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A High Protein Diet Improves Exercise Performance Outcomes to Workouts Completed on Gravity-Independent Hardware

Original Research

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Abstract

Introduction: Space flight diets include a 55:30:15 (carbohydrate:fat:protein) ratio. Yet, recent missions see astronauts exercise 2-4 hours daily for up to seven days a week. Perhaps, a high protein diet (45:25:30) is more conducive to longer missions and their high exercise volumes.

Methods: Twelve men and ten women followed each diet (55:30:15, 45:25:30) for 14 days. After each diet concluded subjects did a workout comprised of four exercises for three 60-second sets each whereby their total work volume was recorded. Respiratory quotients and net energy costs were measured at workouts. Blood lactate concentrations ($[BLa^-]$) were measured before and five minutes post-exercise. Total work and respiratory data were compared with two-way ANOVAs. $[BLa^-]$ were assessed with a three-way ANOVA.

Results: $[BLa^-]$ differences occurred by time (post-exercise 9.1 ± 2.2 > pre-exercise 2.0 ± 0.3 $\text{mmol} \cdot \text{L}^{-1}$, $p < 0.0001$) and for total work by gender (men 1095 ± 122 > women 971 ± 85 kilojoules, $p = 0.03$) and diet (45:25:30 1082 ± 90 > 55:30:15 1037 ± 132 > pre-diet 981 ± 91 kilojoules, $p = 0.00023$).

Conclusions: A high protein diet led to greater total work. Such diets may best abate exercise performance deficits incurred with long-term missions.

Key Words: Metabolism, Total Work, Ergogenic

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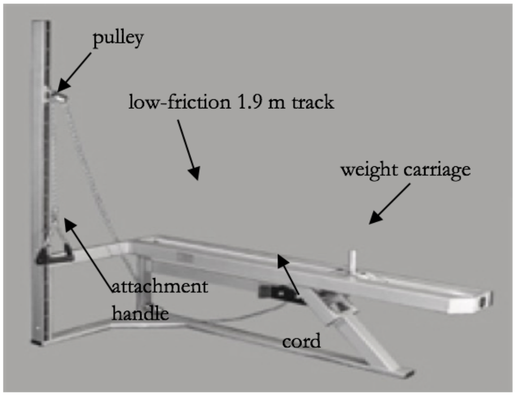
Introduction

Current NASA space flight requirements state macronutrient guidelines for astronauts include 55% of total daily energy intake from carbohydrates, 30% from fats, and 15% from proteins.[1] The diet's intent is to meet the metabolic demands imposed upon astronauts by microgravity and were originally based on the World Health Organization's predictions of energy requirements for moderately active persons.[1,2] This diet successfully served astronauts when their in-flight activities and operational demands entailed little to no physical exertion, and mission durations lasted less than 30 days.[3] In contrast recent International Space Station flights last 6-12 months, as astronauts workout 2-4 hours daily for up to seven days per week at an average metabolic cost of 1450 kcals for 2½ hours of exercise.[4] With no gravitational forces acting upon the body in microgravity, high volumes of exercise are thought essential to limit musculoskeletal health and performance losses and comprise a large amount of daily in-flight activity.[5] In addition metabolic rates rise in microgravity, and are exacerbated by concurrent in-flight exercise.[3,6] Versus similar tasks on Earth, metabolism in microgravity is much higher, with peak rates of 500 $\text{kcals} \cdot \text{h}^{-1}$ for extravehicular activities (EVAs) and average energy costs for long term EVAs of 200-250 $\text{kcals} \cdot \text{h}^{-1}$.[7,8] Higher metabolic rates are in part attributed to the added energy demand to liberate excess body heat, as its removal in low gravity environments is not as efficient as it is on Earth.[4,6,8]

