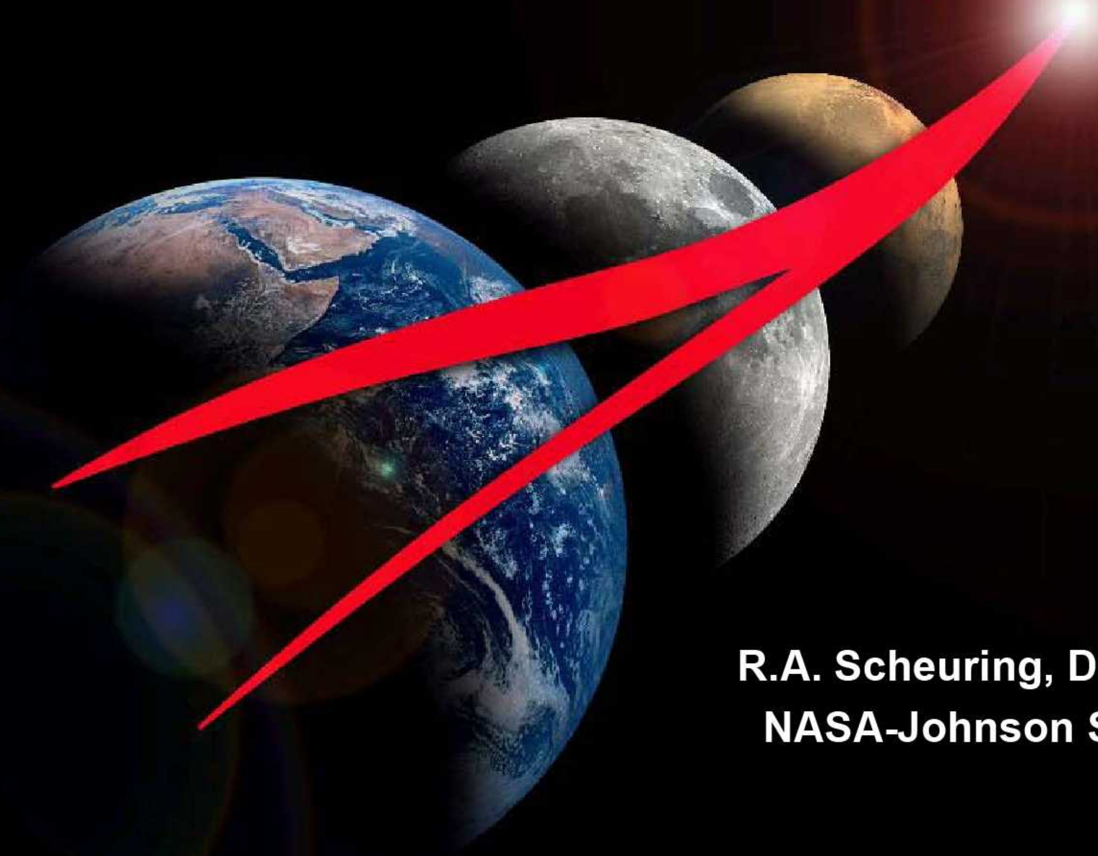
Musculoskeletal Changes, Injuries and Rehabilitation Associated with Spaceflight



R.A. Scheuring, DO, MS, FAAFP
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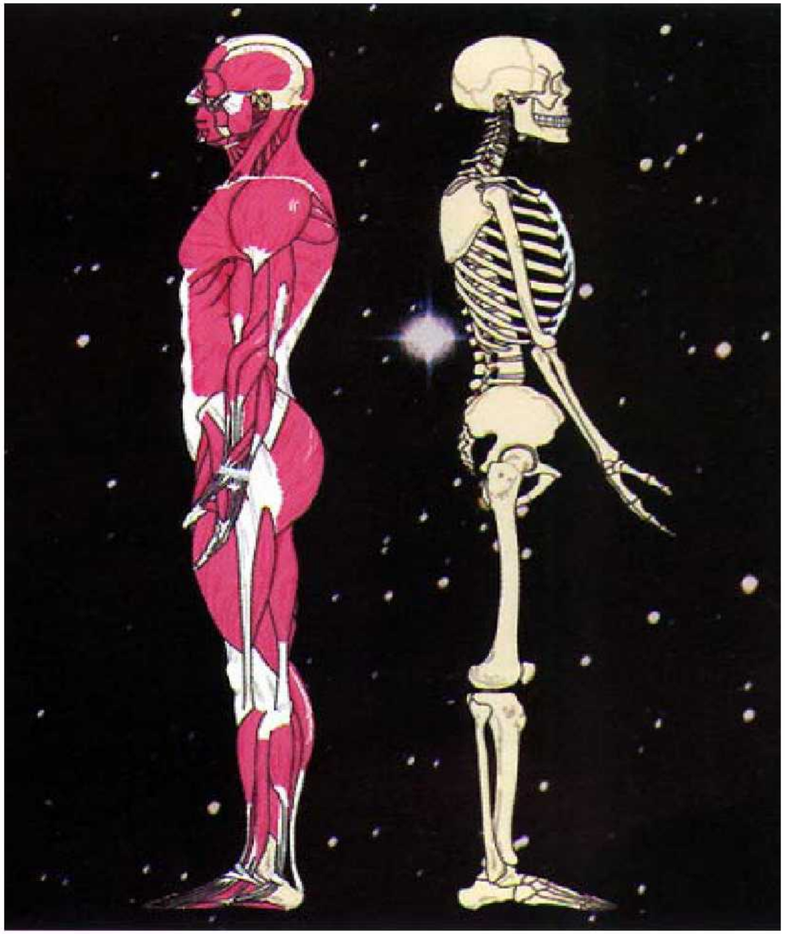
CONSTELLATION

Background

- **Unique aspects of astronaut training for space missions**
- **Musculoskeletal changes in microgravity**
- **Injuries**
  - Mission phases
    - Pre-flight
    - In-flight
    - Post-flight
- **Post-mission rehabilitation**

Training in Unusual Circumstances

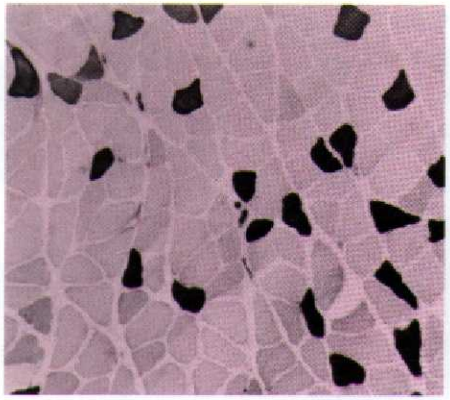
Muscle and Bone in Space



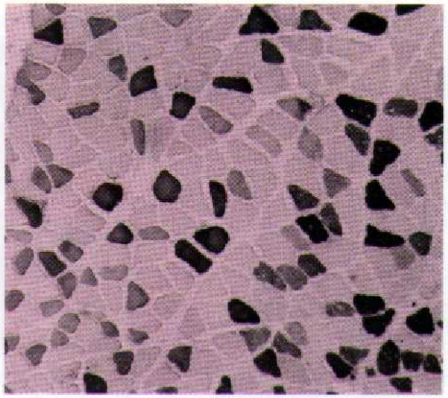
Effects of Spaceflight on Muscle

- Decrease in body mass
- Decrease in leg volume
- Atrophy of the antigravity muscles (thigh, calf)
  - decrease in leg strength (approx 20-30%)
  - extensor muscles more affected than flexor muscles

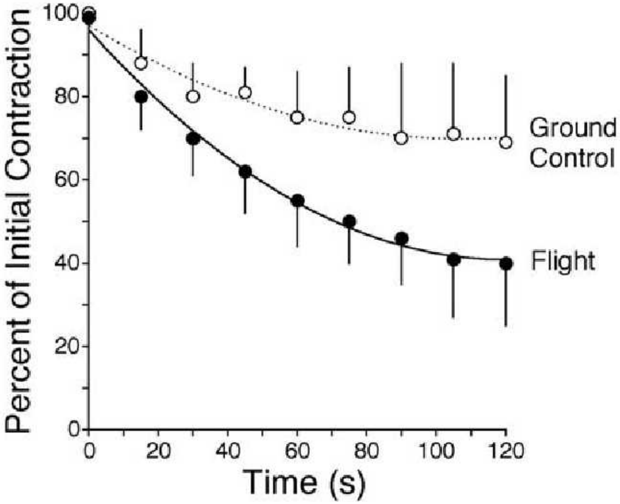
- Data in flown rats showed an increase in number of Type II, “fast twitch” muscle fibers (those which are useful for quick body movements but more prone to fatigue)



