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Quantifying Extravehicular Activity Performance Degradation Due To Sustenance Deprivation

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QUANTIFYING EXTRAVEHICULAR ACTIVITY PERFORMANCE DEGRADATION DUE TO SUSTENANCE DEPRIVATION

by

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Bachelor of Science, University of Nevada, Reno, 2008

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Eryn Andrews Beisner

May 1, 2018

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To Bill and Jill Andrews,

My parents who took me to my first shuttle launch and told me I could do it too.

To Matthew Beisner,
My husband who pushed me to do the hard things.

ABSTRACT

Modern EVAs (spacewalks) performed onboard the International Space Station require astronauts to endure up to twelve hours of intense mental and physical exertion without food, as they do not stop to eat nor do they currently have the capabilities to consume sustenance in their spacesuits. With the future of space exploration taking aim at the Moon, Mars, and beyond, EVAs are expected to become more demanding than ever. This is a pilot study to attempt to quantify astronaut performance during an EVA to determine if there is significant performance degradation because of acute starvation. Astronauts conducting EVA training at NASA's Neutral Buoyancy lab were measured in cognitive and physiological domains during EVA training to gauge how their performance was affected. Additionally a basic feeding system with a protein supplement was tested to determine if performance could be improved. Result revealed there was not a significant degradation in test scores due to acute starvation, and while there was some improvement with the protein supplement, it was not statistically significant for all but one test domain. The Working Memory domain did show a statistically significant score improvement. Test subject feedback indicated a strong preference for the protein supplement as well as enthusiastic support for future spacesuit designs and/or EVA protocols to include food throughout the duration of a spacewalk as a human factors consideration.

CHAPTER I

INTRODUCTION

Extravehicular Activity (EVA), aka spacewalking, is perhaps the most critical aspect of human spaceflight. Astronauts don pressurized suits and leave the relative safety of a spacecraft to conduct repairs, maintenance, and scientific research. Remote operations and robotics help reduce the need for physical human presence but cannot replace it. There are many situations where only human dexterity and intuition can get the job done. Astronauts complete hundreds of hours of training for an EVA long before they even leave the planet; rehearsing every technique, every step of the procedure over and over again in order to execute a flawless performance.

Spacewalking lasts several hours and is inherently dangerous. Working in a pressurized suit in space means astronauts are exposed to extreme temperatures (varying approximately ± 200 °F) and high levels of space radiation and risk of hypoxia, hypercapnia, ebullism, and sudden decompression (Pilmanis & Sears, 2003). Micrometeoroids or an unseen sharp edge can tear a hole in the suit causing uncontrolled decompression and an agonizing death. An accident during Apollo spacesuit testing demonstrated this risk when the suited subject's spacesuit suddenly decompressed in a vacuum chamber (Pant, 2015). Mistakes in space can happen in an instant and have the very real potential to be deadly (read the Soyuz 11 crew tragedy in Evans, 2013).

Astronauts must operate at their peak performance, mentally and physically, at all times to respond to unforeseen circumstances throughout a spacewalk.

Problem Statement

EVAs onboard the International Space Station (ISS) are all-day events wherein astronauts do not stop to eat, nor do they have the capabilities to consume sustenance in their spacesuits. Totaling the time it takes to prepare, execute, and conclude an EVA day, astronauts typically endure ten to twelve hours without food and very little water. The NASA Space Flight Human-System Standard, Vol. 2, for suited nutrition recommends the following:

> "The [assumed] system shall provide a means for crew nutrition while suited. Rationale: Additional nutrients, including fluids, are necessary during suited operations as crewmember energy expenditure is greater during those activities. Additional kilocalories, based on metabolic energy replacement requirements from moderate to heavy EVA tasks, allow the crewmember to maintain lean body weight during the course of the mission. Lean body (especially muscular) weight maintenance is a key component of preserving crew health during the missions and keeping performance at a level required to complete mission objectives. During a surface EVA, crewmembers will most likely be suited for 10 hours, including approximately 7 hours on the surface expending energy. Nutritional supply during suited operations allows the crewmembers to maintain high performance levels throughout the duration of the EVA. Apollo astronauts strongly recommended the availability of a high-energy substance, either liquid or solid, for consumption during a surface EVA. During contingency microgravity EVAs and/or for EVAs less than 4 hours in duration, this capability is not required. During long-duration suited operations, such as an unplanned pressure reduction scenario, the crew is to be able to consume nutrition from an external source to maintain crew performance."

To date, this recommendation has not been satisfied with the current spacesuit capabilities. With the future of human space exploration taking aim at the Moon, Mars, and beyond, EVAs are likely to become more demanding than ever. The lack of sustenance during these periods of sustained, high intensity work disregards a major human factor and potentially increases the likelihood of a catastrophic event.

Research Hypothesis

While it may seem intuitive that food deprivation affects human performance (as most people have experienced this firsthand), currently no standards are employed to gauge this impact on astronauts during EVA. The following research intends to address two key points:

1) There is a quantifiable degradation in astronauts' cognitive and physiological performance during EVA because of acute sustenance deprivation.

2) Astronaut performance will improve above baseline expectations if given in-suit sustenance.

This research conducted an experiment on astronauts to determine whether their physical and cognitive abilities during an EVA were impacted by acute starvation, as well as to test if their performance could be improved utilizing a basic in-suit feeding system.

Literature Review

Astronauts require specific diets to combat the challenges of spaceflight (osteoporosis, muscle atrophy, sodium-induced acidity, etc…). There has been extensive research into understanding how to best nourish humans living in space (Finkelstein & Taylor, 1960; Lane, 1992; Levi, 2010; Perchonok & Bourland, 2002) but little to no investigation into nutrition for an EVA. Table 1 lists the NASA-recommended nutritional composition for men and women necessary to support astronaut performance in spaceflight.

