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Human Powered Centrifuges on the Moon or Mars

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Abstract Exposure to microgravity leads to "cardiovascular deconditioning" (CVD), because of the fluids shift toward the thorax. CVD is characterised by: 1) a decrease of plasma and interstitial fluid volumes, 2) a relative increase of the erythrocytes mass, 3) a decrease of arterial diastolic pressure, of the stroke volume, of the end-diastolic volume and of the left ventricular mass. CVD can be expected to occur also in astronauts living permanently on Lunar or Martian bases, since on these celestial bodies the acceleration of gravity is about 0.165 and 0.379 the Earth value. In these conditions, cycling on appropriately constructed tracks may be useful to recreate artificial gravity and to allow the astronauts to perform physical exercise. Indeed, a cyclist riding a bicycle on a circular track, generates an outward acceleration vector which depends on the radius of the track and on the ground speed. The vectorial sum of this last and the acceleration of gravity acts in the head to feet direction, thus increasing the effects of gravity on the cardiovascular system. We propose to construct on a Lunar or Martian base a circular "track tunnel" with a radius of 25 m. We show here that when cycling on this track tunnel at speeds between 10 to 15 $\mathrm{m \cdot s^{-1}}$, astronauts will generate a g vector acting along the head to feet axis ranging from 0.44 to 0.99 of the Earth value. We suggest that the logistics and feasibility of these track-tunnels should be studied in view of their possible implementation.

Keywords Cardiovascular deconditioning · Countermeasures · Microgravity · Space flight

Introduction

Since the early years of the Space flight era it was clear that exposure to real or simulated microgravity leads to a series of consequences on the function of several physiological systems, the most relevant of which occur at the hormonal, musculoskeletal and cardiovascular level (Pavy-Le Traon et al. 2007; Charles et al. 1994; Hinghofer-Szalkay 1996). The paragraphs that follow are devoted to a discussion of a possible means for preventing cardiovascular deconditioning (CVD) during exposure to zero-, Lunar- or Martian gravity. This approach is likely to reduce substantially also the effects of microgravity on the hormonal and musculoskeletal systems. These, however, will not be considered here.

Cardiovascular Deconditioning

The first effect of the physiological response to prolonged exposure to microgravity is the shift of body fluids toward the head and thorax, leading to a distension of the central vasculature. This is "read" as a fluid-volume overload, mainly by the so called volume sensors of the cardiovascular system located in the walls of the vena cava, of the pulmonary vasculature and of the atria. An integrated two-step cardiovascular-neuro-endocrine response follows: 1) an immediate reduction of total peripheral resistance together with a slowing down of heart rate and a reduction of cardiac inotropism and 2) a reduction of the circulating volume, because of increased water excretion by the

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kidney. The kidney is “informed” about the circulatory overfilling by circulating hormones and, probably, by a decrease of sympathetic tone of its arterioles.

The hormones involved in the renal response to prolonged exposure to microgravity are mainly renin-angiotensin, aldosterone and antidiuretic hormone (ADH). The functional loop increasing the renal excretion of water and electrolytes, similar to the Henry–Gauer reflex, is started by the onset of microgravity exposure which causes the fluid shift. The consequent rise of the venous (low) pressure brings about an increase of the filling pressure of the right atrium (preload). A central reflexive inhibition of the release of ADH, aldosterone and renin-angiotensin leads finally to the increased renal excretion of water and electrolytes. Renal excretion of sodium and water is synergistically regulated by atrial natriuretic peptide as well, a hormone released by atrial cells stretched by the increased venous return.

According to Gazenko et al. (1985) and Yegorov et al. (1988a, b), the relatively rapid responses of the cardiovascular system to microgravity exposure are: 1) a decrease of plasma volume, 2) a decrease of circulating blood and interstitial fluid volumes, 3) a relative increase of the mass of erythrocytes and haemoglobin and 4) a decrease of arterial blood diastolic pressure. Delayed adaptive reactions include a further decrease in circulating blood volume, due to inhibited erythropoiesis, and a consequent decrease of erythrocyte mass and haemoglobin concentration (Lane et al. 1996). The blood flow to the heart reaches a new equilibrium point characterised by decreased stroke volume (SV) and diastolic blood pressure.

