

Body acceleration distribution and O₂ uptake in humans during running and jumping

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BHATTACHARYA, A., E. P. McCUTCHEON, E. SHVARTZ, AND J. E. GREENLEAF. *Body acceleration distribution and O₂ uptake in humans during running and jumping*. *J. Appl. Physiol.: Respirat. Environ. Exercise Physiol.* 49(5): 881-887, 1980.— Body acceleration distribution and its relation to the mode of generation were determined in eight young males (19-26 yr) who walked and ran on a treadmill operated at four speeds and jumped on a trampoline at four heights. With increasing treadmill speed, peak acceleration at the ankle ($A_a = 3.0-2.0 G_z$) always exceeded that at the back and forehead ($A_b = 0.9-5.0 G_z$, and $A_h = 0.8-3.9 G_z$); these acceleration profiles included higher frequency components than those during jumping. Corresponding ranges of oxygen uptake ($\dot{V}O_2$) and heart rate (HR) were 0.8-3.0 l/min and 90-180 beats/min, respectively. With increasing jumping height, acceleration levels were more symmetrically distributed ($A_a = 3.0-7.0 G_z$, $A_b = 3.9-6.0 G_z$, and $A_h = 3.0-5.6 G_z$); $\dot{V}O_2$ and HR ranges were 1.1-2.5 l/min and 102-175 beats/min, respectively. $\dot{V}O_2$ was linearly related to HR for both types of exercise. The results indicate that, for similar levels of HR and $\dot{V}O_2$, the magnitude of the biomechanical stimuli is greater with jumping on a trampoline than with running, a finding that might help identify acceleration parameters needed for the design of remedial procedures to avert deconditioning in persons exposed to weightlessness.

biomechanical stressors; exercise; treadmill; trampoline; metabolism; heart rate

WITH TERRESTRIAL LOCOMOTION the cardiovascular and musculoskeletal systems are affected not only by the changes in metabolic energy expenditure with changes in speed but also by the varying levels of interaction between 1) gravitational-potential energy and kinetic energy, and 2) energy storage and release by internal elastic elements of the musculoskeletal system (4). With each step or stride the center of mass of the body must be lifted and reaccelerated (external work), and the kinetic energy of the limbs must be changed relative to the center of mass (internal work) (26). Since such interchanges of energy with movement are inescapable on earth, gravity loading of the body and its time-varying attributes are likely to be highly significant factors for the maintenance of gravitational adaptation. For example, the orthostatic intolerance following prolonged sitting in a chair, water immersion, bed rest, or weightlessness is corrected by ordinary upright activity (19).

Because of the apparent significance of body movement for physiological conditioning, various exercise regimens have been employed during exposure to weight-

lessness (22) and bed rest (11, 25) in the attempt to ameliorate the deleterious cardiovascular and musculoskeletal changes. Although isotonic exercise during bed rest or space flight stimulates metabolism and increases oxygen uptake, it does not prevent signs of cardiovascular deconditioning in response to the subsequent stress of the upright posture. Furthermore, recent evidence suggests that isotonic exercise training may lead to reductions in orthostatic and acceleration tolerances because of some as yet undefined impairment in the blood pressure control system (16, 20, 24). During bed rest, isometric exercise training was more effective than isotonic exercise for partial restoration of the significant reduction in post-bed-rest head-to-foot (+ G_z) acceleration tolerance (16). Since the vertical force component (parallel to the long axis of the body) was absent in the exercise programs of these bed-rest and space-flight studies, the degree of body segment acceleration was likely to have been much less than that associated with similar activity in the upright position. However, acceleration gradients in the long axis of the body and the relation between acceleration distribution and metabolism were not evaluated.

Because of the inseparable connection between acceleration of body components and body movement, determination of the relation of such acceleration to metabolic cost seems appropriate. Controlled dynamic acceleration gradients can be applied to the body with whole-body oscillation techniques (1, 8). However, testing the efficacy of such procedures in humans requires information about the range of oscillation frequencies and amplitudes that would be safe and effective. There is also a need to identify acceleration parameters that could be applied with minimal increase in metabolism. Prior studies of acceleration distribution, oxygen uptake, and heart rate on the treadmill were aimed at separating and quantitating external and internal work (26). As a result, acceleration data were not directly correlated with metabolic and cardiovascular variables. Furthermore, simultaneous measurements of the necessary variables have not been reported previously for trampoline exercise. In other studies, the accelerometers were located on various parts of the body to approximate the acceleration distribution with upright movement at 1 G (6, 7, 15, 17, 26), but no previous reports relate body segment acceleration and the accompanying metabolic and cardiac responses for widely differing types or levels of exercise. Passive restrained humans and animals exposed to increasing fre-

quency and amplitude of $\pm G_z$ and $\pm G_x$ (front-to-back) vibration forces develop increased heart rate and metabolic activity (2, 9, 13, 18). These responses, measured during whole-body vibration, resemble those during mild exercise and suggest that perhaps body vibration could be used in place of exercise.