Ground control

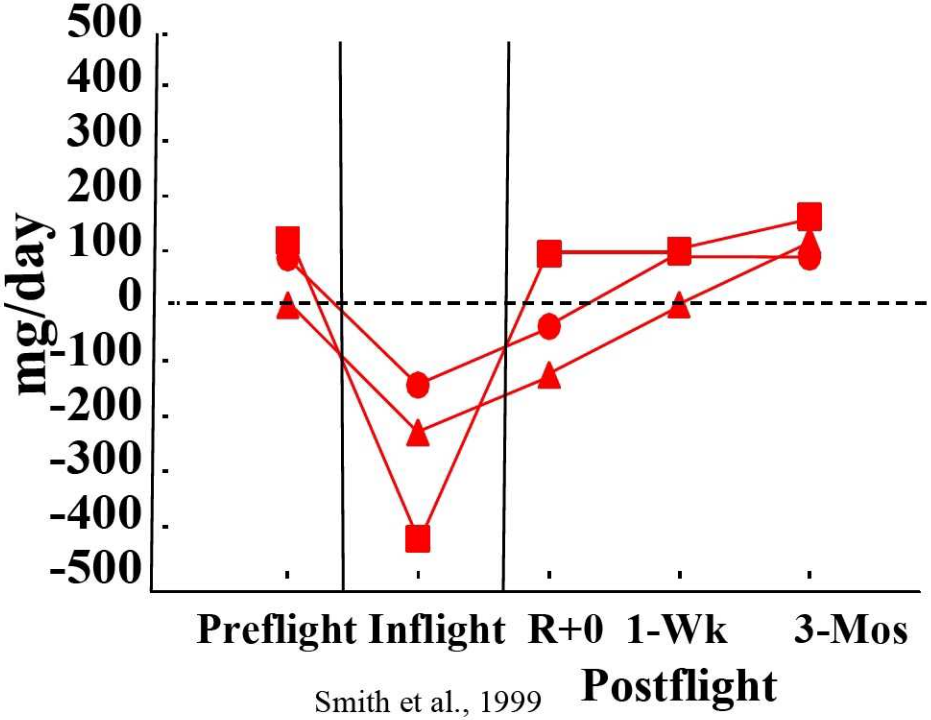


Flight



Bone Health assessments

Bone Ca Balance (V_{o+} - V_{o-})



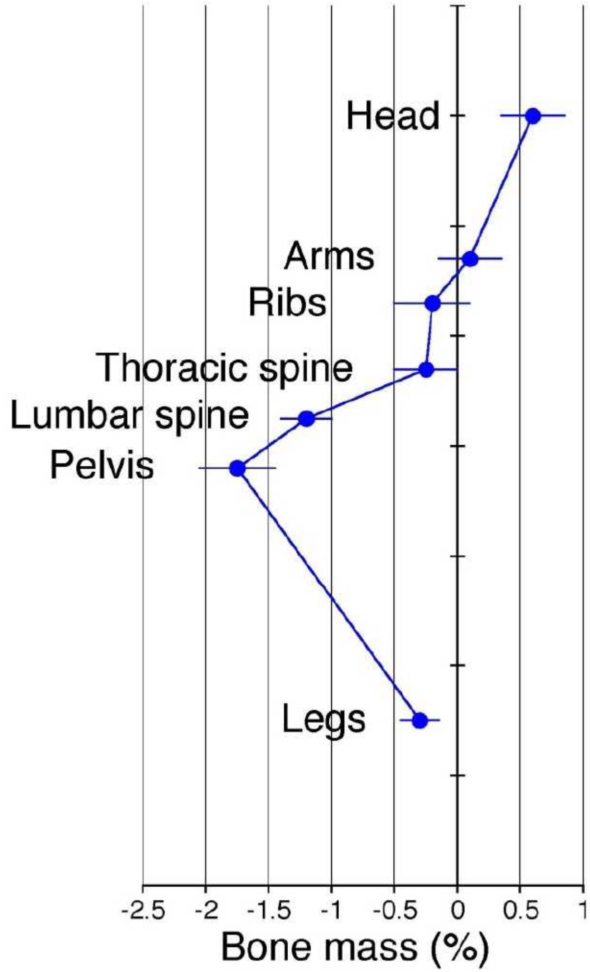
Smith et al., 1999

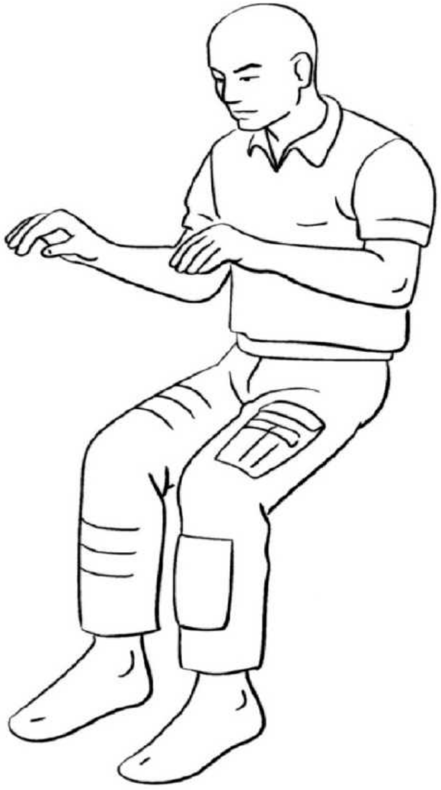
Bone Ca Loss ~ 250 mg/d

Bone Ca Gain ~ 100 mg/d

Recovery: 2-3 x mission

Bone Loss during Spaceflight by Region





Clemente, G. Fundamentals of Space Medicine, 2003.

Perturbations in bone remodeling result in osteoporosis

Risk Factor	Bone Formation	Bone Resorption
Spaceflight* ("Skeletal unloading")	–↓	↑
Aging	↓	–
Glucocorticoids	↓	↑
Estrogen Deficiency (**Menopause** is not a disease)	↑↑	↑↑
Alcohol	↓	–
Metabolic diseases of High Bone Turnover	↑↑	↑↑

