Comparison of Metabolic Costs of Active and Passive Treadmills

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INTRODUCTION

A passive treadmill designed for exercise in flight[1] was selected as the primary device for Shuttle. During the design phase, the theoretical performance of the passive treadmill was verified as necessary and determined to the extent possible; e.g., in 1976, when a prototype passive treadmill was compared to a standard motor-driven unit to verify the theoretical metabolic equivalence of the two, only three subjects and a few points on the curve were obtained.

In 1981, the Lyndon B. Johnson Space Center (JSC) and the University of Houston began a program to verify kinesiologic and metabolic equivalence of the Shuttle treadmill and conventional active treadmills. This program was progressing slowly when the opportunity to fly the only existing Shuttle treadmill arose. For expediency, a series of metabolic measurements was made in the JSC cardiovascular laboratory. The passive treadmill unit used for these measurements is also the flight unit. The results of these studies and a brief discussion of pertinent features of the treadmill are limited to 1 g operation. A consideration of effects of weightlessness and other flight operations aspects is in preparation.

DEVELOPMENT

Design goals for the passive treadmill were to
- Provide 1 g equivalent truncal/leg forces during walking, jogging, running
- Provide accurate and variable speed control range to + 6 mph (now demonstrated to 10 mph)
- Provide workloads equivalent to 1 g grades of > 20 percent
- Establish minimum size, weight
- Operate independently of ship power, control, and other interfaces; i.e., operate as a passive, or subject-driven unit with integral controls and displays
- Provide for assembly and disassembly without tools in less than 5 minutes for Shuttle locker stowage
- Provide simple operation procedures
- Provide the capability for measurement of external work and other factors (not funded)

In 1976, a contract was let with Whitmore Enterprises, San Antonio, Texas, to develop a prototype treadmill to meet these goals. This development was a joint design effort between Dr. William E. Thornton of JSC and Mr. Henry B. Whitmore. The contractor performed the detailed mechanical design and construction. Two large mechanical prototypes were built and used to investigate design and functional aspects. Following this study, a flight prototype was designed using, insofar as possible, flight-qualified materials and procedures. This flight prototype is the unit considered in this report.

Though the physics of the prototype development is straightforward, the equivalence of walking/running on motor-driven and passive treadmills was verified as possible during the design and construction phase. In June and July 1976, metabolic costs were first compared using a borrowed commercial motor-driven treadmill and metabolic gas-measuring equipment located in the astronaut gym. Only three subjects were available and few data points at several speeds and elevations were collected in the short time the equipment was allowed to remain in the area. Although incomplete, the metabolic data (table I) showed maximum differences of only a few percent between the two devices. Numerous other tests such as treadmill energy consumption, speed control, etc., were performed during these development tests; resulting data are not considered pertinent to this report.

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[1] FOD/Life Sciences conferences, JSC, 1977.

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TABLE I.- ACTIVE/PASSIVE TREADMILL RESULTS, 1976

Date	Subject	Treadmill (a)	Elevation, percent	Speed, mph	O_2 uptake, ml/km/min	Heart rate, bpm	Heart rate/ belt speed, bpm/mph
June 15	WT	A	11.1	3.92	—	127	32.4
	WT	P	11.1	3.66	—	120.5	32.9
June 29	WT	A	11.1	4.15	33.9	132	31.8
June 16	WT	A	11.1	3.83	31.1	—	—
	WT	P	11.1	3.79	33.1	—	—
	WT	P	11.1	3.79	33.4	—	—
June 30	ST	P	10.9	4.54	40.6	161	35.4
	ST	A	10.9	4.52	40.1	158	34.9
	WT	P	8.6	4.41	34.7	131	29.7
	WT	A	8.6	4.52	36.7	136	30.1

[a] A = active, P = passive.

HARDWARE DESIGN

Figure 1 is a schematic of the treadmill arrangement. The active area of the treadmill is only 12 by 18 inches as dictated by Shuttle constraints. The walking surface is a continuous segmented aluminum tread supported by precision antifriction bearings and coupled to a flywheel (3)/brake (4) and tachometer (8) by means of pulleys and belts. Speed can be displayed and recorded to any degree of resolution and accuracy by appropriate meters (6) and other instrumentation. The inertia of the flywheel prevents large speed variations when no force is present, as between steps when the subject is running. The servo controlled (5) (velocity) brake (4) is sharply applied when a given speed set by the control (7) is reached. Instrumentation for external work measurement has not been added because of funding restrictions.

