BIOMECHANICS OF GYMNASTICS AND DIVING

SPACE AGE BIOMECHANICS: WEIGHTLESSNESS

Orwyn Sampson, Ph.D.
United States Air Force Academy

Weightlessness

There is a common misunderstanding about weightlessness. We have developed the notion that weightlessness and space go together and that people become weightless whenever they go beyond the earth's atmosphere.

We have acquired this notion naturally. For years now, we have become accustomed to seeing astronauts and cosmonauts floating around inside their spacecrafts once they achieve earth orbit. Since the orbit altitude usually 150-300 miles, is beyond our atmosphere, it is natural to associate weightlessness with a lack of atmosphere, ie, with space. This association is natural, but in fact, it is only coincidental.

According to Newton, every object in the universe attracts every other object. He expressed it this way: $G = g.m_1 \text{ x } M_2/r^2$. What this says is that the amount of attraction that exists between two objects is directly related to their masses and inversely related to the distance they are from each other. Because gravity is universal, a state of absolute weightlessness could exist only if you were present in an empty universe. Since that is hardly feasible, our understanding of weightlessness needs to be adjusted. To understand it properly, we need a frame of reference. To illustrate, on earth, we experience our mass as weight because the earth pushes up on us opposing gravity's pull. If the earth suddenly gave way, we would no longer experience our mass as weight because there would be nothing to oppose the pull of gravity.

When space travelers appear to be weightless in orbit, as we have just been reminded, they are not free of gravity. Instead, they are falling. They are still being attracted to the earth and are falling toward it, but because they have a forward velocity (of some 17,000 mph), they keep missing it. Since their spacecraft is also falling, using it as a frame of reference, they are indeed weightless. In other words, they are weightless relative to their spacecraft.

Therefore, what we have come to regard as weightlessness is simply a state of free fall in which our frame of reference is moving in the same direction and at the same speed as we are. This being the case, it is now easier to see that weightlessness has nothing to do with space per se. Indeed, we experience weightlessness within our atmosphere every time we are free from support and are allowed to fall. When a pilot noses his plane over after a gradual climb, or an elevator descends abruptly, we experience weightlessness. The only difference is in the duration. Because this is such a fundamental concept, let us illustrate it another way by considering an implausible situation.

Suppose we built a skyscraper 250 miles high. The person living in the penthouse, to be sure, would require supplemental air to breathe because our atmosphere does not support life much beyond about five miles elevation. However, he or she would not be weightless. In fact, their weight would be diminished by a mere 12%, and not because of space, but because they are now 250 miles further from the center of the earth.

As we move out from the earth, our weight indeed diminishes. However, distance from the earth is not the only factor. The penthouse dweller and the space traveler are the same distance from earth, but one still has weight, the other does not. The difference, of course, is accounted for by the fact that the space traveler and his spacecraft are both falling.

To put this in even clearer perspective, imagine a view of the earth from the moon. The diameter of the moon's orbit around the earth is 8,000 miles. The shuttle altitude is 250 miles. On an 8,000-mile scale, 250 miles is not very far out into space. Clearly, these space travelers have not escaped the earth's pull of gravity.

What is the correct relationship between space and weight? The short answer is that space facilitates free fall better than air does so it is easier to orbit in space than within our atmosphere; that is the key. While it is possible to orbit within our atmosphere, air provides so much resistance that the cost of achieving and maintaining a forward velocity of 17,000 mps would be astronomical. Conversely, in space, where there is practically no impediment to movement, speeds of that magnitude or greater, once achieved, can be maintained with no additional power.

Because of these facts, those in the space business tend to shy away from the term weightlessness because it implies a lack of gravity, which is a physical impossibility. Instead, they prefer to use the term microgravity. For our purposes, the two can be used interchangeably.

We have a lifelong war with gravity which we eventually lose. (Interestingly, even the word for the hole that represents our final resting place comes from the word gravity.) With the advent of space travel, mankind faces a radically new experience, a longterm gravity diminished existence.

As of the first of this year, more than 200 people have traveled beyond our atmosphere with a collective experience of 18.6 man years in space. Eventually, with the advent of space stations and trips within and beyond our solar system, the experience can be extended perhaps indefinitely.

Weightlessness is an exhilarating experience and one that facilitates bodily motion and the movement of other objects, but there are costs associated with it.

Physiological Effects

We'll briefly examine these costs from a physiological standpoint.

