HUMAN FLIGHT AND EXERCISE IN MICROGRAVITY

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Early experimenters in human flight learned, sometimes with fatal consequences, that the human body lacks the muscular power to fly (1). Indeed, the power demands are so great that only relatively small animals (less than 12 kg) are able to fly actively due to the interplay of morphologic scaling (muscle mass, wing area, power output) and organism weight (2). But this might not be true in a space station. Could humans fly in air when subject to microgravity? How demanding would such flight be?

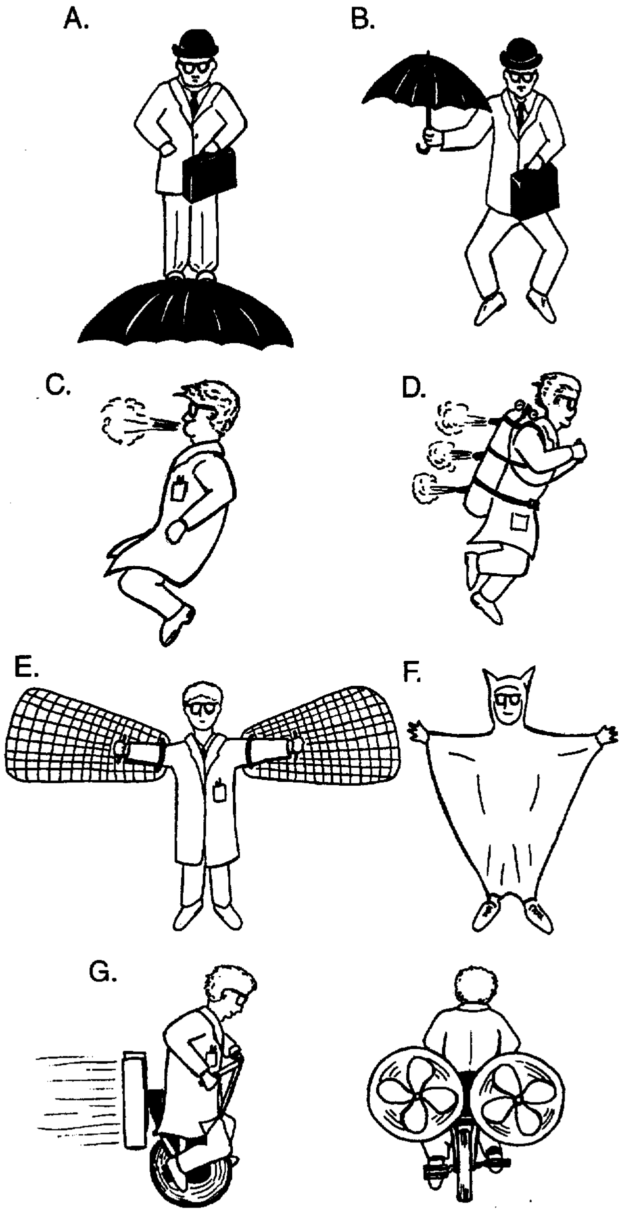
Human locomotion evolved in the earth's gravitational field and provides a poor basis for transport in space. When we try to move without gravity we find that we are largely helpless. In space stations, we can traverse open spaces by pushing off of a surface in the direction we wish to travel. But, once contact with the surface is lost we can not change our speed or direction of travel. Even changes in body orientation become a challenge. Similarly, we become trapped if we find ourselves stationary away from a solid surface. Thus, our dependence on gravity and solid substrates poses real problems for sustained habitation of space stations or long-term space travel.

There are at least three possible solutions to this problem. Space stations could be filled with substrates; surfaces or railings that would allow astronauts ready access to solid surfaces on which to push or pull. Filling the station with substrates, however, would defeat any benefit that could be gained from having open spaces in a station. Alternatively, the station could rotate to generate artificial gravity. Unfortunately, a rotating station would interfere with astronomical observations, the collection of solar energy, microgravity experiments, and industrial production. Finally, it might be possible for humans to use some mechanism of flight to move through a space station. Although we can't fly on Earth, the absence of significant gravitational force in a space station might tip the balance in our favor.