The final effect of the above compensatory mechanisms, as the time of exposure to microgravity increases, is the establishment of a new set point of the cardiocirculatory system, different from that which is in force on Earth, and defined CVD. CVD also includes carotid baroreceptor resetting. Indeed, when living in the terrestrial eugravitational environment, the prevailing blood pressure at the carotid sinus level, where arterial baroreceptors are located, is equal to the pressure at the aortic bulbus minus a quantity equal to “$\rho \cdot g \cdot h$”, where h is the vertical distance between the two anatomical sites. In microgravity, the hydrostatic pressure component “$\rho \cdot g \cdot h$” tends to zero, this leading to a corresponding increase of carotid distending pressure (CDP). In turn this gives rise to a carotid baroreceptor vagal-cardiac reflex whose overall, chronotropic and inotropic effects on myocardium lead to a decreased effectiveness of the cardiac pump. The sigmoid relationship between CDP and R–R intervals of the heart beats shows a down-regulated resetting of the carotid baroreceptor’s response which becomes apparent even after short (4–5 days) exposure to microgravity. The reduced R–R interval response to CDP persists up to 10 days after landing, contributing to the orthostatic hypotension (Fritsch et al. 1992).

The most relevant effects of real or simulated microgravity on heart function before, during and after Space flights are the decreases of the SV (ml), of the ventricular end-diastolic volume and of the estimated left ventricular mass (Charles et al. 1994; Dorfman et al. 2007; Henry et al. 1977). In addition, echocardiographical studies show that cardiac function and myocardial contractility do not deteriorate. In fact, by plotting ventricular end-diastolic volume versus SV, the curves follow a straight line despite decreased cardiac size and SV (Charles et al. 1994). It can be concluded that the apparently reduced ventricular mechanical performance is due to extrinsic causes (Frank–Starling mechanism) rather than to intrinsic ones (changes of myocardium mass and/or contractility).

The above-described physiological adaptations to microgravity or, better, deconditioning to eugravity, give rise to problems upon return to Earth of Space crews. The term “cardiovascular deconditioning” (Bungo and Johnson 1983; Bungo et al. 1987) summarises the different symptoms affecting the Space crews upon reentry to Earth. They are mainly dizziness, increased heart rate and heart palpitations, an inability to assume the standing position (orthostatic intolerance), pre-syncopal feelings due to postural stress and reduced exercise capacity. Orthostatic intolerance and a pre-syncopal feeling, approaching loss of consciousness, are due to inadequate perfusion of the brain. The impairment of the overall cardiocirculatory response to gravitational stress is caused by the impaired control of blood pressure due to the resetting of carotid baroreceptors and to the loss of fluid volume and to the consequent mismatching of the beat-to-beat adjustment of SV to venous return. The decreased exercise capacity, however, is only in part attributable to the cardiocirculatory deconditioning since a fraction of it is due to musculoskeletal decay, which is also an effect of microgravity exposure (di Prampero and Narici 2003).

The changes induced by microgravity that were described above tend to favour orthostatic intolerance. However, it was observed that, in a subset of astronauts able to better withstand the post-flight orthostatic stress, the aortic compliance decreased, as compared to their orthostatic intolerant colleagues (Delp 2007;

Tuday et al. 2007). This observation was also reproduced on rats after hind-limb suspension (Hwang et al. 2007). Thus, the adaptation of the cardiovascular system to real or simulated microgravity is a complex phenomenon that it will not be discussed further. Suffice it to say that the final result of the balance among the factors that favour orthostatic intolerance and those that oppose it is generally tilted towards the former, a fact that is reversed in a relatively short time upon reentry to normal gravity. Indeed, complete recovery of cardiovascular function is reported at about 10 days after short-term Space flights (4–10 days), whereas, a period of 4 weeks is required for full recovery of longer (8–12 months) Space flights (Churchill and Bungo 1997).

Countermeasures to CVD

Since the early reports of CVD following short and prolonged Space missions, scientist have studied and tested different countermeasures to prevent both CVD and reduced exercise capacity. Nowadays, countermeasures include: 1) on-board physical exercise consisting of cycloergometric and/or treadmill exercises for at least 2 h per day; 2) utilisation of special elasticised suits ("Penguin" suits) providing passive stress of antigravity muscles of the legs and torso, worn by astronauts for approximately 8 $\text{h} \cdot \text{day}^{-1}$; 3) lower body negative pressure devices and 4) ingestion of water and salt tablets, up to 1 l of saline solution, just before the reentry and landing manoeuvres. However, these countermeasures are only partially effective.