The harness bungee arrangement to apply equivalent body loads in weightlessness (fig. 1) was not used in these studies.

1 Tread
2 Pulleys
3 Flywheel
4 Brake
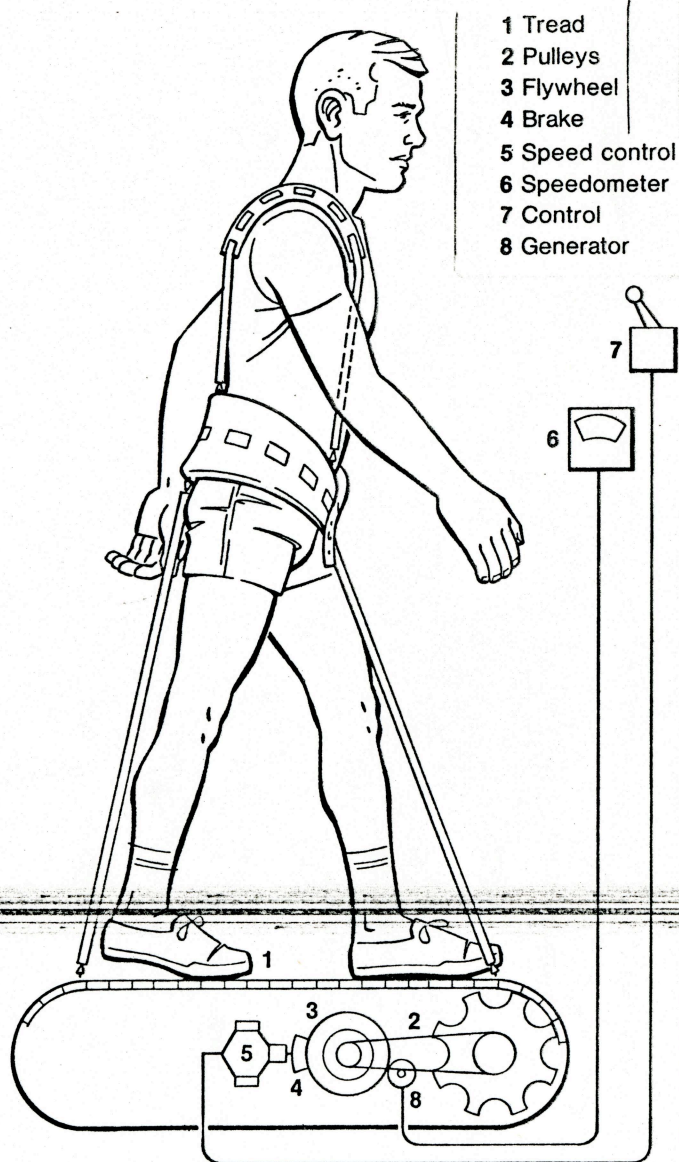5 Speed control
6 Speedometer
7 Control
8 Generator

Figure 1.- Sketch of passive treadmill operation in weightlessness with schematic of mechanical functions. The harness and elastic bungees are not required for 1g use.

The passive speed control functions as follows. Above a small elevation angle, the subject will exceed the internal force of a treadmill without a brake and treadmill speed will increase until, no longer able to keep up, the subject will slip off the back (lower end) of the treadmill. Using a treadmill with a speed control brake, as the subject reaches a speed at which braking action occurs, he/she will tend to move forward or up the treadmill and must slightly reduce speed to avoid running off the opposite end. The result is that the subject operates within a small range of speeds that are essentially constant.

A subject-driven treadmill can extract the same energy as a motor-driven treadmill at the same speed and angle; i.e., from elementary physics, once the internal friction of the passive unit is equaled, the external work becomes equal on the two units for the same speeds and angles. In this case, a small angle and low speed are required for the passive treadmill to equal the motor-driven treadmill. Once the speed and angle are determined, any differences that occur must arise from other factors, chief of which, in this instance, is size (i.e., the small tread area, which modifies locomotion and its energy cost).

ADDITIONAL TESTING

In spring of 1981, a series of evaluations was started at the University of Houston, Clear Lake City, to further document fundamental characteristics such as speed control, metabolic costs, and kinesiology (including foot/ground forces). Though speed variation is simple to measure[2] using meter sticks and stopwatches, many inconsistencies in the metabolic gas analysis and pulse rate instrumentation were encountered. Heart rates from personally counted electrocardiogram (EKG) records showed negligibly small differences in response to equivalent speeds/grade between the active Quinton treadmill (QTM) and the passive Thornton treadmill (TTM).