In-flight exercise is essential to preserve astronaut health. Since exercise countermeasures comprise a large amount of daily in-flight activity, perhaps a diet geared towards enhanced physical performance would be more beneficial. Important to such determinations is exercise hardware which effectively operates in microgravity. Such hardware must impart mechanical loading stimuli without the customary requirement of gravity to impart exercise resistance. One such device is high-speed gravity-independent hardware known as an Inertial Exercise Trainer (IET; Impulse Training Systems, Newnan GA). The IET enables performance of numerous exercises at very high movement velocities and repetition rates. IET resistance is provided by a modest amount of mass added to its weight carriage. As repetitions are performed the carriage slides along a low-friction 1.9 m track parallel to the Earth's surface.[9] Thus torques exerted to perform repetitions are unrelated to the forces from Earth's gravitational pull. A side view photograph of the IET appears in Figure 1.

Figure 1. Side view photograph of the IET (Impulse Training Systems, Newnan GA).



While the established in-flight diet's 55:30:15 carbohydrate:fat:protein ratio adequately served astronauts on earlier sojourns an optimal diet, in terms of modern and future long-term space missions that include high volumes of exercise, has yet to be determined. Our project compares metabolic and exercise performance responses of a 55:30:15 ratio routinely prescribed to astronauts to one with a 45:25:30 ratio. The greatest difference between the two diets is the macronutrient allotment for protein intake. Thus, our study examines if a higher protein intake is efficacious for workout performance done on the IET. With a randomized, within-subjects design, participants received one of the two diets over two weeks, followed by a resistive exercise workout on the IET and then the opposite dietary treatment. We hypothesize the high protein diet (45:25:30) is more conducive to longer missions and their high volumes of in-flight exercise.

Methods

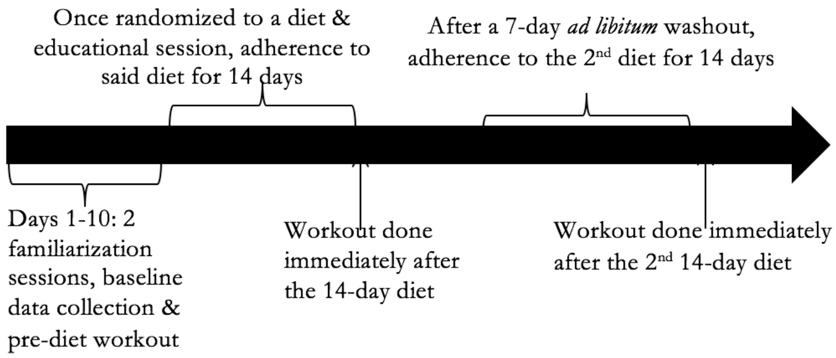
Participants

Prior to subject admittance, this protocol received approval from a university-based institutional review board. Subjects provided informed written consent, then filled out a medical questionnaire which stated they were in good health and free of the following conditions: diabetes, asthma, hypertension, tachycardia, ischemia, arrhythmias, hyperthyroidism, and convulsive disorders. Each subject (12 men, 10 women) made five visits to our laboratory. Briefly, the first three visits occurred before the start of their first diet. They included a series of baseline (pre-diet) data collection procedures that culminated in their first (pre-diet) workout. The fourth and fifth visits were workouts that occurred immediately after the conclusion of each 14-day diet.

Timeline

Per subject, they adhered to the experimental design in Figure 2. A randomized within-subjects crossover design was used for our study. Each subject's project involvement lasted 47 days, during which time they adhered to each of the two diets under inquiry for 14 days each. The two diets were separated by a seven-day washout period in which subjects ate whatever they wished. Per subject, the sequence of their diets was determined by a coin flip during the baseline data collection period.

Figure 2. Current study's timeline, and overview of the experimental design, per subject.