The only way to prevent at one and the same time the decay of the cardiovascular function and of the musculoskeletal system, is "artificial gravity" the main aim of which is to create in space an acceleration vector mimicking gravity, thus generating hydrostatic gradients in the circulatory system of the astronauts and reproducing gravity proprioception during exercise. To this aim short radius centrifuges located on board of the space stations have been propose by several authors (Burton 1994; Burton and Meeker 1997; Cardus 1994; Vil-Viliams et al. 1997). These will not be discussed here, but, with a few exceptions (Greenleaf et al. 1997), these systems need an external power supply and their mechanics is not easily compatible with an exercising subject.

To overcome these drawbacks, in 1991 Antonutto et al. proposed the Twin Bikes System consisting of two coupled bicycles, ridden by two astronauts, counter-rotating along the inner wall of a cylindrical Space module (Antonutto et al. 1991; di Prampero 2000). However, the small diameter of the Space module places severe limitations to the practical application of these ideas.

Aim of the Study

The occurrence of CVD is not limited to space flight, but it is likely to manifest itself also in astronauts living in manned bases on the Moon or Mars.

Indeed, on these celestial bodies, the acceleration of gravity is substantially smaller than on Earth, amounting to:

$$g_{\text{Moon}} = 1.62\ \text{m}\cdot\text{s}^{-2}\ (0.165\ \text{g})$$

$$g_{\text{Mars}} = 3.72\ \text{m}\cdot\text{s}^{-2}\ (0.379\ \text{g})$$

Hence, on the Moon or on Mars the hydrostatic component of the blood pressure ($\Delta P = \rho \cdot g \cdot h$) is reduced in direct proportion to the corresponding acceleration of gravity. Thus, on Lunar or Martian bases, the arterial pressure at the carotid bifurcation and at the feet of standing astronauts of average stature, for an arterial pressure of 100 mmHg in the aortic bulbus are substantially different from those prevailing on Earth, as shown in Table 1. As a consequence, astronauts living for long periods on Lunar or Martian bases will likely undergo CVD. To avoid this last we propose that astronauts living for long periods of time on Lunar or Martian bases undergo exercise daily, riding a bicycle along a curved path. With this in mind and considering the dimension of the lunar station proposed by Grandl (2007), we will discuss below the effects of cycling on a circular track with a radius of 25 m (Fig. 1). For these tracks to be operational on the Moon or Mars, they must be enclosed in appropriate structures within which the air is maintained at a predetermined pressure and temperature. Hence, they will here be defined "track tunnels".

Table 1 Arterial pressure (mmHg) at the carotid bifurcation and at the feet of standing astronauts of average stature, for an arterial pressure of 100 mmHg in the aortic bulbus on Moon, Mars and Earth

	Head (mmHg)	Feet (mmHg)	Head · Feet^{-1}	g ($\text{m}\cdot\text{s}^{-2}$)
Moon	97	113	0.86	1.62
Mars	92	130	0.71	3.72
Earth	80	180	0.44	9.81

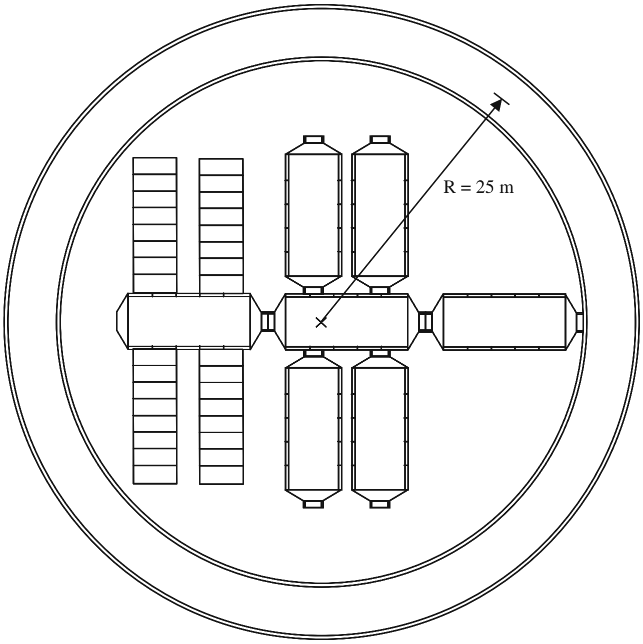

Fig. 1 Schematic view of a cycling tunnel positioned around the Lunar Base (R = radius of track tunnel). After Grandl (2007), modified (Grandl 2007). R: Radius of "track tunnel" ($R = 25$ m)