Therefore, the present study was designed to determine the distribution of acceleration amplitude and frequency profiles and the accompanying oxygen uptake and heart rate responses for two typical stressful human activities that cover a wide range of body displacement: treadmill running and trampoline jumping.

PROCEDURE AND METHODS

Accelerations in the head-to-foot direction were measured at three points on the body: the lateral ankle (A_a), the lumbosacral region of the back (A_b), and the forehead (A_h) in eight men [mean age 23 ± 5 (SD) yr, wt 79 ± 7 kg, and ht 176.2 ± 7.9 cm] during level treadmill walking and running at four velocities and trampoline jumping at four heights. Corresponding oxygen uptake ($\dot{V}O_2$) and heart rate (HR) were also measured. All experiments were conducted in the afternoon at room temperature (T_a 24°C).

Subjects. The subjects were university students who gave their informed consent and who were in good physical condition with no abnormalities evident from a thorough general medical examination. Though all had prior experience with treadmill and trampoline exercise, reproducibility of their exercise techniques was ensured by familiarization sessions on the laboratory treadmill and trampoline devices.

Treadmill protocol. Each subject wore shorts and new running shoes (Nike) to standardize the damping effect of the shoes on the acceleration levels. Each experimental session began with measurement of body weight, followed by application of electrocardiogram electrodes. The accelerometers in their holders were then attached; placement over bony areas minimized relative movement between the holder and the body segment (Fig. 1). Each subject walked or ran at four speeds in a selected randomized order: 4.8 km/h for 10 min, 8.1 km/h for 8 min, 9.6 km/h for 7 min, and 11.3 km/h for 6 min, with 5- to 10-min rest periods between runs. During the last minute at each speed, the volume of expired gas was measured with a modified high-velocity valve (Otis-McKerrow) in the line to a flowmeter (Parkinson-Cowan). Gas samples were collected in duplicate 200-ml oiled syringes and analyzed for O_2 (Beckman E2) and CO_2 (Godart Capnograph) content (25).

Trampoline protocol. These experiments were conducted at least 1 wk after the treadmill tests. The regulation trampoline bed (American Athletic Equipment) was 2.74×4.56 m and made of nylon webbing supported by springs. An adjustable net placed over the trampoline bed allowed the subjects to calibrate their jumping height above the bed by touching the net with the tops of their heads. All instrumentation was the same as that used for the treadmill tests, except the expired gas volume was measured with the Kofranyi-Michaelis (K-M) flowmeter, and the samples for analysis were obtained immediately

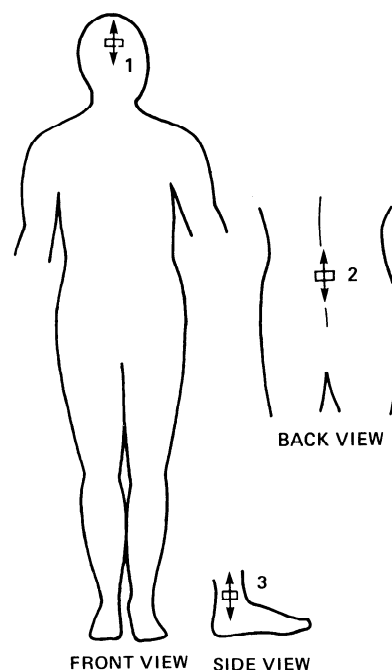


FIG. 1. Location of accelerometers. 1, forehead; 2, lumbosacral area of back near center of gravity; 3, lateral ankle.

after the end of the jumping period (within 10 s) directly from the respiratory valve (Collins). The K-M flowmeter was calibrated with the Parkinson-Cowan flowmeter. Each phase of the sequence included a 2-min warm-up, followed by 5 min of jumping. The four heights, measured by the distance the subjects' feet were elevated above the trampoline bed, were 18, 37, 75, and 100 cm. A 5- to 10-min rest period was provided between each jumping level.

In every test, the subjects were loaded identically with a backpack (5 kg in wt) containing the telemetry transmitter and the K-M gas flowmeter. The K-M meter was used to measure the volume of expired gas only during the trampoline tests.

Signal acquisition. The outputs from three single-axis accelerometers and one electrocardiographic lead were obtained with a battery-powered telemetry unit (Konigsberg Instruments, model T-41-1, wt 400 g). The telemetry unit converted the analog input to a multiplexed pulse width, modulated format that frequency-modulated a transmitter. The transmitted signal was decoded by a custom-designed receiver-demodulator and recorded on eight-channel direct-writing (Brush) and analog tape (Lockheed) recorders.