Exposure to microgravity has three major effects on human bodies. These include:

1. Changes in body-environment orientation (nervous system effects).
2. Changes in body fluid distribution (circulatory system effects).
3. Changes in body structure (primarily muscular system and skeletal system effects).

A primary function of the nervous system is basic orientation or orientation of your body with respect to your environment. This involves both sensory and response activities on your part. The primary sensory mechanisms include: vision, the inner ear, and somatosensory receptors (including the kinesthetic sensors). The response activities include: eye movement, changes in head position, and altered posture. When the environment varies, or is perceived to vary, beyond certain limits, the sensations can be disorienting and may produce motion sickness. This occurs in a microgravity environment.

More than half of all space travelers get sick in microgravity. The condition is labeled space motion sickness (SMS). These are some of the symptoms: nausea, headache, anorexia, vomiting, etc. SMS starts almost immediately for some astronauts and can last up to four days.

A study of generic motion sickness reveals some interesting facts:

1. It is not limited to man. In fact, nearly every species exhibits susceptibility including horses, cows, monkeys, chimpanzees, seals, various kinds of birds, sheep and cats. Even fish, under the right conditions, exhibit motion sickness.

2. The only common characteristic of all the motions producing the syndrome is varying acceleration to the head. Moreover, in spite of the great variability of symptoms exhibited within and between individuals, one fact stands out: individuals not possessing a functioning vestibular labyrinth (e.g., some deaf mutes) are not susceptible to motion sickness.

The vestibular labyrinth, or vestibular apparatus, is located in the inner ear and is continuous with the structure responsible for hearing, the membranous cochlea. It contains two types of sensory receptors: Otolith organs which sense linear accelerations (including gravity) and semicircular canals which sense angular accelerations.

The otolith organs (viz. the utricle and saccule) are linear accelerometers and provide the central nervous system with a continuous estimate of head position with respect to the upright. The semicircular canals are rotary accelerometers and detect rotations in the three basic planes of reference. Microgravity alters the activity of the otolith organs but not the semicircular canals. This leads to sensory conflict and space motion sickness.

Although the exact nature of SMS remains a mystery, it is not a permanent condition and is treatable with drugs and biofeedback techniques.

The circulatory, or cardiovascular, system provides the primary mechanism for maintaining the body's internal environment. It is a transportation system. A dynamic transportation system which is also affected by gravity.

On earth, in a standing position, body fluids are under the influence of gravity and tend to be pulled toward the feet leading to a hydrostatic gradient and pooling.

Microgravity has two effects: one is an immediate effect of redistributed body fluids resulting from decreased hydrostatic pressure. This leads to thin legs and a puffy face. This headward shift of fluids is interpreted by the body as an increase in blood volume. The circulatory system adapts to this sensed "volume overload" quickly. Within the first day or two, up to two liters of excess body fluids are excreted and the number of red blood cells is also reduced. The second effect of microgravity is a longterm effect in which the heart muscle atrophies and certain changes are seen in the blood which are described collectively as "spaceflight anemia". Due to these changes, there is increased likelihood of shock if hemorrhage occurs and, upon reentry to a 1-G environment orthostatic tolerance is significantly diminished. Recovery may take days to weeks.

Measures employed to counter the adverse effects of microgravity on the circulatory system have taken a variety of forms and include:

1. Inflight aerobic and strength training exercises.
2. Lower body negative pressure.
3. Oral rehydration (within two hours of reentry).
4. Drugs
5. Hormones.
6. And the use of Anti-G suits postflight.

Microgravity alters the body composition of two major systems; the muscular system and the skeletal system. Let's look first at the muscular system. As you know, skeletal muscles are the motors of body movement and are uniquely the organs of the will. Muscle is highly responsive to the load level place on it and will hypertrophy or atrophy accordingly. It is composed of several different types of cells in terms of their ability to produce tension. Two general categories are: first, type I muscle fibers which are slow-twitch and are associated with endurance and second, type II muscle fibers which are fast-twitch and are associated with strength and power.

The effects of gravity are seen in the different muscles of the body. The muscles of the lower extremities are larger than those in the upper extremities and contain more slow-twitch fibers. This is understandable since they must move greater loads than their upper extremity counterparts and since gravity is unrelenting, they must exhibit greater endurance. Short-term space flights do not impact muscles to a significant degree. There is a decrease in body weight, but this is mostly water. In longterm flights, both body water loss and negative nitrogen balance are seen.