METHODS

Force and energetic estimations - The force and energetic estimates made here are intended to provide the correct order of magnitude for the purpose of comparing different modes of locomotion. The amplitude and frequency of limb motion are based on realistic and sustainable values commonly found during locomotion on earth. Force estimates are typically based on drag, lift, and added mass coefficients of near unity. The initial acceleration is estimated from the net locomotor force applied to an astronaut of 70 kg. Energetic estimates consider only the dominant power source over the course of one cycle during acceleration. The cruise velocity is either a maximum derived from forces or a reasonable

Figure 1



limit based on anatomical or practical considerations. The typical start up time and distance are velocity divided by acceleration and velocity squared divided by acceleration, respectively.

Drag-based models - Two drag-based systems were modeled. In the first case, a 2-m diameter umbrella was attached to the feet and the astronaut cycled the umbrella by jumping up and down (Fig. 1a). Because the shape and orientation of the umbrella did not change during the cycle, forward progress was dependent on the small difference in drag during the power and recovery strokes. In the second model, the astronaut held an umbrella in his/her hand and pulled down with the umbrella oriented to maximize drag and then brought it up sideways to minimize drag on the recovery stroke (Fig. 1b).

Jet models - Two systems of jet propulsion were modeled. The first consisted of nothing more than the astronaut exhaling forcefully through pursed lips to produce a jet of air (Fig. 1c). Inhalation draws in air from many directions at once thereby generating little directional force. The second system consisted of a jet produced from a tank of pressurized air (Fig 1d). The tank was approximately the size of scuba tank and held a pressure of 30 atmospheres. The tank was filled with a hand pump.

Wing-based models - Three systems were considered, 0.5 m^2 wings attached to the arms (Fig. 1e), a bat suit that spread from arms to legs (Fig. 1f), and a pedal-propeller apparatus (space bike) that turned two 0.3 m radius propellers (Fig. 1g).

Simulation of drag-based flight with two umbrellas held in arms - We also measured the forces generated when subjects cycled two umbrellas held in their arms to simulate drag-based flight. Subjects stood on a force plate (Kistler 9281B) and raised and lowered two umbrellas at a frequency of approximately 0.75 Hz. The subject oriented the umbrellas to maximize drag on the down-stroke (i.e., power stroke) and then turned the umbrellas 90 degrees to minimize drag on the up-stroke (i.e., recovery stroke). Vertical forces were measured with the force plate, sampled at 200 Hz with a data acquisition system (BioPac Systems, Inc.), and recorded on a Macintosh computer. Locomotor performance in zero gravity was calculated as follows. Body weight was subtracted from the signal and instantaneous accelerations of the person were calculated from Newton's second law of motion. Instantaneous acceleration was integrated once to yield the velocity and again to find the distance traveled.

RESULTS AND DISCUSSION

Drag-based propulsion - Many aquatic animals utilize some form of drag-based propulsion. In contrast, only very small organisms with high surface to volume ratios (i.e., hatching spiders with a long strand of silk and some plant seeds) exhibit drag-based transport in air. It is the low density of air relative to the density of the organism that makes drag-based propulsion ineffective in air when subject to gravity. Nonetheless, both the modeling (Table 1) and the force-plate experiment indicate (Fig. 2) that drag-based propulsion would work for humans in the microgravity environment of a space station. The force plate measurements show that umbrellas provide a reasonable amount of thrust. The typical acceleration of 0.07 m/s^2 compares favorably with our theoretical calculations when corrected for differences in area and frequency. Thus, with wing membranes the size of an average umbrella astronauts could reach speeds of 3 m/s in 12 to 30 s.

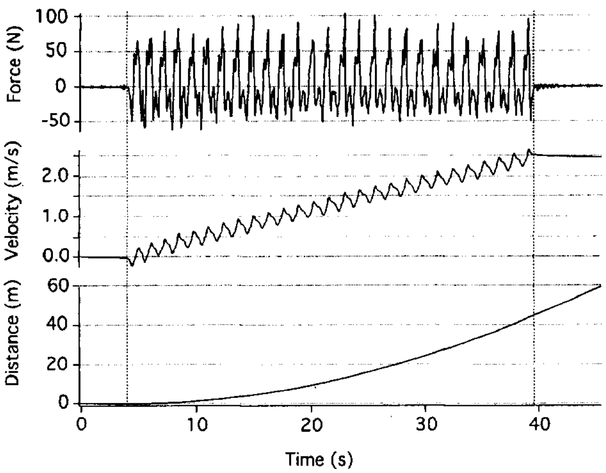
The most important distinction between the two drag-based models analyzed in this study was that drag was not minimized on the recovery stroke in the leg-pumping model, but was minimized on the recovery stroke in the arm-pumping model. The performance of the two models illustrates the importance of minimizing drag on the recovery stroke. Due to the greater muscular power available in our legs than our arms, a drag-based system that utilized leg pumping would maximize acceleration and stamina. Nevertheless, the limited range of motion in the joints of our legs would limit maneuverability and turning agility.