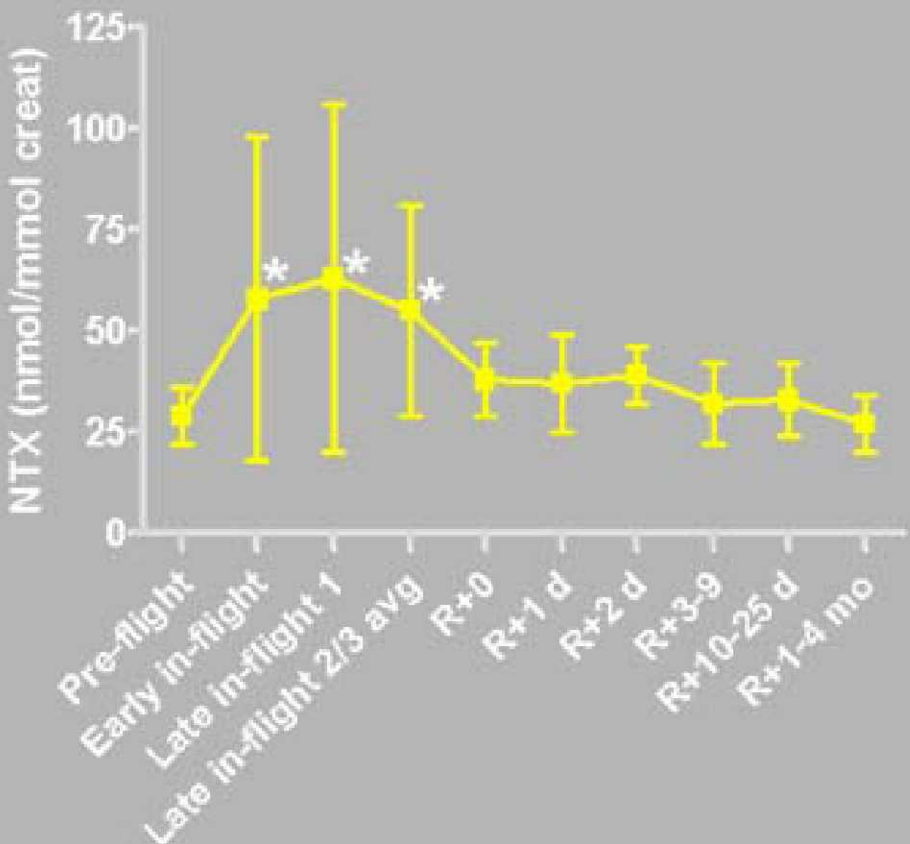
Muscle/Bone Loss during Spaceflight

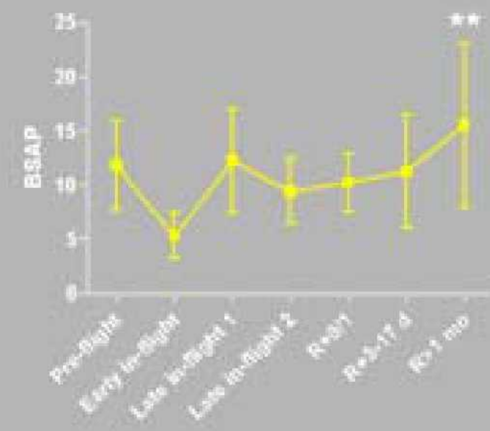
- Decrease in weight bearing causes bone demineralization, 1% - 2.4% per month in lower extremities and spine and decreased muscle strength and mass

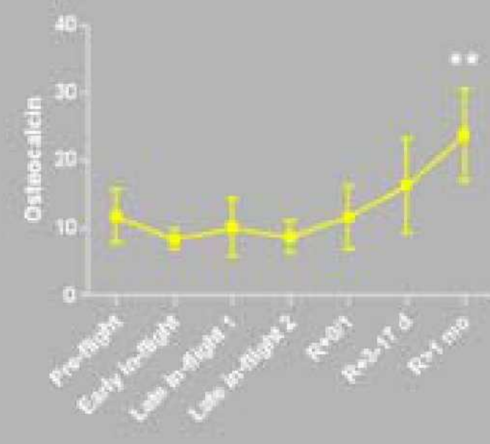
Konieczynski, D. D., Truty, M. J., and Biewener, A. A. ***Evaluation of a bone's in vivo 24-hour loading history for physical exercise compared with background loading***. J Orthop Res 16; 1998, 29-37

Bone turnover markers <u>suggest</u> that bone degradation is increased, formation is uncoupled from resorption, and bone gain and loss are unbalanced

averaged over entire skeleton.



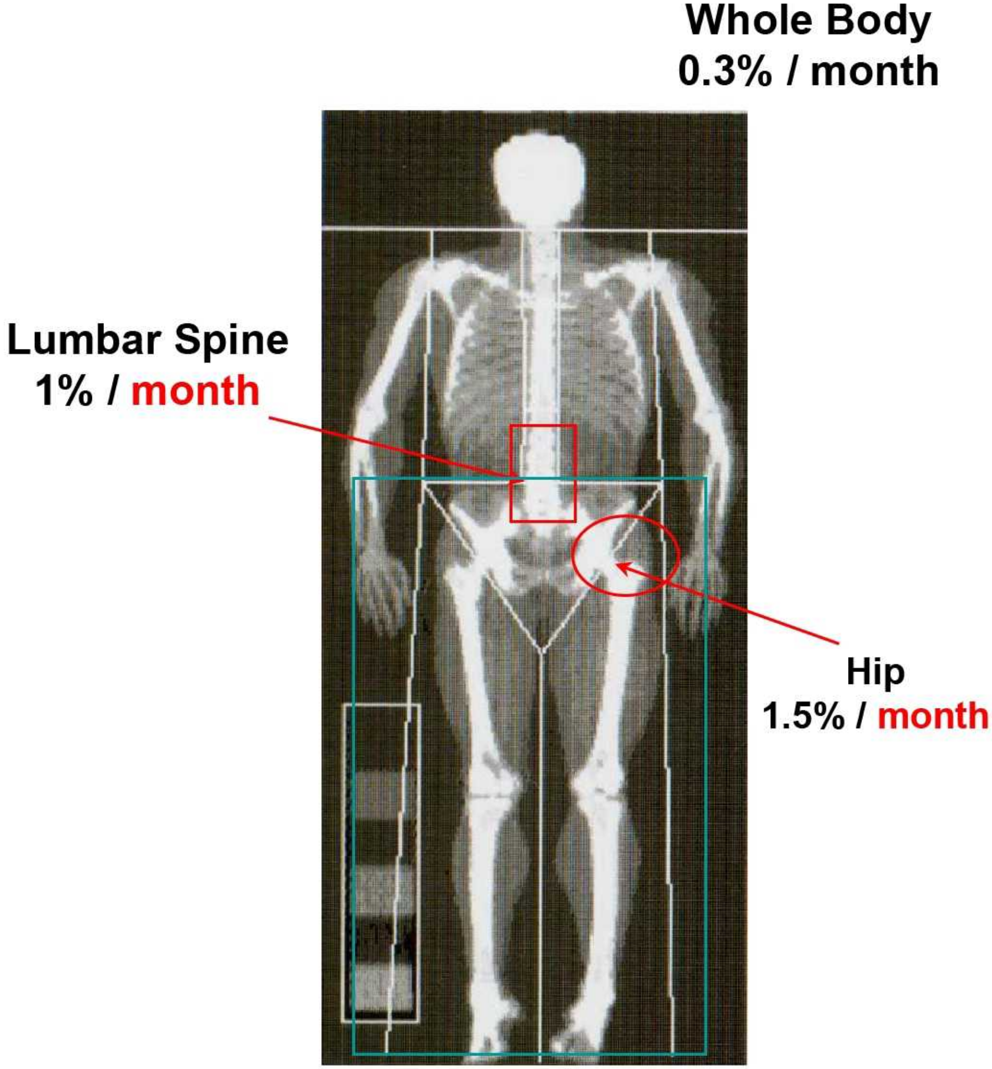




(Smith et al, JBMR 2005)

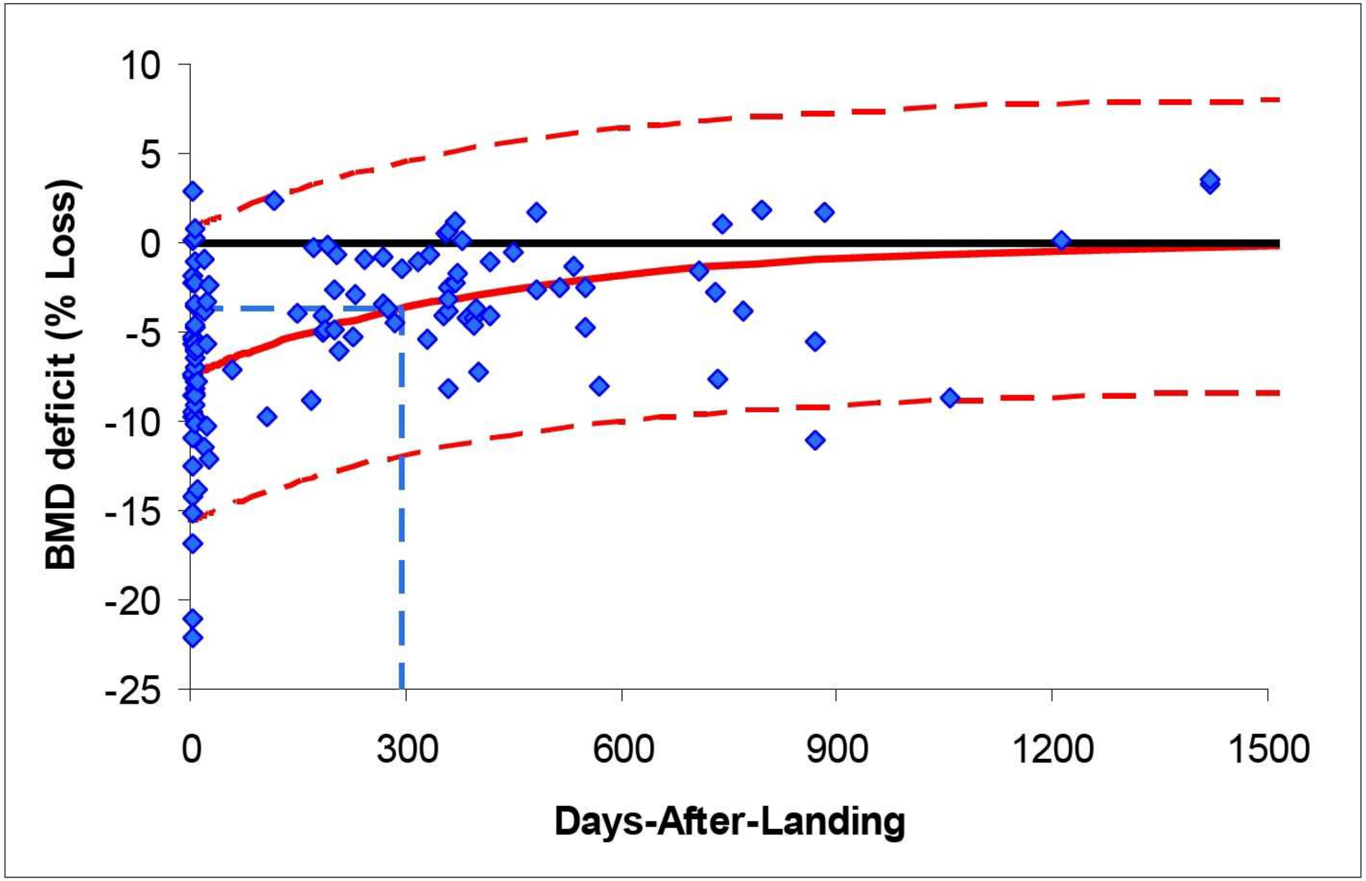
DXA: BMD losses are specific to weight-bearing bones*, rapid, not necessarily linear.

