NASA STUDENT RESEARCH PROJECT • GRADES 9–12

How Do Astronauts Stay Strong in Space?

Optimizing Exercise on the Advanced Resistive Exercise Device (ARED)

Understanding how a machine that simulates gravity keeps astronaut bones and muscles healthy — and how we can make it work even better.

~2%	1–3 Mo.	600 lbs	4 Types
Bone Lost / Month	Mission Length	ARED Max Load	Exercise Devices

Grade Level	9th-12th grade
Subject Areas	Biology, Physics, Health Science, Engineering Design
Duration	8–10 weeks in class; final product is a 1–3 month exercise plan
Equipment Focus	ARED (Advanced Resistive Exercise Device) — primary focus
NASA Program	Astronaut Strength, Conditioning & Rehabilitation (ASCR)
Big Idea	Can we tell if an astronaut's exercise plan is working — while they're still in space?

1. The Big Problem: We Can't Tell If It's Working

Imagine you're a doctor responsible for an astronaut's health. Your patient is aboard the International Space Station — floating 250 miles above Earth — doing two hours of exercise every single day. But here's the scary part: you have no way of knowing whether that exercise is actually protecting their bones and muscles until they land back on Earth and you run tests.

That's the real situation NASA's flight surgeons face today. There is no real-time way to check if an astronaut's exercise plan is doing its job while they're in orbit. There is ability to take some simple tests such as measuring the thigh circumfrence and some blood work that can infer the current health of the bones and muscles. This project asks: Can we change that? Can we design a system — and a smarter exercise plan — that tells us in orbit whether the plan is working?

🚀 Your mission: Learn how the ARED works, understand what bones and muscles need to stay healthy, and design a 1–3 month exercise plan for commercial crew astronauts that could actually be monitored in real time.

1.1 Why Bones and Muscles Break Down in Space

On Earth, gravity is constantly pulling you down. Your skeleton and muscles work all day — even just standing up — to resist that pull. This constant low-level loading is what keeps bones dense and muscles strong.

In microgravity (what astronauts experience as 'weightlessness'), that loading disappears almost entirely. The reduction in vitamin D due to lack of sun exposure also contributes to the mismatch in osteocyte and osteoblast function. Crew takes supplements, but it doesn't stop the bone loss.

The result:

- Bones start dissolving faster than they rebuild — astronauts can lose about 1–2% of bone density every month at locations like the hip and lower spine.
- Muscles — especially leg and back muscles that fight gravity on Earth — shrink rapidly
- The heart and cardiovascular system weaken because they no longer have to pump blood upward against gravity
- Returning astronauts often struggle to walk and need extended periods of physical rehabilitation

On Earth	In Microgravity
Gravity constantly loads bones and muscles	Gravity loading disappears — no natural stimulus
Bone-forming cells (osteoblasts) keep pace	Bone-dissolving cells (osteoclasts) dominate
Standing, walking, carrying bags = free exercise	Every movement must be deliberately exercised
1 month off your feet = some muscle loss	1 month in orbit = significant bone AND muscle loss
Doctors can monitor you with regular check-ups	Doctors can only assess you after you return to Earth

1.2 The Current Feedback Problem

Here is what the current process looks like — and where the gap is:

Current loop: Pre-flight plan designed → Astronaut exercises in orbit → Returns to Earth → Flight surgeon runs bone scan → Finds problem → Too late to fix it

What we want instead:

Goal loop: Pre-flight plan designed → Astronaut exercises in orbit → Real-time data shows if bones/muscles are being loaded adequately → Plan adjusted mid-mission → Problem prevented →Flight surgeon runs bone scan → Finds no problem → No fix needed

2. Meet the ARED: Your Space Gym

The Advanced Resistive Exercise Device (ARED) is the most important piece of exercise equipment on the International Space Station. It is essentially a full weight room squeezed into one machine — designed to work in an environment where dumbbells would just float away.

