INTER-INDIVIDUAL VARIABILITY IN ASTRONAUT STRENGTH RESPONSE TO LONG-DURATION SPACEFLIGHT MAY BE DICTATED BY IN-FLIGHT EXERCISE

HUMAN PHYSIOLOGY, PERFORMANCE, PROTECTION & OPERATIONS

Alyssa N. Varanoske[1], Nicole C. Strock[1], Elisabeth R. Spector[1], Dillon J. Frisco[2], Brian J. Prejean[1], Karina Marshall-Goebel[3], Renita S. Fincke[3]

[1]KBR (NASA Johnson Space Center), Houston, TX, USA; [2]JES Technologies (NASA Johnson Space Center), Houston, TX, USA; [3]NASA Johnson Space Center, Houston, TX, USA

Abstract

BACKGROUND: Deconditioning induced by prolonged microgravity exposure during spaceflight hinders physical capacity. Examination of pre- to post-flight isokinetic strength measures show a mean loss of strength; however, considerable variability between crewmembers exists. As in-flight exercise differs between crew, an examination of exercise training variables contributing to strength preservation is necessary. The purpose of this analysis was to examine in-flight exercise of astronauts who maintain strength compared to those with the greatest decrements in strength from pre- to post-flight.

METHODS: The database of NASA International Space Station (ISS) crew who completed pre- and post-flight knee isokinetic testing (n = 87) was used to identify "responders" (R) and "non-responders" (NR) to in-flight exercise (≥ 90-day flight duration). R were those that maintained or improved strength (mean of knee extension and flexion at 60°/sec) (n = 14; 5.6 ± 7.8%), and NR were those with the most severe decrements (n = 14; -32.8 ± 4.1%) from pre- to post-flight. In-flight daily exercise records (cycle ergometer, treadmill, resistance exercise) were aggregated on a weekly basis. Independent t-tests or Mann-Whitney U tests were used to compare groups for in-flight exercise variables (i.e., frequency, time, intensity, volume).

RESULTS: In-flight cycle ergometer frequency (2.4 ± 0.8 vs. 3.3 ± 1.0 days/wk; $p = 0.021$), total time (78.5 ± 20.4 vs. 114.0 ± 49.3 min/wk; $p = 0.021$), and active time (59.3 ± 17.2 vs. 86.9 ± 44.1 min/wk; $p = 0.050$) were greater in NR than R, but no differences for cycle intensity were observed. Treadmill distance traveled per session was greater in R than NR (4.6 ± 0.8 vs 3.6 ± 1.3 km/sess, $p = 0.031$), but no differences for treadmill frequency, total time, or active time were observed. Lower body resistance exercise intensity relative to pre-flight body weight was greater in R than NR (110.0 ± 16.5 vs 88.7 ± 25.0%; $p = 0.012$), but no differences in upper body or core resistance exercise intensity, volume, or frequency were observed.

CONCLUSIONS: The unique musculoskeletal loading provided by treadmill running at the expense of cycle ergometry, combined with using higher relative lower body loads during resistance training, may contribute to preserving strength in ISS crewmembers during long-duration spaceflight.

Background

- Prolonged microgravity exposure during spaceflight incudes muscle mass and strength loss, which can hinder physical capacity and increase the risk of injury[1-3].
- Exercise training is currently the primary countermeasure to mitigate muscle mass and strength loss during spaceflight.
- Decades of research have culminated in the design and implementation of the most comprehensive in-flight exercise countermeasure devices and prescriptions for astronauts aboard the International Space Station (ISS). Current exercise devices include (***Figure 1***):
  - Resistance: Advanced Resistive Exercise Device (**ARED**)
  - Aerobic: Treadmill 2 with Vibration Isolation and Stabilization (**T2**)
  - Aerobic: Cycle Ergometer with Vibration Isolation and Stabilization (**CEVIS**)
- Examination of average pre- to post-flight strength changes show that exercise performed by ISS crew preserves strength better than that on early space missions.
- However, these numbers represent an aggregate of all crew data and do not consider the variability in individual responses.
  - Some ISS crew experience decreases in strength exceeding the NASA 3001 standards (i.e., >20% decrease, NASA STD-3001 Volume 1-Revision C[4]), whereas others show improvements from pre- to post-flight.
- Understanding the variability of the exercise response is important in the development of exercise prescriptions and is key in understanding the appropriate dose of exercise and hardware countermeasure use[5-7].
- As in-flight exercise training differs between crewmembers, a further examination of training variables contributing to strength preservation is necessary.