Accelerometers. The sensitive piezoresistive accelerometers (Endevco model 2265-20, ± 20 G, 20–35 mV/G) were approximately $0.8 \times 1.3 \times 1.6$ cm and weighed about 6 g. They were placed in Plexiglas holders that were taped to the skin to maintain orientation in the $\pm G_z$ axis. The frequency response of the holders was flat from 0–2 kHz, and the frequency response to the accelerometers in the holders through the entire signal acquisition and processing system was flat from 0.3–70.0 Hz. Static calibrations of the accelerometers were performed before and after each experiment.

RESULTS

Normalized for body weight, peak accelerations (A_a , A_b , and A_h) increased progressively with both increased treadmill speed and jumping height (Figs. 2 and 3). With walking and running, A_a (range 0.031–0.130 G_z/kg) always exceeded A_b (range 0.013–0.056 G_z/kg), which always exceeded A_h (range 0.009–0.410 G_z/kg). The respective raw $+G_z$ ranges were 3.0–12.0, 0.90–5.0, and 0.80–3.90 G_z . The increase in normalized G_z at the ankle was essentially linear with increasing treadmill speed, while those for A_b and A_h were curvilinear. With jumping, the acceleration levels were more nearly the same (Fig. 3). The normalized $+G_z$ ranges were $A_a = 0.045$ –0.073, $A_b = 0.048$ –0.086, and $A_h = 0.044$ –0.086 G_z/kg ; and the respective raw $+G_z$ ranges were 3.0–7.0, 3.9–6.0, and 3.0–5.6 G_z . With the exception of A_a at the 100-cm height, there was a linear relation between normalized G_z and jumping height at the three body locations (Fig. 3).

The regression of normalized oxygen uptake on equilibrium levels of heart rate was essentially the same (linear) in the treadmill and trampoline experiments (Fig. 4). Ranges of oxygen uptake and heart rates were 0.8–3.0 l/min and 90–180 beats/min, respectively, during running and 1.1–2.5 l/min and 102–175 beats/min, respectively, during jumping.

However, the relation between normalized oxygen uptake and normalized peak back acceleration, which was located near the center of body mass and represents a major component of external work output (4), depended on the type of exercise (Fig. 5). At equivalent levels of oxygen uptake, there were significantly greater levels of back acceleration with jumping compared with running.

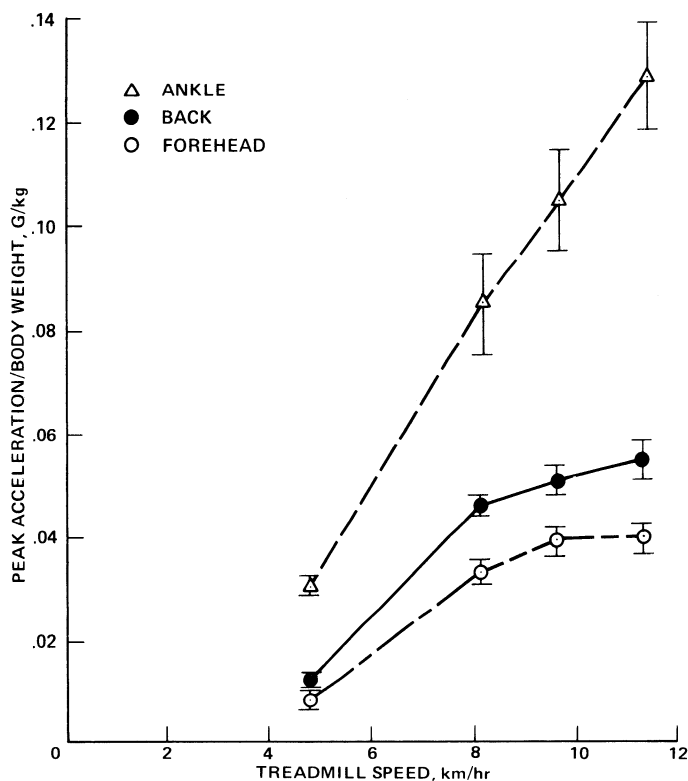


FIG. 2. Regression of normalized peak acceleration at ankle, back, and forehead on treadmill speed. Values are means \pm SE.