Areal BMD g/cm2	**%/Month** Change ± SD
Lumbar Spine	-1.06±0.63*
Femoral Neck	-1.15±0.84*
Trochanter	-1.56±0.99*
Total Body	-0.35±0.25*
Pelvis	-1.35±0.54*
Arm	-0.04±0.88
Leg	-0.34±0.33*
*p<0.01, n=16-18	LeBlanc et al, 2000



Recovery of BMD with return to gravity

$L_t = L_0 * exp^{ln(0.5)*t/HL}$

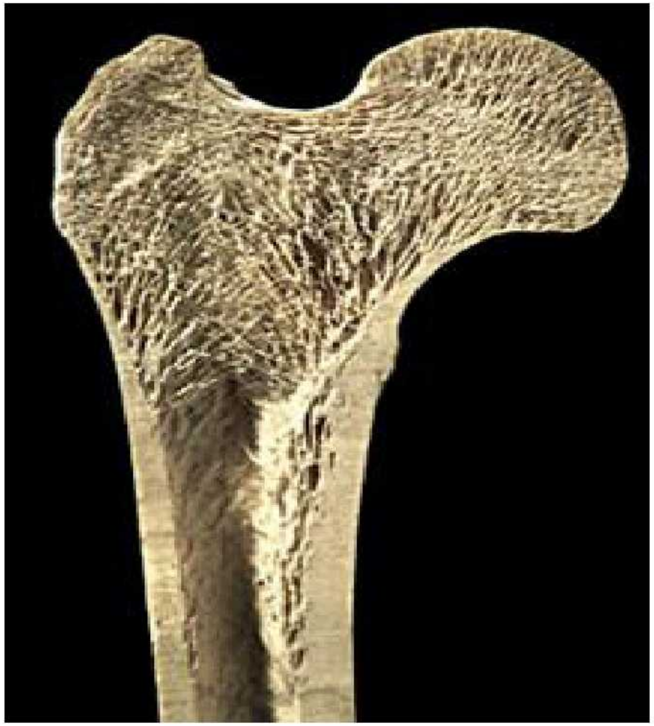


Trochanter BMD of ISS & Mir Crewmembers
Loss0=7.4% Recovery Half-life=276 d

QCT After Flight: Greater percentage loss vBMD in trabecular bone compartment (n=16 ISS)

CONSTELLATION

NOT detectable by DXA



Index DXA	%/Month Change ± SD	Index QCT	%/Month Change ± SD
aBMD Lumbar Spine	1.06±0.63*	Integral vBMD Lumbar Spine	0.9±0.5
		Trabecular vBMD Lumbar Spine	0.7±0.6
aBMD Femoral Neck	1.15±0.84*	Integral vBMD Femoral Neck	1.2±0.7
		Trabecular vBMD Femoral Neck	2.7±1.9
aBMD Trochanter	1.56±0.99*	Integral vBMD Trochanter	1.5+0.9
*p<0.01, n=16-18		Trabecular vBMD Trochanter	2.2+0.9

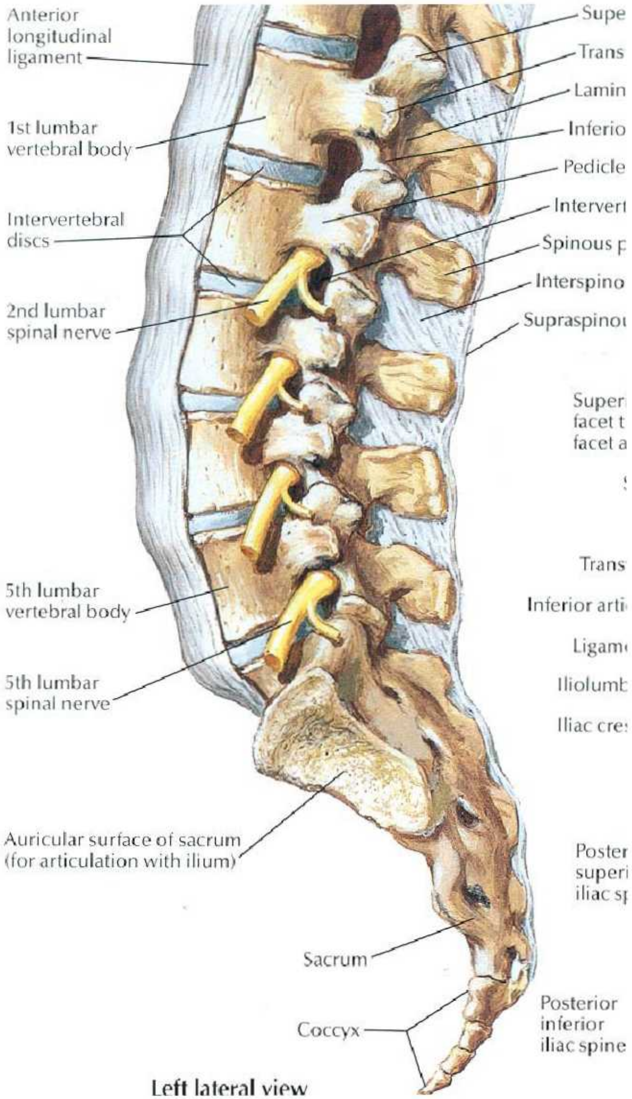
LeBlanc, J M Neuron Interact, 2000;
Lang , J Bone Miner Res, 2004;
Vico, The Lancet 2000

Musculoskeletal Changes

Clinical

- Incidence - All crewmembers are affected
- Symptoms- Acute
  - Back pain (53-68% incidence on orbit to some degree)
    - Kertsman EL, **Scheuring RA**, Barnes MG, Dekorse TB, Saile LG. Space Adaptation Back Pain: A Retrospective Study. Aviat Space Environ Med. In press, 2010
    - Sayson JV, Hargens AR. Pathophysiology of Low Back Pain during Exposure to Microgravity. Aviat Space Environ Med 2008 April; 79 (2): 365-73.
    - Wing PC, Tsang IK, Susak L, et al. Back pain and spinal changes in microgravity. Orthop Clin North Am 1991; 22: 255-62
  - Fatigue (less flexibility and endurance)

Musculoskeletal Changes



Acute

- Postural change with stretching of tendons and ligaments. Increase in on-orbit height by 2-6 cm