Baseline (pre-diet) data collection procedures

Prior to their first 14-day diet, subjects underwent a series of procedures during their first ten days of participation. Referred to as baseline data collection procedures, they included: anthropometry, body composition and basal metabolic rate determinations, a coin flip, two familiarizations and one educational sessions, and concluded with a pre-diet workout. Anthropometric measurements were recorded for subject height, body mass, as well as arm, leg and torso lengths. Heights and body masses were measured as subjects stood on a stadiometer (Saltner Brecknell, Brooklyn NY) barefooted. Length measurements occurred in triplicate with a cloth tape as they assumed a relaxed upright posture. They were recorded from the left sides of subject's bodies and then averaged. Leg lengths equaled the distance between the anterior superior iliac spine to the fibula's lateral malleolus. Arm lengths spanned the distance from the acromioclavicular joint to the styloid process of the ulna. Torso lengths equaled the distance from their acromioclavicular joint to their anterior superior iliac spine. A bioimpedance unit (RJL Systems; Clinton Township, MI) measured body composition when subjects were well rested and hydrated. Anthropometric measurements lasted 30 minutes.

Subjects also had their basal metabolic rate assessed as they laid supine while their respiratory gases (O_2, CO_2) were measured by a metabolic cart (Parvo Medics; Salt Lake City, UT). Metabolic data were collected one morning before their first meal during their ten-day pre-diet period (Figure 2). Basal metabolic rates were used to determine subject's kilocalorie intakes during their study involvement so they maintained a neutral energy balance throughout the project. They also helped design meal plans and provide subjects with proper advice at educational sessions. Metabolic data collection was supervised by the principal investigator and lasted 30 minutes.

While all of our subjects were in good health, none had previously used the IET. Thus, during the ten-day pre-diet period they each did two familiarization sessions on the IET, in which they practiced repetitions at a submaximal level of effort to become accustomed to the novelty of its operation. At each familiarization session four exercises were performed on the IET in the following order: standing knee extension, standing hip extension, standing row and standing pulldown. With an attachment cuff around their left ankle, the standing leg extension exercise entailed repetitive flexion and extension at the knee, as subjects otherwise remained motionless. With the same cuff wrapped around the arch of their left foot, they did the standing hip extension with simultaneous flexion and extension at the left hip and knee joints. For the standing row subjects grasped an attachment handle with their left hands and pulled it (via concurrent elbow flexion and shoulder hyperextension) towards them before the antagonistic actions at each joint retuned the handle back to its original position. Finally, standing pulldowns required subjects to grab an attachment handle with both hands and, as they maintained a slight degree of elbow flexion, repetitive extension and flexion at the shoulder joints. Per subject, pulley positions for each exercise were held constant. A 3.4 kg load was added to carriage to bring its total resistance to 4.4 kg for each exercise. Familiarization sessions lasted 25 minutes each and were done under the direction of the principal investigator. Figure 3 depicts the four IET exercises.

Figure 3. The four IET exercises, performed at familiarization sessions and workouts.

Starting with a coin flip to determine the sequence in which their diets were prescribed, subjects participated in an educational session during the ten-day pre-diet period. Educational sessions were performed by a registered dietician who was a member of the project's investigative team. Its purpose was to inform subjects how to adhere to the project's diets. Participants were taught how to count macronutrient grams and given a sample menu. No distinction was made between animal and plant proteins since participants were not provided with food. Subjects adhered to a mixed protein diet, as research that compared animal- to plant-based protein sources on exercise performance outcomes produced similar results.[10] Body composition and metabolic rate data were used to formulate each of the subject's diets. Sessions typically lasted 30 minutes.

Finally, at the end of the ten-day pre-diet period, each subject performed a workout on the IET with the same exercises and weight carriage load used at familiarization sessions. The workout's purpose was to assess subject's exercise performance devoid of our study's dietary influences. Starting with a five-minute warm-up on a cycle ergometer (Ergotest; Stockholm, Sweden), subjects then did three one-minute sets separated by 60-second rest periods per exercise. They did as many repetitions as possible in good form on the IET, which was instrumented with a position sensor (Balluf Inc.; Florence, KY) and load cell (Transducer Techniques; Temecula, CA) to quantify exercise performance. Per workout, the volume of work performed was recorded for statistical analysis.