Theory and Calculations

Cycling along a curved path induces a centrifugal acceleration vector given by:

$$a_c = v^2 \cdot R^{-1}$$

where v is the ground speed and R the radius of curvature of the cyclist's path. Since a_c is applied horizontally outwards, to compensate for it the cyclist must lean inwards so that the vectorial sum of a_c and the constant acceleration of gravity lies in the plane which includes the centre of mass of the system and the points of contact between wheels and terrain (Fig. 2). So, the resulting vector (g') can be calculated by simple geometry as:

$$g' = \left(g_{cb}^2 + a_c^2\right)^{0.5}$$

where g_{cb} is the acceleration of gravity on the celestial body considered ($g_{\mathrm{Moon}} = 1.62\ \mathrm{m} \cdot \mathrm{s}^{-2}$ and $g_{\mathrm{Mars}} = 3.72\ \mathrm{m} \cdot s^{-2}$).

It can therefore be readily calculated that for v ranging from 10 to 15 $\mathrm{m} \cdot \mathrm{s}^{-1}$ (36 to 54 $\mathrm{km} \cdot \mathrm{h}^{-1}$) and R = 25 m, g' ranges from 4.32 to 9.14 $\mathrm{m} \cdot \mathrm{s}^{-2}$ on the Moon andfrom 5.46 to 9.74 $\mathrm{m} \cdot \mathrm{s}^{-2}$ on Mars, i.e. from 44 to 99% of the Earth gravity. So, a cyclist riding a bicycle on a circular track, in its curved parts will generate a force acting in the head to feet direction which can be expected to mimic to a certain extent the effects of Earth gravity on the cardiovascular system. Indeed, it can be calculated that, under these conditions, and assuming $v = 10\ \mathrm{m} \cdot \mathrm{s}^{-1}$ the arterial pressure prevailing at the carotid bifurcation, assuming an average systolic pressure of 100 mmHg in the aortic bulbus amounts to 91 mmHg on the Moon and 89 mmHg on Mars (Table 1). For greater speeds, these blood pressure values become progressively closer to those prevailing on Earth (Table 1), which will be attained for v of about 15 $\mathrm{m} \cdot \mathrm{s}^{-1}$.

In view of the biomechanical characteristics of cycling (di Prampero 2000), the speed and mechanical power values necessary to achieve sufficiently large values of the vector simulating gravity (g') can be easily calculated (Fig. 3).

The highest mechanical power values reported in Fig. 3 are likely to exceed those attainable in aerobic conditions by the "average" astronauts. However, the mechanical power necessary to achieve a given speed and hence a given g' can be reduced by lowering the air density in the track tunnel. The relationship between mechanical power and speed for a barometric pressure of 250 mmHg (33.3 kPa) and a temperature of 20°C is reported in Fig. 4. However, the partial pressure of

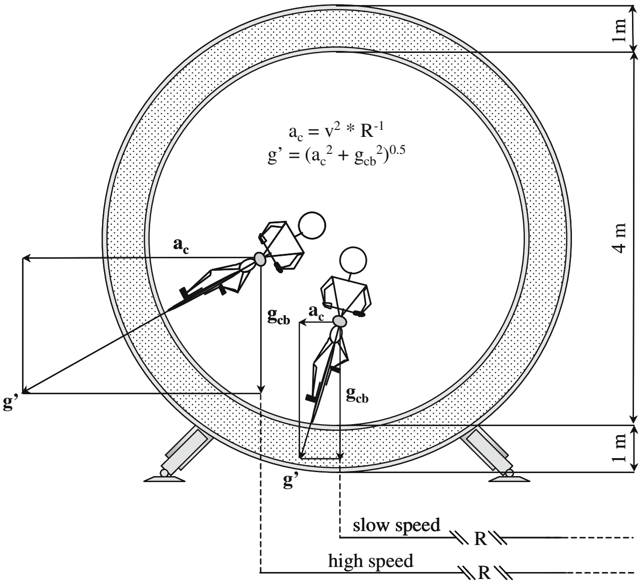

Fig. 2 Schematic frontal view of a cyclist pedalling on the curved path of a "lunar or Martian track tunnel". To compensate for the outwards acceleration (a_c), itself a function of the radius of gyration (R) and of the ground speed (v), $a_c = v^2 \cdot R^{-1}$, the cyclist leans inwards so that the vectorial sum (g') of a_c and the gravity on the celestial body (g_{cb}) lies in the plane that includes the centre of mass (*grey circles*) and the points of contact between the wheels and the terrain. The two values for v result in progressively larger a_c (and hence g') values. In addition, the angle between g' and the vertical increases with a_c, so that the track must be appropriately constructed to avoid skidding

