Status Review of Flight Exercise Hardware, Johnson Space Center

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Background

Most space flight hardware has unique characteristics imposed by the environment including: shock and vibration, weightlessness, severe restrictions on power consumption, size, weight, and operating time and complexity. It must meet a plethora of safety, reliability and quality control requirements. Exercise devices are no exception and in addition must frequently be designed to overcome the absence of weight. Absence of weight may require substitution of mechanical forces in some situations such as in the treadmill where bungee forces replace subject weight. In other situations absence of weight is an advantage, for example, a seat is not required in bicycles or rowing machines. At the same time there are currently no natural exercises in space, e.g. locomotion, climbing, sports, etc. and relatively little upper extremity and truncal work, thus to maintain physical capacity for normal function on return to Earth, exercise devices, machines, must be supplied. Such machines become increasingly important as mission durations increase. There is virtually no literature on design of such machines for use on Earth to say nothing of space. Further, there has been surprisingly little work to date in the area of space exercise. The following is a brief catalog of major exercise gear that is qualified for flight or is at a point in development that could result in flight within a year and which can be used on Extended Duration Orbiter (EDO) flights. There may well be other devices that could meet this criterion but which are unknown to us even after a thorough survey.

Every attempt has been made to describe capacities and limits such that investigators or mission planners could utilize these items in planning. Also it should provide information to those generally interested in this area.

Format: Devices are in three categories:

I. *Flight qualified* is existing hardware which has flown or has been designed, built and tested for flight.

II. *Flight designs* which are either in or ready for construction which will meet flight specifications.

III. *Prototypes* are finished hardware near or in flight configuration usually being tested as part of the development process for flight hardware.

Each piece of equipment is identified with its designer(s)/fabricator and is *briefly* described in general with its history and status, technical characteristics and pertinent bioengineering features. The latter are considered especially important for effective use in designing exercise protocols or prescriptions. Machine forces, type as well as magnitude, and motion are critical to results. Currently there is virtually nothing in the literature or in exercise machine descriptions which quantitatively characterize forces, and all too often, little on force magnitudes. Hence there is a brief description of the terms used in Appendix A.

A summary of the devices is given with their potential applications and Appendix C has a bibliography which reflects the paucity of literature on the subject.*

Abbreviations, acronyms and definitions

BW	body weight
EDO	Extended Duration Orbiter
GEGS	GE Government Services
JSC	Johnson Space Center
K	KRUG Life Sciences
SSF	Space Station Freedom
STS	Space Transportation System
T	W. Thornton
TM	treadmill
W	H. Whitmore
WE	Whitmore Enterprise
one-g prototype	a test article which may be configured for but is not flight qualified
flight prototype	test or first article which is flight qualified
flight qualified	item constructed by procedures and of materials which meet requirements specified for flight performance, including safety features, also meets flight specifications

*Time did not allow conversion to MKS system.

Section I. - FLIGHT HARDWARE

1. Treadmill, NASA, MK I (T, W/ WE)

Figure 1.— MK I TM on Shuttle middeck.

DESCRIPTION

This device is the current standard Shuttle exercise device, designed in 1974 to meet many restrictions imposed by Shuttle constraints at that time. A schematic similar to it is shown in Figure 2. The moving tread consists of jointed aluminum sections supported by ball bearing bogies running in a track. The tread is coupled to a flywheel, brake, and tachometer through a pulley and belt system. Speed limits may be set at seven different levels by a rapid onset centrifugal brake. Earth equivalent body weight loading is accomplished using a harness and rubber bungee system. Length of the bungee cords can be adjusted to allow the equivalent subject weight loading to be increased or decreased. Tread speed is provided by an external indicator.

This treadmill version is passive (subject driven) and therefore in weightlessness the subject must lean forward tilting the force vector to overcome the mechanical friction. This is equivalent

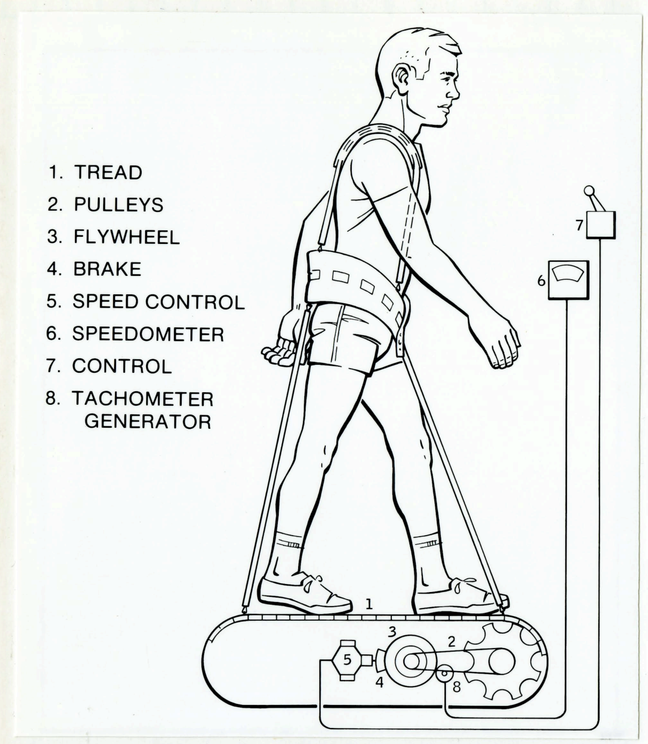

Figure 2.— MK I TM schematic.

to running uphill on Earth. The minimum one-g equivalent grade for this model is approximately 8%. As long as a passive treadmill has enough inertia not to slow down greatly between steps and the tread is of adequate size, the metabolic load provided by a passive treadmill will be the same as that provided by an active (motor driven) treadmill. Figure 3 depicts a comparison of the oxygen uptake of subjects exercising on a large motor driven unit and on this treadmill.