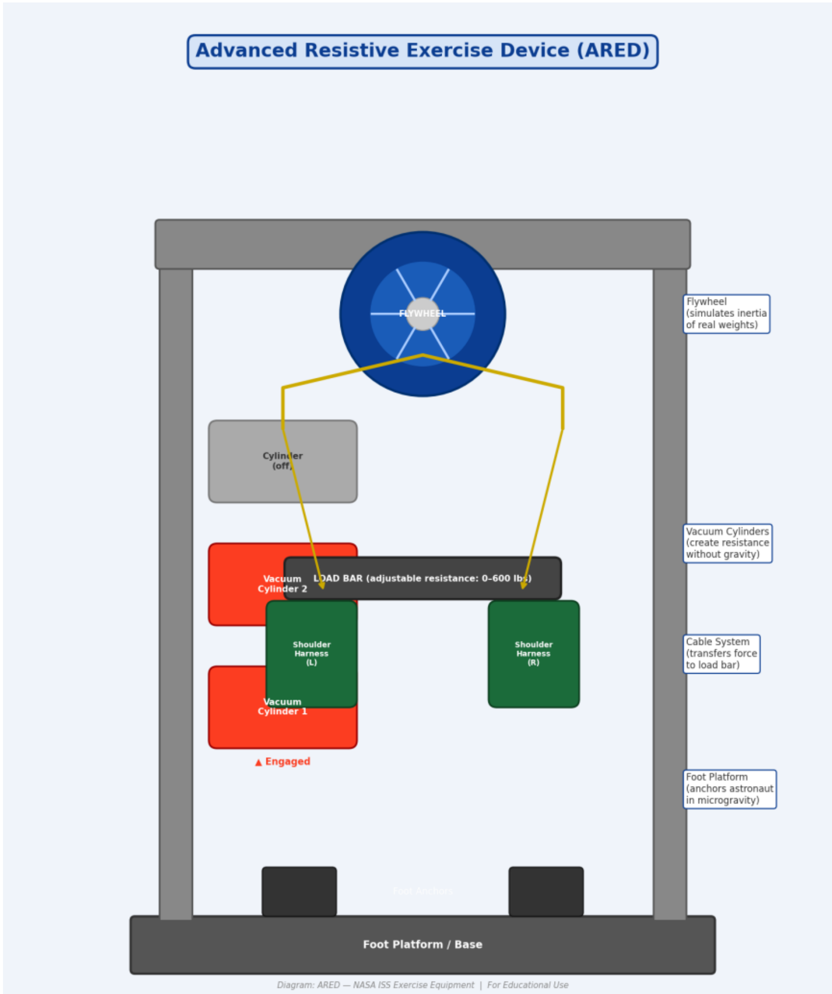

Figure 1: Labeled diagram of the ARED showing its key components — flywheel, vacuum cylinders, load bar, shoulder harnesses, and foot platform.

Real NASA Photographs — ARED in Action

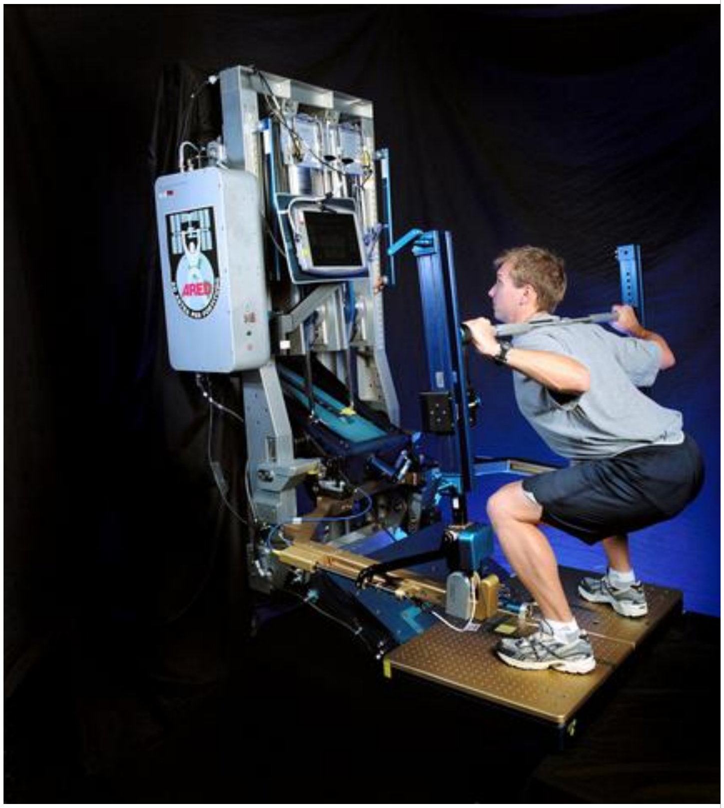

Photo A: Engineer demonstrating a squat on the ARED prior to ISS installation. The load bar across the shoulders, vacuum cylinder housing (left), and foot platform are clearly visible.

Photo B: NASA astronaut Kjell Lindgren performing a deadlift on the ARED aboard the ISS (Expedition 44, 2015). Note the foot anchor platform, blue frame uprights, and laptop used to log exercise data.

Credit: NASA/JSC (public domain). Left: pre-flight ARED demonstration. Right: ISS Expedition 44.

2.1 The Core Problem ARED Solves

Traditional weight training relies on gravity pulling a barbell or dumbbell downward to create resistance. In microgravity, there is no 'down.' A 200-pound barbell weighs nothing aboard the ISS. So NASA engineers had to invent a completely different way to create resistance — one that doesn't depend on gravity at all.

2.2 How ARED Creates Resistance: Two Systems Working Together

System 1 — Evacuated (Vacuum) Cylinder Canisters

The ARED contains a series of canisters from which almost all air has been removed — creating a near-vacuum inside. When an astronaut pulls the load bar upward, pistons push against this vacuum, creating resistance. The more canisters engaged, the higher the resistance. This can be adjusted from nearly zero up to about 600 pounds of force equivalent — covering everything from light warm-up sets to heavy deadlifts.

System 2 — The Flywheel

Here's where it gets clever. On Earth when you lift a barbell, you're not just fighting gravity — you're also fighting inertia. The weight resists being accelerated upward and resists being decelerated at the top. This inertial quality makes free-weight training feel different from machine training, and it is actually important for how muscles are trained.

The ARED includes a spinning flywheel that mimics this inertial quality. As the astronaut lifts, the flywheel spins up — and that spinning mass provides resistance when the movement decelerates. The result is a more realistic 'feel' that better replicates lifting actual weights.