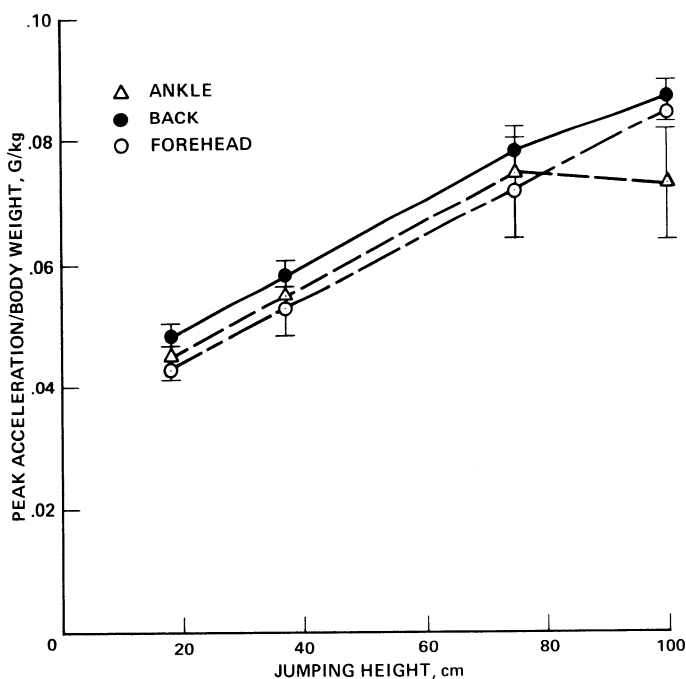


FIG. 3. Regression of normalized peak acceleration at ankle, back, and forehead on trampoline-jumping height. Values are means \pm SE.

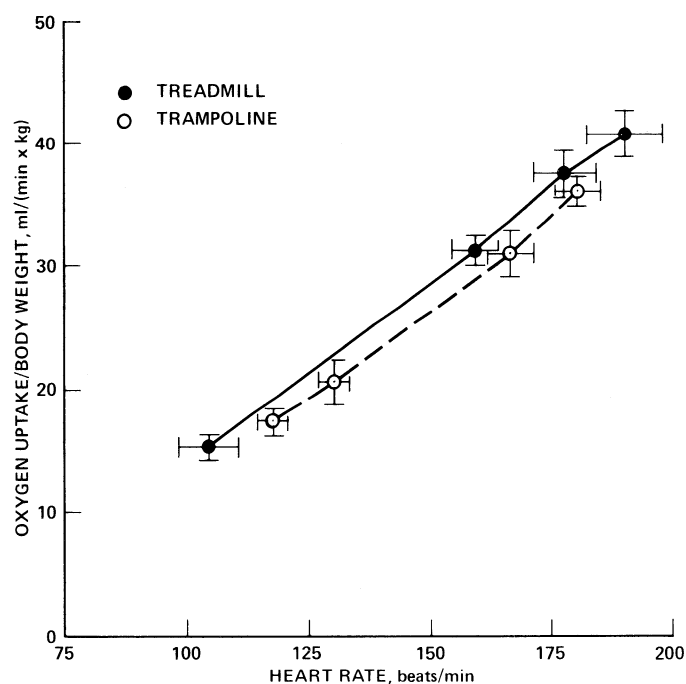


FIG. 4. Regression of normalized oxygen uptake on heart rate during treadmill and trampoline experiments. Values are means \pm SE.

The difference in back acceleration between the two curves was consistent and averaged about 0.035 G/kg ; the greatest difference was about 68%.

Because one major difference between the two forms of exercise was the time of foot contact with the base surface, the relation between normalized oxygen uptake and back acceleration loading per unit time was determined (Fig. 6). This peak back acceleration loading rate (F) was calculated from the product of the normalized A_b and the step or jump frequency. With F below 4.0,

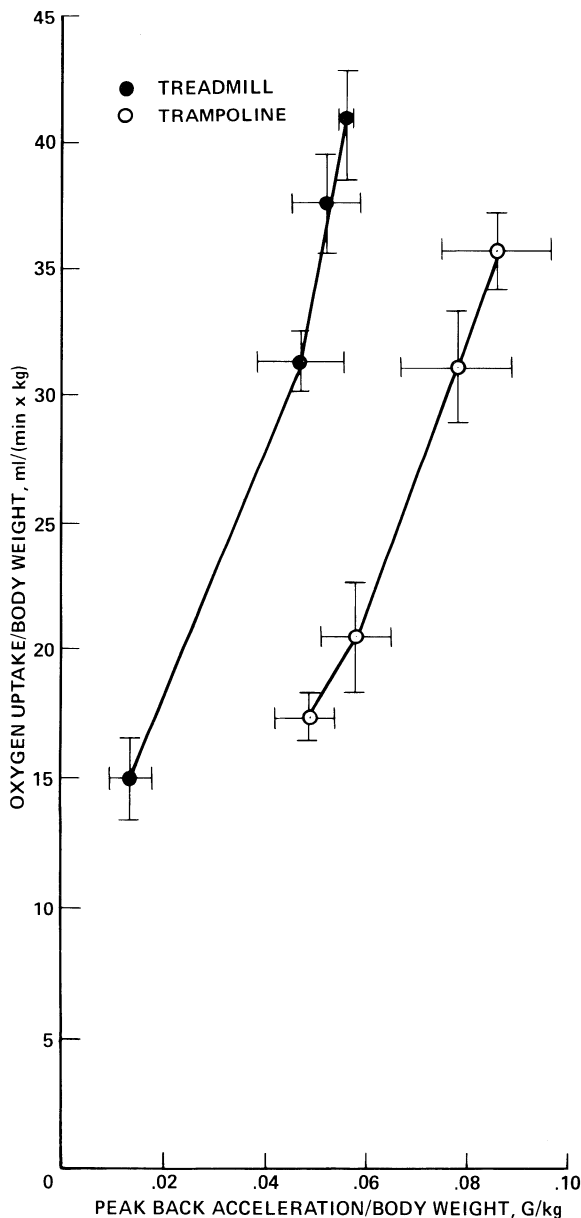


FIG. 5. Regression of normalized oxygen uptake on normalized peak back acceleration during treadmill and trampoline experiments. Values are means \pm SE.