Food diaries, compliance and habitual activity

Subjects were required to conform to the isocaloric and macronutrient (either 55:30:15 or 45:25:30) requirements of each 14-day diet. To demonstrate compliance, subjects provided daily food diaries which included an itemized list of the quantities and types of foods eaten. When applicable they provided food labels to quantify their kilocalorie and macronutrient intakes. Diaries were analyzed with software (ESHA Research; Salem, OR) to measure macronutrient intakes and adherence to the dietary treatments. Diaries were collected daily and sent to our project's registered dietician to monitor compliance. A lack of adherence meant their dietary data were eliminated from statistical analysis. Throughout each 14-day period subjects were asked to maintain their normal habitual activity. Immediately after each 14-day diet period subjects participated in another IET workout.

Post-diet IET workouts

The exercise protocol followed for the two post-diet workouts included additional measurements to those of the pre-diet workout. For post-diet workouts subjects arrived to the laboratory well-rested, and were told to refrain from strenuous activity for 24 hours prior. When they arrived to the laboratory they sat comfortably as they were attached to the metabolic cart and donned a nose clip. They sat for at least ten minutes as their respiratory gases were collected for their resting (pre-exercise) respiratory quotient (RQ) and O_2 uptake values. The latter value was used to calculate the net caloric cost (NCC) of workouts. The metabolic cart was calibrated in accordance to the manufacturer's guidelines prior to each post-diet workout. The cart provided breath-by-breath gas values that were averaged over 15-second intervals as subjects sat quietly. Individual O_2 and CO_2 values deviated less than 5% from the eventual average pre-exercise value per gas.

During the ten minutes they sat, subjects also provided a pre-exercise blood lactate concentration ([BLa$^-$]) measurement. Under aseptic conditions, [BLa$^-$] measurements entailed 1-2 drops of subject's fingertip blood placed on a test strip inserted within a calibrated analyzer (Accusport; Hawthorne, NY). Once RQ and O_2 uptake values stabilized, they did a five-minute stationary cycle ergometer warm-up that was identical to that used at the pre-diet workout. They pedaled against one kilopond of resistance at a rate to elicit a 75-90 watt workload. Subjects remained tethered to the metabolic cart and nose clip as they rode. Upon the warm-up's completion, they began the IET portion of workouts. They did the same four exercises as for the familiarization sessions in the same sequence. In addition, the same protocol (sets, load, rest periods, pulley settings, etc.) was employed as for the pre-diet workout. Per exercise, they did as many repetitions as possible in good form. Verbal instructions and encouragement were offered throughout workouts. They remained attached to the metabolic cart and wore the nose clip throughout the IET portion of workouts. The volume of work performed was summed for a workout's four exercises and used for statistical analysis.

After the final IET set concluded, subjects again sat down as their O_2 uptake values continued to be monitored. They stayed tethered to the metabolic cart and wore the nose clip until O_2 their uptakes returned to pre-exercise levels. At five minutes, post-exercise subjects submitted to a second [BLa$^-$] measurement. To determine NCC values from the post-diet workouts, we quantified net O_2 uptakes from the exercise bout. Net O_2 uptakes equaled the sum of the differences between each individual and the pre-exercise O_2 value produced from workouts. Net O_2 uptake, measured in liters, was converted to NCC by multiplying it by five, the non–steady-state equivalent of kilocalories expended per liter of O_2 consumed.[11] RQ values were collected and averaged from the pre-exercise period once O_2 and CO_2 values stabilized. Thus, we measured pre-exercise RQ, and the NCC resultant from exercise, values for each workout. RQ, NCC and [BLa$^-$] values were used for statistical analysis.

Statistical Analyses

Given the large effect sizes seen with exercise, a sample of 20, comprised of equal numbers of men and women, was deemed sufficient to detect diet- and gender-based differences. Our data were examined for outliers with Z-scores, with values which exceeded +/- 1.96 removed from further analyses. We examined our data for ANOVA assumptions (normality, independence, equal variances). Our study included four dependent variables: RQ, NCC, [BLa$^-$] and work volume. RQ and NCC were each compared with 2(gender) x 2(diet) ANOVAs, with repeated measures for diet. [BLa$^-$] was assessed with a 2(gender) x 2(time) x 2(diet) ANOVA, with repeated measures for time and diet. Work volume was compared with a 2(gender) x 3(diet) ANOVA, with repeated measures for diet. An $\alpha = 0.05$ denoted significance, and t-tests identified the source of our differences.

