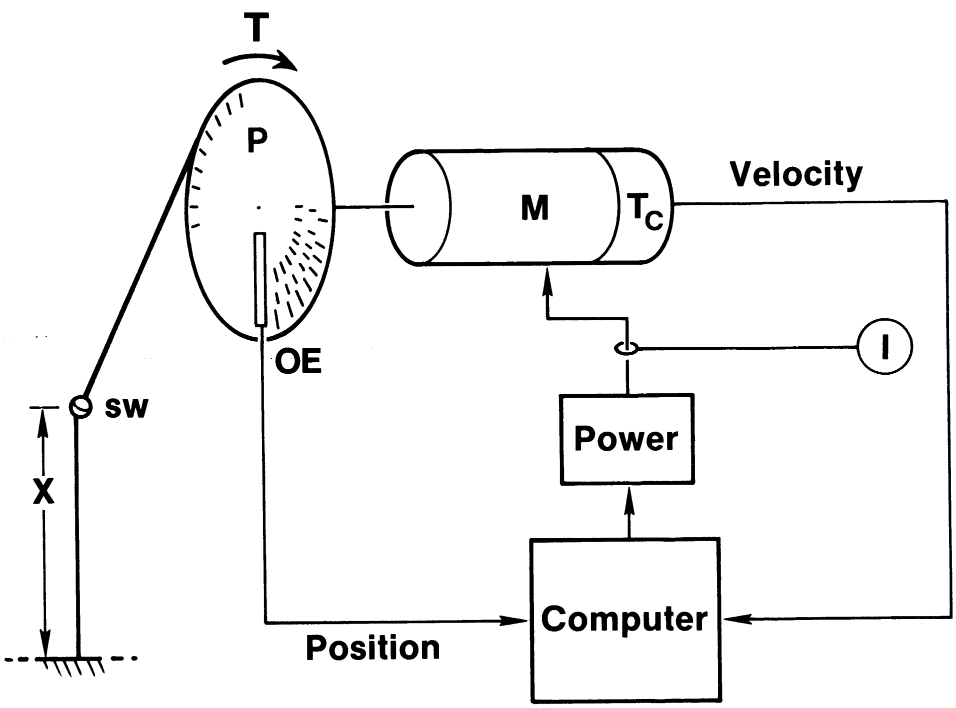

Figure 14.- Diagram of combined sensor and constant force generator. The **X** is a tether, **SW** a swivel, **T** is corrective torque provided by the pulley (**P**) which contains an optical position encoder whose output is fed to the computer. Torque for correction of position is generated by a motor (**M**) whose torque is proportional to its drive current (**I**). **G** is a large ratio gear reduction and T_c is a tachometer to produce a signal for rate damping.

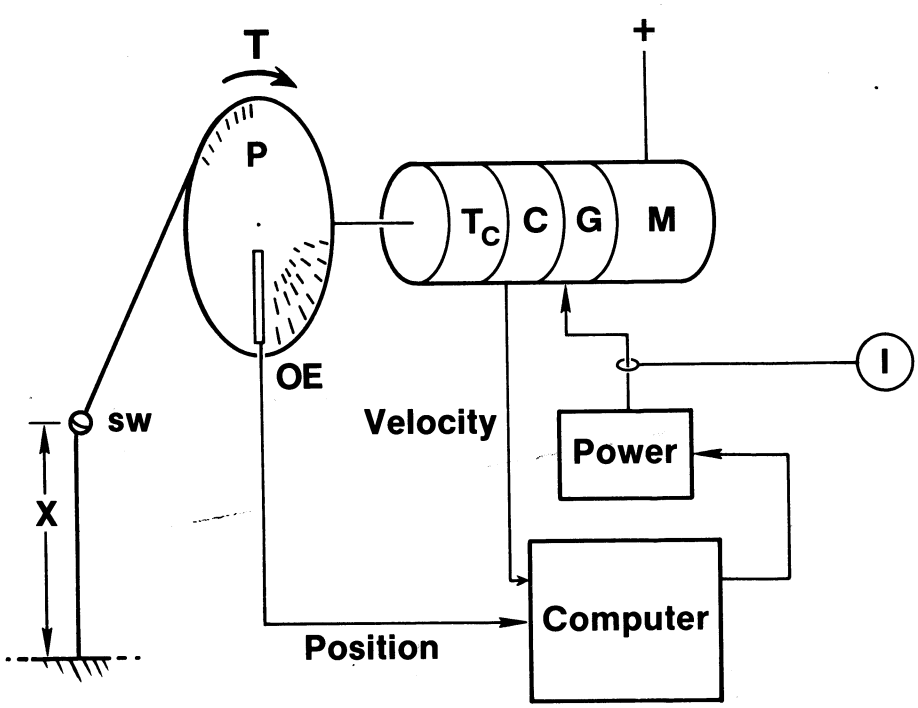

Figure 15.- Alternative form of combined sensor and constant force generator. This is the same as figure 14 except the motor runs continuously and torque from it is applied to the tachometer (T_c) and gear train through a clutch (**C**) whose transmitted torque is proportional to a control current (**I**).