oxygen uptake (and heart rate) was significantly higher during running than during jumping. With $F \geq 4.0$, there was no significant difference in oxygen uptake between the two regimens.

Inspection of the analog acceleration traces obtained during the two experiments (Fig. 7) indicated that the frequency components of the acceleration profile were higher with running and walking than with jumping, a finding substantiated by analyzing the frequency spectra of the acceleration profiles. Spectral analysis of the wave form from the ankle indicated that the frequency components during running ranged from 1 to 18 Hz, depending on running speed; the frequency content of the forehead and back acceleration profiles were relatively low. During jumping, the frequency contents of the acceleration wave forms from the ankle, back, and forehead were

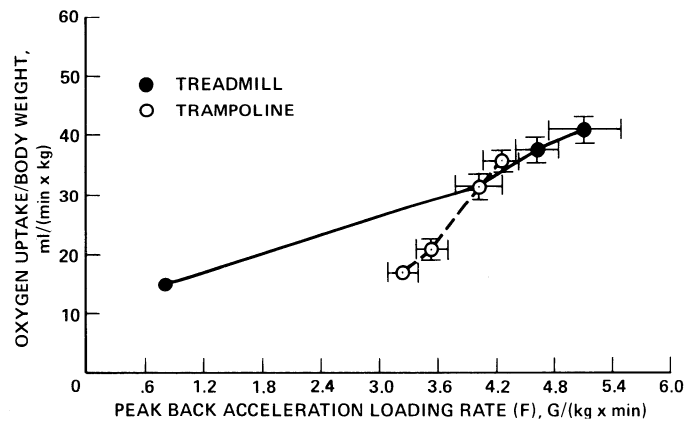


FIG. 6. Regression of normalized oxygen uptake on peak back-acceleration loading rate (F) during treadmill and trampoline experiments. Values are means \pm SE.

approximately equal and ranged from 0.78 to 4.00 Hz, depending on jumping height.

DISCUSSION

The overall magnitude of the distributed acceleration was somewhat greater with trampoline than with treadmill exercise. Compared with jumping values, the peak acceleration at the ankle during running was either similar to or exceeded that produced on the trampoline, but the accelerations recorded at the back and head were significantly lower. The accelerations at all three sites (ankle, back, head) during jumping were similar, indicating that impact forces were transmitted throughout the body with little attenuation. This effect occurs because acceleration propagation through the long axis of the body is much more symmetrical with trampoline jumping than with walking and running (17, 23). Acceleration at the ankle, which occurred very near the point of body contact with the surface, can be regarded as an approximate representation of the impact loading exerted on the body as a result of contact of the feet with the surface. This assumption is supported by results of experiments with humans suddenly decelerated downward on contracted calf muscles; the damped oscillatory accelerations obtained with force platform measurements (13) were similar to those recorded at the ankle in the present study.

The two principal factors contributing to this difference in accelerations between the two types of exercise were variations in body alignment and damping. During trampoline exercise, the motion was in the vertical ($\pm G_z$) direction. When the feet struck the trampoline bed, the ankle, back, and head were practically aligned. Under these conditions, the principal component of the impact force was directed through the body parallel to the spinal axis, in the axis of the acceleration measurement sites. In the treadmill mode, on the other hand, the force at impact is divided into both vertical and forward components. Thus, when the heel struck the surface, it was not aligned with the back and head, and only a component of the principal force was experienced in these segments. However, the back and head were relatively well aligned, and similar levels of acceleration occurred in these two regions.