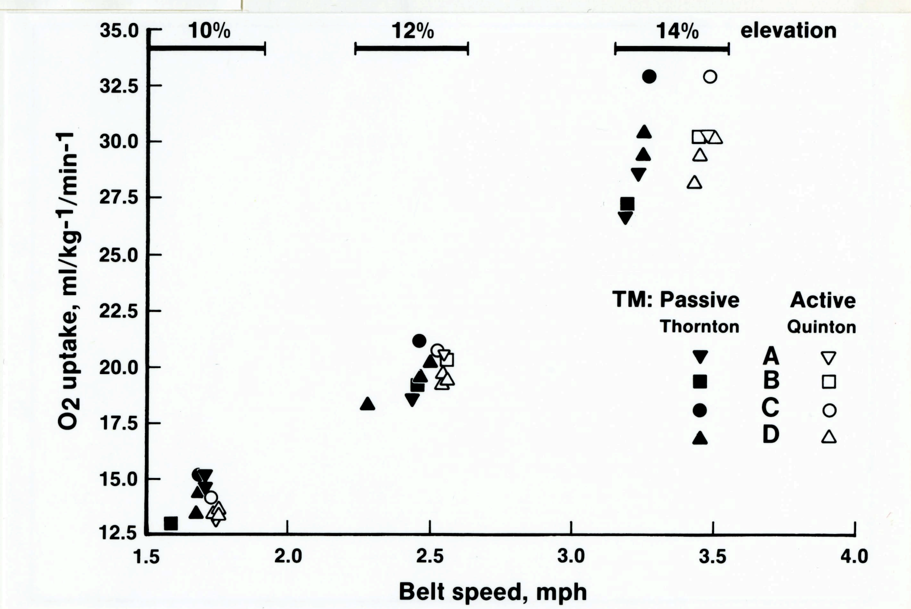

Figure 3.— Active- vs. Passive-TM O_2 uptake.

HISTORY-STATUS

This device is a direct outgrowth of Skylab experience and is an attempt to provide Earth equivalent locomotor loads to the flight crew to preserve the integrity and strength of the bones and muscles (primarily leg and back) used for normal one-g ambulation. This aerobic exercise will also maintain cardio-respiratory capacity.

A one-g prototype was constructed and tested in 1974. This unit flew some 10+ missions on Shuttle. A somewhat degraded version (Figure 1) of this prototype was purchased and has been subsequently flown as standard equipment on Shuttle. Currently it is the only exercise device flying on U.S. programs, but it is not used in any systematic fashion.

Some of the features which will be improved for the next generation treadmill are the small tread area (12 by 28 inches), the noise due to the metal tread, the elastic harness-bungee restraint system, and instrumentation.

TECHNICAL CHARACTERISTICS

Size	42.75 × 18.75 × 20.5 inches in stowed position (handle down)
Weight	70.5 lb (including instrument package and bungee cords and harness)
Belt Inertia	4.4+ slugs equivalent (calculated)
Speed	2-6+ miles per hour
Equivalent grade	varies with speed but nominally 8%
Tread	segmented aluminum
Speed Control	rapid onset mechanical brake adjustable to 7 limit speeds
Noise	85 dBA at operator level
Subject weight equivalent load	four bungees with a vertical force range of approximately 50 - 200 pounds F_z (force variation $< \pm 3\%$ with normal vertical excursion of body in locomotion)
Operational envelope (normally mounted on Shuttle middeck)	approximately 2 × 4 × 8 ft
Instrumentation Static Force, F_z (available as an accessory)	Velocity, Time, Distance external scale ± 5 lb

BIOENGINEERING

Treadmill vs overground locomotion has been extensively studied on Earth and only negligible differences were found. Such locomotion requires peak foot ground forces of ~ 1.0 to 5.0 × body weight (BW) (typically 1.3 BW walking and 2.5-3.0 BW jogging) which in turn impose several times this load on associated bones at typical repetition rates of 100-150+ min^{-1}. Metabolic rates during jogging typically range from 60-80+ percent maximum $\dot{V}O_2$. Treadmill maximum $\dot{V}O_2$ are usually taken as a reference standard (100% capacity).

Although often misunderstood, there is no difference in locomotion or effect of it between active and passive treadmills above some minimum elevation (or equivalent in zero G) required to drive the passive treadmill. A force must be applied to the tread axis to equal the friction at a given velocity on a passive TM. This is done by elevating the treadmill relative to the gravity vector of Earth, i.e., producing a force gradient along the tread. Locomotion of *any* treadmill above zero elevation on Earth puts energy *into* the machine. In weightlessness the subject *"leans"* forward against the rear bungee load and achieves the same effect. A less satisfactory alternative is to hold the handle and *push* the tread.

Other considerations in treadmill design are adequate tread length, and sufficient inertia to prevent significant variation in tread speed during the step cycle. This is the $K_3\ddot{X}$ term in Eq 1.1a and is achieved by a geared (up) flywheel in the MK I TM.

Horizontal Tread Forces F_X(at fixed speed) and equal grades:

MK I TM	Typical TM on Earth
Eq. 1.1a $F_X = K_1 + K_2\dot{X}' + K_3\ddot{X}$	Eq. 1.1b. $F'_X = K'_1 + K'_2\dot{X} + K'_3\ddot{X}'$

Another common problem in treadmill design is means of speed control. This is typically accomplished on Earth by a variable speed motor, sometimes servo controlled. This motor normally provides the power used by $K'_1 + K'_2\dot{X}$ but must reduce it to allow the machine to absorb the subject's power at any elevation above zero. In order to control speed in the MK I TM, the constant K_2, Eq 1.1a, is sharply increased by braking action above the desired limit speed and the subject becomes part of a servo loop which controls speed surprisingly well (Figure 4).