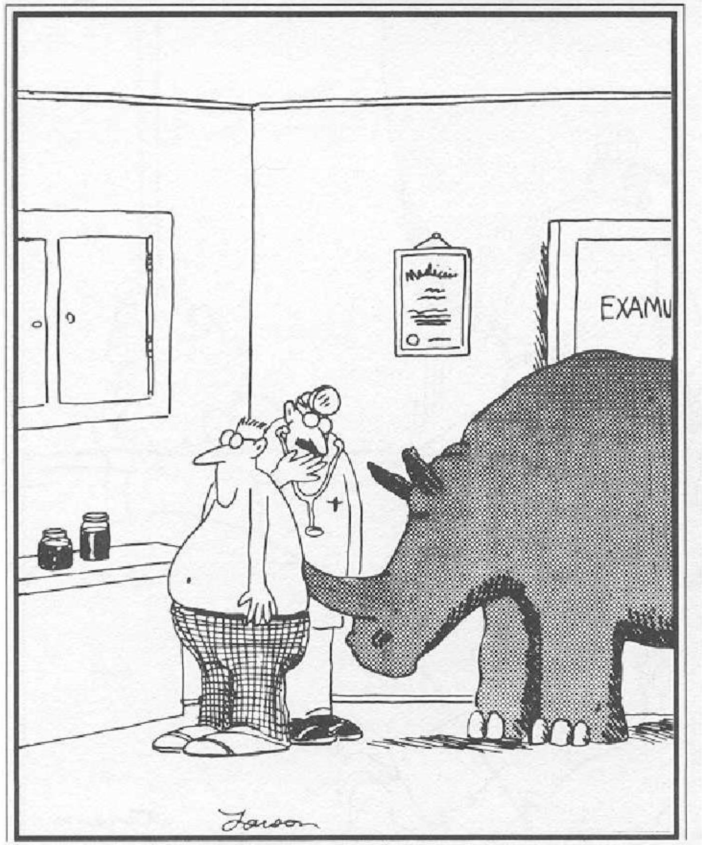
Musculoskeletal Changes

Chronic

- Muscle atrophy
- Intervertebral disc changes and HNP
  - Johnston S, Campbell M, **Scheuring RA**, Feiveson A. Increased Incidence of Herniated Nucleus Pulposus among U.S. Astronauts. Aviat Space Environ Med. In Press, ASEM-S-08-001881, 2010.
- Skeletal changes and loss of total body calcium have been noted in both humans and animals exposed to microgravity from 7 to 237 days.
  - Nicogossian AE. ***Space Physiology and Medicine***, 1989. Lea and Febiger, Philadelphia
  - Baldwin KM, Herrick RE, McCue SA (1993). ***Substrate oxidation capacity in rodent skeletal muscle: effects of exposure to zero gravity***. J. Appl. Physiol. 75(6): 2466-2470

Effects of Long duration space flight on calcium metabolism

- Kidney Stones
  - Due to increased urine and fecal calcium
- Possible fractures
- Disk Disease



"Wait a minute here, Mr. Crumbley . . . Maybe it isn't kidney stones after all."

Musculoskeletal System Loss and Potential Complications/ Countermeasures

- Countermeasures in Practice
  - For Muscular strength and endurance preservation
    - Aerobic (TVIS, CEVIS) and resistive exercise (RED)
    - NAC and other supplements/pharmacologics
  - For Reduced bone strength/ Increased Injury or Fracture Risk:
    1) Resistive exercise hardware
    2) Pharmacologic- e.g. Bisphosphonates
  - For Urinary Calcium Excretion- Risk of Calculi
    1) Increased Fluid Intake (2-3L/day)
    2) Resistive exercise
    3) Pharmacologic- e.g. inhibitor K^+ Citrate or K^+Mg^+ Citrate
    4) Contingency Management Strategy
- Countermeasures under consideration/ preparation
    1) Artificial gravity in transit
    2) PTH, Peptides

Exercise Countermeasures: In-Flight

- Treadmill
  - Neurovestibular
  - Cardiovascular
  - Musculoskeletal
- Cycle Ergometer
  - Cardiovascular
- Resistive Exercise Device
  - Musculoskeletal

TVIS

RED

CEVIS

Countermeasures

- Rx: 2 daily 1-hour sessions of exercise
- Other exercise options
  - Traction on “bungee cords”
  - Historically the “Exer-Genie” was used during the Apollo missions

Photos NASA

In-Flight Medical Conditions Incidence Comparisons (events/person-year)

- **Sleep Disturbance: 3.80**
- **Sprain/Strain/Contusion: 3.34**
- **Skin rash: 3.29**
- **Skin abrasion/laceration: 3.11**
- **Eye foreign body abrasion: 2.60**
- **Cough (URI): 1.35**
- **UTI (females): 1.29**
- **Diarrhea: 1.21**

In-Flight Musculoskeletal Injuries

RESEARCH ARTICLE

Musculoskeletal Injuries and Minor Trauma in Space: Incidence and Injury Mechanisms in U.S. Astronauts

RICHARD A. SCHEURING, CHARLES H. MATHERS,
JEFFREY A. JONES, AND MARY L. WEAR

SCHEURING RA, MATHERS CH, JONES JA, WEAR ML. *Musculoskeletal injuries and minor trauma in space: incidence and injury mechanisms in U.S. astronauts.* Aviat Space Environ Med 2009; 80:117–24.

Introduction: Astronauts have sustained musculoskeletal injuries and minor trauma in space, but our knowledge of these injuries is based mainly on anecdotal reports. The purpose of our study was to catalog and analyze all in-flight musculoskeletal injuries occurring throughout the U.S. space program to date. ***Methods:*** A database on in-flight musculoskeletal injuries among U.S. astronauts was generated from records at the Johnson Space Center. ***Results:*** A total of 219 in-flight musculoskeletal injuries were identified, 198 occurring in men and 21 in women. Incidence over the course of the space program was 0.021 per flight day for men and 0.015 for women. Hand injuries represented the most common location of injuries, with abrasions and small lacerations representing common manifestations of these injuries. Crew activity in the spacecraft cabin such as translating between modules, aerobic and resistive exercise, and injuries caused by the extravehicular activity (EVA) suit components were the leading causes of musculoskeletal injuries. Exercise-related injuries accounted for an incidence of 0.003 per day and exercise is the most frequent source of injuries in astronauts living aboard the International Space Station (ISS). Interaction with EVA suit components accounted for an incidence of 0.26 injuries per EVA. ***Discussion:*** Hand injuries were among the most common events occurring in U.S. astronauts during spaceflight. Identifying the incidence and mechanism of in-flight injuries will allow flight surgeons to quantify the amount of medical supplies needed in the design of next-generation spacecraft. Engineers can use in-flight injury data to further refine the EVA suit and vehicle components.

Keywords: astronaut, NASA, strain, sprain, abrasion, contusion, laceration, dislocation, EVA, injury.

NASA ASTRONAUTS face a variety of occupational hazards throughout their career. In addition to the risks inherent to space travel, astronauts perform physically demanding tasks in unfamiliar environments. Coupled with bone and muscle mass loss due to the effects of microgravity on the human body, one could hypothesize that astronauts may be at increased risk for sustaining musculoskeletal injuries while conducting space operations. Indeed, anecdotal reports from astronauts and postflight mission debriefings in all NASA spaceflight programs support this theory, as many astronauts have noted in-flight musculoskeletal injuries. However, until recently, our understanding of these injuries was based primarily on anecdotal reports, without evidence-based data to support these claims.

Jennings and Bagian conducted a study examining the terrestrial-based orthopedic injury history of astronauts during the period of 1987 to 1995 (5). The authors found astronauts sustained numerous fractures, serious ligament, cartilage, or soft tissue injuries, resulting in 28 orthopedic surgical procedures during this period. Knee injuries accounted for 19 of the surgical interventions, while running, skiing, and basketball were the activities most frequently associated with injuries. The authors recommended the hiring of full-time personal trainers and the designation of a facility for training purposes at Johnson Space Center, both of which are now in place as manifested in the Astronaut Strength, Conditioning, and Rehabilitation (ASCR) program. Jennings and Bagian recognized the importance of understanding the mechanism of injury or trauma, noting that it was "time to move beyond documentation of injuries and treatment to providing a program that strives to prevent or mitigate training-related injuries." This important study is often cited in discussions regarding musculoskeletal injuries and prevention in astronauts, but did not address in-flight occurrences.

An article printed in the Longitudinal Study of Astronaut Health (LSAH) newsletter in December 1999 examined the musculoskeletal injury rates of shuttle astronauts between Shuttle Transport System (STS)-1 and STS-89 (12). The authors found an overall greater in-flight injury rate among astronauts than comparison participants in the LSAH. Interestingly, they also found a threefold higher injury rate within astronauts' mission period, defined as 1 yr preflight to 1 yr postflight, versus the rate outside the mission period. This raised questions as to how much of this increase was attributed to preflight training, postflight injury due to de-conditioning, or in-flight injury.

