Muscle and Bone in Space

Effects of Space Flight on the Musculo-Skeletal System

Gilles Clément  
International Space University  
Strasbourg, France

Doug Hamilton  
Wyle Laboratories & NASA  
Johnson Space Center  
Houston, USA
• How the musculo-skeletal system works in Earth gravity to ensure upright posture, movements and storage of nutrients (calcium)

• Physiology of muscle and bone

• The effects of space flight on muscle and bone

• Implications of such changes for long-term missions, and potential countermeasures
Humans have about 700 muscles in their bodies.

There are 3 types of muscles:

- Their sole function is **contraction** (they all work by shortening).
- Contractions of skeletal muscles are coordinated by the **brain**.
Skeletal Muscles

- **Skeletal muscle** is the largest tissue in the body, accounting for 40-45% of the total body weight.

- Each end of a skeletal muscle is attached to a bone by **tendons**.

- Skeletal muscles work in pairs: one muscle contracts to pull a bone forward, the other to pull it back.

- The **anti-gravity muscles**, also known as postural muscles, owe their importance and strength to the presence of gravity.
Muscle Contraction

• Muscles are composed of fibers

• Each fiber is made up of myofibrils, consisting of many filaments (myosin and actin), the engines of the muscle

• Together, the actin and myosin provide all the muscle’s movement and force as they slide together (contraction) and apart (during relaxation)

• In healthy muscles, there is a continual process of muscle protein production and breakdown

• When protein breakdown occurs more rapidly than protein production, there is a loss of muscle mass
• **Contraction** refers to the active process of generating a force in a muscle

• The force exerted by a contracting muscle on an object is the muscle **tension**

• The force exerted on a muscle by the weight of an object is the **load**

• When a muscle shortens and lift a load, the muscle contraction is **isotonic** (constant tension)

• When shortening is prevented by a load that is greater than muscle tension, the muscle contraction is **isometric** (constant length)
Mechanisms of Muscle Contraction

- Motor neuron from spinal cord innervates muscle
- Action potential opens channel in bilipid membrane
- Acetylcholine (ACh) is released and binds to channel
- Channel of ~0.65 nm allows positive ions in (primarily Na,K,Ca)
- Na+ influx reduces negative potential inside cell
- This depolarizes the membrane and allows a large Ca++ influx
- Ca++ causes change of actin filament sub-components, uncovers binding sight between actin and myosin
- ATP (produced by mitochondria) is "waiting" for binding sight
- As a result, ATP is cleaved into energy and ADP
- ATP energy causes myosin head to "snap" and moves actin
- Release of ADP causes myosin head to "snap back" to next site
- Series causes a ratcheting motion resulting in muscle contraction
- Pumps then activate to remove Ca++ and relax contraction
- ACh esterase breaks ACh down into acetate ions and choline
- Choline is recycled, acetate is a toxic byproduct (lactic acid which forms "crystals" that "cut" muscle tissue and generates soreness!)
• Basic source is Adenosine Tri-Phosphate or ATP

ATP is the universal currency of biological energy

~ represent high energy phosphate bonds.
Each one releases 7,500 calories when broken
Energy for Muscle Contraction

- Basic source is **Adenosine Tri-Phosphate** or **ATP**
- The amount of ATP present in the muscle cells is only sufficient to sustain maximal muscle power for 5-6 seconds
- New ATP must be formed continuously:
  - creatine phosphate: can sustain 10-15 more sec of muscle activity
  - anaerobic step of glucose breakdown: for another 30-40 sec “bursts” of energy
  - aerobic system: provides unlimited time muscle activity (as long as nutrients last)
Muscle Activity

- The filament’s force is **all or nothing**. When called upon, it always applies the same amount of force at the same speed.

- There are 2 kinds of muscle fibers:
  - Type I, or “slow twitch”, are **slow-moving but high-endurance fibers**. Use oxygen. Marathon runners typically develop those in the soleus muscle in the calf for prolonged lower leg muscle activity.
  - Type II, or “fast twitch”, are **high-speed, high-output fibers**. Sprinters and weight-lifters typically develop those in the gastocnemius muscle in the calf and in the biceps muscle for quick, powerful “bursts” of movement. They fatigue rapidly (use glycogen rather than oxygen).