Table 1. NASA's Nutritional Composition Recommended For Spaceflight (Perchonok et al., 2012)

Nutrients	**Daily Dietary Intake**
Protein	0.8 g/kg And ≤ 35% of the total daily energy intake And 2/3 of the amount in the form of animal protein and 1/3 in the form of vegetable protein
Carbohydrate	50-55% of the total daily energy intake
Fat	25-35% of the total daily energy intake
Ω-6 Fatty Acids	14 g
Ω-3 Fatty Acids	1.1 - 1.6 g
Saturated fat	<7% of total calories
Trans fatty acids	<1% of total calories
Cholesterol	< 300 mg/day
Fiber	10-14 grams/4187 kJ
Fluid	≥ 2000 mL
Vitamin A	700-900 µg
Vitamin D	25 µg
Vitamin K	Women: 90 µg Men: 120 µg
Vitamin E	15 mg
Vitamin C	90 mg
Vitamin B12	2.4 µg
Vitamin B6	1.7 mg
Thiamin	Women: 1.1 µmol Men: 1.2 µmol
Riboflavin	1.3 mg
Folate	400 µg
Niacin	16 mg NE
Biotin	30 µg
Pantothenic Acid	30 mg
Calcium	1200 - 2000 mg
Phosphorus	700 mg And ≤ 1.5 x calcium intake
Magnesium	Women: 320 mg Men: 420 mg And ≤ 350 mg from supplements only
Sodium	1500 - 2300 mg
Potassium	4.7 g
Iron	8 - 10 mg
Copper	0.5 - 9 mg
Manganese	Women: 1.8 mg Men: 2.3 mg
Fluoride	Women: 3 mg Men: 4 mg
Zinc	11 mg

One of the first things to happen to the human body in a new environment is the physical adaptation to reflect the new energy balance, i.e., the energy available versus the energy required. Excessive physical exertion combined with inadequate caloric replenishment means that the human body must rely on its own biological energy reserves to maintain functionality. This creates a “negative energy balance” (Westerterp-Plantenga, 1999). Duration of survival with a negative energy balance can vary for each individual; dependent upon body weight, genetics, dehydration, and other health considerations but the average length of time is approximately three weeks (though there are well documented cases of survivors of hunger strikes lasting over to 40 days).

An acute negative energy balance is a regular occurrence in human physiology, during sleep called ‘fasting’. The body’s metabolism slows to adjust for the decreased energy output and new energy balance. This lowered metabolism is the Basal Metabolic Rate (BMR): the minimum amount of energy a person expends in a given period to keep the body functioning in a state of rest (Basal Metabolic Rate; 2018). An overnight fast typically lasts twelve hours and ends once a person awakens and eats; hence “break-fast”. Then the metabolic rate increases as more energy is expended throughout the working hours, becoming the Working Metabolic Rate (WMR).

To accommodate the energy requirements necessary for the day’s activities regular caloric intake from meals and snacks are required to maintain the energy balance. When IF occurs the body is deprived of the supplemental caloric intake necessary to support the demand of the WMR. This creates a negative energy balance and forces the body to rely on its own energy reserves; exactly what astronauts must endure for a spacewalk.

ISS EVAs can require astronauts to work up to twelve consecutive hours in some circumstances without food, similar to the practice of IF. Additionally EVAs are metabolically demanding on the human body, requiring up to 500 kilocalories per hour due to the nature of working in a pressurized suit and the microgravity environment (Waligora, 1977; Waligora & Horrigan, 1977). This kind of demand can quickly create a negative energy balance.

For example: If the average astronaut currently in NASA's Astronaut Corp is male, 40 years old, 175 cm (5'9") in height, and weighs roughly 80 kg (175 lbs), his BMR can be roughly approximated by using the Mifflin St Jeor Equation (Mifflin et al., 1990).

$$P = \left(\frac{10.0m}{1\ \text{kg}} + \frac{6.25h}{1\ \text{cm}} - \frac{5.0a}{1\ \text{year}} + s \right) \frac{\text{kcal}}{\text{day}}$$

Equation 1. Mifflin St. Jeor equation for calculating BMR

P is total heat production at complete rest, ***m*** is mass (kg), ***h*** is height (cm), ***a*** is age (years), and ***s*** is a coefficient based on sex with +5 for males and -161 for females. Using this equation the astronaut's BMR is approximately 1687 kcal/day, or about 70 kcal/hr. So if this astronaut were to simply exist in a resting state, inside the EMU for 6 hours, he would use 420 kcal just maintaining body weight and functionality. Astronauts have been recorded using almost 200 kcal/hr during EVA training (see Neutral Buoyancy Lab section for more information) which means over the same 6 hour EVA, this astronaut would use 1200 calories spacewalking in addition to supporting body weight and function. Without sustenance, this creates an additioanl negative energy blance of -780 kcal beyond the 420 kcal used by his BMR.

Effects of IF during a spacewalk

While it can take many weeks to succumb to a negative energy balance, the impacts to human performance can occur within hours. An interesting example of this is the practice of Intermittent Fasting (IF) amongst Muslims during Ramadan wherein religion mandates fasting (the abstention of sustenance) between sunrise and sunset, approximately twelve hours, for a month. One study analyzed the effects of this fasting ritual on physiological and behavioral variables and found a correlation between the timing of Ramadan and an increase in traffic accidents (Roky et al., 2004). Bigard et al. (1998) found that Ramadan fasting in fighter pilots demonstrated an impairment in muscular performance.

To better understand the possible consequences of such an energy imbalance for astronauts during EVA, an Earthly comparison was made to athletes that observe IF since they undergo similar situations of prolonged physical and mental exertions without caloric replenishment. Unfortunately there is sparse literature in this field (even less on acute impacts since the studies took place throughout the month-long Ramadan, whereas EVAs occur within a day) and further research is needed to determine the effects of exercising in an extreme environments.