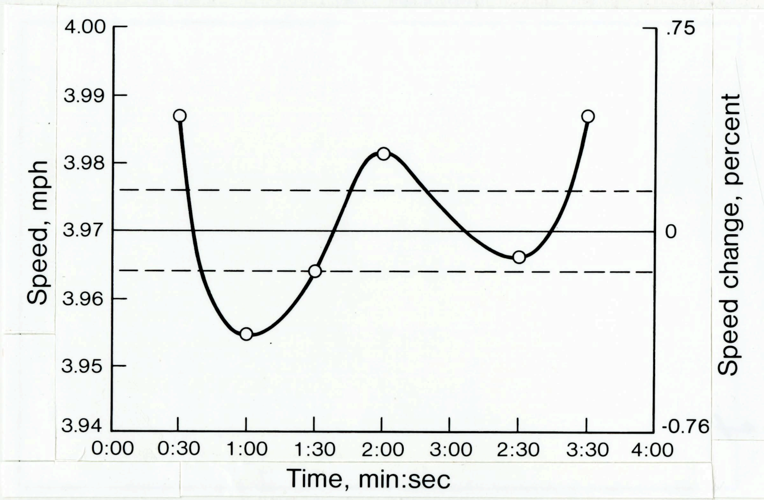

Figure 4.— Speed variations of MK I TM, dashed lines are typical range of variations of large commercial TM.

Vertical Subject Loads:

MK I TM (elastic bungees in zero G)	Typical TM (one g)
Eq. 1.2a $F_z = K_4 Z \pm \Delta Z + K_5\ddot{Z}$	Eq. 1.2b $F'_z = K'_4 + K'_5\ddot{Z}$

Ignoring the effects of vertical movements of individual body parts, the vertical forces from such a system are equivalent if K_4, or mean bungee tension, is equal to body weight, K'_4, except for the term $K_4\Delta Z$, the change in tension of the bungees with *vertical* subject movement during locomotion. This effect is reduced by using long bungees, and ΔZ is also small.

EXPERIENCE

This unit was designed in 1974 with many recognized limitations imposed by STS requirements and very limited funding. These include: noise, small tread surface, lack of adequate instrumentation and bungee/harness problems. Such problems are addressed in the MK II TM as curently designed.

A brief study of kinesiology in flight vs one g on the MK I TM has been done and the necessary force and complete kinematic studies are now awaiting flight opportunities. A series of KC-135 flights have been made, but these studies were neither in steady state conditions nor adequately controlled.

2. SLS-1 Bicycle Ergometer (GEGS/GEGS)

Figure 5.— SLS-1 bicycle ergometer showing the extensive restraint system.

DESCRIPTION

This ergometer was designed to provide metabolic loading by a standard exercise on the SLS-1 mission. The equipment consists of a variable work load, driven by hands or feet, that is controlled by the subject's heart rate, manual adjustment, or computer control. It is operational in the one-g environment with the subject seated or supine. Major assemblies of this ergometer require calibration once a year to assure optimum performance and accuracy. It is a commercial ergometer load unit (constant power) repackaged with accessories for this mission.

HISTORY/STATUS

Two units were designed, fabricated and flight qualified for use in the Spacelab module. There are no known plans for this unit other than future Spacelab missions. It has been tested in "zero-G" flights.

TECHNICAL CHARACTERISTICS

Size, without subject	24 × 25 × 49 in.	Input power (load)	10-350W
Weight	190 lb	Pedal speed range	40-80 RPM
Power, operating	50W		

Subject force load is servo driven by pedal rate to provide force to maintain constant input power, i.e., constant subject load. Load may be heart rate controlled.

INSTRUMENTATION

Work load, pedal rate, heart rate.This unit would require extensive revision to fit the Shuttle middeck.

BIOENGINEERING

Because of its simplicity of motion and pedal forces, bicycle ergometry has many advantages as a standard metabolic load for the body and can provide up to approximately 100% of treadmill maximum $\dot{V}O_2$ loading. This makes it an excellent cardiorespiratory exercise training device. As demonstrated on Skylab, it is not useful for locomotor musculoskeletal loading since maximum forces are a fraction of BW.

Good bicycle ergometers produce subject forces of the form shown (Eq. 2.1), and this is accomplished by the SLS-1 ergometer,

Eq. 2.1 $$F = K_{b1} + K_{b2}\,\dot{\theta}^n + K_{b3}\,\ddot{\theta}$$

with the viscous friction and inertial components $K_{b2}\,\dot{\theta}^n$ and $K_{b3}\,\ddot{\theta}$ respectively being predominant. The constant K_{b2} is varied inversly with velocity $F(\theta)$ to maintain fixed input power in constant load machines such as this one.

A major difference between weightlessness and one g is the need for a seat. Low pedal forces and absence of body weight make a seat useless in flight. A pair of side rails allow normal operation with slightly extended legs.

There are small, probably negligible biomechanical differences from riding on Earth.

EXPERIENCE

There is no flight experience with this device but complaints have been registered about the restraint system in one g. Conversely, hundreds of hours experience were gathered on an earlier, now extinct, Skylab bike ergometer which functioned well after restraint problems were resolved.

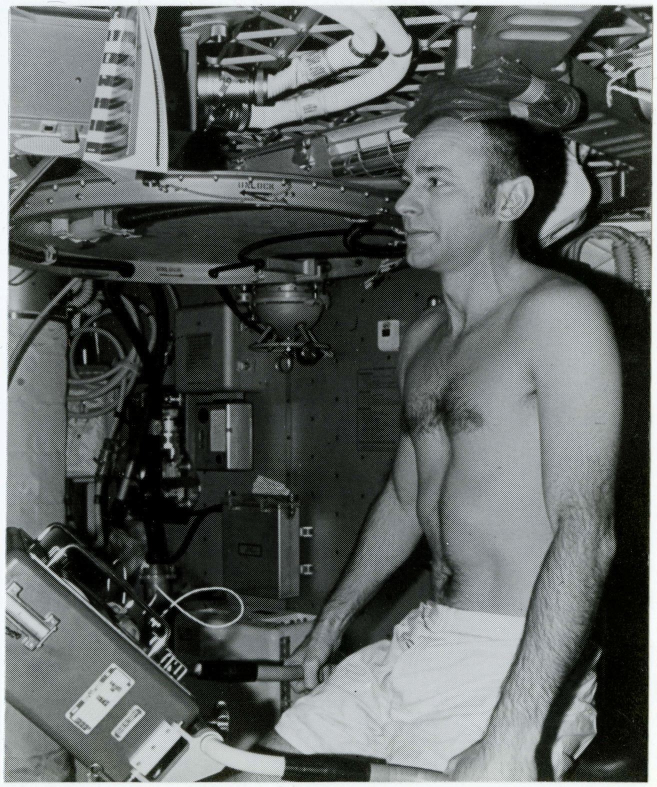

Figure 6.— Skylab 2 Cdr. Bean riding the bike using arm and head to provide counterforces.