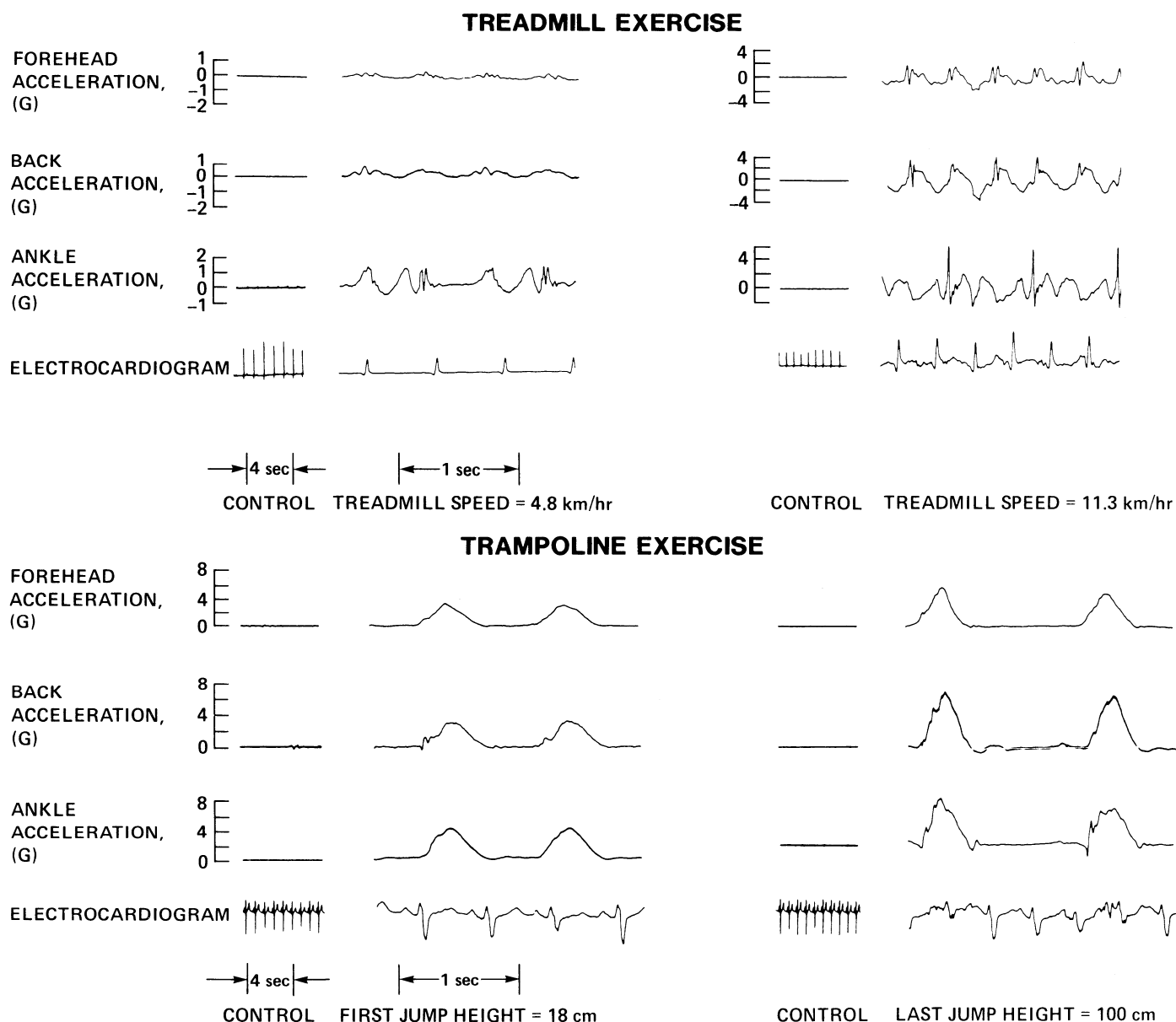


FIG. 7. Typical records of the electrocardiogram, and forehead, back, and ankle acceleration wave forms during treadmill and trampoline exercise for one subject.

During trampoline exercise, not only the peak amplitude but also the frequency spectra of the accelerations were approximately equal for all three sites. On the treadmill, both the amplitude and frequency content were reduced at the back and head. For the trampoline, the impact forces were assumed to be transmitted with little change because the time constant of the force produced was of such length that body damping was not significant. The frequency dependence of damping has been shown in both humans and animals (10, 14). Below 2 Hz, damping is minimal. At 2 Hz, the mechanical impedance modulus of the restrained sitting infrahuman primate is close to that of an equivalent inert mass. The impedance modulus and damping coefficients then increase to reach a peak at 7–8 Hz. At frequencies above 8 Hz, the coefficients tend to decrease slightly, with values below those that would occur with an equivalent inert mass. The net result is more marked damping for the

higher frequency treadmill accelerations. In this context, a factor to be considered is that the oscillatory frequency induced by impact decreases with increasing load (3). The weight of the backpack may have reduced the acceleration frequency content, but the alteration should have been slight inasmuch as the added weight was only 6–7% of body weight.

As the acceleration of body components and body movements are interrelated, it is appropriate to determine the relation of such acceleration to metabolic cost. The energy exchange between body segments is different in walking, running, and jumping. The cause of the difference in the relation between energy requirements and the acceleration levels for the two types of exercise is unclear. Part of the uncertainty arises from the factors affecting force transmission through the body. In addition, there is a fundamental difference between the two exercise modes. During running at lower speeds, muscle

contraction is more sustained than in trampoline jumping. Thus, there is a region in which running is inherently a more costly form of exercise. Furthermore, for trotting, running, and hopping, the elastic "bounce" of the body minimizes the increase in energy expenditure with increased speed (4, 12). For isotonic exercise, the elastic recoil of stretched contracted muscle can reduce energy expenditure by as much as 40%.