Previous studies that assessed physiological results were mostly inconclusive, ranging from negligible (Aziz et al., 2010; Aziz et al., 2011; Karli et al., 2007; Leiper et al., 2008) to significant reduction in physical abilities (Zerguini et al., 2007; Chaouachi et al., 2012; Chtourou et al., 2011; Degoutte et al., 2006; Zerguini, 2007). In the study Meckel et al. (2008) male soccer players performed a series of fitness tests before and after Ramadan and showed a substantial decrease in aerobic capacity, speed, and jumping height but had no significant effect on sprint performance. Chaouachi et al. (2009) evaluated the influence of IF on aerobic and anaerobic exercise performance in elite judo athletes. The athletes performed squat jumps, countermovement jumps, 30 second repeated jump, and a 30-meter sprint before, during, and after Ramadan. Results showed the 30-meter sprint performance, squat jumps, and countermovement jumps did not change but average power during the 30 second repeated jump test was slightly lower at the end of Ramadan. The wide range of results these studies is likely due to data collection method differences and the lack of a standardized testing environment, as athletes had their own methods for adapting their diet to accommodate for the demands of IF during their physical training.

Cognition studies on athletes observing IF are also extremely limited and the results are highly varied and domain-specific for both athletes and non-athletes alike. The most commonly tested cognitive domains were short-term memory, visual attention, executive function (working memory), information processing, and verbal function. Limited information suggests that acute deprivation adversely affects some cognitive functions (Tian et al., 2011; Roky et al., 2000; Ali & Amir, 1989; Wilson & Morley, 2003; Doniger et al., 2006; Alsharidah et al., 2016) while others not only remained unaffected (Green et al., 1995; Liebermeister & Schroter, 1983; Gutiérrez et al., 2001; Kemps & Tiggemann, 2005; Lieberman et al., 2008) but even improved as a result of short-term fasting (Najafabadi et al., 2015; Green et al., 1997). Again standardization was a challenge due to methodological differences, lack of sensitive computerized instruments, and lesser understood factors such as specific diet composition, changes to circadian rhythm, and time-of-day testing as a result of IF.

Performance Improvement

Limited research suggests that consuming the correct type of sustenance during a physical workout can improve physical performance (Baker et al., 2014). Studies that administered either a carbohydrate supplement or a carbohydrate + protein supplement while athletes exercised on a cycle ergometer to exhaustion resulted in significant improvements in time-to-fatigue and reduced post-exercise muscle damage (Saunders et al., 2004; Ivy et al., 2003). Another study found that carbohydrate-only ingestion during prolonged strenuous exercise delayed fatigue by approximately 45 minutes (Coggan & Coyle, 1991). In Van Esson and Gibala (2006) however, they found that adding 2% protein to a 6% carbohydrate drink provided no additional performance benefit during a task that closely simulated the manner in which athletes typically compete, though they did note that rate of ingestion of the sustenance during exercise may influence the results.

CHAPTER II

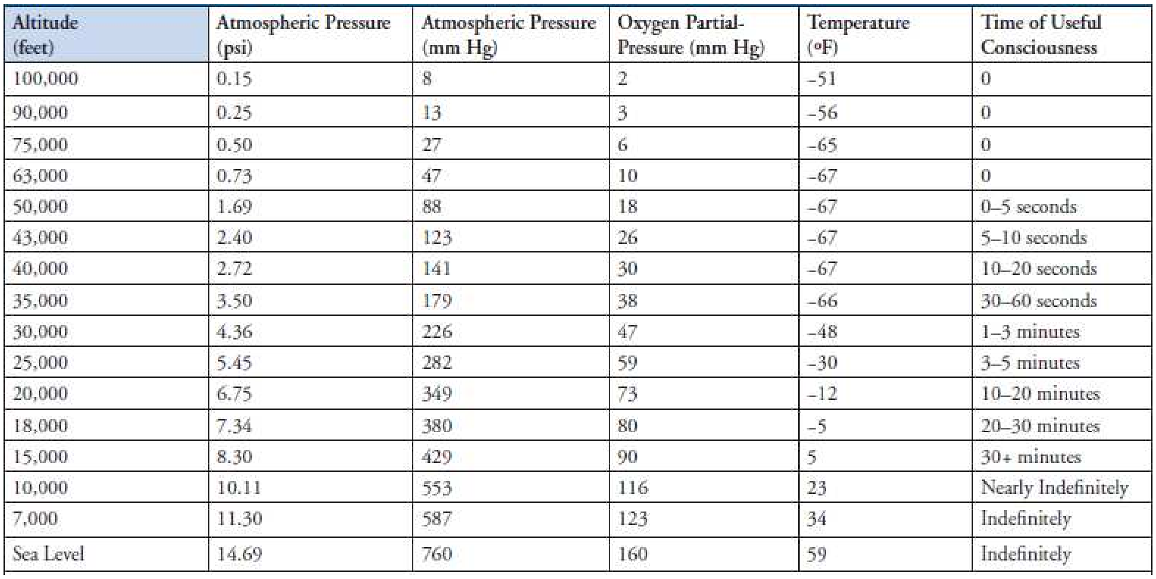
EVOLUTION OF U.S. SPACESUITS, FOOD, AND PREBREATHE PROTOCOLS

In order to understand how eating during an EVA is not currently an option (much to the surprise of most people), this section will present a high-level overview of the evolution of U.S. spacesuits and EVA protocols, to present the subtle changes that lead to the status quo. It is important to note that there is no singular starting point for the history of the modern spacesuit; rather many simultaneous beginnings from numerous sources that eventually merged into what we know today as the Extravehicular Mobility Unit, or EMU (pronounced E-M-U) for short. This chapter will address the highlights of this history and the important elements of spacesuit development as it pertains to eating during an EVA.