Results

We exceeded the sample size required to detect inter-gender and -diet based differences. No subjects were injured from IET workouts. Our data met all the ANOVA assumptions, and our Z-score analyses revealed no statistical outliers. However, one subject was not compliant to a diet examined in this study. Their workout data for that diet were excluded from analysis. All other subjects were compliant to both diets and study treatments. Anthropometric data, partitioned by gender as well as pooled for the total sample, appear in Table 1.

Table 1. Anthropometric (Mean ± SD) values.

	WOMEN (N = 10)	**MEN (N = 12)**	**POOLED (N = 22)**
HEIGHT (CM)	162.8 ± 6.3	179.0 ± 5.5	171.6 ± 9.8
MASS (KG)	68.4 ± 10.1	80.6 ± 11.4	75.1 ± 12.7
TOTAL LEG LENGTH (CM)	88.2 ± 8.2	94.3 ± 5.9	91.4 ± 7.5
TOTAL ARM LENGTH (CM)	65.1 ± 8.2	72.9 ± 6.2	69.2 ± 8.4
TOTAL TORSO LENGTH (CM)	35.2 ± 10.1	42.0 ± 5.5	38.7 ± 8.4
BODY FAT (%)	31.6 ± 7.6	14.8 ± 1.4	22.8 ± 10.3
FAT FREE MASS (KG)	46.8 ± 3.5	69.7 ± 9.0	58.8 ± 13.6

Pre-exercise RQ values collected from each of the two post-diet workouts appear in Table 2. They included a significant effect for diet whereby 55:30:15 > 45:25:30. NCC values collected from the two post-diet workouts appear in Table 3. Results include non-significant differences. [BLa^{-}] values collected from each post-diet workout appear in Table 4. Results included a significant effect for time, with post-workout values greater than those for pre-workout. [BLa^{-}] results also include a trend ($p = 0.07$) for significant gender differences (men > women). Finally work volume results appear in Table 5. Post-hoc analysis revealed significant effects for gender (men > women) and diet (45:25:30 > 55:30:15 > pre-diet).

Table 2. Pre-exercise RQ (Mean ± SD) values.

	55:30:15 Diet (N = 22)	**45:25:30 Diet (N = 21)**
WOMEN	0.905 ± 0.13*	0.8625 ± 0.09
MEN	0.941 ± 0.10*	0.936 ± 0.12

*: Significant diet (55:30:15 > 45:25:30) difference

Table 3. NCC (Mean ± SD; in kilocalories) values.

	55:30:15 Diet (N = 22)	**45:25:30 Diet (N = 21)**
WOMEN	101.5 ± 37.0	100.7 ± 41.1
MEN	127.0 ± 35.0	120.4 ± 45.7

Table 4. [BLa^{-}] (Mean ± SD; in mmol · L^{-1}) values.

	55:30:15 Diet (N = 22)		**45:25:30 Diet (N = 21)**	
	Pre-exercise	**Post-exercise**	**Pre-exercise**	**Post-exercise**
WOMEN	1.7 ± 0.6	9.0 ± 2.8*	1.6 ± 0.6	8.2 ± 2.8*
MEN	2.2 ± 0.7	9.3 ± 3.8*	2.4 ± 1.0	9.8 ± 2.8*

*: Significant time (Pre-exercise < Post-exercise) difference, $p < 0.0001$

Table 5. Work volume (Mean ± SD; in kilojoules) values.