Interestingly, the loss in muscle occurs mainly in the lower extremities. Three crew members in Skylab 2 (28 days), and three in Skylab 3 (84 days) were tested for changes in arm strength. These six crew members demonstrated little change in arm strength. Only four crew members were tested for leg strength changes. They all demonstrated a decrease in leg strength. The mean for the group was a 20% decrease in leg strength and a 10% decrease in leg volume. In addition to the loss of muscle mass, the muscles tend to "speed up". In other words, the atrophy appears to occur primarily in slow-twitch fibers.

It has been reported that fit individuals lose greater amounts of muscle mass than unfit individuals. At first glance, this seems incredible until you consider what has already been demonstrated, that leg muscles atrophy more than arm muscles in space flight. Since arm muscles are basically gravity independent, they are less affected. The legs, conversely, are "overtrained" for microgravity and lose the most mass. The same is true for overall physical fitness. In space, those individuals with greater muscle mass will lose it faster than those with less. This differential loss must be kept in perspective, however. At no time is it declared that less strength is "better than" more strength. Muscle mass and strength are positively correlated aspects of human biology. A strong muscle, by definition, has a greater capacity than a weak one. Legs can produce greater force than arms. Physically fit individuals can exert more force than unfit individuals. Under atrophy, it is this increased capacity that is affected. Under identical conditions and with no countermeasures, the legs of a strong astronaut will lose mass and strength at a faster rate than the legs of a weaker astronaut. But the former will remain stronger than the latter at every stage of the flight. He/she will also withstand the postflight stresses better and will recover faster.

Upon return from spaceflight, muscle atrophy and corresponding losses in strength contribute to several problems:

1. Orthostatic intolerance is the tendency for your blood to be drawn away from your head when you assume an upright position. This can cause fainting if you stand up too quickly.
2. Decreased physical fitness from loss of strength and endurance is also a problem.

3. As is osteopenia or weak bones caused partly by decreased muscular forces.

Muscle atrophy can be effectively countered by means of:
1. Exercise — the Soviets have been especially successful in this area through the use of spring-loaded resistance devices, treadmills, and bicycles.
2. Electrical stimulation.
3. Hormones.

A second bodily system that experiences decay in microgravity is the skeletal system. The skeletal system enhances body movement and also serves as a storehouse for calcium. It is designed primarily for terrestrial use. Its health depends on several significant factors including gravity, muscular force, nutrition, and hormonal activity. Osteopenia (literally, "poor bones") is a consistently reported physiological response to spaceflight. It occurs because the ongoing processes of bone resorption exceed those of bone formation.

Space flight osteopenia is more severe than bedrest-osteopenia and may not be completely reversible. Bedrest-osteopenia plateaus, but spaceflight osteopenia has one element that does not. Spaceflight osteopenia is even more serious than post-menopausal osteopenia (1% of the total mineral mass is lost in microgravity per month vs 1/2% per month for post-menopausal women). A related factor in osteopenia is muscle atrophy because of the stress effect muscles have on bones. Postflight there is increased likelihood of bone fracture (especially in the legs and spine) and an increased likelihood of kidney stone formation. Two countermeasures have shown some benefit in retarding bone loss. These include exercise and diet, but osteopenia is not totally prevented or reversed using either countermeasure and it remains a serious effect of microgravity.

Let us review what has been said about the physiological effects of microgravity: for nearly three decades, we've begun to venture into space. Information gathered during these trips demonstrates that humans undergo profound, but to a large extent, reversible, physiological changes in microgravity. These changes occur during two general phases: an acute phase in the first hours and days of the mission; and an adaptive phase lasting days, weeks, and beyond. With the exception of bone demineralization, countermeasures have proven to be effective. Therefore, there is optimism that humans can endure much longer space flights.

Implications for Biomechanics

What does all this mean for biomechanics: I think there are three major implications:

1. One has to do with moving oneself in a microgravity environment — the experience of truly being a "free body". A group of American gymnasts, highly skilled movers, had a chance to taste that experience aboard a NASA 707 aircraft and they had a ball.
2. A second implication has to do with moving other objects in space. This calls for a concentrated review of the physics of movement in terms of forces, centers of gravity, torques, mass, etc.
3. And a third implication has to do with training programs; programs for countering the adverse effects of weightlessness and preparing space travelers for skilled, efficient movement in microgravity.

In summary, a new perspective on weightlessness has been obtained. In addition, we have reviewed its physiological effects in terms of body orientation, body fluid shifts, and body compositional changes. And, finally, we suggested some implications for those of us involved in biomechanics which will enable us to focus our attention and efforts on some brand new challenges.