Early Pressure Suits

Early experiments concerning vacuums and pressure invariably involved observations within Earth's atmosphere, which begins at sea levels and extends to 120,000 miles up. The atmosphere is not homogeneous but rather divided into invisible layers. The first layer is the troposphere and varies in thickness; between 5 to 9 miles between the poles and the equator respectively. From there the stratosphere takes over until approximately 160,000 feet. As the altitude increases, the effects of Earth's gravity weaken; the gases that comprise the atmosphere become less dense. For the human body the most important atmospheric gas is oxygen (O_2) within a certain pressure range in order for lungs to adequately function. In the stratosphere and beyond, the decreased partial pressure of O_2 will cause a person to lose consciousness from hypoxia (lack of O_2) and die. See Table 2 for the correlation of altitude and time of useful consciousness due to decreased O_2 partial pressure. At altitudes above 28,000 feet, the body requires 100 percent O_2 to remain conscious for any useful time. Breathing 100% O_2 at 34,000 feet is physiologically equivalent to breathing air at sea level. Breathing 100% O_2 at 40,000 feet is equivalent to breathing air at 10,000 feet. At altitudes between 40,000 and 50,000 feet breathing has to be assisted by positive pressure. This increases the ability of the body to absorb the O_2 into the blood stream (Jenkins, 2012).

Table 2. U.S. Naval Flight Surgeon's Manual, Naval Aerospace Medical Institute, Third Edition, 1991. Atmospheric Data



Altitude (feet)	Atmospheric Pressure (psi)	Atmospheric Pressure (mm Hg)	Oxygen Partial-Pressure (mm Hg)	Temperature (°F)	Time of Useful Consciousness
100,000	0.15	8	2	-51	0
90,000	0.25	13	3	-56	0
75,000	0.50	27	6	-65	0
63,000	0.73	47	10	-67	0
50,000	1.69	88	18	-67	0–5 seconds
43,000	2.40	123	26	-67	5–10 seconds
40,000	2.72	141	30	-67	10–20 seconds
35,000	3.50	179	38	-66	30–60 seconds
30,000	4.36	226	47	-48	1–3 minutes
25,000	5.45	282	59	-30	3–5 minutes
20,000	6.75	349	73	-12	10–20 minutes
18,000	7.34	380	80	-5	20–30 minutes
15,000	8.30	429	90	5	30+ minutes
10,000	10.11	553	116	23	Nearly Indefinitely
7,000	11.30	587	123	34	Indefinitely
Sea Level	14.69	760	160	59	Indefinitely

Changes in the partial pressure of O_2 dramatically affect respiratory functions within the human body and rapid decrease in the partial pressure of O_2 may quickly result in physiological impairment. Although a person may not notice this impairment at lower altitudes, the effects are cumulative and grow progressively worse as altitude increases.

Additionally the decrease in the partial pressure of nitrogen (N_2), especially at high altitude, can lead to a condition called “Decompression Sickness”. Decompression sickness (DCS), also called “the bends” or “caisson disease” arises from bubbles precipitating from dissolved gasses (primarily N_2) within the body. Bubbles can become trapped in body joints and organs, causing symptoms ranging from joint pain and rashes to paralysis and death (Vann, 1989). DCS most commonly presents as a scuba diving hazard but may be experienced in other depressurization events such as working in caissons, flying in unpressurized aircraft, and space-based extra-vehicular activity. Between scientific exploration and military aviation advancements into the upper atmospheric layers, overcoming the challenges of hypoxia and DCS lead to the development of pressure suits as a countermeasure, which are the ancestors of the modern space suit.

The EMU, used for spacewalks onboard the ISS, is a full pressure suit meaning the wearer is completely isolated and protected from the external environment. The EMU’s integrated life support systems allow for temperature control, radiation protection, carbon dioxide (CO_2) removal, radio communications, and O_2 for suit pressure and breathing. In many ways, it is more like a small spaceship than just a suit. The EMU can trace its lineage to the first pressure suits, developed in the 1930s.

The first concepts of a pressure suit drew inspiration from early 20th century salvage dive suits. The U.S. Navy and Army, as well as private contractors and academic institutions, developed numerous variations of a pressure suit. The suits (Figure 1) more or less satisfied the requirement for pressure but were clunky, largely immobile, and offered little to no thermal protection experienced at high altitudes. They were not a practical option for pilots, which was the driving factor for the U.S. military (who had the most funding for such endeavors).