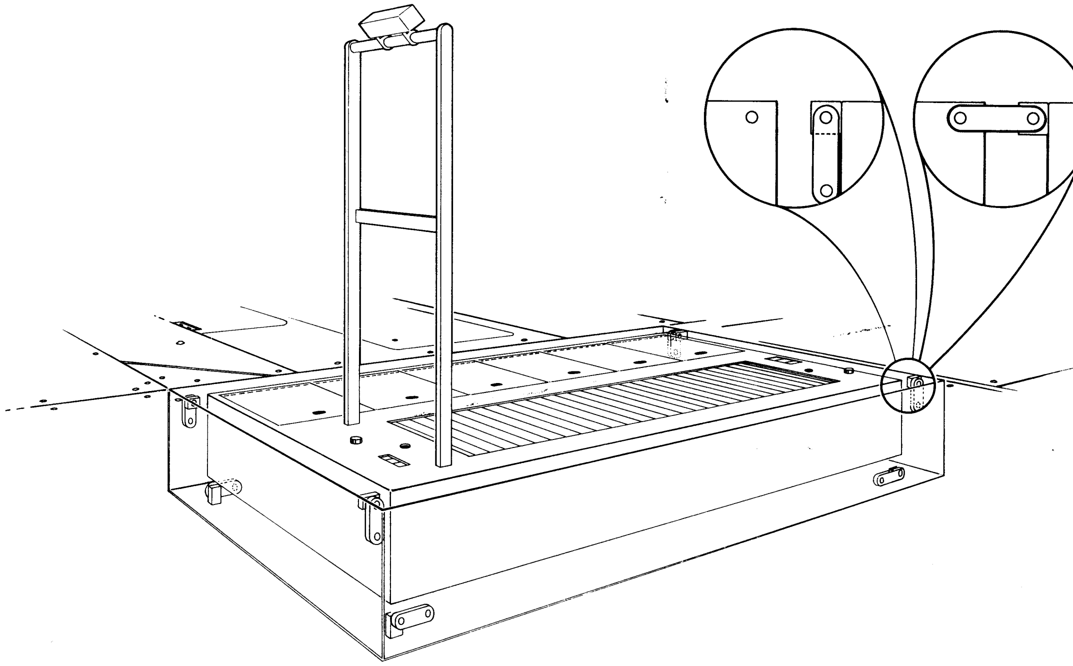

Figure 16.- Conceptual sketches of an isolated treadmill with storage lockers for a counterpoise. Links shown in dotted outline would be attached as required.

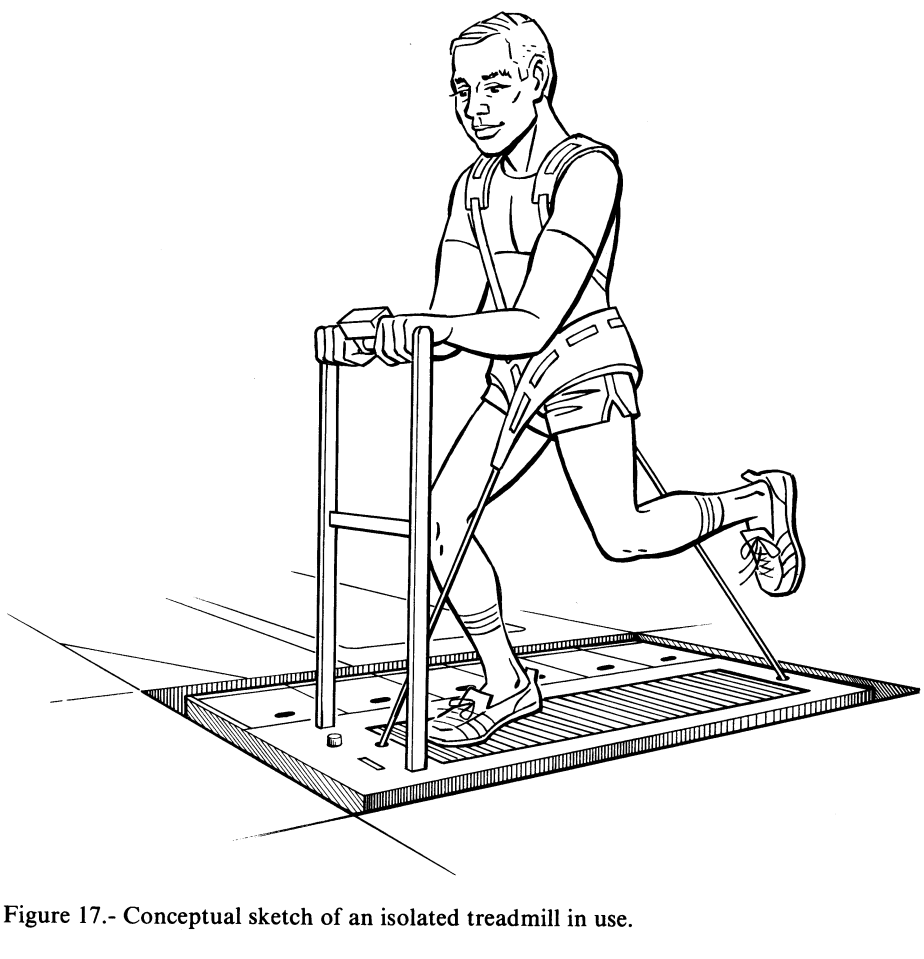

Figure 17.- Conceptual sketch of an isolated treadmill in use.

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16. Abstract

Stringent limits (one micro-g) for shock and vibration have been placed on Space Station. There are many planned operations which will exceed this limit by one to two orders-of-magnitude or more. One of the major shock and vibration sources is the treadmill (TM) exercise which produces cyclic forces of one to five Hz and up to three times body weight of the person using it. Current isolation means, neither active nor passive, can attenuate such forces to the desired level, hence some alternative must be used. One method for meeting such levels is to provide adequate counterpoise mass to the TM to allow it to be used while floating freely. To prevent drift and structural contact, a dynamic tethering system, whose forces will never exceed allowable limits, yet will allow appreciable motion will maintain the assembly's position. Concept and design of this system is described.

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