- The average person has about 50%-50% of Type I and Type II fibers throughout the body.
Muscular Exercise

• Strength and endurance can be increased by **exercise** (training)

• Capacity of a muscle for activity can be altered:
  – by **transformation** of one type of fiber to another: e.g. muscle required to perform endurance-type activity will develop more Type I fibers and number of blood capillaries will increase
  – by the **growth** in size (hypertrophy) of the muscles fibers: e.g. weightlifting will induce hypertrophy in Type II fibers, with an increase in synthesis of actin and myosin filaments

• Endurance exercise also produces changes in the **respiratory** and **circulatory** systems, which improves the delivery of oxygen and nutrients to the muscle fibers
Muscle Atrophy

- **Denervation atrophy**: If the nerve fibers to a muscle are severed or the motor neurons destroyed, the denervated muscle fibers become progressively smaller, their content of actin and myosin decreases, and connective tissue prolifers around the muscle fibers.

- **Disuse atrophy**: A muscle can also atrophy with its nerve supply intact if it is not used for a long period of time.

- Atrophy occurs when muscle can not breakdown ATP as fast.
Effects of Spaceflight on Muscle

- Decrease in body mass
• Decrease in **body mass**
• Decrease in **leg volume**

![Graph showing leg volume changes over days postflight](image)

**Formula for Volume Calculation**

\[
\text{volume} = \pi h \left( \frac{R^2 + Rr + r^2}{3} \right)
\]

where \( R, r = \frac{\text{circumference} (c)}{2\pi} \)
Effects of Spaceflight on Muscle

- Decrease in **body mass**
- Decrease in **leg volume**
- Atrophy of the **antigravity** muscles (thigh, calf)
  - seen on muscle scans/biopsies
  - decrease in leg muscle strength
  - **extensor** muscles more affected than flexor muscles
- Data in flown rats showed an increase in number of **Type II**, “fast twitch” muscle fibers (those which are useful for quick body movements but more prone to fatigue)
• 2 daily 1.5-hour sessions of exercise:
  – Treadmill with axial loading
  – Cycle ergometer
  – Interim resistive exercise
  – Traction on “bungee cords”

• 4-day cycle:
  – Day 1, low load but high intensity
  – Day 2, moderate load at moderate intensity
  – Day 3, high load at low intensity
  – Day 4, ad lib
"Penguin Suit"

The inside of the suit contains a system of elastic, straps, and buckles that can be used to adjust the fit and tension of the suit.
Muscle Atrophy—Challenges

- **Exercise** alone has not prevented muscle atrophy during spaceflight

- The increase in fast-switch fibers could result in a higher susceptibility to contraction damage (sprain)

- Muscle atrophy caused by weightlessness participates in postural instability and locomotion difficulties **after spaceflight**

- Astronauts data are complicated by prior physical **fitness** and in-flight exercise **countermeasures** or **work loads** (e.g. EVA)

- Muscle **development** was disrupted when gravity-loading exercise was removed from immature rats flown on Neurolab

- The muscle weakness, fatigue, faulty coordination, and muscle soreness that astronauts experience after spaceflight mimics the changes seen in **bed-rest** patients and the **elderly**
Function of Bone

• **Structural organ**
  – Weight-bearing bones: support and make the body mobile (spine, skeleton)
  – Protective bones: shield our delicate internal organs (skull, ribs)

• **Mineral reservoir**
  – Life began in a primordial sea rich in potassium and magnesium and poor in sodium and calcium
  – With time, geological changes altered the composition to one which is rich in sodium and calcium
  – As organisms became multicellular they needed to also control their extracellular milieu
  – An adult contains approximately 1000 grams of calcium:
    • 99% in the skeleton
    • 1% in the extracellular space and soft tissues
Weight Bearing Bone

- Excessive mass versus fragility
- Could make fracture probability equal to zero if all bones were large
- Bear (heavy bone, reduced mobility) vs. Bird (light bone, flight)
- Natural selection gives minimum structure
The anti-gravity bones are responsible for bearing the weight of the body in a gravitational environment.
The Major Parts of a Long Bone

- 2 extremities, cylindrical midshaft and hollow center (which contains the bone marrow)
- Bone can be layered around a blood vessel (lamellar bone)
Bone Remodeling

Bone tissue is remodeled every 5 months by:

- (a) Activation (stress)
- (b) Resorption (osteoclasts) 3 weeks
- (c) Formation (osteoblasts) > 4 months

Osteoblasts = builders
Osteoclasts = crushers

Lujan and White (1995)
Bone Growth

- Bone contains a matrix of collagen fibers which provide a milieu for the deposition of **calcium crystals** (hydroxyapatite). These crystals give its strength to the bone.