A typical record of short term speed variations on the TTM is shown in figure 2. These data were obtained by accurately measuring the tread length and then timing a fixed number of revolutions; e.g., number of passages of a mark past an index. A manual stopwatch with a resolution of 0.01 seconds was used. The dotted lines represent typical variations in a synchronous motor-driven unit measured in the same way and probably more nearly represent the accuracy limits of this method of measurement than actual variation.

Figure 2.- Typical speed variations under fixed elevation and speed for a subject as manually measured with a 0.01 second resolution stopwatch.

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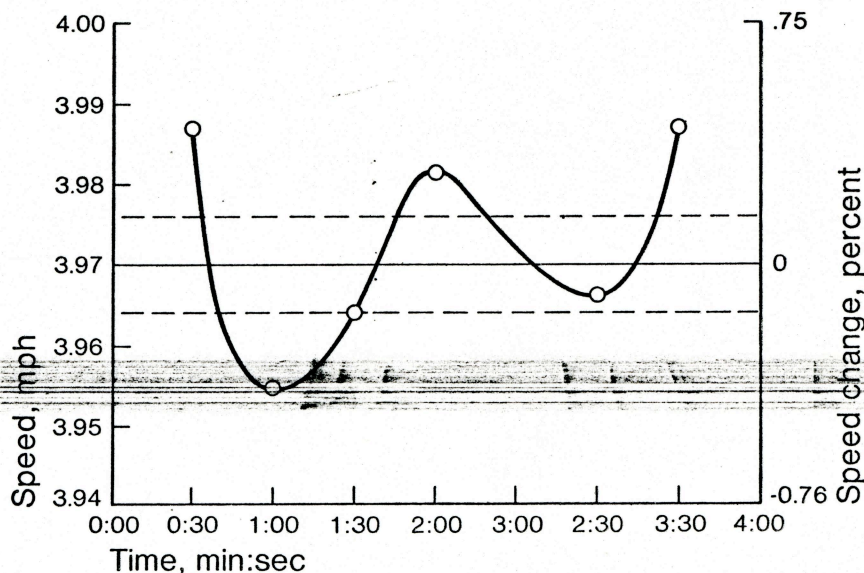
[2]During these tests, a speed control mechanism adapted from a bicycle to set the brake/servo was used. This mechanism was subject to several difficulties including hysteresis and creep.

During the period of time that the University of Houston was revamping their instrumentation and a precision speed control was being added to the treadmill, the Shuttle Government Funded Equipment (GFE) Project Office directed that the prototype be readied for a potential flight on STS-2. Any additional measurements before turning the unit over for preparation were to be made in 3 days. For expediency, the JSC cardiovascular stress laboratory was used and a comparison of metabolic costs on the passive treadmill compared to a standard Quinton treadmill was made with a small group of subjects.

In view of the time and the facilities restraints, a number of compromises were necessary, especially as to the number of runs. The program basically consisted of respiratory gas studies and heart rate measurement by EKG for four voluntary subjects representative of the astronaut population as they walked on each treadmill using the Bruce stage I to III speed and elevation protocol.

Subjects were instrumented with standard clinical electrocardiographic monitor leads so that heart rate could be integrated into the JSC Cardiovascular Data Aquisition System (CVDAS). The CVDAS collects and displays for one-half minute intervals, the following parameters.

1. Oxygen (O_2) consumption (l/min, $\dot{V}O_2$/ml/kg body weight (where $\dot{V}$ = volume/time = l/min))
2. Carbon dioxide (CO_2) production (l/min)
3. Minute volume (l/min)
4. Respiratory exchange rate ((CO_2 l/min)/(O_2 l/min))
5. Respiratory rate (cycles/min)
6. Heart rate (beats/minute (bpm))
7. Systolic and diastolic blood pressure (not recorded in this protocol)
8. Exercise times (min)
9. Treadmill speed and elevation (mph and percent grade)