3. Rowing Machine NASA MK I (T, W/WE)

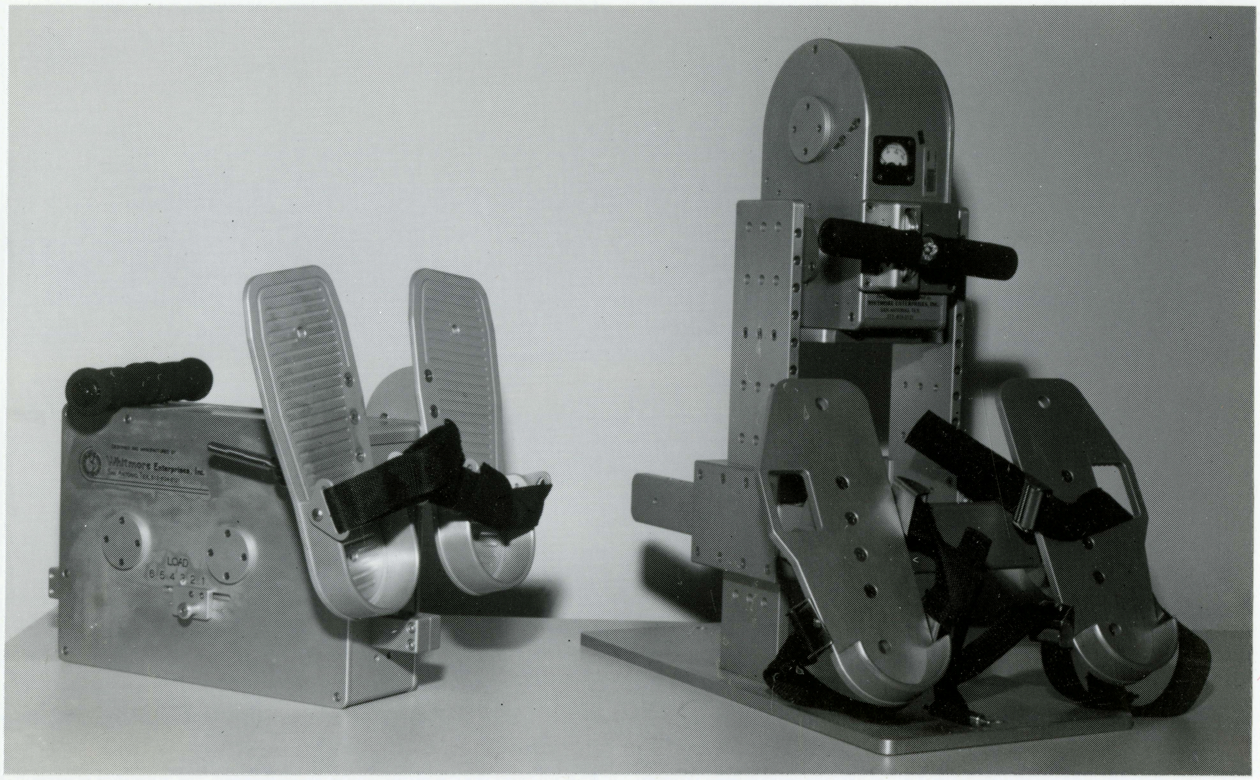

Figure 7.— Flight prototype (left) and one-g prototype (right) rowing machines. Size may be judged by foot plates. The flight unit will be attached to standard Shuttle middeck mounts and foot restraints adjusted such that subject is at an angle to the machine.

DESCRIPTION

This rower is a compact device which allows a close approximation of the magnitudes and types of force and motion seen with well-designed rowing machines in a one-g environment. A supporting seat is not required in weightlessness. Exercise forces and foot restraints will keep the astronaut aligned with the device. A handle and cable replace the oar, similar to the arrangements used in conventional machines. Six discrete load levels are available with continuous mean power inputs to 300 W. The device can be stored in a Shuttle locker and requires no external power.

HISTORY/STATUS

The passive Faraday disc load unit was designed in 1966 and has been extensively used since then, proving to be efficient and reliable. A one-g prototype (Figure 8) was constructed and tested, including "Zero-G" flights in 1987. The flight version was delivered earlier this year, certified for flight and is currently awaiting a flight opportunity.

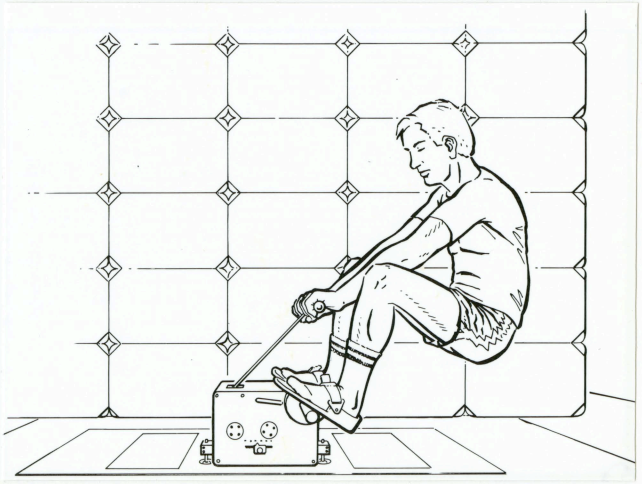

Figure 8.— Sketch of MK I rowing machine in use on middeck.