We know that astronauts sustain injuries during the preflight period, especially during training sessions in

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This manuscript was received for review in January 2008. It was accepted for publication in November 2008.

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DOI: 10.3357/ASEM.2270.2009

Introduction

- **Known**
  - US Astronauts suffer musculoskeletal injuries during pre-flight and post-flight phases

    Jennings RT, Bagian JP. Musculoskeletal injury review in the US space program. Aviat Space Environ Med 1996, 67(8): 762-766.

    Viegas SF, Williams D, Jones J, Strauss S, Clark J. Physical demands and injuries to the upper extremity associated with the space program. J Hand Surg 2004, 29A(3): 359-366.
  - A review of astronaut injuries published in the longitudinal study of astronaut health (LSAH) for shuttle astronauts between STS-1 and STS-89 revealed a greater *in-flight* injury rate among crewmembers than their age and sex-matched cohorts

    Wear M. Injury rate of shuttle astronauts. The Longitudinal Study of Astronaut Health Newsletter, December 1999, 8(2): 1,4

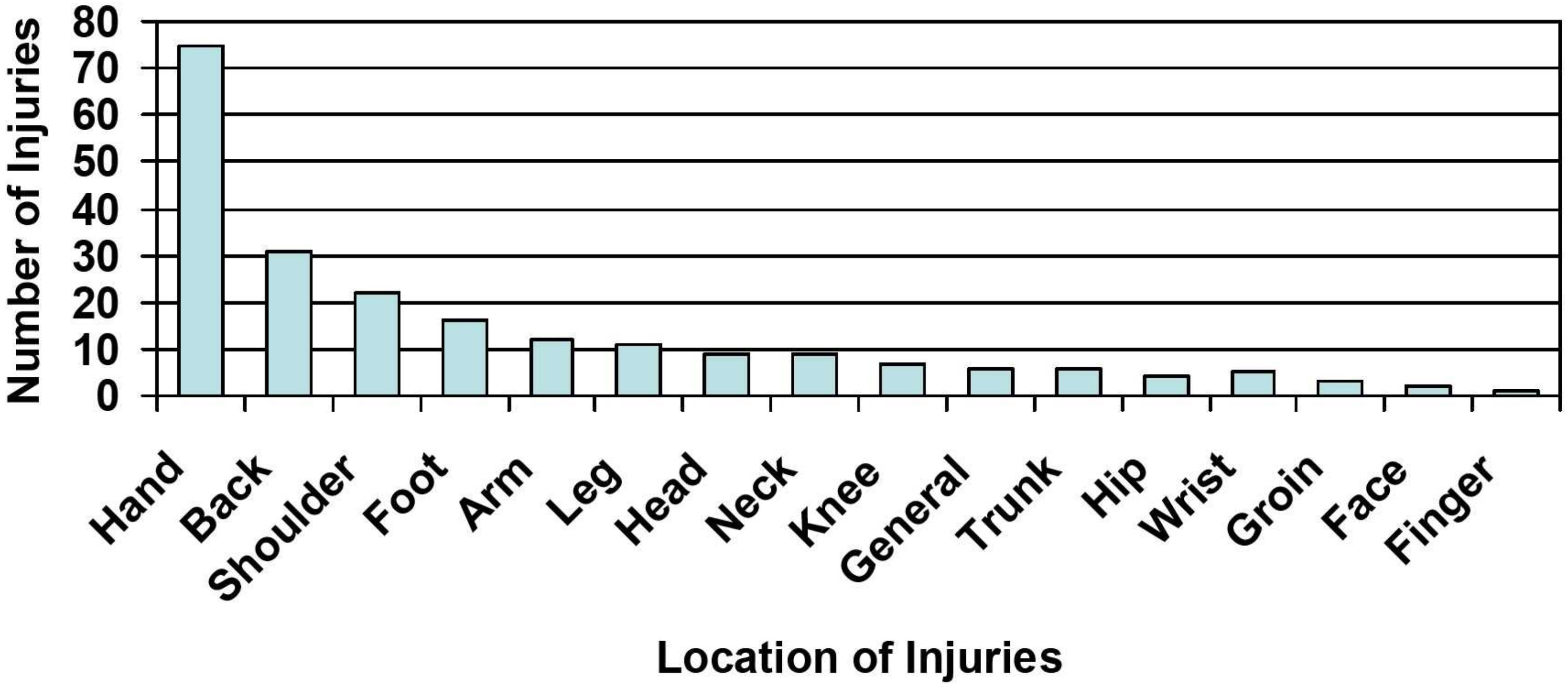
Methods

- **To examine in-flight musculoskeletal injuries and minor trauma, our results included:**
  - Abrasions
  - Contusions
  - Lacerations
  - Sprains
  - Strains
  - Dislocations.

Results

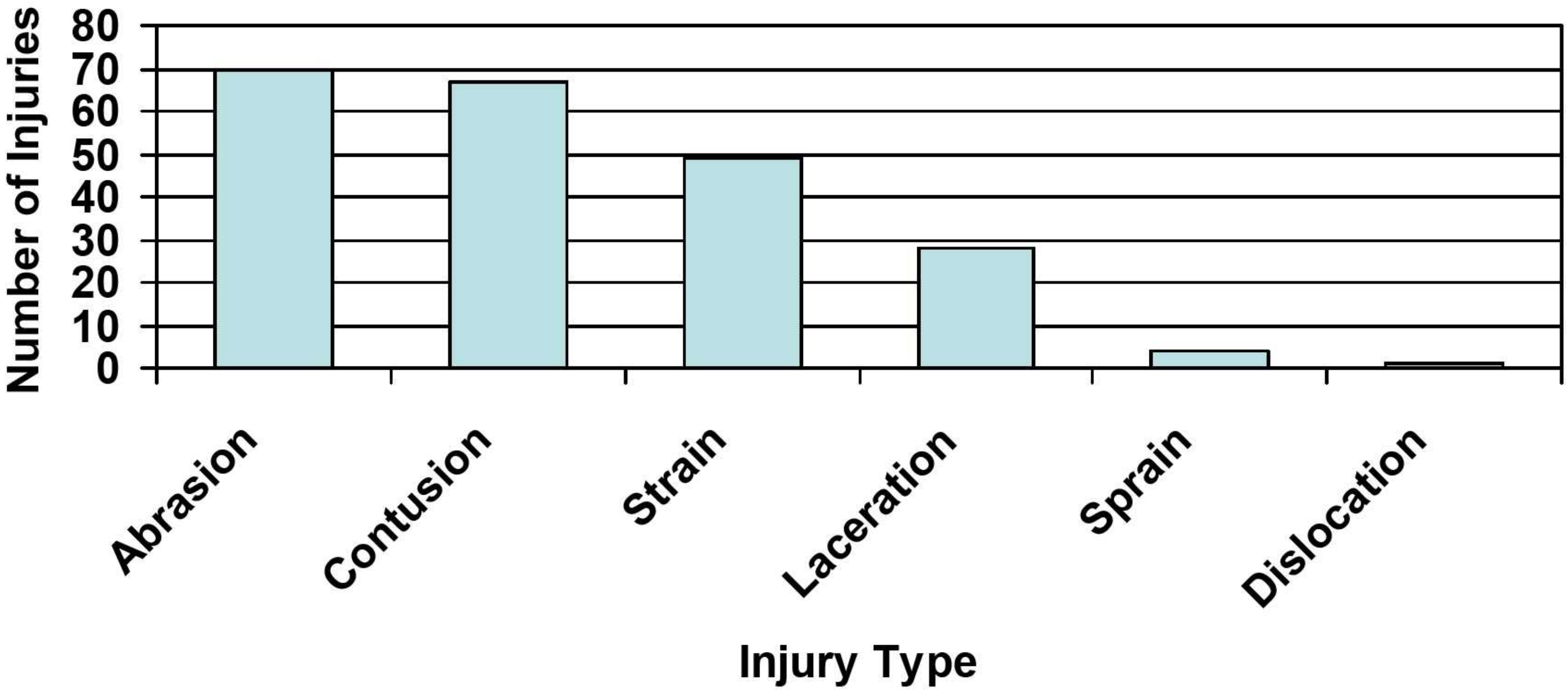
- A total of 369 in-flight musculoskeletal conditions were found, from which 219 in-flight musculoskeletal injuries were identified
  - 21 in women and 198 in men.
  - Incidence over the course of the space program was 0.021 per flight day for men and 0.015 for women.
  - Hand injuries represented the most common location of injuries throughout the U.S. space program, with abrasions and small lacerations representing common manifestations of these injuries.
  - Exercise-related injuries accounted for an incidence rate of 0.003 per day.