Purpose

- To compare aggregated in-flight exercise training variables (i.e., intensity, frequency, time, volume, type) of ISS astronauts who maintain or improve strength compared to those with the greatest decrements in strength from pre- to post-flight.

Methods

Figure 1: ISS crewmembers completing nominal in-flight exercise on ARED (left); T2 (center); CEVIS (right). Source: NASA

- The cohort included ISS crew who had a ≥90 day flight (launch to landing) and completed pre-flight (PRE) and post-flight (POST) knee isokinetic testing (Biodex, Shirley, NY, USA) (n = 87)
  - PRE: 9 months before Launch (L-9mo) or 3 months before Launch (L-3mo)
  - POST: 5 days after return to Earth (R+5)
- Crewmember's data were arranged by their relative percent change in knee isokinetic strength (mean of knee extension and flexion at 60°/sec) from PRE to POST
  - **"Responders" (R):** Crewmembers who maintained or improved strength from PRE to POST within the measurement error of the Biodex device (1%) (n = 14; 11M/ 3F)
  - **"Non-Responders" (NR):** Crewmembers who experienced the most severe decrements in strength from PRE to POST (matched for sample size of R; n = 14; 10M/4F)
- Individual in-flight exercise training variable data were aggregated on a weekly basis and averaged as follows:
  - **ARED:** grouped into *lower-body* (heel raises, squat, and deadlift), *upper body* (bench press, bicep curls, shoulder press, shrugs, triceps, rows, forearm curls), and *core* (cable side bends, cable sit-ups, cable spinal extension) exercises
    - Frequency (sets/week), volume (reps/week), intensity [calculated only for primary lifts in lower and upper body (% pre-flight body weight)]
  - **T2:**
    - Frequency (days/week), intensity (% pre-flight maximal heart rate, distance traveled, % pre-flight body weight loaded), time (total min/week, active min/week)
  - **CEVIS:**
    - Frequency (days/week), intensity (% pre-flight maximal heart rate, cycle power resistance), time (total min/week, active min/week)
- Independent t-tests or Mann-Whitney U tests (when normality was violated) were used to compare groups for in-flight exercise variables between R and NR; α set to 0.05.

Results

- 16.1% (n = 14) were defined as R and 16.1% (n = 14) were defined as NR (***Figure 2***)
  - R mean change: 5.6 ± 7.8%
  - NR mean change: -32.8 ± 4.1%
  - Average change in isokinetic knee strength from PRE to POST: -13.2%
- 25.7% of crewmembers lost greater than 20% of isokinetic knee strength from PRE to POST

Figure 2: Individual changes in isokinetic knee strength (mean of knee flexion and extension at 60°/s) from PRE to POST (n = 87). Each bar represents data for an individual crewmember. Responders (R, n = 14; blue), Non-responders (NR, n = 14; red).

Results

- NR were stronger than R at PRE ($p < 0.05$). No other group differences between demographic variables were observed at PRE (***Table 1***).
- In-mission ARED, T2, and CEVIS exercise training variables (frequency, time, volume, and intensity) are presented in ***Figures 3-5***.

	Non-Responders (NR)	Responders (R)	p-value
n (males/females)	14 (10/4)	14 (11/3)	
Age (y)	45.9 ± 5.3	47.1 ± 5.6	0.432
Height (cm)	176.0 ± 9.1	173.0 ± 6.4	0.339
Body mass (kg)	78.9 ± 11.9	76.5 ± 10.4	0.579
Lean mass (kg)	54.8 ± 9.8	54.4 ± 8.6	0.914
Flight duration (days)	184.0 ± 35.3	161.0 ± 33.8	0.087
Knee extension strength 60° (N/m)	206.0 ± 55.5	175.0 ± 29.6	0.076
Knee flexion strength 60° (N/m)	**123.0 ± 32.5**	102.0 ± 18.6	**0.040**
Average knee strength 60° (N/m)	**165.0 ± 41.8**	138.0 ± 21.7	**0.047**