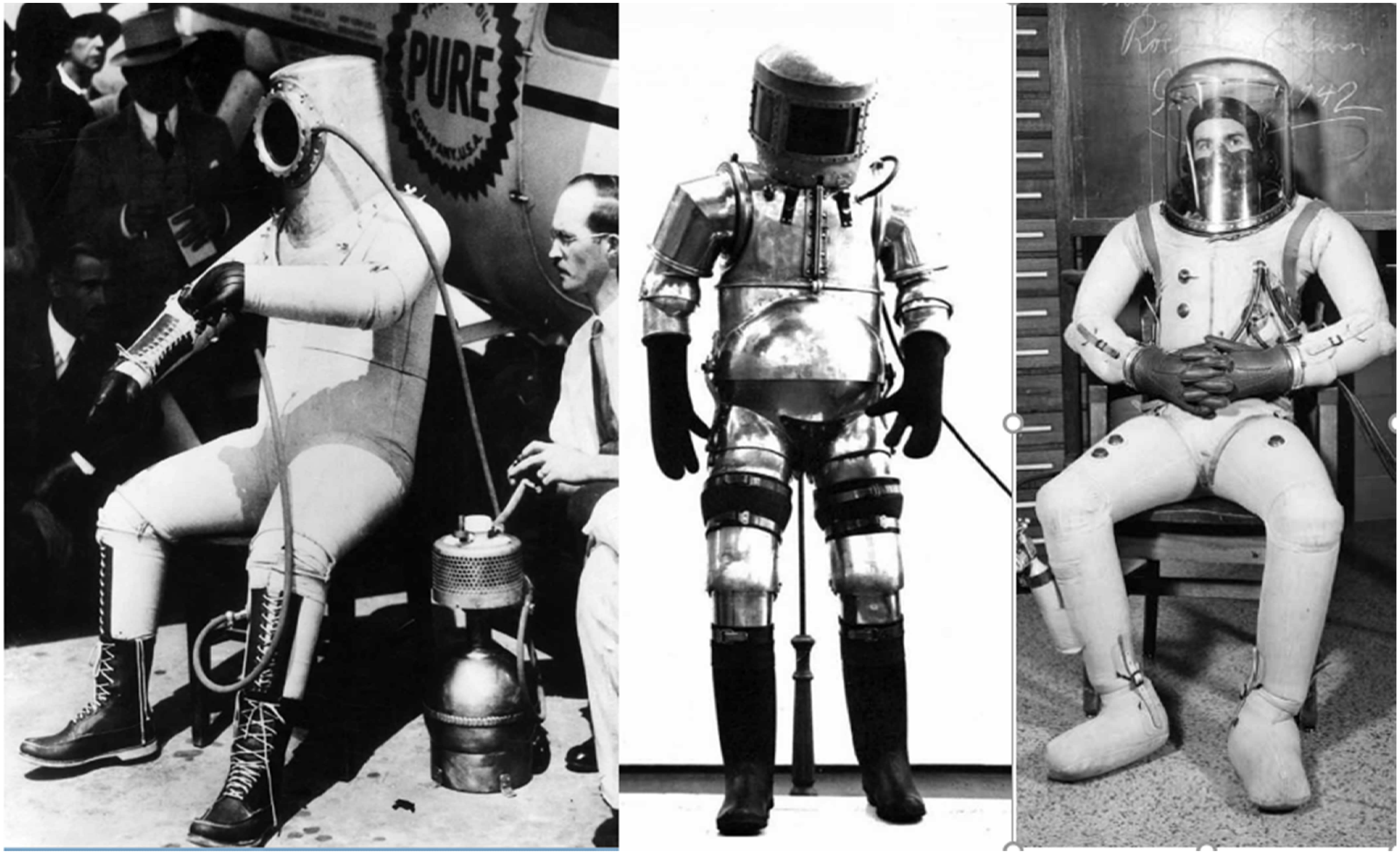


Figure 1. Early pressure suit concepts based on commercial salvage dive suits. Photo: Thomas & McMann; 2012

North American X-15 Pressure Suit

In 1955 the National Advisory Committee for Aeronautics (NACA) and the U.S. Air Force (USAF) experimented with a high-speed rocket-powered research aircraft, called the North American X-15. Considered the world's first space plane, the X-15 set speed and altitude records in the 1960s as well as the official world record for the highest speed ever recorded by a manned, powered aircraft, in October 1967 when William J. Knight flew Mach 6.72 (4,520 miles per hour) at 102,100 feet. That record remains unbroken to this day (Gibbs, 2015). NASA considered the X-15 for continued space operations by launching on top of SM-64 Navaho missile, but the program was canceled when they decided to pursue Project Mercury instead.

Achieving such great heights required the cockpit be pressurized to with N_2 gas while the pilot wore a pressure suit and breathed pure O_2. The USAF released a Request For Proposal (RFP) for private contractors to bid on a contract to develop the pressure suit. The requirements were as follows (Jenkins, 2012):

- Provides a minimum of 12 hours of protection above 55,000 feet and temperatures as low as -40 ºF to the highest cockpit temperature envisioned for aircraft flying at a true airspeed of 1,200 knots.
- Provide G force protection equivalent to the USAF G-suit.
- Weigh less than 30 pounds
- Operate at an internal pressure of 5 psi
- Provide sufficient O_2 partial pressure, adequate counter-pressure, and suitable ventilation

The USAF awarded development contracts to the David Clark Company (DCC) and the International Latex Corporation (ILC). ILC had never built a pressure suit and the prototype presented to the USAF proved to be unwieldy and had painful pressure points, (however the experienced gained by ILC would later set the groundwork for the Apollo spacesuits). Ultimately the USAF awarded the full contract to DCC and after a series of prototypes and redesigns, the A/P22S series pressure suit became the first standardized full pressure suit used by joint USAF and the Central Intelligence Agency (CIA) operations (Figure 2).

Figure 2. A/P22S-4 full pressure suit. Photo:NASA

The A/P22S series full pressure suit featured a restraint layer, which prevented over expansion of the suit at reduced atmospheric pressures and eliminated the need for bellows at the limb joints. This made the suit much more comfortable to wear and enhanced the range of motion. Additionally the suit could break into sections to allow for easier donning. Since the cockpit of the X-15 was pressurized with N_2 and the pilot was breathing pure O_2, the pilot had to keep the helmet closed and sealed at all times. This prevented the pilot from eating or drinking during flight. Despite this, the A/P22S series pressure suit set the standard for future pressure suits. Future iterations would continue to improve on pilot comfort, mobility, and include a feeding/drinking system.

Lockheed U-2 Pressure Suit

As post World War II political tensions between the U.S. and the Union of Soviet Socialist Republics (USSR) began to rise and the U.S. needed a way to observe and monitor Soviet Union's military capabilities. The Soviet Union's aggressive air defense strategy challenged conventional reconnaissance methods by preventing U.S. planes from photographing their assets as they flew over Soviet air space. The highest-flying aircraft available at the time, the English Electric Canberra, topped out at 48,000 feet but the Soviet Union's radar technology was believed to be capable of tracking as high as 65,000 feet. Given the technological constraints at the time, direct manned reconnaissance methods were still favored over other remote sensing capabilities.

Eventually Lockheed's Advanced Development Programs received a contract from the U.S. government to design a plane capable of reaching heights beyond what the U.S.S.R. could detect for extended periods, enabling the pilots to gather intelligence without detection or interference from Soviet Union countermeasures.

The Lockheed U-2 was an ultra-high altitude reconnaissance aircraft, operated by the USAF, capable of flying at heights exceeding 70,000 feet (U.S. Air Force U-2S/TU-2S

Fact Sheet, n.d.). Typical missions lasted between 10 and 12 hours (though the plane was physically capable of staying aloft longer, pilot fatigue and other physiological limitations became a considerable issue). It has been used for scientific research, communications purposes, and of course intelligence gathering. The U.S. government initially developed a cover story for the U-2 under the guise of high altitude atmospheric and weather research to collect information on the jet stream, cosmic ray particles, and ozone; the aircraft were even labeled with the NACA logo. The early U-2 training flights actually did carry NACA instruments but the pilots worked for the CIA and the NACA had no say in where or when the data were collected (Jenkins, 2012).