Respiratory data were collected as the subject inspired sea level room air through a two-way low-impedance mouthpiece and as expired air passed into an open circuit spirometer coupled with a mass spectrometer. Associated computer hardware/software allow for real-time presentation of the data. Heart rates were confirmed by manual counting of the EKG complexes.
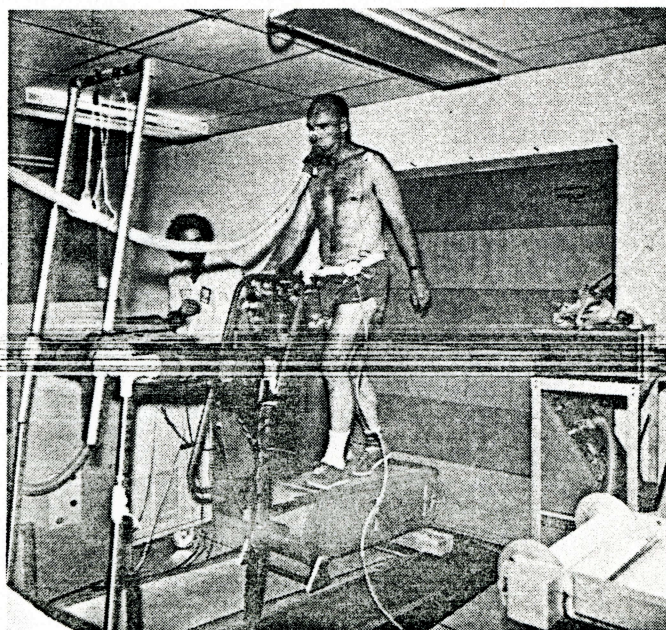

Figure 3.- Photograph of arrangement for measurement of metabolic cost TTM mounted on the Quinton model laboratory treadmill. Here is an obvious disparity in the size of the two treadmills. Also the TTM weighs +40 pounds and requires no power while the QTM weighs +1000 pounds with a 3Φ 200-V ac motor. In spite of this, the range of speeds and elevations of the two devices is essentially equal.

A wooden bracket was added to the QTM platform which allowed the TTM to be on/off (fig. 3). It was intended that the TTM tread would be exactly parallel to that of the QTM and that the same mechanism and instrumentation for elevation would be common to both. Unfortunately, the platform height was too low and there was insufficient time to change it such that the TTM elevation was 1 percent above the QTM. While the runs were made with this 1-percent error, a correction factor was obtained from incremental measurements and applied to the data.

Elevation was measured directly by linear measurements and angles were calculated to an accuracy of 0.1-percent grade at the end of each run. Speeds were calibrated and monitored by measuring the treadmill belt to 0.25 inch and timing a fixed number of revolutions of the belt with a 0.01-second digital stopwatch; speed was then calculated using these measurements. The TTM was set to an approximate speed by a small indicator for the electric tachometer and actual speed measured as above. Speeds were continually measured or monitored through every run on both treadmills.

Four volunteers representative of the physical range of the astronaut population (table II) made a total of 14 runs at the three levels on the QTM and TTM.

Test protocol consisted of 4 minutes at each exercise level on one or the other treadmill. After a minimum rest period of 30 minutes, the run would be repeated on the other treadmill in random order. One subject made multiple runs over the 3-day period to ensure repeatability of the methodology and also made a series of runs at fixed grades including near maximum speed.

TABLE II.- SUBJECT CHARACTERISTICS

Subject	Weight, kg	Height, cm	$\dot{V}O_2$ max, ml/min/kg	Age, yr
A	68.5	171.4	48.1 48.1	35
B	72.6	172.7	49.3 49.3	35
C	74.8	180.0	63.9 63.9	40
D	92.1	185.4	50.8 50.8	52

RESULTS

The subject population was reasonably matched in oxygen uptake/body weight as a function of work level; hence, a series of measurements was made by one subject (D) at the standard speeds/grades and the grades plus 1 percent on the Quinton treadmill. Results are shown in table III. The difference in values obtained were subtracted from the TTM values to obtain conservative correction for the 1-percent greater elevation. Heart rates were obtained by manually counting EKG complexes from records for 1-minute intervals for the period measured. Oxygen values are usually the mean of four each 30-second interval but were only taken when a stable plateau had been reached.