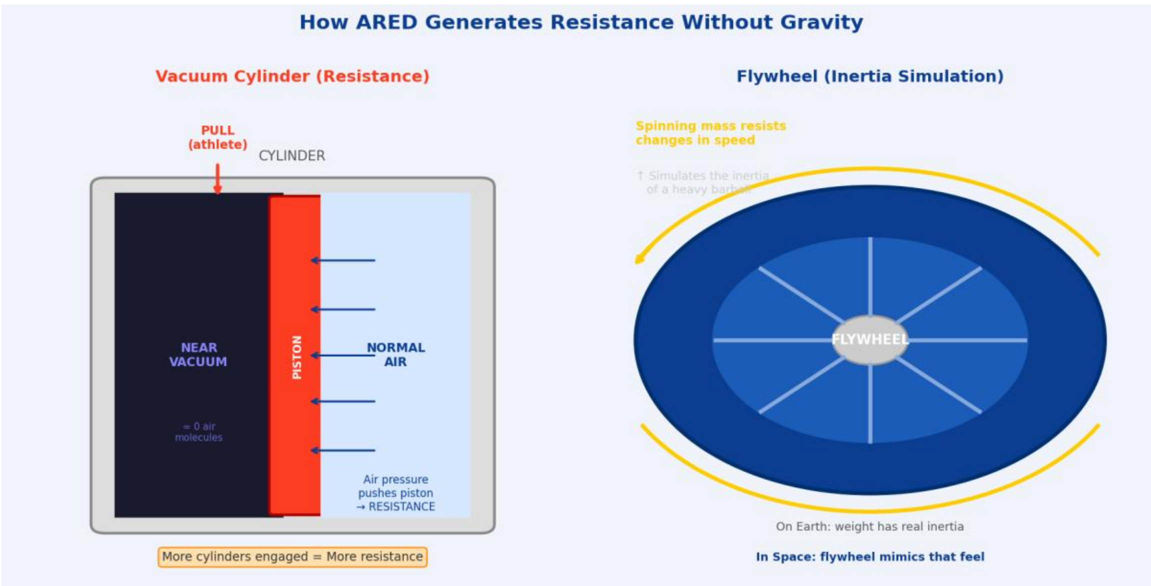

Figure 2: How ARED generates resistance — the vacuum cylinder creates force via air pressure differential, while the circular flywheel simulates the inertia of a real barbell.

2.3 What Exercises Can Astronauts Do on the ARED?

Exercise	Muscles & Bones Targeted	Why It Matters in Space
Squat	Quadriceps, glutes, hamstrings; lumbar spine, hip, femur	Primary load-bearing exercise; simulates standing and walking
Deadlift	Hamstrings, glutes, lower back; lumbar spine, femoral neck	Develops posterior chain; high spinal compression load
Heel Raise	Calf muscles (gastrocnemius, soleus); tibia, calcaneus	Targets calf muscles most vulnerable to microgravity atrophy
Bench Press	Pectorals, triceps, shoulders; sternum, clavicle	Upper-body strength maintenance; easier to preserve than lower body
Overhead Press	Shoulders, triceps; cervical/thoracic spine	Shoulder stability; important for spacewalk tasks
Bent-Over Row	Back muscles, biceps; thoracic spine	Posture maintenance; counteracts forward hunching in microgravity
Hip Abduction	Hip abductors, glutes; femoral head	Hip joint stability; protects the hip — a major fracture risk site

2.4 What the ARED Can't Do

The ARED is impressive, but it is not a perfect substitute for Earth-based weight training. Understanding these limitations is central to this project:

- No bodyweight loading: On Earth a squat loads your spine with both the barbell AND your own bodyweight. In orbit, your bodyweight contributes nothing — the ARED must compensate for this entirely. This is affectively a point load, with all the load at a single point location, which can result in significant discomfort.
- Different force profile: Earth free-weights produce force in a purely downward direction. ARED forces are applied through a cable system, which can change joint angles and muscle activation slightly
- Inertia approximation: The flywheel approximates inertia but is not identical to the complex inertial properties of a loaded barbell
- No impact loading: The ARED cannot replicate the bone-jarring impact of running or jumping — which is one of the most effective stimuli for bone formation

> 💡 **Key insight: Because of these limitations, the ARED is always used alongside other equipment. The treadmill (with bungee harness) adds impact loading. CEVIS adds cardiovascular conditioning. Resistive cords add supplemental movements. Together they form a complete countermeasure system.**

2.5 The Other Equipment: How All Four Work Together

Device	What It Does	Main Benefit	Key Limitation
ARED	Resistance training via vacuum cylinders + flywheel	Heavy loading for bones and muscles; up to 600 lbs	No bodyweight; no impact; inertia is approximated
T2 Treadmill + Bungee Harness	Running/walking with downward pull from bungee straps	Cardiovascular fitness + some impact bone loading	Bungee typically set to 70–80% body weight — less than real running
CEVIS Ergonomic Cycle	Stationary cycling (no weight-bearing)	Excellent cardiovascular conditioning; very low injury risk	No bone loading — legs don't carry weight on a bike
Resistive/Bungee Cords	Elastic bands for supplemental resistance exercises	Flexible; many exercises possible; can target small muscles	Hard to measure exact load; lower maximum resistance

3. The Science: What Bones and Muscles Actually Need

3.1 How Bones Respond to Loading (Wolff's Law)

In 1892, a German surgeon named Julius Wolff observed that bone grows stronger in response to the forces placed on it — and weaker when those forces are removed. This is called Wolff's Law, and it explains why exercise is so important for bone health.