O_2 in inspired humidified air (PIO_2) at 250 mmHg is extremely low, amounting to about 42.6 mmHg = [(250–47) · 0.21], essentially equal to that prevailing on the summit of Mt. Everest (8848 m a.s.l.). Therefore, to allow the astronaut exercising at high intensities and for sufficiently long times, the gas contained in the "track tunnel" should be appropriately enriched in O_2, so as to bring its inspiratory fraction to about 0.60. Indeed, under these conditions, the PIO_2 in the humidified inspired air would be about 120 mmHg, sufficient to maintain the haemoglobin saturation at lungs' level close to 100%.

It seems interesting to point out that, when performing extra vehicular activities (EVA), the astronauts' space suit is filled with pure O_2 at a barometric pressure ranging from about 200 to about 300 mmHg (Newman and Barratt 1997; Powell et al. 1993). So the composition and pressure we are proposing (FIO_2 = 0.6; P_B = 250 mmHg) is not far from the one that the astronauts can tolerate for many hours during EVA, and fully compatible with recommendations for the design of space habitats (Brunelli 1993).

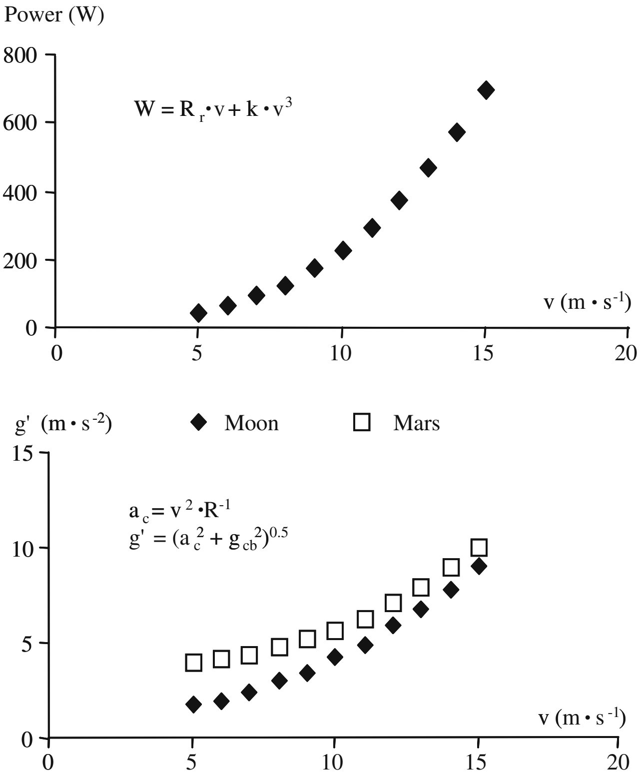

Fig. 3 *Upper panel*: the mechanical power (*W*) when riding a standard racing bicycle in dropped posture in air at sea level (760 mmHg) and 20°C is plotted as a function of the speed ($m \cdot s^{-1}$). Power was calculated on the basis of the values of rolling resistance (R_r = 5.8 $J \cdot m^{-1}$) and aerodynamic constant (k = 0.193 $N \cdot s^2 \cdot m^{-2}$) reported by (di Prampero 2000) for a typical cyclist. *Lower panel*: the vectorial sum of the outward acceleration and the acceleration of gravity is reported as a function of the speed on the Moon (g_{Moon} = 1.62 $m \cdot s^{-2}$) and on Mars (g_{Mars} = 3.72 $m \cdot s^{-2}$)