TABLE III.-

| Time, min	Grade, percent	Speed, mph	O_2 uptake, ml/kg/min	$\Delta O_2/\Delta$ percent, ml/kg/min
2 to 4	10	1.75	13.5	—
2 to 4	11	1.78	13.9	+0.4
6 to 8	12	2.55	19.8	—
6 to 8	13	2.57	21.5	+1.7
10 to 12	14	3.45	29.4	—
10 to 12	15	3.49	31.1	+1.7

Raw and corrected oxygen uptake and raw heart-rate values are shown in table IV and plotted in figure 4. The slope of the uptake versus speed will obviously vary with grade but should be approximately linear over the restricted ranges for each grade. The heart rates could not be used for comparison because of the 1-percent grade discrepancy; however, it is obvious that individual rates were comparable for given speed/elevation of the treadmills.

Individual values for a given treadmill and speed level were very close. The values for one subject, who was an outstanding runner, were at the upper range of the group on both treadmills, especially at the highest levels; and the first run on the TTM for this subject yielded values significantly higher than on succeeding runs. This first run was not plotted in figure 4. A repeat run by the subject on the TTM produced much more consistent results and, had there been time for additional runs on both treadmills, the subject would probably have been much closer to the group.

The TTM has slightly higher metabolic costs at all grades used. Because of the decision to mix grades and speeds (per a clinical protocol) and in view of the small amount of time available, the individual effects of these factors directly could not be evaluated. An evaluation may be obliquely approached by normalizing the oxygen consumption for treadmill speed and taking the mean for each treadmill at each of the three grades. These results and their differences (table V) are consistent with experience and observation of use of the TTM; i.e., low speed walking was more difficult to manage because of the limited tread space. Running at near maximum rates was less difficult. If subject D values are eliminated at 14-percent elevation (his values are clearly not typical) the nominal difference of +2 percent is barely significant. This difference and the larger difference at low speeds may be readily explained by the small tread area of the current TTM because it is well known that minor changes in footing make significant differences in locomotor energy costs. For example, a slippery floor may

Figure 4.- Plot of oxygen uptake versus speed obtained from active and passive treadmills at three different elevations.
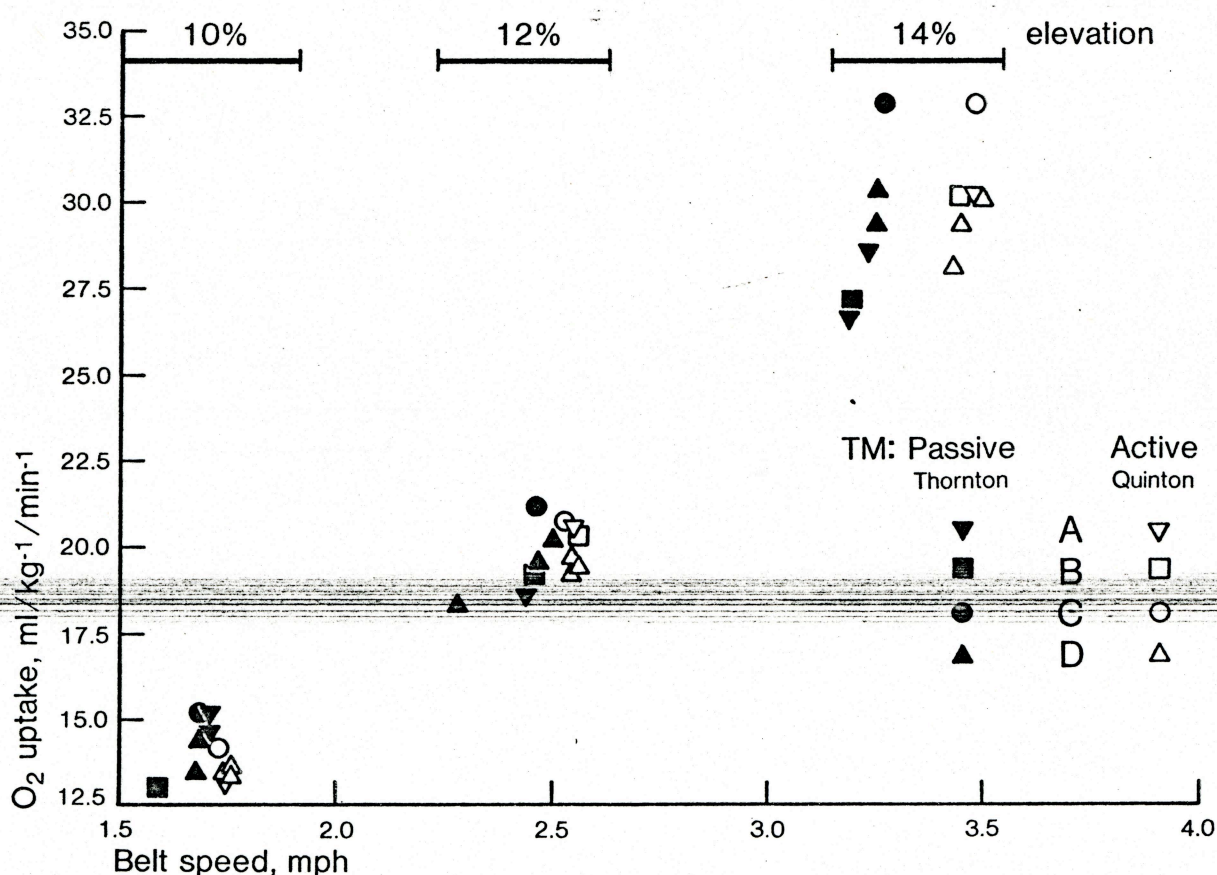
more than double the cost of level walking; also, foot placement requires attention of the subject with this model. As supporting evidence for the cost factor resulting from small tread area, no significantly increased costs were seen in the prototype passive treadmills, which had large tread areas. The effects of restricting tread areas was being investigated in 1976 when the work was stopped.