When a bone bends slightly under load (called bone strain), special cells called osteoblasts are triggered to lay down new bone material, making the bone denser and stronger. The key thresholds researchers have identified:

- Below ~200 microstrain: Bone is resorbed (dissolved) — the body treats it as unnecessary
- 200–1,500 microstrain: Normal maintenance — bone stays about the same
- 1,500–3,000 microstrain: Bone formation is actively stimulated — bone gets stronger
- Above ~15,000 microstrain: Risk of stress fracture

A normal walk generates about 400–800 microstrain in the tibia. Running produces 1,500–2,500. Heavy squats can generate 3,000+ microstrain in the lumbar vertebrae — right in the sweet spot for bone growth. This is why high-load exercise is so important for astronauts.

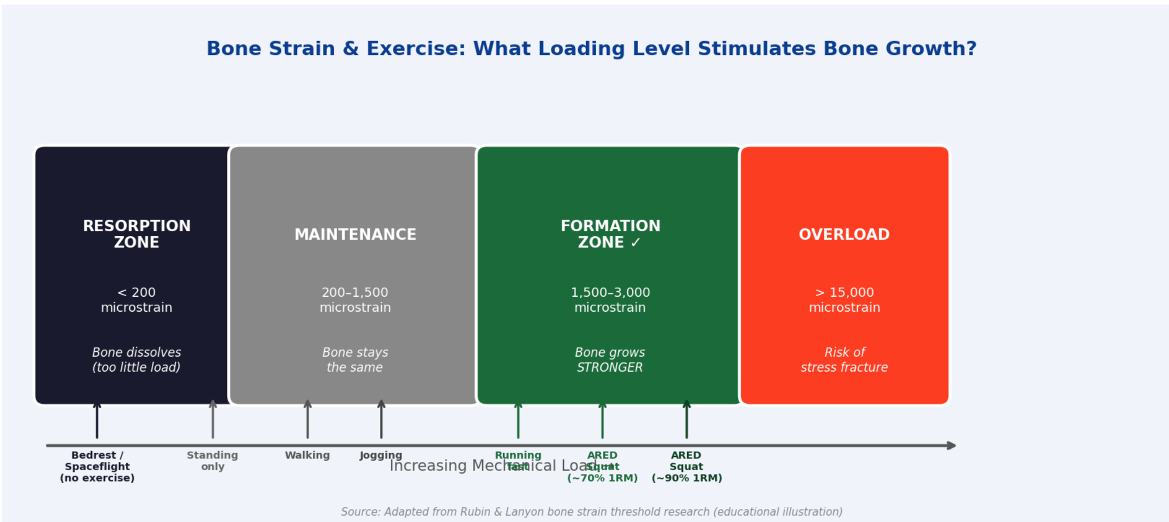

Figure 3: Bone strain zones and the exercises that reach each level. The green 'Formation Zone' is the target for astronaut exercise — ARED squats at high load are among the few exercises that reliably reach it.

3.2 Earth Research on Heavy Loading and Bone

Studies on Earth have given us important clues about what kinds of exercise protect bone most effectively:

- High-load squats (above 80% of the maximum weight a person can lift once): Back squats at heavy loads generate compressive forces of 2–4 times body weight on the lumbar spine — directly stimulating bone formation at one of the sites most at risk in spaceflight
- How fast you load matters: Rapid, explosive movements stimulate bone more than slow movements at the same weight — the speed of loading appears to be its own signal to bone cells
- Eccentric loading (lowering the weight under control): Produces higher muscle tension than lifting the same weight, giving a stronger muscle stimulus
- Progressive overload: To keep getting stronger (and keep stimulating bone), you must gradually increase load, reps, or difficulty over time — the body adapts and needs new challenges
- Impact loading: Running and jumping generate high-rate loading spikes that are especially good bone stimuli — even a few minutes of jumping per day shows measurable effects in studies

3.3 Biomechanics: Understanding Forces on the Body

Biomechanics is the study of how forces affect the body during movement. To understand whether the ARED is adequately loading bones and muscles, you need to think in terms of forces and moments (torques).

Concept	Plain-Language Explanation	Spaceflight Relevance
Ground Reaction Force (GRF)	The force the ground pushes back up on you when you stand, walk, or run — equal and opposite to how hard you push down	Running on Earth = 2–3x bodyweight GRF. With bungee harness at 75% BW load, orbit GRF is much lower
Force = Mass × Acceleration	Newton's 2nd Law — to create force in space without mass (bodyweight), you need the ARED's mechanical system	ARED must generate the force your bodyweight would on Earth
Torque (Joint Moment)	Rotational force at a joint = Force × distance from the joint (moment arm). Muscles must generate torque to control movement	Deeper squats = longer moment arm at the knee = more quad force required
Volume Load	Sets × Reps × Weight lifted = total training stress for the week	Tracking weekly volume load tells us whether muscles received adequate stimulus
Progressive Overload	Gradually increasing demands so the body keeps adapting	Essential for preventing plateaus in an 8–12 week mission plan