The best solution might include devices on both the arms and legs that passively spread to maximize drag

Table 1. Parameters and predicted performance of different flight mechanisms.

Model	Size (m^2)	Mass (kg)	Initial acceleration (ms^{-2})	Cruise velocity (m/s)	Start up time (s)	Start up distance (m)	Peak force (g)	Energy (J/cycle)
Umbrella attached to feet	3.14	0.5	0.023	0.9	40	35	0.15	900
Umbrella in hand	1.62	0.5	0.24	3.0	12	38	0.15	150
Exhaling to produce jet	____	____	0.004	2.4	610	1500	0.0001	1
Compressed air jet	____	10	0.6	6.0	10	30	0.1 - 1.0	____
Diving fins	1	0.5	0.001	2.0	2000	4000	0.0001	1
Wings on arms	2.5	2.0	0.01	1.0	100	100	0.3	1
Bat suit	2.0	0.2	0.01	1.0	100	100	0.3	1
Space bike	1.0	10	0.6	6.0	6	17	0.3	____

Figure 2



on the power stroke and collapsed to minimize drag on the recovery stroke. Such devices might be designed so that they would telescope and fold out of the way (e.g., beside the astronaut's appendages), when not being used for flight. The use of both arms and legs would significantly increase the rates of acceleration, possibly approaching 0.5 m/s^2, and would improve maneuverability. Although drag-based propulsion would allow astronauts to maneuver in a space station, both acceleration and the ability to change the direction of travel would be limited by the fact that propulsive forces could be generated during only half of the cycle.

Jet-based propulsion - There are many examples of aquatic animals that make use of jet based propulsion: jellyfish, squid, and octopus. In contrast, we know of no examples of animals that use jet propulsion in air, in part because thrust is proportional to fluid density and therefore insufficient to overcome gravity. But could jet propulsion work in air if there wasn't significant gravity?

Our modeling indicates that there would be serious limitations to transport via jet propulsion (Table 1). Both the exceptionally low rate of acceleration and the difficulty of aligning the propulsive force with the center of mass of the astronaut disqualify forceful exhalation as a means of transport. In contrast, significant rates of acceleration (0.6 ms^{-2}) could be achieved with a jet from a tank of compressed air, but the high pressure required (30 atmospheres) would be dangerous in a space station and would require substantial investment of time and energy to recharge the tank. Recharge of the tank with a hand pump, for example, could require 300 pumping cycles, approximately 150 N of force towards the end of the filling, and 5 minutes of pumping at 1 Hz. The alternative is to bring compressors and pressure tanks to the space station at enormous cost.

Wing-based propulsion - Animals fly with wing-based propulsion in both water and air. When flying in air, most of the wing force is invested in the production of vertical lift with only a small horizontal thrust needed to counteract drag. When flying in water, neutral buoyancy obviates the need for any lift force and the wing force is oriented horizontally to produce thrust. The shift in wing force from lift to thrust arises solely from changes in the density of the fluid medium relative to that of the organism. Consequently, animals in water can generate thrust on both the up- and down-strokes (e.g., penguins, puffins, seals, etc.) which requires two reversals of the low pressure side of the wing in each wingbeat. Animals flying in air generate thrust primarily during the down-stroke since they cannot afford the negative lift force implied by generating thrust during the up-stroke. Humans flying in microgravity, however, would be able to generate thrust on both the up- and down-strokes. In spite of this advantage, our modeling suggests that performance would be relatively limited compared to drag-based propulsion (Table 1). Acceleration from wing thrust would be roughly an order of magnitude lower than that generated from our drag-based models.