TECHNICAL CHARACTERISTICS

This rower has six settings which allow for different resistance loads to be applied. The load unit consists of an adjustable flux permanent magnet assembly on a Faraday disc with large fixed inertia. This is connected to the cable and handle through a transmission and unilateral clutch.

Size	12 × 16 × 24 inches with foot supports attached
Weight	26.5 lb (Shuttle locker stowable)
Load inertia (slugs)	>10
Stroke	10 ft max
Stroke rate	0-30+ min^{-1}
Operational envelope	approximately 3.5 × 4 × 5 ft
Power, mean	300 Watts continuous - 400 W - 15 min
Max load force	450 lb
Noise level	<65 dBA at 3 ft

INSTRUMENTATION

A calibrated tachometer on the flywheel provides indication of work rate as a function of six load levels. This information is available as a voltage analog from which forces and stroke rate may be derived.

BIOENGINEERING

Forces vary greatly during the various phases of actual rowing e.g. stroke phase oar forces include: water drag against the oar, water inertia accelerated by oar, drag and inertia of boat and load, and individual rower's inertia. Pertinent return phase forces include: rower's inertia, oar weight and inertia, and boat drag and inertia. Quality rowing machines provide several levels of inertia and resistance to simulate boat and oar load plus the inherent rowers inertia. This simplified simulation of actual forces is widely accepted. The same forces are simulated in the MK I flight machine.

Typical, near maximum performance forces from a well-designed rowing machine on Earth are shown in Figure 9.

As can be seen from force curves and kinesiology, this exercise provides moderately heavy arm and back, but relatively small leg force loads. Motion is unique to this exercise, involving many body elements in repetition which can produce metabolic loads equal to or even exceeding that of locomotion. The rower serves as a good device for cardiovascular maintenance and provides exercise to arm, back, and to some extent, leg muscle groups.

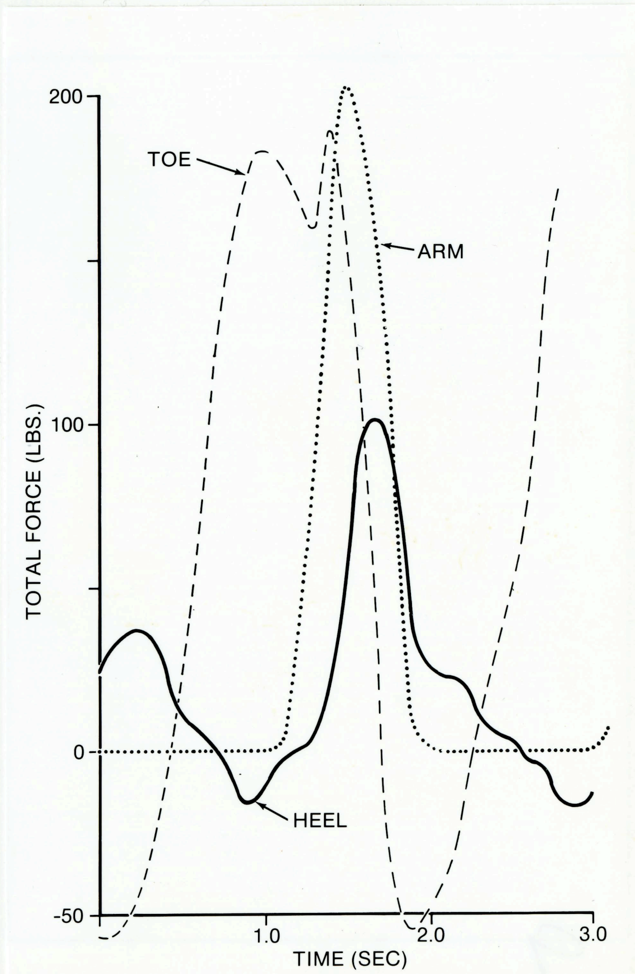

Figure 9.— Forces from maximum effort by trained 200 lb subject on a quality commercial rowing machine. Handle, foot and toe forces are shown. From JSC Internal Study, Thornton, 1986.

Oar (handle forces). A conventional rower produces forces of the form:

Eq. 3.1 $$F_r = K_{r1} + K_{r2}\dot{X}^n + K_{r3}\ddot{X}$$

By changing gear ratios both resistance and inertia are increased.

The present rowing machine has fixed inertia and variable resistive drag elements but limited size and funding required a gearing ratio which varies with the stroke length, X. This can be simply corrected but there will be biomechanical differences whose effect are best measured and remain to be done.

EXPERIENCE

Zero-G flights and limited one g use indicate that the device is a good approximation of commercial devices.