3.4 The ARED Squat vs. a Real Squat — A Closer Look

The squat is the most important exercise on the ARED. Here is a comparison that shows why the ARED squat is both effective and slightly different from an Earth squat:

Force Source	Earth Squat (200 lb barbell, 180 lb person)	ARED Squat (same load setting)
Bodyweight	180 lbs acts downward on spine	~0 lbs — weightlessness removes this component
Bar/device load	200 lbs downward	200 lbs via vacuum cylinders + flywheel
Inertial component	Real inertia from 200 lb mass	Flywheel approximates inertia — not identical
Total spinal load	~380 lbs + muscle forces	~200 lbs + muscle forces — significantly less
Impact/strain rate	Moderate (controlled descent)	Similar — flywheel adds inertial deceleration
Net bone stimulus	High — at or above formation threshold	Good, but lower than Earth equivalent at same setting

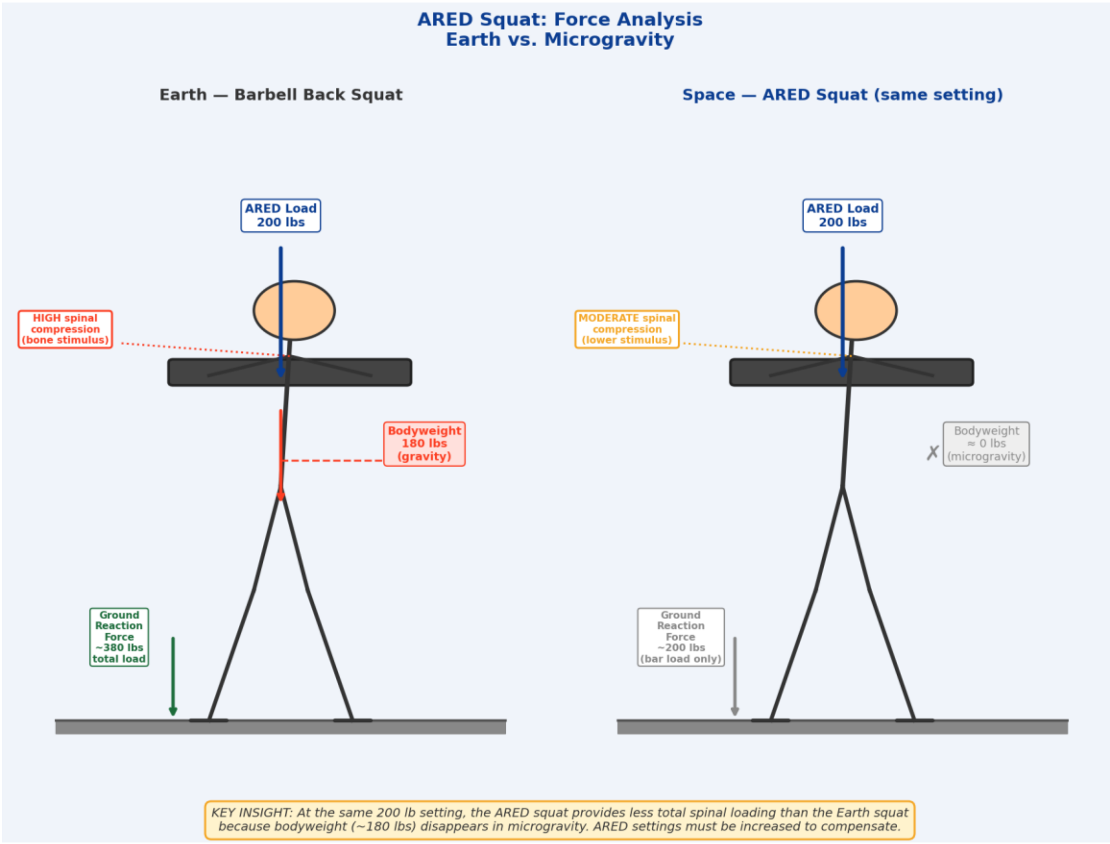

Figure 4: Force analysis comparing an Earth barbell squat to an ARED squat at the same load setting. Bodyweight disappears in microgravity, reducing total spinal loading — ARED settings must be higher to compensate.

> 🔑 **This comparison reveals why exercise prescription in space is so challenging — and why simply telling astronauts to 'do squats' is not enough. The load must be carefully tuned to compensate for the missing bodyweight component.**

4. The ASCR Program: NASA's Exercise Coaches

The Astronaut Strength, Conditioning, and Rehabilitation (ASCR) Program is the team of exercise scientists and physical therapists at NASA who design, monitor, and adjust astronaut exercise plans before, during, and after spaceflight.

4.1 What the ASCR Does

- Pre-flight (up to 2 years before launch): Evaluate each astronaut's baseline fitness, bone density, muscle strength, and cardiovascular health. Design a personalized exercise plan for the mission.
- During flight: Receive weekly exercise logs transmitted from the ISS. Advise the astronaut via video call. Adjust the plan if the astronaut reports problems. Cannot directly measure bone density or muscle health in orbit.