Finally, to demonstrate the capacity of this version of the TTM, an extended run was made by subject D at a fixed grade, covering virtually the entire range of the speed control[3] used and finishing with a run of +40 ml/kg/min in a 92-kilogram man, which is equivalent to 0.31 horsepower input. Figure 5 is a plot of this run. This particular unit, the first of its design, has seen dozens of hours of use without a single failure or service since it was delivered in 1976.

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[3]This treadmill has demonstrated a capacity to 10 mph with a proper control.

TABLE IV.-

Subject	Treadmill (a)	Elevation angle, percent	Speed, mph	O_2 uptake, ml/kg/min	Correction ΔO_2	O_2 uptake corrected for 1-percent grade Δ	O_2 uptake/speed, ml/kg/min/mph	Heart rate/bpm^{-1}
D	Q	10	1.76	13.4	—	13.4	7.61	82.5
		12	2.56	19.4	—	19.4	7.58	92.3
		14	3.43	28.1	—	28.1	8.19	118.0
D	Q	10	1.76	13.7	—	13.7	7.78	82.3
		12	2.55	19.2	—	19.2	7.53	96
		14	3.49	30.1	—	30.1	8.62	121.8
D	Q	10	1.75	13.5	—	13.5	7.71	78
		12	2.55	19.8	—	19.8	7.76	92.5
		14	3.45	29.4	—	29.4	8.52	117
D	T	11	1.68	13.9	0.4	13.5	8.04	83.7
		13	2.28	20.0	1.7	18.3	8.03	98.3
		15	3.25	32.0	1.7	30.3	9.32	127
D	T	11	1.69	15.5	.4	15.1	9.17	85.3
		13	2.47	21.3	1.7	19.6	7.94	100
		15	3.25	31.0	1.7	29.3	9.02	124.5
A	Q	10	1.75	13.1	—	13.1	7.49	91.6
		12	2.55	20.6	—	20.6	8.08	109
		14	3.48	30.2	—	30.2	8.68	134.3
A	T	11	1.71	15.5	.4	15.1	8.83	(b)
		13	2.5	21.9	1.7	20.2	8.08	(b)
		15	3.19	28.3	1.7	26.6	8.34	(b)
A	T	11	1.70	14.9	.4	14.5	8.52	90
		13	2.44	20.2	1.7	18.5	7.58	106.3
		15	3.23	30.2	1.7	28.5	8.82	131.6
B	Q	10	1.74	(b)	—	(b)	(b)	105
		12	2.56	20.3	—	20.3	7.93	123
		14	3.45	30.2	—	30.2	8.75	156.5
B	T	11	1.59	13.4	.4	13.	8.18	107
		13	2.46	20.9	1.7	19.2	7.80	124
		15	3.19	28.7	1.7	27.0	8.46	153
C	Q	10	1.73	14.1	—	14.1	8.15	82.3
		12	2.54	20.6	—	20.6	8.11	103.3
		14	3.48	32.8	—	32.8	9.43	133.0
C-1strun	T	13	1.69	15.5	.4	16.4	9.37	98.5
		15	2.46	22.8	1.7	23.2	9.35	119
		17	3.27	34.6	1.7	32.3	9.94	142
C-2ndrun	T	13	1.75	16.8	.4	15.1	8.93	94
		15	2.48	24.9	1.7	21.1	8.58	112
		17	3.25	34.0	1.7	32.9	10.06	143.5

[a]Q = Quinton, T = Thornton.   [b]Data lost.