- A layer of cartilage called the **growth plate** is where the bone grow longer by increasing its thickness which is later calcified with hydroxyapatite.
Muscle and Bone

**Calcium Balance**

**Bone**
- Absorption: 0.3-0.5 g
- Secretion: 0.3-0.5 g

**Kidney**
- Filtration: 5-7 g
- Reabsorption: 4.9-6.7 g
- Urine: 0.15-0.3 g
- Secretion: 0.1-0.2 g
- Absorption: 0.25-0.5 g

**Blood**
- Absorption: 0.25-0.5 g
- Reabsorption: 4.9-6.7 g

**Intestine**
- Diet: 0.5-1.5 g
- Feces: 0.35-0.6 g

**Urine**
- 0.15-0.3 g
On Earth, osteoporosis is a bone disease in which the bone mass is reduced by 0.5-2.0% per year.

Approximately 500,000 hip fractures secondary to osteoporosis occur annually in the U.S.

By age 80, 25% of women and 15% of men will suffer a hip fracture. 10% of these patients will die as a result of this fracture.

The hospital care costs for these patients will reach 5 billion dollars annually. The cost from non-hospital care facilities is an order of magnitude greater.
Bone Loss during Spaceflight

- **Vostok:** Increased fecal and urinary calcium first noticed
- **Gemini:** Loss of approximately 2-4% of bone mass in heel after 4-11 days of spaceflight
- **Apollo:** 3-5% decrease in bone mass after 10 days
- **Soyuz:** 8-10% decrease in bone density
- **Skylab:** 1-3% per month loss in bone mineral
- **Mir:** 10% loss of trabecular bone from lumbar spine in one cosmonaut after a 1-year mission
- **Shuttle-Mir:**
  - With countermeasures: 5.4% decrease in bone density in tibia. Did not return to preflight level in some individuals
  - Without countermeasures: 1.3-1.5% **per month** decrease in bone density (worst case: 15-22% total in some bones)
- **ISS:** Preliminary data similar to Shuttle-Mir
Bone Loss during Spaceflight

Postflight changes in bone density compared to preflight
Compiled data from Gemini 7, Skylab 2-4, and Shuttle missions (each data point represents the mean ± SD of n= 2 to 14 subjects)
During a mission to Mars, a 45-year-old astronaut could see bone deterioration reach the weakened state of severe osteoporosis.
Definition of Stress and Strain

- Mechanical loads (stress) causes slight deformation called **strain**
- Bone length changes of 0.1% correspond to 1,000 **microstrain** (µs)
- The amount of microstrain is dependent on loading, elasticity and geometry of the bone
- Physiological window: 1500-2500 µs

\[ \varepsilon = \text{Strain} = \frac{(l - lo)}{lo} \]
• An **upper** limit strain must be exceeded to provoke **remodeling to increase bone mass**

• Mechanical strain below a **lower** limit will provoke **adaptive remodeling to reduce mass**

• Normal **remodeling** activity is associated with compressive strains between 200-2500 µs

• Tension has an upper limit of 1500-1700 µs

• Dimensional changes in excess of 25,000 µs will result in fractures
A turkey standing on a vibrating platform which stimulates muscle and bone interaction, thus promoting bone growth.

After a year of daily 20-minute sessions, sheep showed the robust striations of increased density (lower right).

Control sheep showed normal bone (lower left).

National Geographic, Jan. 2001
Bone Density Measurements

• **Description:**
  - Pre- and postflight whole body bone density scan
  - Pre- and postflight bone density local scans:
    - Proximal femur (hip)
    - Lumbar spine (back)
    - Calcaneous (heel)

• **Objectives:**
  - To assess effectiveness of countermeasures
  - To assess postflight recovery
  - To predict long-term bone fracture risk
  - To determine return-to-flight status
Bone Loss—Challenges

- Bone loss during spaceflight is about 1-3% per month. What will be the new state for bone after very long missions?
- What is the fracture risk for such changes in bone density and structure?
- Risk of renal (kidney) stone formation
- Will reduced Mars gravity be enough for preventing further bone loss?
- How should bones be loaded in reduced gravity?
- Which countermeasure (mechanical loading, exercise, diet, drugs, artificial gravity) work best?
Muscle and Bone Summary

• **Muscle**
  – Decrease in body mass, and leg muscle size and strength
  – Increase in number of “fast twitch” muscle fibers

• **Bone**
  – Continuous decrease in bone mass and density
  – Risk of bone fracture and renal stones probably increases during long-duration spaceflight

• **Countermeasures and Issues**
  – Experience of long-duration missions indicates that current in-flight countermeasures are not optimal; Using the current methods, humans would not be operational after landing on Mars
  – Is Mars gravity sufficient for regaining normal muscle and bone function?
Additional Reading

- Integrative Physiology in Space. *European J Physiol* 441, Number 2-3, (Supplement), 2000