To achieve such altitudes DCC was contracted again to develop a flight suit capable of withstanding the reduced atmospheric pressure in the U-2's cockpit (Figure 3). Many of the features of the U-2 pressure suit were similar to the A/P22S full pressure suit because they were designed almost simultaneously and by the same engineers at DCC. The A/P22S pressure suit was developed for more standard USAF operations whereas the U-2 suit was considered a special and clandestine project. Since both projects had very similar end users, it made sense their requirements would overlap.

Figure 3. U-2 pressure suit by the David Clark Company. Photo:NASA

Among the novel features of the U-2 pressure suits was a urine-collection system (later added to the A/P22S-6 series pressure suit) and an in-suit food delivery system. The U-2 pressure suits utilized the same helmet as the A/P22S-6 helmet but had a drinking and feeding port installed at the lower-right front of the helmet. The port mechanically sealed using a spring-loaded metal flap. For water, the pilot could insert a straw and drink from a water bottle (Figure 4). Food was a mostly liquidized, toothpaste-like, version of its solid state. It came in thin aluminum tubes that used a probe to insert through the port and then squeezed out (Figure 5).

Figure 4. U-2 pilot drinking water through helmet port. Photo: USAF

Figure 5. Tube food and port probe. Photo: Tozer, J. L.; 2013

The Department of Defense Combat Feeding Directorate at Natick Soldier Research, Development and Engineering Center in Massachusetts created the tube food and they are still used today. Portion sizes are usually around 5 oz. and contain anywhere between 130-300 calories, depending on the type (Tozer, 2013). When the first U-2 pilots flew, their tube food options were limited to beef stew, vegetarian, and applesauce. Since those days the menu has expanded to over a dozen choices and includes items like caffeinated chocolate pudding and Chicken à la King (Operational Rations of the Department of Defense, 2012).

Project Mercury

The successful launch of the Soviet Union satellite “Sputnik” on October 4, 1957 signaled the beginning of the space race between the U.S. and the U.S.S.R. The U.S. responded by officially establishing NASA in 1958 and tasked them with winning the technology war between the two nations. NACA merged into NASA and though they had a lot of experience with rocket planes, extreme altitudes, and pressure suits, putting a man into space was a wholly new level of manned flight. Time was of the essence and thus NASA’s aptly named its fledgling orbital flight program Project Mercury, after the Roman god Mercury who was very fast.

Project Mercury launched only six flights during its program life from 1958 to 1963. Pressurized capsules atop Redstone and Atlas rockets carried astronauts into suborbital and orbital flights around the Earth. The astronauts wore a modified version of the U.S. Navy’s Mark IV high altitude pressure suit, developed by the B.F. Goodrich Company. NASA tested both the Navy Mark IV suit and the X-15 high-altitude suit, and chose the Mark IV because it was less bulky and could be easily modified for the tiny space capsule (Figure 6).

Figure 6. Astronaut Gordon Cooper in the Mark IV space suit. Photo: NASA

The Mercury suit was worn "soft" or unpressurized and served only as a backup in the event the spacecraft cabin lost pressure. The suits were suitable only for launch and entry and never intended for EVA (there were no EVAs in Project Mercury). The faceplate of the helmet could retract, allowing astronauts to feed themselves directly rather than through a helmet feeding port (Figure 7).

Figure 7. Astronaut in Mark IV suit eating food pouch. Photo: NASA

John Glenn was the first American to eat in space aboard Friendship 7 in 1962. At that time it was not known if ingestion and absorption of nutrients were possible in a state of zero gravity. He ate tube food (applesauce) and xylose sugar tablets with water, demonstrating that people could eat, swallow, and digest food in a weightless environment (*Food In Space*, n.d.). Astronauts in later Mercury missions ate food that came in bite-sized cubes or freeze-dried powders in addition to the tube food. The astronauts reported the space food to be generally unappetizing, rehydrating freeze-dried foods difficult, and disliked having to squeeze tubes or collect crumbs (*Food For Spaceflight*, n.d.).

Project Gemini

NASA took the lessons learned from Project Mercury and applied them to the next step in manned spaceflight: Project Gemini. NASA's end goal was to put a man on the Moon and Project Gemini developed and practiced the skills needed to achieve that goal. One of the many major successes of the program was the first U.S. EVA.

On June 3, 1965 Astronauts James McDivitt and Ed White depressurized and opened the hatch of their capsule, orbiting the Earth. While still tethered by an umbilical which provided life support, Ed White left his seat and floated approximately 15 feet away from the capsule, earning him the record of the first U.S. spacewalker. The astronauts wore the David Clark Company G4C flight suits (Figure 8): America's first, actual space suit (as the Project Mercury suit was never exposed to space). The suit was used on all subsequent flights, except the Gemini 7 long-duration mission that used the slightly modified version G-5C suit.

Figure 8. Project Gemini space suit. Photo: NASA

In total, nine spacewalks were performed during Project Gemini. The first U.S. spacewalk lasted only 20 minutes; the longest Gemini spacewalk (Buzz Aldrin on Gemini 12) last 2 hours and 29 minutes. Since the EVAs were considerably short, there was no need to eat in suit. Gemini astronauts ate food within the pressurized capsule the same way the Mercury astronauts did. There were some improvements over the Mercury food. However, cube food was coated with gelatin to reduce crumbling and the freeze-dried foods were made to reconstitute easier. Gemini astronauts also had an improved menu with food choices such as shrimp cocktail, chicken and vegetables, butterscotch pudding, and applesauce (*Food For Spaceflight*, 2002).

Project Gemini was pivotal for realizing the importance of spaceflight nutrition. Nutritional data gathered from the missions indicated a health risk associated with inadequate caloric and nutrient intake, especially as mission length increases. Reports showed that the average caloric intake during the Mercury and Gemini missions was about 1,880 +/- 415 kcal per day, consistently lower than necessary to maintain body weight for a male (about 2,870 kcal/ day), resulting in body mass loss in all astronauts (Perchonok et al., 2012).