4. Body Weight Load for Isotonic Exercise (T, W/WE)

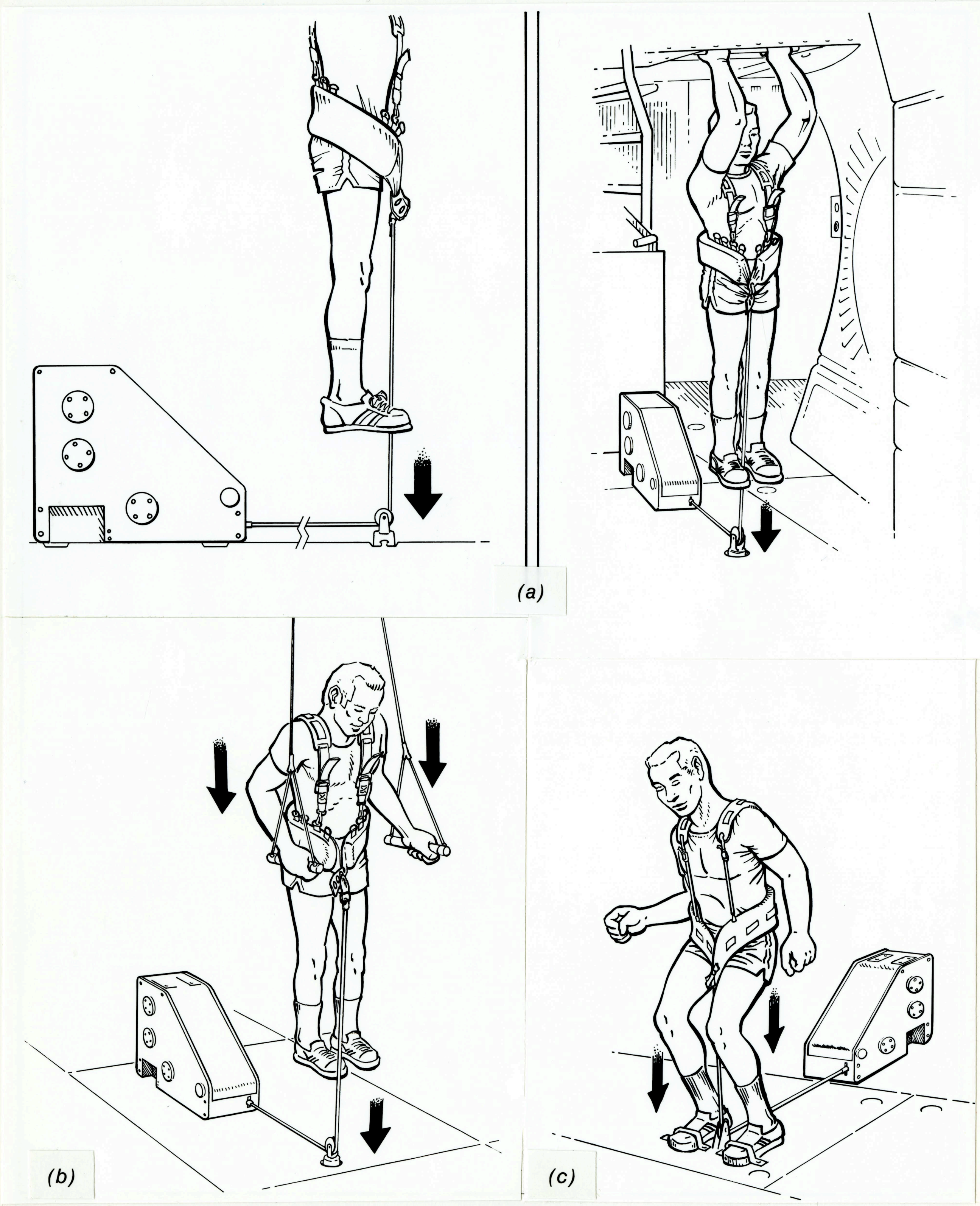

Figure 10.— (a) Arrangement of body load unit and harness to allow pull ups using existing bar on Shuttle middeck. (b) Arrangement for "dips" using same equipment plus two handles. (c) "Squat" arrangement.

DESCRIPTION

This device was designed to replace the force of body weight on a subject in weightlessness allowing some common heavy isotonic exercise such as chins, dips, squats, etc. (Figure 10a,b,c). It is locker stowable and is used with the MK I treadmill harness and a few simple adjuncts on the Shuttle middeck. A cable transmits the forces. Since loads of up to 250 lbs. are available, safety limits are important and while extension velocities are unlimited, return velocities cannot exceed 2 ft sec^{-1}.

BACKGROUND/STATUS

It was originally conceived as an adjunct to the isometric dynamometer to study neuromuscular inhibition and possibly reverse its effects. However, its simplicity makes it attractive as an exercise device whenever body weight is required. One flight item has been delivered and awaits a flight opportunity.

TECHNICAL CHARACTERISTICS

Size	9 × 16.5 × 20.25 in.
Weight	82 lb
Power	none
Force	selectable 100, 150, 200, 250 pounds ±2% through stroke
Cable stroke	4 feet - a few inches of initial displacement are required to develop full force.

A series of springs supply forces which are made constant by mechanical linkage. Inertia is very low. To avoid the potential damage from "dropping" 250 lbs. the return velocity is limited to 2 ft sec^{-1}, i.e., below this rate force is unaffected but goes to zero when this rate is reached. Extension velocity is unlimited.

BIOENGINEERING

By simply replacing body weight with a constant force in weightlessness the total axial force F_z becomes almost exactly equal to forces on Earth for "vertical" body motions. Coupling to the body is by way of cable and body harness. This force unit will attach to a middeck stud with a cable pulley to another stud (figure 10a). A handle in the Shuttle structure will allow chinning, two hand grips supported from this will allow dips (figure 10b), and squats may be done by simply standing over the pully (figure 10c). The exercises chosen are frequently used on Earth for crew conditioning and more importantly are the key motions involved in emergency egress. At low velocities where acceleration is neglegible, external weights may be simulated. The large increments in force were the result of inadequate funds available, but this principle could be used to produce smaller increments or even continuous variation with inertia that could simulate external weights.

Body Weight Exercise:

Zero G with constant force	Earth
Eq. 4.1a $F_z = K_9 + k_{10}\ddot{Z}$	Eq. 4.1b $F'_z = K'_9 + k_{10}\ddot{Z}$

where K = selected constant force (equivalent body weight)