- Post-flight: Monitor the astronaut's recovery. Conduct DXA bone scans, strength tests, and cardiovascular assessments. Compare results to pre-flight baseline. Use findings to improve future crew exercise plans.

4.2 The Monitoring Gap

The most significant limitation of the current ASCR system is that in-flight monitoring relies almost entirely on self-reported data and exercise logs. The ASCR team knows what exercises were done, at what load, for how many sets and reps — but they cannot directly verify:

- Whether the loads prescribed are actually stimulating bone formation
- Whether muscle activation during ARED exercises is equivalent to Earth-based equivalents
- Whether an individual astronaut's bone is responding normally or unusually to the exercise
- Whether cardiovascular adaptations are progressing as expected

This is the core problem your project addresses. The ASCR has excellent tools before and after flight — the gap is during flight.

4.3 How This Project Connects to Real NASA Research

NASA's Human Research Program (HRP) lists bone fracture risk as one of its 30 identified spaceflight health risks. The HRP actively funds research into better in-flight monitoring and countermeasures. Your project mirrors real work being done by NASA scientists and could contribute ideas to that effort.

5. What You Will Learn

By the end of this project, you will be able to:

1. Explain in your own words why microgravity causes bone and muscle loss, and how the body's response to loading can slow or prevent it
2. Describe how the ARED generates resistance without gravity, and compare its mechanism to Earth-based free weights
3. Use basic physics (force, torque, Newton's Laws) to analyze how exercises load bones and joints
4. Read and summarize scientific research papers on bone physiology and exercise
5. Apply exercise science principles — overload, specificity, recovery — to design a realistic astronaut exercise plan
6. Create a 1–3 month, week-by-week ARED exercise schedule for a commercial crew mission, with specific exercises, loads, sets, and reps for each week
7. Identify what data would need to be measured in orbit to know whether the exercise plan is working
8. Communicate your findings clearly through a written plan and a presentation

6. Your Research Questions

6.1 Central Question

If we cannot run bone scans or muscle tests in orbit, what data could we collect during exercise that would tell us — in real time — whether an astronaut's bones and muscles are receiving enough stimulus to stay healthy?

6.2 Questions to Guide Your Research

- How much force does a bone need to sense before it starts growing stronger — and how do we express that in a measurable way?
- How does the ARED's resistance compare to the total loading of the same exercise on Earth (including bodyweight)?
- What exercises on the ARED best target the bones most at risk in spaceflight — the lumbar spine, hip, and femoral neck?
- What sensors exist today (in phones, fitness trackers, research equipment) that could measure exercise loading in the body?
- How does a well-designed exercise plan change week by week to keep challenging the body?
- What exercises in the ASCR program target the bones most at risk (lumbar spine, hip, femoral neck) — and how could we know they're working?

7. Project Activities

This project has six activities completed over 8–10 weeks. Each builds on the previous one.

Activity 1: ARED Deep Dive — Understanding the Machine

Before you can improve exercise plans, you need to understand the equipment. Research how the ARED works and compare it to Earth-based weight training:

- Draw a labeled diagram of the ARED, identifying the vacuum cylinders, flywheel, load bar, and shoulder harness
- Research the physics of the flywheel: what is moment of inertia, and why does a spinning mass create resistance?
- Compare the ARED squat to an Earth barbell squat — list at least three differences in how force is applied
- Look up at least two published studies that validated the ARED (tested whether it actually loads muscles and bones as intended) and summarize their findings
- Identify one limitation of the ARED and propose one possible engineering improvement

Deliverable: Labeled ARED diagram + one-page comparison report (ARED vs. Earth squat) + summary of two research studies

Activity 2: Bone & Muscle Science Research

Research the biology and physics of bone and muscle adaptation to exercise and microgravity. Focus areas:

- Wolff's Law: explain what it is and find one study that demonstrates it
- Bone remodeling cycle: draw and label the process including osteoblasts, osteoclasts, and the role of loading
- Find one Earth-based study on high-load squats and bone density — what did the researchers find? What loads were used?
- Explain what 'microstrain' means and what levels are associated with bone growth vs. bone loss
- Summarize in plain language what happens to astronaut bones over a 6-month ISS mission without adequate exercise

Deliverable: Annotated bibliography (minimum 6 sources, at least 3 from peer-reviewed journals) + 1-page science summary written for a general audience

Activity 3: Biomechanics Lab — Forces in Motion

Apply physics to understand how exercise loads the body. You will use Newton's Laws and basic geometry to estimate forces. No advanced math is required — just F = ma and torque = force × distance.

- Calculate the approximate compressive load on the lumbar spine during an Earth squat at 70% of a 150-pound bodyweight person's max load — show your work
- Estimate how much of that spinal load is missing when the same exercise is done on the ARED in microgravity
- Draw a free-body diagram of a squat at parallel depth, labeling gravity, barbell force, joint reaction forces, and muscle forces
- Research: what ground reaction force (in multiples of body weight) does normal walking generate? Running? How does the ARED compensate for the missing bodyweight component in microgravity?
- Identify which ARED exercise puts the greatest estimated load on (a) the lumbar spine and (b) the hip joint — and explain your reasoning

Deliverable: Biomechanics worksheet with completed calculations + annotated free-body diagram + one-paragraph written explanation of how microgravity changes the loading equation for ARED exercises

Activity 4: Design a 1–3 Month ARED Exercise Protocol

This is the main product of the project. You will design a complete, week-by-week ARED exercise protocol for a commercial crew mission lasting 1 to 3 months. Every exercise in the plan must be performed on the ARED. Your plan must be grounded in the science you researched.