Results



Number of Injuries
80
70
60
50
40
30
20
10
0
Hand
Back
Shoulder
Foot
Arm
Leg
Head
Neck
Knee
General
Trunk
Hip
Wrist
Groin
Face
Finger
Location of Injuries

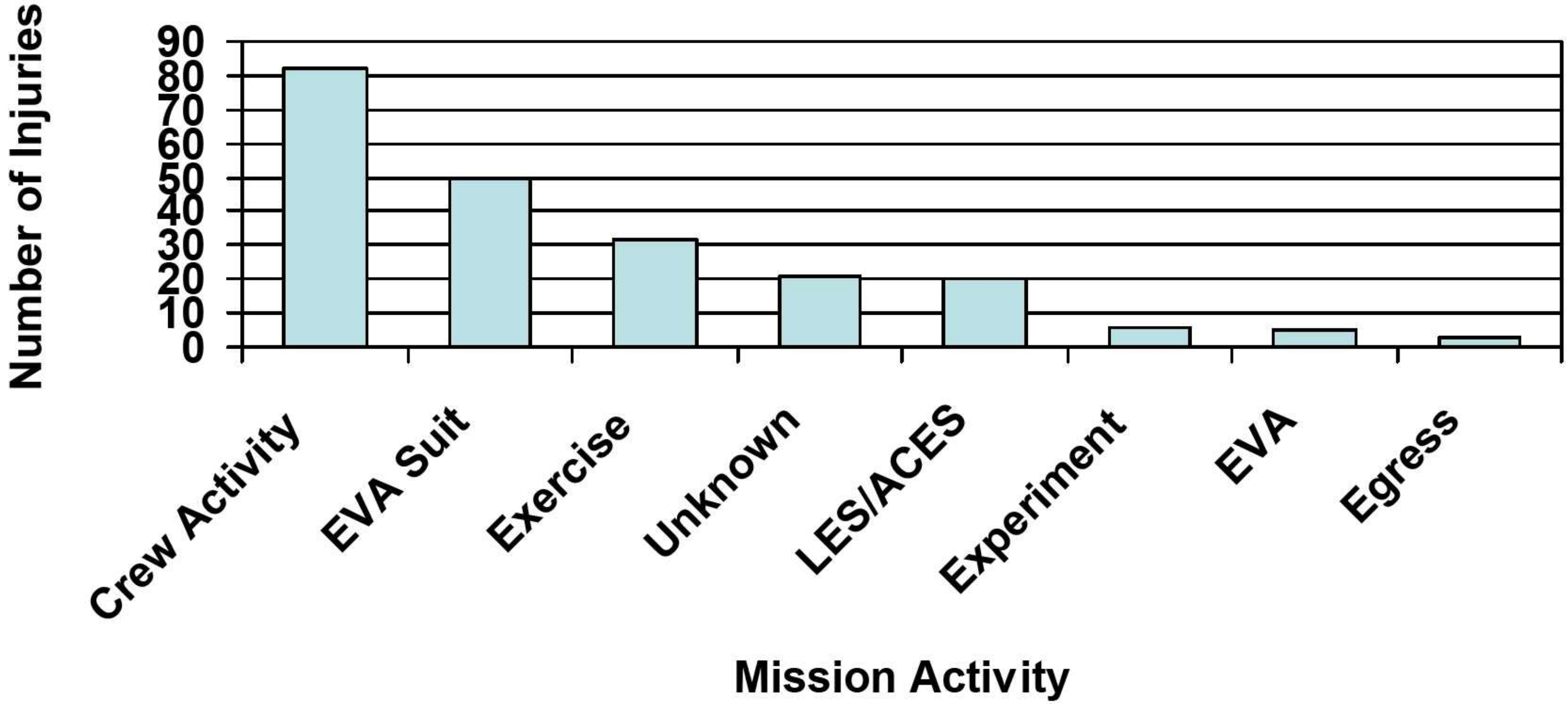
Results



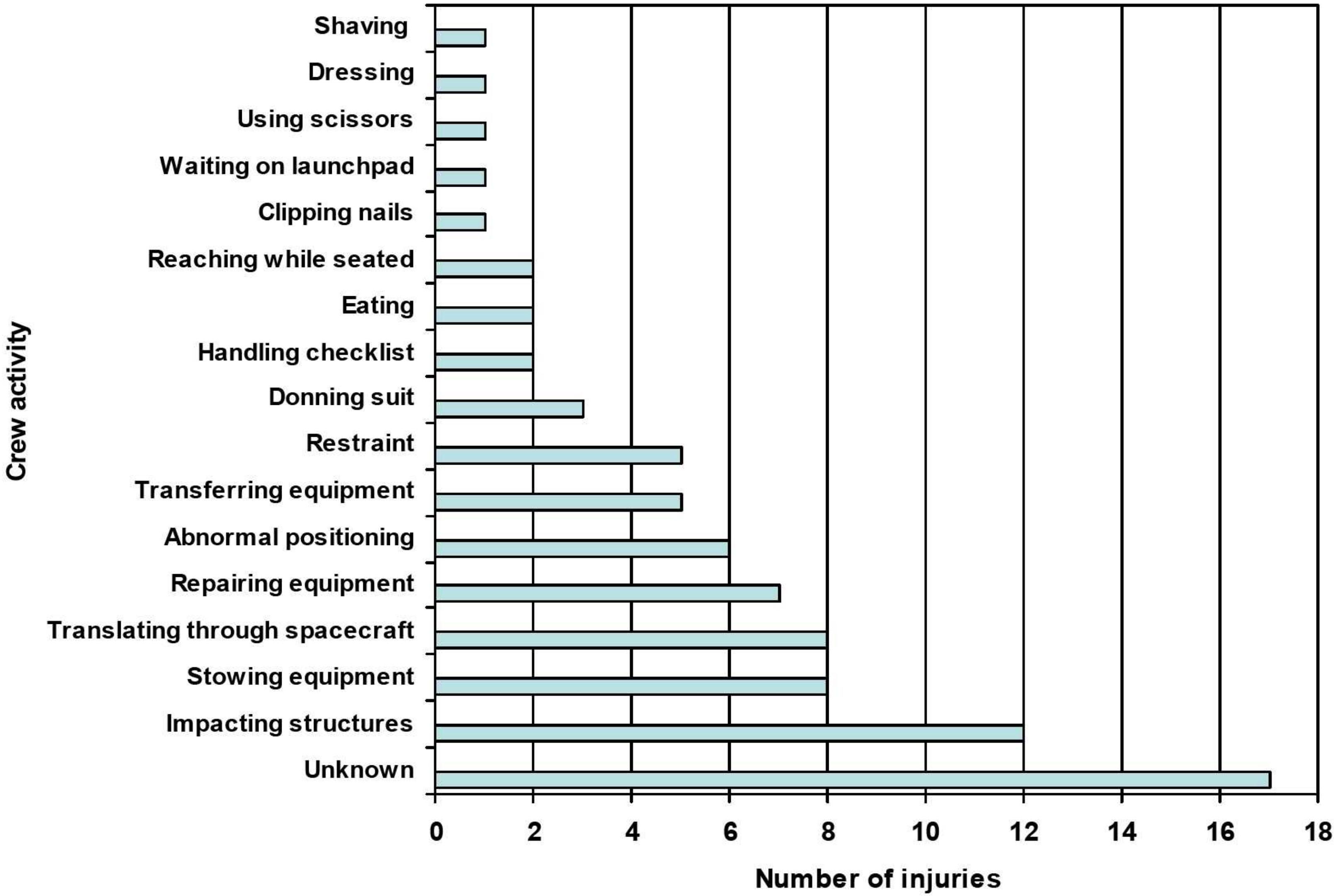
Number of Injuries
80
70
60
50
40
30
20
10
0
Abrasion
Contusion
Strain
Laceration
Sprain
Dislocation
Injury Type

Results

- Crew activity in the spacecraft cabin such as translating between modules, exercise, and injuries caused by the extravehicular activity (EVA) suit components were the leading causes of musculoskeletal injuries throughout the space program.