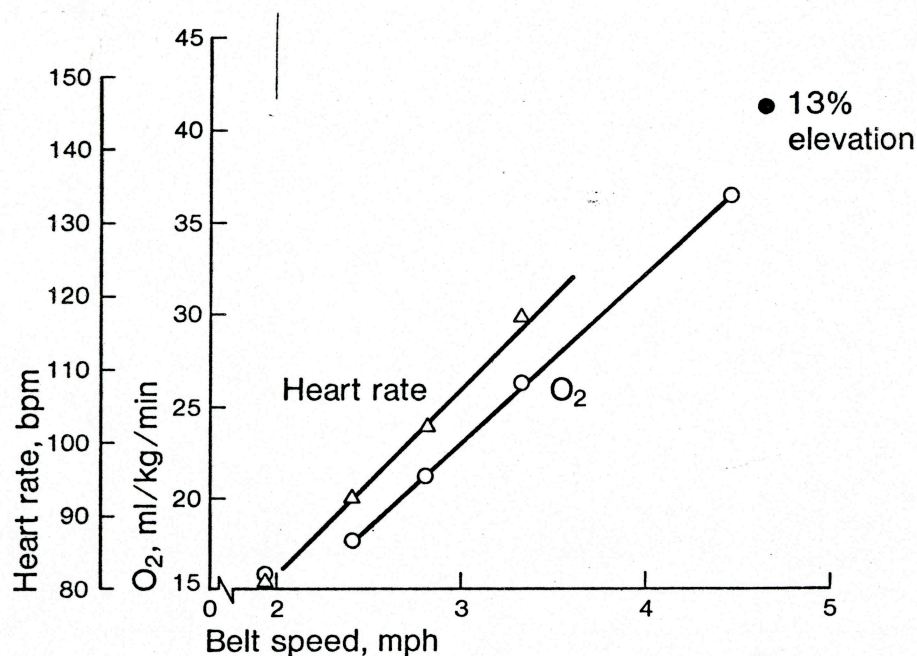## TABLE V.- Normalized means of O_2 consumption for TTM and QTM; i.e., $VO_2/Velocity = ml/Kg/min/mph$

Treadmill (a)	Percent grade		
	10	12	14
Q	7.75 ± .24 (S.D.)	7.83 ± .25	8.70 ± .40
T	8.59 ± .48	7.99 ± .37	b8.91 ± .36
			c9.14 ± .60
Δ percent, Q T	10.8	2.0	b2.4
			c5.1

[a]Q = Quinton, T = Thornton.
[b]With subject D.
[c]Without subject D.

Figure 5.- Oxygen and heart rate versus speed on TTM at 10-percent elevation.

Comment

This test was a demonstration of the obvious: work costs of an active and passive treadmill are, indeed must be, the same. Any differences such as the one seen here must arise from differences in some feature of the treadmills; e.g., inertia, speed control, or in this case restricted tread area. This latter effect can be demonstrated on a standard treadmill by progressively blocking off the tread area and measuring the difference. The progressive blocking of the tread area was tested on an informal basis in the design of this unit to determine the minimum acceptable area, which is now being used.

Of far more concern than oxygen uptake is proper design of force restraints and kinesiology in weightlessness, speed control, and similar areas, for simply producing aerobic work is an elementary task. The question of measuring external work with the treadmill in weightlessness frequently arises. This is a simple procedure and will not be discussed; but however, difficulties in understanding how it can be done should not be confused with the ability to do it.

The speed control characteristics were briefly demonstrated and are more than adequate for any foreseeable future use.

At this time, funds should be made available to complete the instrumentation of this design and, as opportunity allows, to investigate the kinesiology and other aspects of this device in weightlessness.

In summary, the TTM is a working tool that will produce any desired level of aerobic load to the cardiovascular system and, equally important, will load the locomotor and other major muscle groups and the weight-bearing skeleton to its 1 g capacity in operational flight. This device will not only be a means for prevention of adaptation of several key body systems to weightlessness in operational space flight but also a means of investigating a number of key areas of physiology, especially mechanisms of orthostasis.