- Structure the protocol in three phases: Adaptation (Weeks 1–2), Main Training (Weeks 3–10), Pre-Return Taper (Weeks 11–12)
- Select a specific set of ARED exercises for each phase — choose from: squat, deadlift, heel raise, bench press, overhead press, bent-over row, hip abduction, and any others you find in ARED research
- For each week, specify: days of exercise, session duration, exercises, sets, reps, and load (expressed as % of 1RM)
- Show how load and volume progressively change week over week — explain the principle of progressive overload in your plan notes
- Include rest days between sessions with a written justification — why does the body need recovery time?
- For every ARED exercise in your plan, document: (a) which bones and muscles are the primary target, (b) the estimated loading level compared to the same exercise on Earth, and (c) one adaptation needed for performing it correctly in microgravity
- Cite at least one research source justifying each phase of the plan and your key load selection decisions

Deliverable: Complete written ARED protocol in table format + individual exercise sheets (one per ARED exercise selected) + week-by-week schedule with research citations

Activity 5: Real-Time Monitoring System Concept

Design a concept for how we could monitor — in orbit, in real time — whether the exercise plan is actually working. This is a creative engineering design challenge.

- Identify three physical measurements that would tell you whether bones and muscles are being adequately loaded (examples to consider: accelerometry, force measurement, heart rate variability, movement velocity)
- Research one technology (a wearable, a sensor, a software algorithm) that could capture one of those measurements
- Sketch a simple system diagram showing: sensors → data → analysis → feedback to crew or ground team
- Define a 'success' signal for Week 6 of your exercise plan — what data would confirm the plan is working?
- Define an 'adjustment trigger' — what data would tell the ASCR team to change the plan?
- List two real-world constraints your system must deal with (e.g., limited power, limited crew time, data transmission delays)

Deliverable: Monitoring system concept proposal (1–2 pages) with a hand-drawn or digital system diagram

Activity 6: Mission Briefing Presentation

Present your complete project as a 'mission briefing' to NASA decision-makers (your class, teacher, or a panel). Your audience needs to understand the problem, your plan, and your monitoring concept — even if they have no background in exercise science.

- Explain the problem: why do astronauts lose bone and muscle, and why can't we tell if exercise is working in orbit?
- Explain how the ARED works and what its key limitations are
- Present your 1–3 month ARED protocol: highlight the key exercise choices, load progressions, and the science behind your decisions
- Present your monitoring concept: what would you measure and why?
- Discuss: what would need to be different or better for your monitoring idea to actually work in space?
- Answer audience questions — be ready to explain your reasoning

Deliverable: 12–18 minute presentation with slides or poster + Q&A period

8. Sample 12-Week ARED Protocol Framework **If you do not meet every day then your schedule will look different. Create a Ghannt chart to make your schedule.**

Use this as a starting point. Expand every row with the specific ARED exercises, sets, reps, and research justification for your final deliverable. All sessions are ARED-based.

Wk	Phase & Focus	ARED Focus	Load Target	Key Goal	Rest Days
1–2	Adaptation — learn ARED movements, build a base	ARED (light load)	40–50% 1RM	Zero injury; build movement quality and exercise habit; measure baseline 1RM	3 days/wk
3–4	Base Building — establish ARED squat and deadlift patterns	ARED	60–65% 1RM; 3×10	Begin bone loading at moderate stimulus; establish ARED movement patterns	2 days/wk
5–6	Hypertrophy — higher volume, moderate-heavy load	ARED	70% 1RM; 4×8–10	Maximize muscle volume stimulus; all major ARED exercises included	2 days/wk
7–8	Strength — heavier load, fewer reps	ARED	80–85% 1RM; 4×5–6	Push ARED load above bone formation threshold; target lumbar spine and hip	2 days/wk
9–10	Peak Loading — max ARED bone stimulus	ARED	85–90% 1RM; 5×3–5	Achieve highest loading of mission; peak bone formation stimulus	2–3 days/wk
11–12	Pre-Return Taper — prepare body for Earth gravity	ARED (reduced load)	70% 1RM; maintain volume	Reduce injury risk; maintain strength; readiness for re-exposure to gravity	3 days/wk

Key terms: 1RM = One Repetition Maximum (the heaviest weight you can lift once). The percentage (e.g., 80% 1RM) tells the astronaut how heavy to go. 3×10 = 3 sets of 10 repetitions.

9. Assessment Rubric **This section is only for teacher use if they choose to use it. It is not requirement**

Each component is scored 1–4. Total possible score: 20 points.