	Pre-Diet Workout (N = 22)	**55:30:15 Post-Diet Workout (N = 22)**	**45:25:30 Post-Diet Workout (N = 21)**
WOMEN	919.2 ± 137.9	978.6 ± 103.7	1015.9 ± 128.7#
MEN	1042.2 ± 142.0*	1095.2 ± 193.4*	1148.5 ± 130.6*#

*: significant gender (Men > Women) difference, $p = 0.03$
#: significant diet (45:25:30 > 55:30:15 > Pre-diet) differences, $p = 0.00023$

Discussion

Our hypothesis was affirmed; while some results, like those for RQ and [BLa^{-}] were not unexpected, the outcome of most interest, and the one that affirmed our hypothesis, is the significantly greater volume of work achieved with higher protein intakes. The NASA Human Research Roadmap cites inadequate nutrition, as well as performance decrements and crew illness due to an inadequate food system, as risks to be addressed.[12] NASA macronutrient guidelines served astronauts well on early space flights.[1,3] Yet as compared to pre-flight values, longer missions saw astronauts incur large body and muscle mass losses.[7,8] To abate those losses and better prepare crew members for in-flight operational tasks, extravehicular activities and emergency egress, exercise countermeasures have been a mainstay aboard missions in recent years.[3,5,7] However in-flight metabolic rates for exercise are inherently much higher than when the same activity occurs on Earth, which is supported by the observation that all physical tasks during space flight evoke higher energy costs than when they occur in 1-G.[6-8,11] Higher metabolic rates exacerbate body and muscle mass losses, which reinforce the importance of in-flight energy and macronutrient guidelines.[3-8] There are additional concerns seen with voluntary reduction of in-flight energy intake, from an average of 37 kcal · kg^{-1} body mass consumed on Earth, to 26.5 kcal · kg^{-1} body mass in microgravity due to decreased appetite, and the longer times spent on mission tasks and exercise while crew members are in flight.[4]

Lower energy intakes lead to declines in muscle protein synthesis.[13] However higher protein intakes, equal to 25-30% of the energy consumed, prevented whole body protein breakdown during bed rest and lean body mass losses during weight reduction programs in athletes, as well as maintained muscle function in the frail elderly.[14-17] These results imply isocaloric diets with a higher protein intakes may also help maintain muscle function and abate lean body mass losses in microgravity.[14-17] We compared two isocaloric treatments with different macronutrient ratios in healthy subjects: the traditional NASA (55:30:15) diet to one with a higher protein (45:25:30) intake. High protein diets demonstrated a protective effect on lean body mass during negative energy balances induced by weight loss or intense physical training.[18-20] While our study attempts to make its results applicable to space flight, such as with workouts done on the gravity-independent IET, a project limitation is the lack of microgravity simulation. Yet our results are not without merit, and imply higher protein intakes may aid in-flight workouts geared towards skeletal muscle strength and mass preservation. This outcome is relevant to in-flight exercise countermeasures, as space flight decreases muscle protein synthesis rates to levels not even predicted from simulation research done on Earth.[21]

The NASA requirement for in-flight carbohydrate consumption was raised to 55% of total energy intake for missions up to 360 days.[21] However, this may be problematic as evidence exists of greater insulin resistance during space flight.[21] In contrast to carbohydrate, while 15% of total energy intake from protein may suffice to maintain health in sedentary persons on Earth, evidence suggests higher protein intakes have positive effects on skeletal muscle and exercise performance.[22,23] The protein RDA is $0.8g \cdot kg^{-1}$ body mass. Prior research showed an increase in protein intake from 1.35 to $2.62\ g \cdot kg^{-1}$ body mass as subjects concurrently strength trained for one month did not augment strength or muscle mass gains.[22] Yet the study offered no evidence that subject's ingested adequate amounts of energy, which could impact strength and muscle mass gains.[22]