On the trampoline, the subjects worked to maintain a constant height for each jumping level. During downward stretching of the trampoline bed, the subject expended energy and accelerated his descent by pushing into the trampoline bed. The bed then acquired sufficient elastic energy, which in conjunction with the leg extension, provided adequate "lift-off" velocity so that the required jumping height was maintained. Correlation of oxygen uptake and body acceleration provides an approximate estimation of the energy required to accelerate the body into and off the trampoline bed. However, the contribution of elastic recoil of stretched contracted muscle to the energy expenditure taking place on the trampoline could not be determined from these data. Differences in the contribution from elastic recoil of muscle cannot completely explain the present results, because for $F > 4.0$ the energy requirements of jumping and running are similar. Another contributing factor could be the energy cost of accelerating the arms relative to the trunk and lower legs. The amount of energy required for this differential acceleration is not known for trampoline exercise, but for walking and running it is significant and increases as the square of running speed (5). On the trampoline, arm movement increased as jumping height increased, but no quantitative data were obtained. Ideally, the acceleration-metabolism linkage would be assessed by determining all component energy expenditures and summing their proportional contribution; but the available techniques are limited, extremely tedious, and impractical for unrestricted or large-amplitude motion (5, 26). The telemetry system permitted relatively unencumbered measurement of body acceleration and heart rate with both forms of exercise. For oxygen uptake measurement during the trampoline studies, expired gas volume was measured with a K-M meter (which the subject carried on his back), and the sample was obtained immediately after the exercise (within 10 s) directly from the respiratory valve. The delay in obtaining the sample caused a negligible error in the oxygen uptake measurements.

In the present study, the values of heart rate and oxygen uptake ranged from resting to nearly maximal levels, regardless of the type of exercise. In both situations, the heart rate and oxygen uptake were related directly, but the corresponding acceleration amplitudes at the back and head were greater for the trampoline

than for the treadmill (Fig. 5). When these data were adjusted to reflect the rate of loading of the body center of mass per unit time (Fig. 6), the difference was maintained only within a limited region ($F < 4.0$).

During typical exercise stress, the acceleration can be repeated at high levels for significant durations and is comparable with that observed during vibration or whole-body oscillation. Within this envelope of exercise-induced acceleration, forces applied to internal structures and organs probably exceeded those recorded on the body surface. When dogs are vibrated along the $\pm G_z$ axis in a horizontal plane, the acceleration induced in the heart and the sternum was approximately $4 G_z$ and $2 G_z$, respectively, while the whole-body acceleration was only $0.75 G_z$ (21).

The results from the present study aid the choice of an acceleration profile and its frequency spectrum for application in cardiovascular and muscular conditioning programs. For example, averting the deconditioning that occurs during the immobilization of bed rest or space flight, due to lack of gravireceptor stimulation (in addition to other factors), requires an acceleration profile that can be delivered at a relatively low metabolic cost. From Fig. 6 it is evident that, for equivalent metabolic cost, an acceleration profile from jumping (for $F < 4.0$) will provide greater stimuli to gravireceptors. On the other hand, if conditioning for impact loads is desired, acceleration profiles that result in $F > 4.0$ would be more appropriate.

Actual modes for delivery of such acceleration profiles as a physical conditioning stimulus or as a countermeasure for deconditioning will require further study, in particular for application to deconditioned subjects who cannot voluntarily perform upright exercise. One such method could be the use of an oscillating bed or platform that could be programmed to produce the desired dynamic acceleration gradients. The present study has provided some levels of oscillation frequency and amplitude for the design of a safe and effective forcing function that may help to counteract deconditioning.

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REFERENCES

1. BHATTACHARYA, A., C. F. KNAPP, E. P. McCUTCHEON, AND R. G. EDWARDS. Parameters for assessing vibration-induced cardiovascular responses in awake dogs. *J. Appl. Physiol.: Respirat. Environ. Exercise Physiol.* 42: 682-689, 1977.
2. BHATTACHARYA, A., C. F. KNAPP, E. P. McCUTCHEON, AND J. M. EVANS. Cardiac responses of dogs to nonsynchronous and heart synchronous whole-body vibration. *J. Appl. Physiol.: Respirat. Environ. Exercise Physiol.* 46: 549-555, 1979.
3. CAVAGNA, G. A. Elastic bounce of the body. *J. Appl. Physiol.* 29: 279-282, 1970.
4. CAVAGNA, G. A., N. C. HEGLUND, AND C. R. TAYLOR. Mechanical work in terrestrial locomotion: two basic mechanisms for minimiz-