K'_9 = body weight = mass gravity

k_{10} = mass

5. Isometric Dynamometer (T, W/WE)

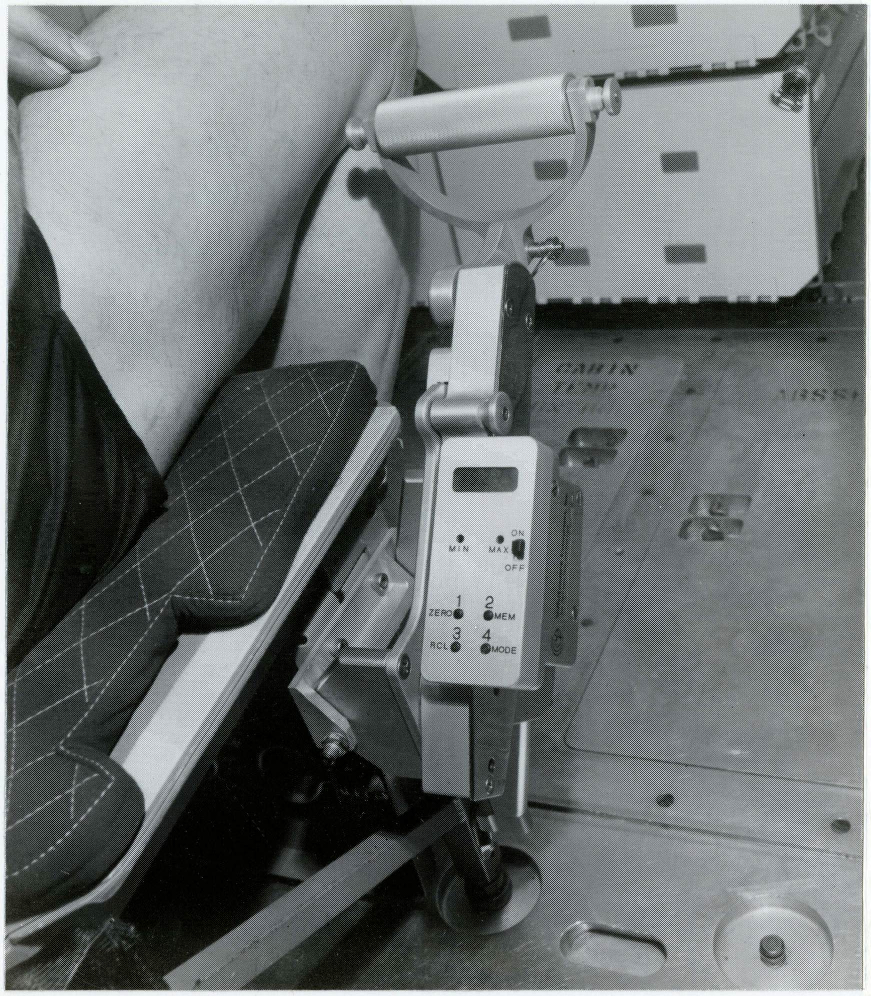

Figure 11.— Flight isometric dynamometer mounted on middeck seat. Handle shown allows elbow (up and down) and shoulder (fore and aft) measurements. By replacing the handle with a stirrup, the unit pivots into a lower position allowing knee (fore and aft) and hip (up and down) movements.

DESCRIPTION

This device is an extremely simple approach to measurement of maximum bidirectional isometric strength of elbow, shoulder, knee and hip. A strain gauge torque element measures, digitally records and displays the maximum force. A handle and heel stirrup allow these measurements from a crewperson in a standard Shuttle seat (Figures 11 and 12). The assembly clips to or can be removed from a standard seat accessory attachment in seconds. It is battery operated and self-contained.

HISTORY/STATUS

This dynamometer was designed to allow on orbit and immediate post landing strength measurements to document neuromuscular inhibition of strength and in conjunction with the isotonic ergometer to study development and possible reversal of this phenomenon in flight. A flight unit has been produced and is certified for flight. Subsequently, alterations have been made to the middeck such that other equipment now interferes with use of the device in the leg position post landing and this problem is being worked. It is currently available for flight use.

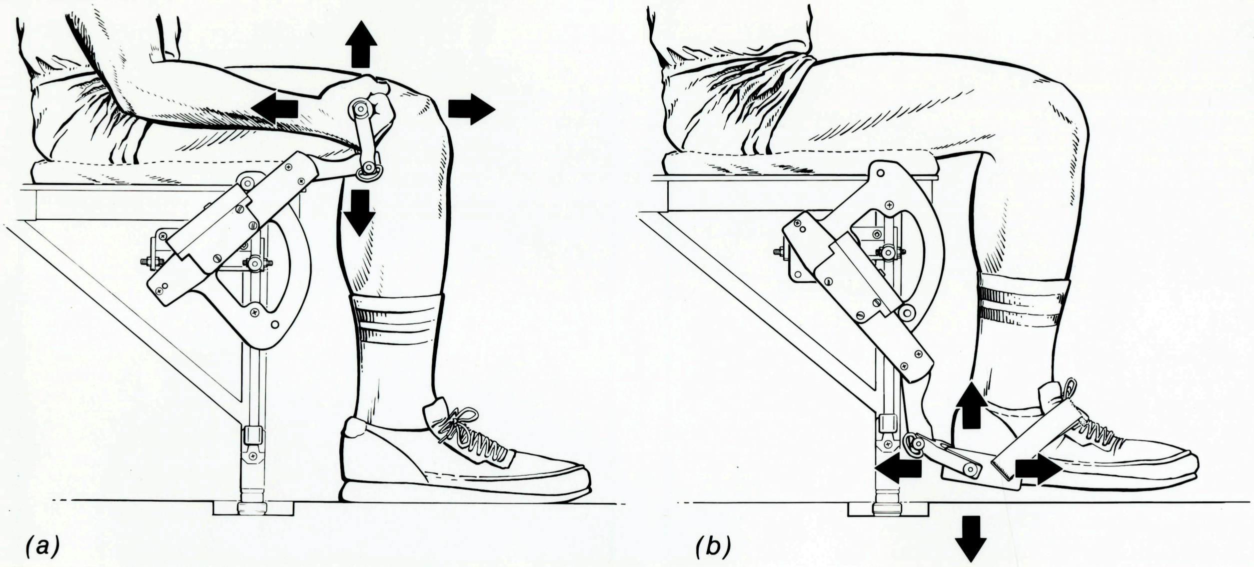

Figure 12.— Isometric dynamometer (a) Arm (elbow and shoulder) measurements. (b) Leg (knee and hip) measurements.