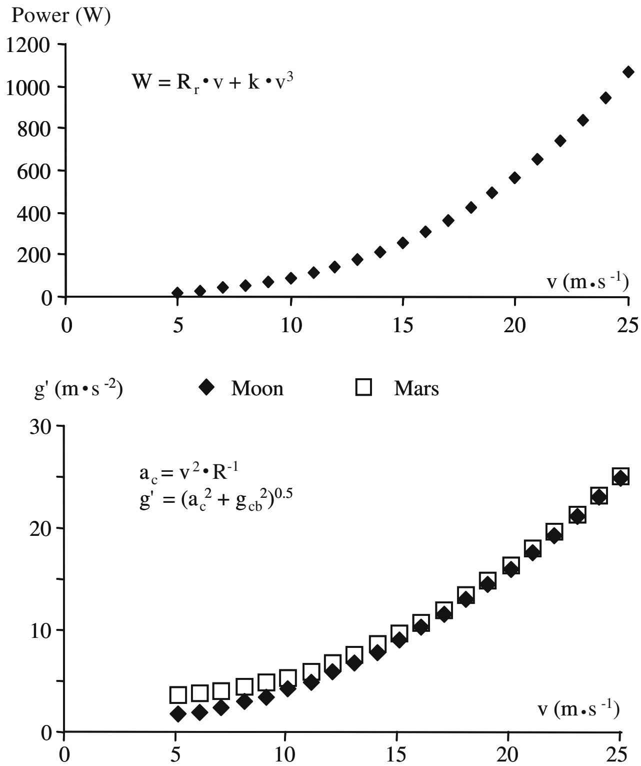

Fig. 4 *Upper panel*: the mechanical power (*W*) when riding a standard racing bicycle in dropped posture in air at barometric pressure of 250 mmHg and 20°C is plotted as a function of the speed ($m \cdot s^{-1}$). Power was calculated on the basis of the values of rolling resistance (R_r = 5.8 $J \cdot m^{-1}$) and aerodynamic constant (k = 0.063 $N \cdot s^2 \cdot m^{-2}$) reported by (di Prampero 2000) for a typical cyclist. *Lower panel*: the vectorial sum of the outward acceleration and the acceleration of gravity is reported as a function of the speed on the Moon (g_{Moon} = 1.62 $m \cdot s^{-2}$) and on Mars (g_{Mars} = 3.72 $m \cdot s^{-2}$)

Discussion and Conclusions

The main aim of the "track tunnels" described above is that of avoiding CVD in astronauts on permanently manned bases on the Moon or on Mars. However, to increase the *g* vector above the value prevailing on the Moon or on Mars, the astronauts will exercise daily on a bicycle at mechanical powers up to 200 W for periods of time that need to be established (see below). Thus, their level of aerobic fitness will also be maintained, in a manner that will depend on the duration and intensity of the imposed exercise schedule. It should also be pointed out that the astronauts will be in the position of performing several "sprints" in the track-tunnel, a fact which will help maintaining a reasonable level of "explosive power of the lower limbs" (Antonutto et al. 1999), once again depending on the number, duration and intensity of the daily sprints. Thus, one non negligible advantage of the proposed track tunnels, as compared to the majority of the artificial gravity systems proposed so far (Clement 2005) is that of combining at one and the same time muscular exercise and artificial gravity, without any additional needs for external power to set the system in motion.

However, for these scenarios to become operational it is mandatory to know the "doses" of g' necessary to avoid cardiocirculatory deconditioning, and to maintain muscle mass, aerobic and anaerobic powers and bone density during prolonged exposure to the Lunar or Martian acceleration of gravity, both in terms of intensity in respect to the Earth acceleration of gravity, and in terms of duration (per day) and frequency (per week) of the exposure. To this aim we suggest that in future bed rest studies these questions be addressed quantitatively. This could be done, having a group of subjects maintaining, for a given fraction of the bed rest exposure, given predetermined angles in respect to the horizontal, in order to change in a predetermined manner the component of gravity acting along their head to feet axis, while simultaneously having them exercising on a cycloergometer at predetermined intensities and for given time periods. Their level of CVD, muscle function and bone density, as assessed immediately post bed rest, will then be compared to that of a matched control group undergoing bed rest without countermeasures.

In addition, further studies on the characteristics of the described system, engineering constraints and manufacturing costs are also needed, in view of its possible installation on Lunar or Martian manned bases, as well as on space vehicles on their way to Mars. Indeed the technical difficulties for building such complex system seem formidable and range from the necessity of constructing the appropriate structure in space or on the Moon or Mars, to the needs of providing them with the selected atmosphere, in terms of pressure and composition, and of removing the CO_2 produced by the exercising astronauts. It should be noted, however, that these obstacles are the same encountered for building manned bases (Nelson 1997). Therefore, we would like to end with an optimistic view on the future implementation of the "track tunnels" described above.

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