- ing energy expenditure. *Am. J. Physiol.* 233 (Regulatory Integrative Comp. Physiol. 2): R243-R261, 1977.
5. CAVAGNA, G. A., AND M. KANEKO. Mechanical work and efficiency in level walking and running. *J. Physiol. London* 268: 467-481, 1977.
 6. CAVAGNA, G. A., F. P. SAIBENE, AND R. MARGARIA. External work in walking. *J. Appl. Physiol.* 18: 1-9, 1963.
 7. CAVAGNA, G. A., F. P. SAIBENE, AND R. MARGARIA. Mechanical work in running. *J. Appl. Physiol.* 19: 249-256, 1964.
 8. CHASE, G. A., C. GRAVE, AND L. B. ROWELL. Independence of changes in functional and performance capacities attending prolonged bed rest. *Aerosp. Med.* 37: 1232-1238, 1966.
 9. CLARK, J. G., J. D. WILLIAMS, W. B. HOOD, JR., AND R. H. MURRAY. Initial cardiovascular response to low frequency whole body vibration in humans and animals. *Aerosp. Med.* 38: 464-467, 1967.
 10. COERMANN, R. R. The mechanical impedance of the human body in sitting and standing position at low frequencies. *Hum. Factors* 4: 227-253, 1962.
 11. CONVERTINO, V. A., R. W. STREMEL, E. M. BERNAUER, AND J. E. GREENLEAF. Cardiorespiratory responses to exercise after bed rest in men and women. *Acta Astronaut.* 4: 895-905, 1977.
 12. DAWSON, T. J., AND C. R. TAYLOR. Energetic cost of locomotion in kangaroos. *Nature London* 246: 313-314, 1973.
 13. DUFFNER, L. R., L. H. HAMILTON, AND M. A. SCHMITZ. Effect of whole body vertical vibration on respiration in human subjects. *J. Appl. Physiol.* 17: 913-916, 1962.
 14. EDWARDS, R. G., J. F. LAFFERTY, AND C. F. KNAPP. Experimental and analytical determinations of the mechanical impedance response of animals to vertical vibration. *J. Biomech.* 9: 55-61, 1976.
 15. GERSTEN, J. W., W. ORR, A. W. SEXTON, AND D. OKIN. External work in level walking. *J. Appl. Physiol.* 26: 286-289, 1969.
 16. GREENLEAF, J. E., R. F. HAINES, E. M. BERNAUER, J. T. MORSE, H. SANDLER, R. ARMBRUSTER, L. SAGAN, AND W. VAN BEAUMONT. G_z tolerance in man after 14-day bedrest periods with isometric and isotonic exercise conditioning. *Aviat. Space Environ. Med.* 46: 671-678, 1975.
 17. GROSSMAN, O. *Erschütterungsmessungen beim Trampolin und Minitrampolinspringer* (Thesis). Zurich, Switzerland: Labor für Biomechanik, Eidg. Tech. Hochschule. 1975.
 18. HOOD, W. B., JR., R. H. MURRAY, C. W. URSCHEL, J. A. BOWERS, AND J. G. CLARK. Cardiopulmonary effects of whole-body vibration in man. *J. Appl. Physiol.* 21: 1725-1731, 1966.
 19. JOHNSTON, R. S., AND L. F. DIETLEIN (Editors). *Biomedical Results from Skylab*. Washington, DC: NASA, 1977. (NASA Spec. Pub. 377).
 20. KLEIN, K. E., H. M. WEGMANN, AND P. KUKLINSKI. Athletic endurance training—advantage for space flight?: The significance of physical fitness for selection and training of spacelab crews. *Aviat. Space Environ. Med.* 48: 215-222, 1977.
 21. KNAPP, C. F., AND J. MARQUIS. Acceleration transmissibility of internal organs in canines exposed to whole body vibration. *Aerosp. Med. Assoc. Preprints* p. 84-85, 1975.
 22. SAWIN, C. F., J. A. RUMMEL, AND E. L. MICHEL. Instrumented personal exercise during long-duration space flights. *Aviat. Space Environ. Med.* 46: 394-400, 1975.
 23. SIMIC, D. *Beitrag zur Optimierung der Schwingeeigenschaften des Fahrzeuges: Physiologische Grundlagen des Schwingungskomforts* (thesis). Berlin, W. Germany: Technischen Universität, 1970.
 24. STEGEMANN, J., A. BUSERT, AND D. BROCK. Influence of fitness on the blood pressure control system in man. *Aerosp. Med.* 45: 45-48, 1974.
 25. STREMEL, R. W., V. A. CONVERTINO, E. M. BERNAUER, AND J. E. GREENLEAF. Cardiorespiratory deconditioning with static and dynamic leg exercise during bed rest. *J. Appl. Physiol.* 41: 905-909, 1976.
 26. WINTER, D. A. A new definition of mechanical work done in human movement. *J. Appl. Physiol.: Respirat. Environ. Exercise Physiol.* 46: 79-83, 1979.