With adequate energy intakes, higher protein consumption may enhance muscle protein synthesis from exercise.[21,23] Small increases in dietary protein, such as going from 15 to 18% of total kilocalorie intake, improves muscle protein synthesis.[23] Other papers also examined protein intake's impact on muscle and exercise performance.[15,16,24-27] They generally show an ergogenic effect from higher protein intake, to concur with current results. Acute post-workout protein ingestion was examined as a treatment to mitigate muscle damage and hasten recovery from resistive exercise.[24] With four independent groups, those who received protein supplementation had a significantly greater restoration of resistive exercise performance 48 hours' post-exercise versus subjects who ingested water or a glucose-based drink.[24] A similar study examined post-workout milk intake as a treatment to abate exercise-induced muscle damage and hasten recovery of sport performance.[25] With two groups, and performance assessed before and at 24, 48 and 72 hours' post-exercise, those who received 500 ml milk post-workout saw smaller increases in sprint and shuttle test performance times 48 and 72 hours into recovery as compared those in control group.[25] Yet these inter-treatment differences were not statistically significant.[25]

While prior research[24,25] exposed subjects to a single treatment, a double-blind crossover study examined whey supplementation for its impact on whole body protein metabolism and recovery from resistive exercise.[26] Trained men ($n = 12$) did two bouts of resistive exercise; at 0 and 10 hours' post-exercise they ingested either whey protein (25 g) or CHO-based (25 g) placebo at both time points.[26] Whey supplementation significantly abated protein breakdown and evoked a higher protein balance 24 hours' post-exercise versus the placebo treatment.[26] With a similar study design and a microgravity analog, protein intake was examined during bed rest in two group of subjects with no crossover.[15] They were assigned to either a 0.6 or 1.0 g protein $\cdot$ kg body $mass^{-1} \cdot day^{-1}$ diet with no crossover during seven days of bed rest.[15] While low protein subjects had a 24% decline in non-oxidative leucine disappearance, those in the high protein group saw their leucine kinetics unchanged by bed rest.[15] Results affirmed bed rest decreases whole-body protein synthesis, yet this decline was abolished by a diet higher in protein.[15]

Since space flight elicits total and lean body mass losses,[7,8] it is important to consider how higher protein intakes might impact such losses. To examine protein's role on lean body mass during weight loss, subjects were monitored for one week to assess their baseline energy needs, followed by a 14-day hypoenergetic diet in which their protein intake was held constant at either 15% ($\sim 1.0\ g \cdot kg^{-1}$) or 35% ($\sim 2.3\ g \cdot kg^{-1}$) of their total energy intake. The higher protein intake evoked significantly less total and lean body mass losses.[16] Those results concur with a recent review,[27] and indirectly support our outcome that a diet comprised of 30% protein led to a significantly higher volume of work from a resistive exercise bout versus the 15% protein condition.[13] However, in contrast to these studies,[15,16,24-26] the review article on protein concluded no relationship between performance restoration and markers of muscle damage when supplementation occurred prior to, or during, bouts of endurance or resistive exercise.[27] Yet the review stated protein may have an ergogenic effect if subjects are in a negative nitrogen and/or energy balance, in agreement with the results of the aforementioned study.[16,27]

Astronauts incur higher metabolic rates that in turn lead to large total and lean body mass losses.[3,6,8] Concurrent in-flight exercise easily exacerbates those losses by inducing even higher metabolic rates.[6,8,21] Thus macronutrient intake is an important consideration for long-term missions that include in-flight exercise countermeasures.[5,8,15,21] The greatest rates of muscle mass and performance losses occur during the early stages of space flights.[28,29] During that time muscle strength rapidly declines by as much as 30% and, while fatigue also plays a role, muscle atrophy is a contributing factor.[28] Our volume of work results, collected on gravity-independent resistive exercise hardware, suggest an isocaloric diet with a macronutrient intake that include a higher protein intake offers a significant ergogenic effect as compared to the traditional NASA diet. Our results imply, in order to better withstand the rigors of long-term space flight and in-flight exercise, macronutrient prescription for crew members may wish to include higher amounts of dietary protein.

Media-Friendly Summary

An exercise bout done on gravity-independent hardware, and preceded by a two-week diet higher in protein than that of the traditional NASA diet, resulted in a significantly greater volume of work performed as compared to that prescribed to astronauts in-flight. The higher protein diet may be more efficacious to abate exercise performance deficits incurred with long-term space flights.

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