Apollo & Skylab

In 1969 the United States became the first and only country to put boots on the Moon. Those boots, worn by 12 moon-walking astronauts, belonged to the Apollo Extravehicular Mobility Unit – the first space suit to use autonomous life support systems (Figure 9). No longer limited by the length of an umbilical, this new freedom meant astronauts could venture further on the surface of the Moon and stay out longer. The first lunar EVA lasted 2 hours and 31 minutes and each successive spacewalk increased in length, with the maximum lasting 7 hours and 37 minutes in 1972 (a world record that would hold until 1992).

“When you're in the suits for seven hours, you've got to have something to eat and drink. So, this step of doubling the time (that is, the length of the EVAs) did a lot of things in terms of how you live and work on the Moon. This is an example."-Astronaut Dave Scott, Apollo 15

The suits were developed by ILC Dover and like the suits of Projects Mercury and Gemini, the Apollo EMU helmet had a port for water and food intake (Figure 10).

Figure 9. Iconic picture of Apollo space suit. Photo: NASA

Figure 10. Demonstration of helmet port for drinking water. Photo: NASA

While a problem with the port was never experienced in flight, there remained a concern over the potential failure of the port to reseal upon removal of a water/food probe. It was primarily designed for contingency scenarios, such as a loss of pressure in the lunar module, requiring the astronauts to remain in their suits for an extended period (up to 115 hours). It is unclear whether crewmembers ever used the port during a lunar EVA. NASA began to experiment with in-suit liquid and food delivery systems and phased out the port option from future helmet designs to avoid the risk of a seal failure (Figure 11).

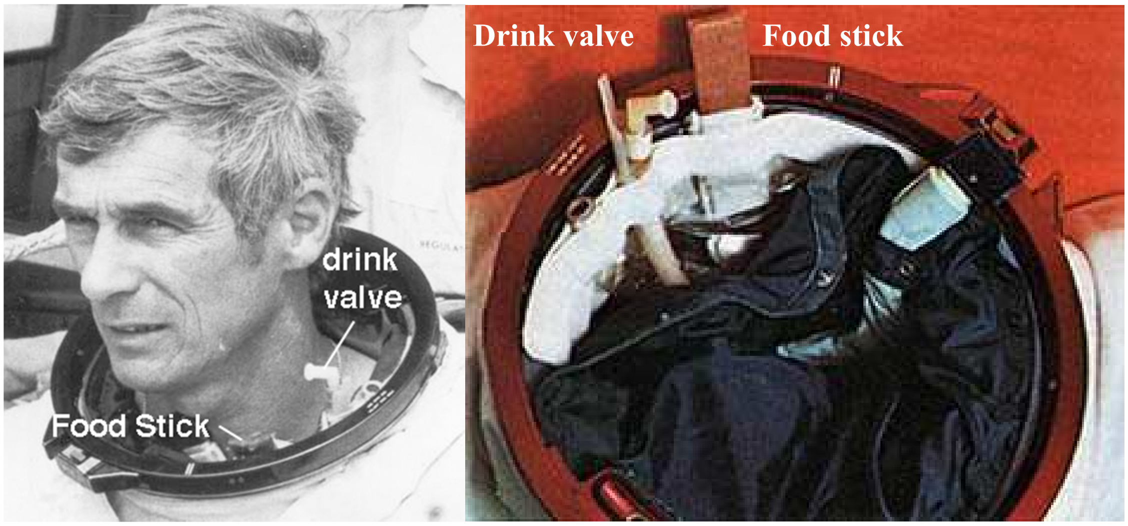


Figure 11. Apollo suit with in-suit liquid and food dispenser. Photo: NASA

The first in-suit liquid dispensing system was a polyurethane bladder fitted with a latex tube and a bite valve. Water or juice was accessed by biting on the valve to open it and sucking on the tube. The bags were mounted inside the suit, in the upper torso area such that astronauts could reach it using only their mouths. The first version of this system was used on Apollo 14 and held only 8 oz. of water. The size of the bag was enlarged to hold 32 oz. for the remaining Apollo spacewalks (NASA, 1973). A similar in-suit liquid delivery system is still used today; now known as the Disposable In-Suit Delivery Bag (DIDB). While this method worked reasonably well, it was not without its drawbacks. Astronauts had the option of water or orange juice and on two occasions, the orange juice leaked during the EVA. The sugary liquid stuck to the suited crewmember in "unintended places" and resulted in skin irritation (Thomas & McMann, 2012). If the bag dislodged and it would displace the bite valve beyond of the astronaut's range of motion (Jones, 2005).

The in-suit food dispensing system was simple in concept, using special food bars composed primarily of natural fruits, gelatin, and wrapped in an edible starch film. The bar inserted into an elastic nylon food dispenser and installed in the neck ring of the suit (Figure 11). Grasping the bar with the teeth and pulling would allow the crewmember to take bites. The fruit bars consisted of approximately 200 calories and were available in seven flavors: apricot, cherry, plum, raspberry, lemon, strawberry, and spiced apple (Huber, 1973). The first use of the food bars were on Apollo 15 and marked the first consumption of solid food in a pressure suit, outside of a space vehicle (Jones, 2005).

The Apollo EMU and its in-suit delivery systems were used for 25 EVAs in total, including the Skylab program. Although there were no significant issues with this system, it was discontinued because the bars were time intensive to prepare and sometimes smeared on the surface of the helmet and impaired visibility when not completely consumed (*NASA's Management and Development of Spacesuits*, 2017).

Space Transportation System (Shuttle)

When the race to the Moon ended and the Apollo program canceled in 1975, there was a shift in the political climate and public support for NASA. The future of the U.S. space program was to be an Earth-orbiting space station, in lieu of further Lunar exploration and development. The space station would be launched and assembled in space with the new Space Transportation System, aka the Shuttle program, which had been proposed to congress on the basis of reducing launch costs via its reusability. Due to ever-increasing budget cuts, NASA was forced to temporarily halt plans for the space station in favor of development and operation of only the Shuttle program (since a space station cannot be built without the Shuttle but the Shuttle could launch without a space station).