Component (Points)	4 — Excellent	3 — Proficient	2 — Developing	1 — Beginning
ARED Understanding (4 pts)	Accurately explains vacuum cylinders, flywheel, and inertia; correctly compares to Earth squat with specific examples	Explains mechanism correctly; comparison mostly accurate; minor gaps	General explanation correct; some confusion about mechanism or comparison	Significant inaccuracies; mechanism not clearly understood
Science Research (4 pts)	6+ good sources; clear, accurate synthesis in student's own words; Wolff's Law and loading thresholds correctly explained	5 sources; mostly accurate; Wolff's Law understood	4 sources; some inaccuracies; loading concepts partially understood	Fewer than 4 sources; limited or inaccurate science content
Biomechanics Work (4 pts)	Calculations correct and clearly shown; free-body diagram accurate; connects forces to bone stimulus clearly	Mostly correct; minor calculation errors; good diagram	Some correct analysis; calculation errors present; diagram incomplete	Calculations missing or largely incorrect; diagram missing
Exercise Plan (5 pts)	Complete 1–3 month ARED protocol; all major ARED exercises included; progressive overload clearly shown; every phase cited to research	Good protocol; mostly complete; overload partially shown; most exercises documented; some citations	Partial protocol; limited exercise variety on ARED; minimal overload progression; few citations	Incomplete protocol; minimal ARED exercises; no progression; no citations
Monitoring Proposal & Presentation (3 pts)	Specific measurable metrics identified; feasible concept; clear diagram;	Reasonable metrics; mostly feasible; good presentation	Vague metrics; presentation unclear in places	No specific metrics; presentation incomplete or missing

	confident presentation with strong Q&A			

10. Resources & Where to Start

10.1 To Understand the ARED

- NASA Technical Reports Server (ntrs.nasa.gov) — search 'ARED validation' or 'Advanced Resistive Exercise Device'
- Loehr, J.A. et al. — 'Musculoskeletal adaptations to training with the Advanced Resistive Exercise Device' — a key validation paper
- NASA Johnson Space Center Exercise Physiology Laboratory publications
- YouTube: NASA official channel — search 'astronaut exercise ISS' for video footage of ARED use

10.2 For Bone Science & Exercise Research

- PubMed (pubmed.ncbi.nlm.nih.gov) — free access to medical and biology research; search 'bone density exercise' or 'microgravity bone loss'
- Rubin, C. & Lanyon, L.E. — foundational research on minimum effective bone strain for formation (classic paper, widely cited)
- English, K.L. et al. — 'High intensity training during spaceflight: Results from the NASA Sprint Study' — shows what high-intensity protocols can do
- Beck, B.R. et al. — research on jumping and bone density outcomes

10.3 For Biomechanics

- Khan Academy Physics — free videos on Newton's Laws, forces, and torque (excellent starting point)
- OpenSim (simtk.org) — free biomechanics simulation software used by real researchers; has tutorials for high school students
- ACSM (American College of Sports Medicine) — exercise prescription guidelines, accessible online

10.4 For Exercise Plan Design

- NASA Human Research Program (humanresearchroadmap.nasa.gov) — explore the 'Bone' and 'Muscle' evidence reports
- ASCR program overview — ask your teacher or search 'NASA ASCR astronaut exercise'
- The 'SPRINT study' protocol — an example of a real NASA in-flight high-intensity exercise study you can model

11. Teacher Notes

11.1 Standards Alignment

- NGSS HS-LS1-2: Develop and use a model to illustrate the hierarchical organization of interacting systems (bone remodeling, musculoskeletal system)
- NGSS HS-PS2-1: Analyze data to support the claim that Newton's Second Law describes the relationship between force, mass, and acceleration
- CCSS Math: Applying ratios and proportional reasoning (force calculations, 1RM percentages)
- CCSS ELA: Writing informational text supported by evidence; presenting information orally

11.2 Grade-Level Scaffolding

- 9th Grade: Focus on Activities 1–3; use the sample exercise plan as a template to fill in rather than creating from scratch; simplify biomechanics to conceptual rather than quantitative
- 10th Grade: Complete all six activities; expect quantitative biomechanics work; require at least 6 research sources
- 11th-12 Grade: Add extension challenge — computational model of weekly bone strain exposure; require 8+ sources; expect comparative analysis of two different exercise plan philosophies

11.3 Recommended Pacing

Weeks	Activities	Teacher Focus
1–2	Activities 1 & 2	Introduce ARED mechanism with video clips; run a short bone physiology mini-lesson; assign research with structured note-taking template
3–4	Activities 2 & 3	Physics review session on forces and torque before the biomechanics lab; provide calculation scaffolds for 9th grade
4–7	Activity 4 (core)	Weekly check-ins on plan progress; provide the sample framework as a scaffold; require citation for each week of the plan
7–8	Activity 5	Show examples of wearable sensor technology (fitness trackers, research-grade IMUs); encourage creative thinking
9–10	Activity 6	Run as a 'NASA mission review board'; invite a guest from kinesiology, physical therapy, or engineering if possible

11.4 Connections to NASA

This project directly addresses NASA HRP Risk #2: Risk of Bone Fracture Due to Spaceflight-Induced Changes to Bone — one of 30 active research risks managed by NASA's Human Research Program. Students can explore the full Human Research Roadmap at humanresearchroadmap.nasa.gov to see how their work connects to real agency priorities. The roadmap is publicly accessible and written at a level high school students can engage with.

Every astronaut who goes to space depends on exercise scientists, physiologists, and engineers working together to keep them healthy.

The work you do in this project reflects real unsolved problems in human spaceflight — and your ideas matter.