Table 1: Pre-flight demographics and strength variables for R and NR. Data are presented as mean ± standard deviation (α = 0.05). 1-RM: 1-repetition maximum

Frequency

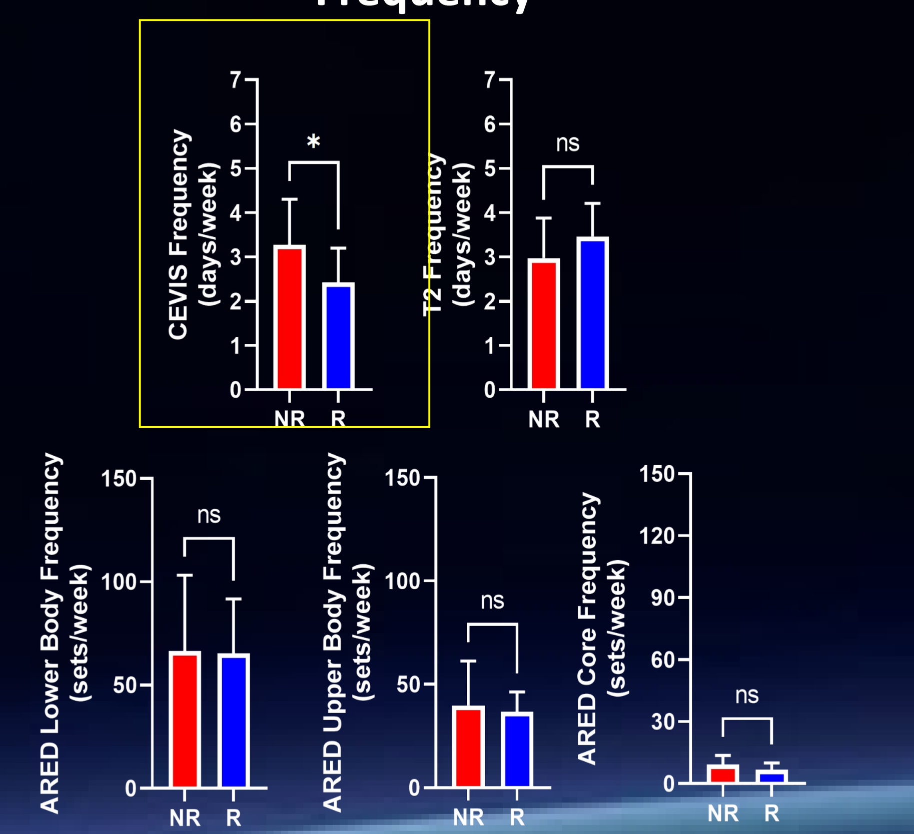

Figure 3: In-flight aerobic and resistance exercise frequency data for R and NR. *$p < 0.05$

- **ARED**: no differences
- **T2**: no differences
- **CEVIS**: frequency greater in NR than R (3.3 ± 1.0 vs. 2.4 ± 0.8 days/wk; $p = 0.021$)