TECHNICAL CHARACTERISTICS

Size	10.75 × 4.75 × 8 in.
Weight	9 lb
Power	batteries, 20+ hours
Torque Range	0-50 ft lbs
Accuracy	±1% F.S.
Resolution	0.1 lb
Linear force (translated) capacity	250 lb max
Locker stowable	
Operating position	right side of Shuttle seat

BIOENGINEERING

Isometric strength is also a good measure of isokinetic strength at low velocity and is appropriate to measurement of strength required in emergency maneuvers. A limitation of this one simple measurement scheme is its sensitivity to off axis forces, i.e., the subject is required to take care in maintaining correct measurement position. A study using the device in one-g showed reproducibility equal to other commonly used methodologies.

6. Stationary Locomotion Apparatus (T/JSC)

Figure 13.— Cdr. Engle jogging in place on STS-2.

DESCRIPTION

Currently, the simplest flyable exercise apparatus to date produces surprising performance. It consists of walking, jogging or jumping in place under a constant load (Figure 13 and 14). Only the body harness and elastic bungees are required; however, the constant force load of the body weight exerciser (Item 4) would function even better.

BACKGROUND

This arrangement was flown on STS-2 and worked well (Figure 14). The hardware is simple, qualified and available.

TECHNICAL CHARACTERISTICS

Force load	equivalent BW (100-225 lb)
Volume stowed	<1/2 ft^3
Weight	5 lb
Power	none
Envelope, operational	2 ft × 3 ft × subject height plus 3 in.

BIOENGINEERING

Stationary locomotion produces major F_z foot-ground forces surprisingly similar to ordinary locomotion (Figure 15). Kinematics are obviously different, but metabolic loads approach those of the treadmill.

The weight force of the individual leg segments are not reproduced. If the constant force generator is used, there is a virtually perfect reproduction of axial and foot ground forces on Earth.

Figure 14.— Sketch of jogging in place on Shuttle middeck. Harness and bungees attached to existing studs comprise the hardware.

Bungee in Zero G

Eq. 6.1a $$F_z = K_1 \cdot (Z \pm \Delta Z) + k_2 \ddot{Z}$$

Earth

Eq.6.1b $$F'_z = K'_1 + k'_2 \ddot{Z}$$

Such an arrangement could provide significant exercise, musculoskeletal for legs and back, and cardiorespiratory under circumstances which preclude more elaborate devices, e.g. Space Station Safe Haven or heavily loaded Shuttles.

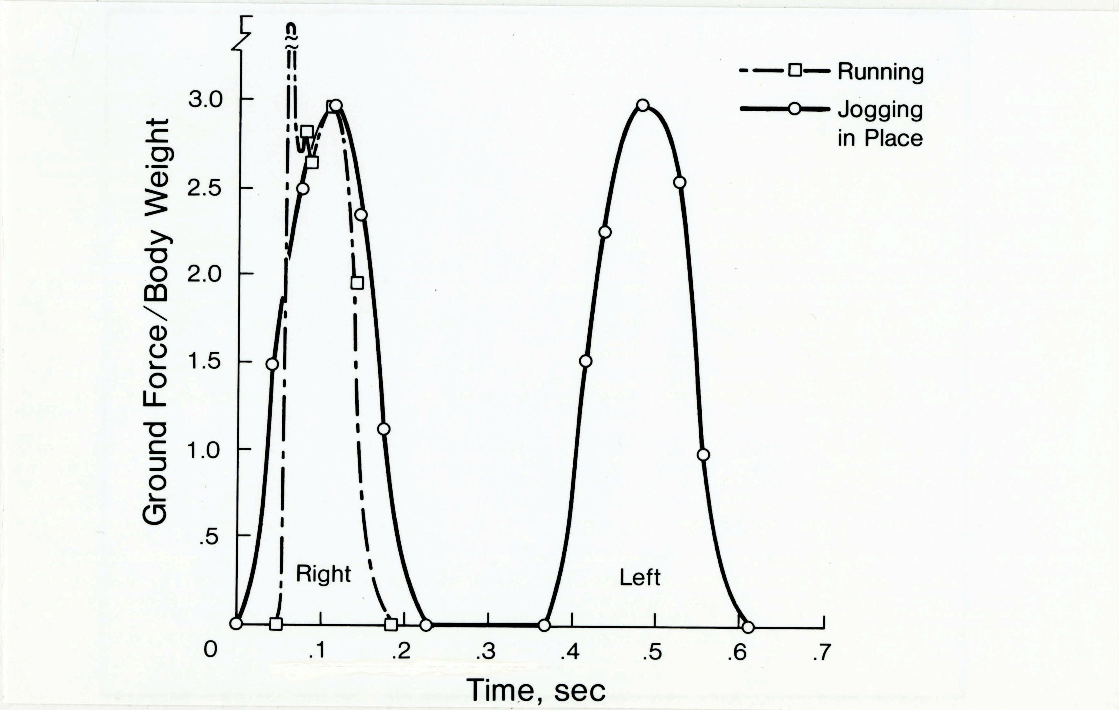

Figure 15.— Foot ground forces from jogging and running in place. Jogging has a prominent heel strike transient while running in place was on toes.

Appendix A

Force equations

The conventional human reference system has been used, e.g.:

Vertical axis - Z

Down +

Up −

Lateral axis - Y

Right +

Left −

Fore-Aft axis- X

Forward +

Backward −

Conventional symbology for differentials of displacement with time are used ,e.g.:

X = displacement

$\dot{X} = \text{velocity} = \frac{dX}{dt}$

$\ddot{X} = \text{acceleration} = \frac{d^2X}{dt^2}$

θ = angular displacement

$\dot{\theta}$ = angular velocity

$\ddot{\theta}$ = angular acceleration

Constants, K, may include one or more fixed values or terms.

As used here, "resistance" is the term of physics, a mechanical quantity which produces force with motion and dissipates energy. Do not confuse this with the general misuse of "resistance" to signify any form of force.

Accurate definitions are not academic niceties for the biomechanical differences between types of forces and effects they produce are immense, e.g. the difference between a spring

$$F_s = K_s X$$

and a mass in a gravitational field

$$F_{weight} = K_m g + K_m \ddot{X}$$

A brief commentary on this is in Thornton, *Work, Exercise and Space Flight*, Sec. III, NASA Conf. Pub-3051, 1986.