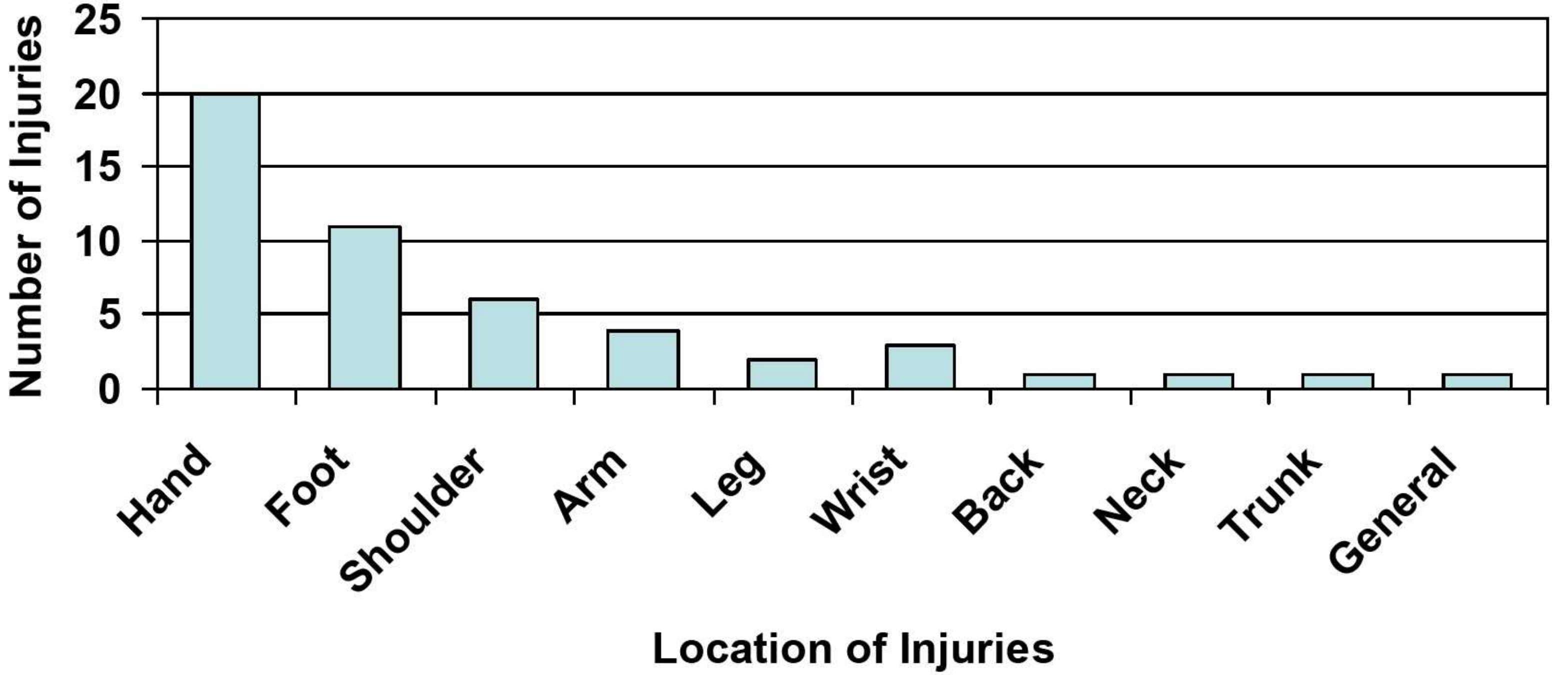


Results


Shaving
Dressing
Using scissors
Waiting on launchpad
Clipping nails
Reaching while seated
Eating
Handling checklist
Donning suit
Restraint
Transferring equipment
Abnormal positioning
Repairing equipment
Translating through spacecraft
Stowing equipment
Impacting structures
Unknown
Crew activity
0
2
4
6
8
10
12
14
16
18
Number of injuries

Results

- The EVA injuries incidence from all sources was 0.05 per hour in 1087.8 hours of EVA activity during the space program to date. This equates to a per day incidence of 1.21 in-flight musculoskeletal injuries or 0.26 injuries per EVA.



Results

- **Apollo Lunar Surface Musculoskeletal Events or Minor Trauma**
  - 9 Events were reported on the lunar surface related to EVA
    - 5 events located in the hand
    - Muscle fatigue during lunar EVA related to activities in the glove (unscrewing core tubes, etc.)
    - Finger soreness attributed to high work load
    - MCP, distal phalanx pain, swelling and abrasions after lunar 3/3 EVA
      - "*Completing a subsequent EVA would have been very difficult on account of how sore and swollen my hands were*"
  - 2 events occurred in the wrist
    - Wrist laceration due to suit wrist ring cutting into skin
    - Wrist soreness where suit sleeve repetitively rubbed on surface
  - 1 event resulted in shoulder strain after EVA 2/3
    - Crewmember injured shoulder during surface drilling activity
      - Required large doses of aspirin to relieve pain
  - 1 event described as general muscle fatigue while covering large distances by foot on the lunar surface

Results

Photo courtesy of Drs. Sam Strauss and Jeff Jones, NASA-JSC

Photo courtesy of Dr. Joseph Dervay, NASA-JSC

- **EVA accounted for an incidence rate of 0.26 injuries per EVA.**
  - EVA injuries occurred primarily in the hands and feet
  - These injuries may represent an exacerbation of pre-flight injury during training in the Neutral Buoyancy Laboratory

Back Up slides

Suggested running head – Herniated Nucleus Pulposus in Astronauts
(Pages:25, Abstract Words:307, Text Words:5,230, References:38, Tables:5, Figures:3)

Risk of Herniated Nucleus Pulposus among U.S. Astronauts

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Results

- **Exercise**
  - High number of minor back injuries occurred while using the exercise equipment on the International Space Station
    - Treadmill with Vibration and Isolation System (TVIS) was associated with 2 injuries
    - Interim Resistive Exercise Device (IRED) accounted for 7 injuries
    - Use of both devices was blamed for the remaining 3 injuries
  - Exercise activity or use of exercise equipment was associated with an injury rate of 0.003 injuries per day

Discussion

- The real power of the in-flight musculoskeletal database is evident when analyzing specific scenarios leading to these injuries.
  - Crew activity, such as stowing equipment, translating through and impacting structures within the spacecraft cabin caused most of the injuries in-flight
    - **This might be of interest to space vehicle design engineers as the interiors of spacecraft such as Skylab and ISS allow for more freedom of movement.**
  - EVA places astronauts in situations of high physical demand, and tests the capability of equipment as it does the men and women performing the activity. We found a relatively large number of injuries that occurred during EVA throughout the space program.

Discussion

- In our initial search for all musculoskeletal conditions in the space program, we found that many Apollo crewmembers who performed EVA on the moon noted problems with their hands. For example, one astronaut remarked, "EVA 1 was clearly the hardest…particularly in the hands. Our fingers were very sore." Another commented that his hands were "very sore after each EVA."
  - **Apollo conducted 2-3 EVA's for 3-7 hours per EVA**
    - **The Constellation program (CxP) will start out with 7 day lunar missions and progress to 6 month stays over the period of 3-4 years**

Discussion

- **Limitations**
  - Though the database contains detailed information on mechanism of injury, the post-flight mission debriefs did not always discuss the other parameters examined, such as exercise, treatment, and post-flight outcome. Thus, the database is incomplete as many entries lack information in these areas.
  - Information about musculoskeletal problems was not always elicited from flight crews, and the manner in which it was collected changed over the course of the space program. In addition, certain entries needed refining as to the accuracy of the diagnosis.

Conclusion

- The in-flight musculoskeletal database provides the foundation for directing operationally-relevant research in space medicine.
  - **This effort will enable medical operations to develop medical kits, training programs, and preventive medicine strategies for future CxP missions**
    - **Quantify medications and medical supplies for next-generation spacecraft**
    - **Objective data for engineers to determine weight requirements**

Conclusion

- Flight surgeons can make specific recommendations to astronauts based on injury data, such as emphasizing hand protection while in-flight

- EVA and spacecraft engineers can examine evidence-based data on injuries and design countermeasures to help prevent them