Time/Volume

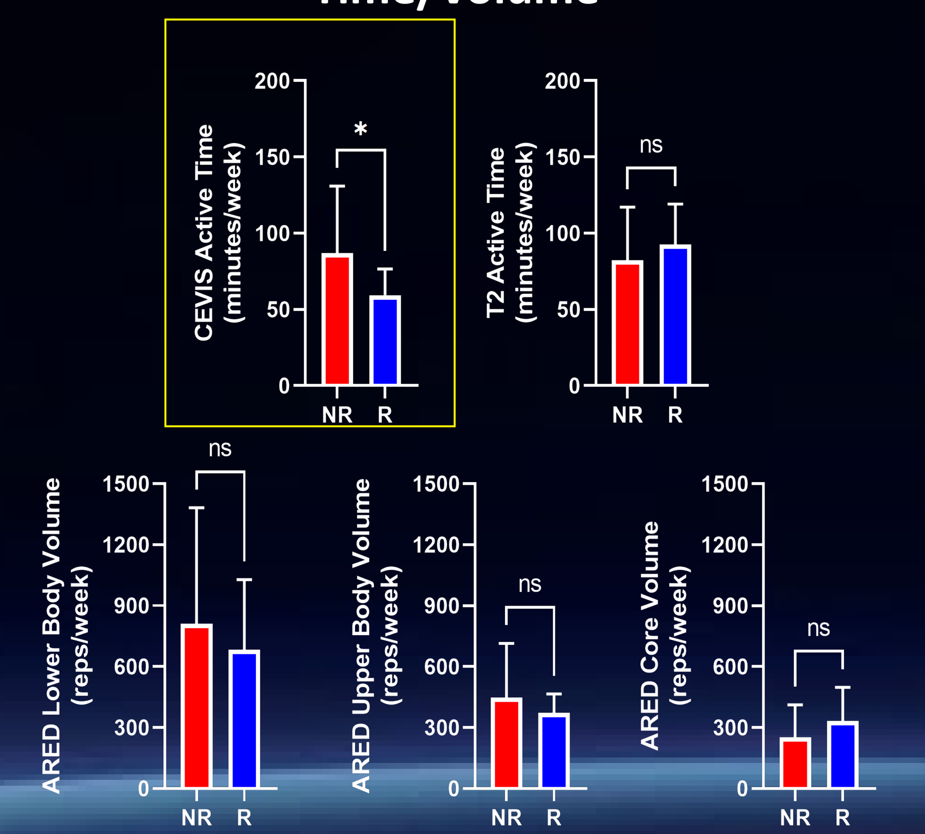

Figure 4: In-flight aerobic and resistance exercise time and volume data for R and NR. *$p < 0.05$

- **ARED**: no differences
- **T2**: no differences
- **CEVIS**: time greater in NR than R (active: 86.9 ± 44.1 vs. 59.3 ± 17.2 min/wk; $p = 0.050$; total: 114.0 ± 49.3 vs. 78.5 ± 20.4 min/wk; $p = 0.021$ [not shown])