The limitation is not due to differences in the effectiveness of wing versus drag force generating mechanisms, but is due to the organization of the human musculo-skeletal system. We simply do not have the joint maneuverability (i.e., flexibility) and musculo-skeletal power to produce significant wing forces. Humans evolved from a lineage that excels at vertical climbing and striding bipedal walking and running. Both modes of transport require limb flexion and extension, and power production that are parallel to the axis of the body. When we climb our arms pull down as our legs push up and the reaction vectors of the forces applied to the substrate are closely aligned with our center of mass. Similarly, when we walk and run the vector of the ground reaction force is closely aligned with our center of mass. The limb motion in both of these activities is very different from that used by flying animals. Compare the wing motion at the shoulder of a flying bird to that of human flapping his or her arms in a similar manner. While birds can flap their wings so that there is symmetrical excursion above (dorsally) and below (ventrally) their body, the range of arm motion in humans is primarily restricted to flapping in the ventral range. This bias results in a thrust force that is not aligned with the center of mass and, therefore, produces a rotational torque on the body. Compare also the size of the flight musculature of a bird to that of the human pectoralis muscle. The pectoral muscles of birds constitutes approximately 17% of their body mass (3). In humans, the pectoralis muscles represent less than 0.5% of body mass. Unfortunately, not only does our joint mobility and musculature deny us the possibility of flight at the Earth's surface, but it would seriously limit our wing-based performance in microgravity.

Appropriately built diving fins would ultimately enable an astronaut to achieve similar speeds in microgravity as those achieved by a diver under water. However, the acceleration would be 1000 times slower due to the ratio of air to water density.

A mechanism that transduced a pedaling motion of the limbs into a flapping of mechanical wings would be more effective than arm flapping. Even more effective would be a pedal mechanism that turned fans such as the system we modeled (Table 1). In terms of all around performance, this space bike would probably represent the best solution to the problem of human transport in a large space station. The fans could be swiveled to provide a directed momentum flux for maneuvering. In addition to offering relatively high acceleration and maneu-verability, an astronaut pedaling a space bike would occupy less volume than an astronaut flapping wings or oscillating drag surfaces.

A transport system that would be simple and provide relatively good maneuverability is a combination of jumping from a surface for acceleration and using wings mounted on the arms to generate turning forces. The forces applied to the ground in a maximum effort jump are large enough to achieve a take-off velocity of 11 m/s in microgravity. Although this is a greater velocity than one would likely want to achieve in a space station; we can use it to estimate the radius of curvature that an astronaut could achieve with wings. For a take-off velocity of 11 ms^{-2} we calculate a typical lift force of 225 N for 2.5 m^2 area wings. This force could produce a centripetal acceleration of 3.2 ms^{-2} for a 70-kg astronaut. Thus, a typical radius of curvature is proportional to the take-off velocity squared and would have a maximum of around 38 m. Although this is poor agility compared to that of animals flying on Earth, these turning radii would allow astronauts to maneuver to some extent.

CONCLUSION

Humans could fly in a space station. Acceleration and turning agility would be much less than we are accustomed to on Earth, but limits on initial acceleration could be overcome, in most cases, by pushing-off from solid surfaces. With an initial take-off jump, relatively small wings mounted on the arms would give an astronaut a capacity to turn and change body orientation in a controlled manner. Because we are not structured to flap our arms as birds and bats do, we could produce greater accelerations using various methods of drag-based propulsion than would be the case if we depended solely on wing forces. Unfortunately, turning agility with drag-based propulsion would be limited by the intermittent generation of turning forces that is necessitated by the recovery stroke. The most versatile system of transport would likely be a space bike that would allow an astronaut to convert the muscular power of the human leg into a directed momentum flux of air.

Most of the flight mechanisms we have discussed would constitute a significant source of exercise. Musculo-skeletal and cardiovascular atrophy in microgravity represents one of the greatest obstacles to extended space travel and long term habitation of space (4,5,6,7). Human flight would offer two advantages over the modes of exercise currently in use. First, because flight is a means of transport it would incorporate exercise into the daily routine and work of the astronauts. If space stations were designed such that flight was necessary, living in space would require a certain basal level of aerobic exercise. Second, current modes of exercise in space, such as running on treadmills or resistance exercise, quickly become boring, and are difficult for many people to maintain over the long haul. In contrast, flight would likely be a satisfying activity. The kind of behavior that biologists classify as play.

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