Intensity

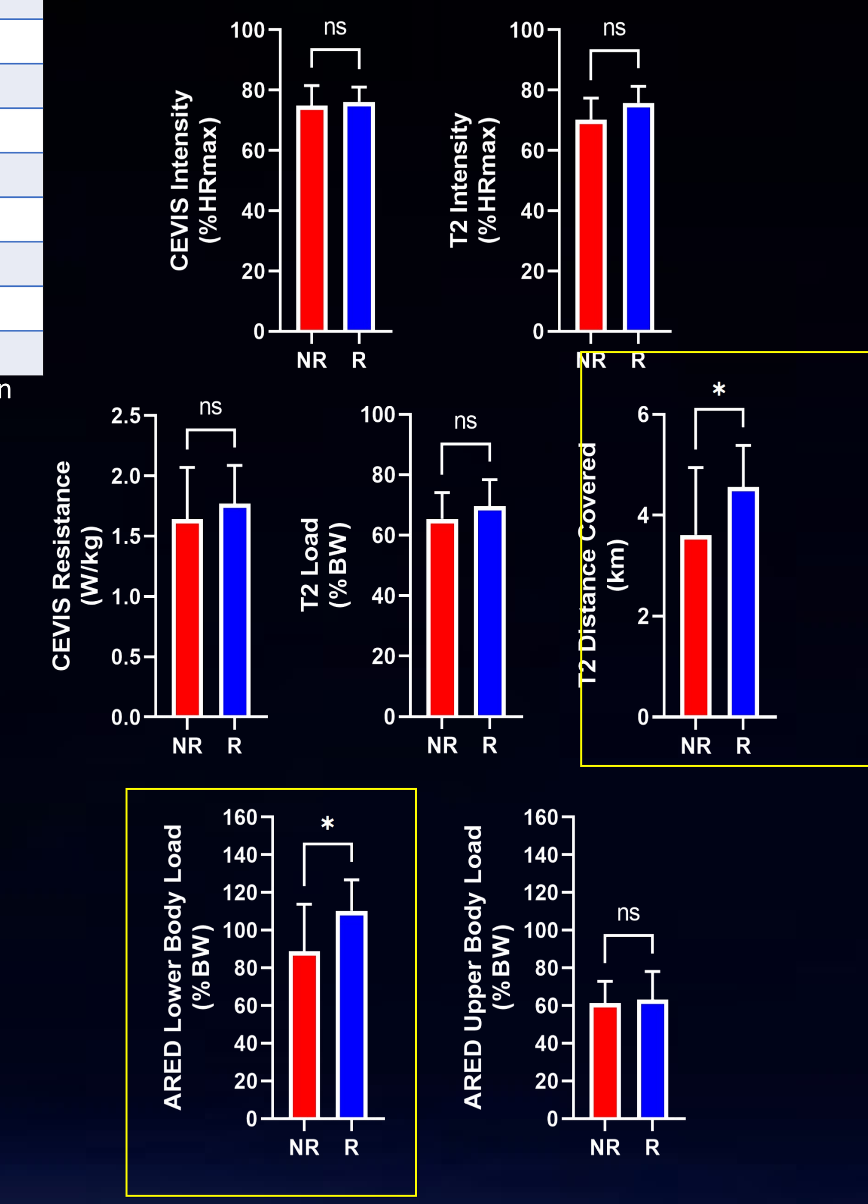

Figure 5: In-flight aerobic and resistance exercise intensity data for R and NR. * $p < 0.05$

- **ARED**: lower body intensity greater in R than NR (110.0 ± 16.5% vs 88.7 ± 25.0%; $p = 0.012$), but no differences in upper body or core intensity
- **T2**: intensity greater in R than NR (distance traveled: 4.6 ± 0.8 vs. 3.6 ± 1.3 km/session, $p = 0.031$), no differences for % max heart rate or % body weight
- **CEVIS**: no difference

Conclusions

- Despite high-quality in-flight exercise capabilities and prescriptions, long-duration spaceflight negatively affects most ISS crew; however some astronauts respond well
  - Understanding the inter-individual variability in the strength response to microgravity exposure is essential for preparing exercise device concepts for human travel to deep space
- R covered a greater weekly distance on the treadmill, whereas NR spent more time per week on the cycle ergometer; R performed lower body resistance exercise at higher load intensities relative to their pre-flight body weight than NR
  - Although categorized as aerobic exercise, the high magnitude and frequency of impact loading experienced during treadmill running, combined with using higher relative lower body loads during resistance training, likely provide greater benefits to protecting strength than loads experienced when cycling
- As NASA moves towards exploration missions (i.e., Artemis and beyond) which pose vehicle volume and power constraints while requiring astronauts to be more physically fit than in previous missions in Low-Earth Orbit, providing treadmill running and high load lower body resistance exercise capabilities may help maintain strength necessary to successfully complete in-mission tasks
- Future research is necessary to evaluate the independent effects of exercise devices and prescriptions on physiological responses during spaceflight, evaluate the interactions of exercise training variables, determine effects of pre-flight fitness and ergogenic aids on these outcomes, and assess changes in strength in-flight

Funded by the NASA Human Research Program

References

1. Comfort P, McMahon JJ, Jones PA, Cuthbert M, Kendall K, Lake JP, et al. Effects of spaceflight on musculoskeletal health: A systematic review and meta-analysis, considerations for interplanetary travel. Sports Med. 2021;51(10):2097-114.
2. Lee PHU, Chung M, Ren Z, Mair DB, Kim DH. Factors mediating spaceflight-induced skeletal muscle atrophy. American Journal of Physiology - Cell Physiology. 2022;322(3):C567-C80.
3. Stein TP. Weight, muscle and bone loss during space flight: another perspective. European Journal of Applied Physiology. 2013;113(9):2171-81.
4. NASA Space Flight Human-System Standard Volume 1: Crew Health. NASA-STD-3001, Volume 1, Revision C2023.
5. Bonafiglia JT, Preobrazenski N, Gurd BJ. A systematic review examining the approaches used to estimate interindividual differences in trainability and classify individual responses to exercise training. Front Physiol. 2021;12:665044.
6. Bonafiglia JT, Preobrazenski N, Islam H, Walsh JJ, Ross R, Johannsen NM, et al. Exploring differences in cardiorespiratory fitness response rates across varying doses of exercise training: A retrospective analysis of eight randomized controlled trials. Sports Med. 2021;51(8):1785-97.
7. Ross R, Goodpaster BH, Koch LG, Sarzynski MA, Kohrt WM, Johannsen NM, et al. Precision exercise medicine: understanding exercise response variability. Br J Sports Med. 2019;53(18):1141-53.