Without the mission of assembling a space station, NASA needed to find ways to make the Shuttle program relevant and politically justifiable until funding could support the space station program. The shuttle was promoted to the public for providing access to space for military and commercial satellites and payloads, as well as academic and scientific purposes such as Earth observation studies and microgravity research. With this new focus, spacewalking became a critical element of U.S. spaceflight and its many tasks because of efficiency, as compared to robotics and other automation, and the ability to respond to unexpected situations (Jordan et al., 2006).

Astronaut and manager of the EVA Office, Gary Harbough reported,

> "In my opinion, one of the major achievements of the Space Shuttle era was the dramatic enhancement in productivity, adaptability, and efficiency of EVA, not to mention the numerous EVA-derived accomplishments. At the beginning of the shuttle era, the extravehicular mobility unit had minimal capability for tools, and overall utility of EVA was limited. However, over the course of the program EVA became a planned event on many missions and ultimately became the fallback option to address a multitude of on-orbit mission objectives and vehicle anomalies. […] EVA became an indispensable part of the Space Shuttle Program. EVA could and did fix whatever problems arose, and became an assumed tool in the holster of the mission planners and managers."

With the spacewalking environment changing from Lunar gravity to microgravity, so too did the requirements of the EMU. ILC Dover and Hamilton Sundstrand received the contract from NASA to develop the next generation EMU. Due to borrowing much of its design from the successful Apollo EMU, the modern EMU bears a strong resemblance to its predecessor but is now modular, meaning it is donned and doffed in pieces. This allows for changing out individual components for repair or replacement without taking the entire suit out of operation. It also allows one suit to be used by multiple people, unlike the Apollo EMU that was customized specifically for the astronaut wearing it (Figure 12).

Figure 12. Extravehicular Mobility Unit used for the Shuttle and ISS programs.
Photo: Author

With the Apollo fruit bars phased out, there were no longer any in-suit food systems for the Shuttle EMU, leaving astronauts with only their 32-ounce DIDB of water. The complexity of the new EMU's Primary Life Support System (PLSS) meant that quality control of the suit's internal environment was of the utmost importance. Orange juice was no longer allowed in the DIDB due to concern over the sugary fluid leaking out and compromising the delicate components that recycled the O_2 and water. For this same reason, solid food is also prohibited within the suit since crumbs and food particles would have the same consequence in the microgravity environment (also it poses the risk of choking during an EVA).

In addition to the new spacesuit design came a new operating pressure and protocols for minimizing the risk of decompression sickness for microgravity EVAs.

> "The target suit pressure was an exercise in balancing competing requirements. The minimum pressure required to sustain human life is 21.4 kPa (3.1 psi) at 100% oxygen. Higher suit pressure allows better oxygenation and decreases the risk of decompression sickness to the EVA crewmember. Lower suit pressure increases crew member flexibility and dexterity, thereby reducing crew fatigue […] Higher suit pressures also require more structural stiffening to maintain suit integrity […] This further exacerbates the decrease in flexibility and dexterity. The final suit pressure selected was 29.6 kPa (4.3 psi), which has proven to be a reasonable compromise between these competing constraints." (Patrick et al., 2011).

Presently, astronauts have to breathe 100% O_2 in preparation for an EVA in order to purge N_2 from their body and reduce the DCS risk. Without this prebreathe protocol, the dissolved N_2 gas in their bodies would form bubbles and potentially cause death. To achieve adequate purging of N_2, the first Shuttle-based EVAs required the astronauts to breathe pure O_2 for four hours. This had the unfortunate side effect of creating inefficient idle time (in space, crew time is valuable!) and resulted in an exceedingly long crew day. An alternative was to lower the entire Shuttle cabin pressure from its nominal pressure of 14.7 psi (sea level) to 10.2 psi twelve hours prior to the EVA. This protocol was preferred for its efficiency, requiring only 40 minutes prebreathing O_2 (the Apollo capsules were pressurized with pure O_2 so prebreathing was not necessary as the N_2 had been purged from crewmembers' bodies by the time they reach the Moon).

The early Shuttle EVAs were short by today's standards, lasting typically only a few hours. This, combined with the new 40-minute prebreathe protocol, meant astronauts only had to endure on average 6 hours or less without food. Astronauts could eat a hearty meal and tolerate this fasting period with relative ease. As the demands and successes of the Shuttle program grew, so did the average length of EVAs. The longest Shuttle-based EVA lasted 8 hours and 56 minutes with STS-102 in 2001 (Thomas & McMann, 2012). To date this also remains the longest spacewalk in history (reference Appendix B for more information on U.S. spacewalks).

International Space Station

After another round of budget cuts and space station redesigns, NASA finally received Congress's approval to begin assembling the International Space Station. The U.S. segment "Unity", aka Node 1, and the Russian segment "Zarya" were the first elements of the ISS and were launched in 1998. Though not originally intended for the ISS, the Shuttle EMU was compatible enough with minor modifications to use for the ISS program. As of March 2018, there have been 209 spacewalks to assemble and maintain the ISS; 158 of those using the EMU (the rest were Russian EVAs).

ISS EVAs required a different approach for prebreathing. It is impossible to reduce the large volume of the ISS pressure (roughly equivalent to a five-bedroom house) to 10.2 psi without wasting N_2 and O_2 supplies, as well as impacting delicate research experiments susceptible to pressure changes. One option was to have the crewmembers exercise before EVA while breathing pure O_2. The increased rate of blood flow and joint movement facilitated the release of N_2. This worked but exhausted the crew prior to the start of the EVA. Another option, called the "campout" protocol, was to isolate the spacewalkers in the ISS airlock overnight and reduce the pressure to 10.2 psi. While effective for reducing the risk of DCS and shortening the O_2 prebreathe time, this isolation took away valuable crew time. Being isolated in the airlock put them at an additional risk if a station emergency occurred, i.e., the airlock would have to repressurize before the hatch could be opened and allow the astronauts to escape to their rescue ship.

The compromise finally reached is called the In-Suit Light Exercise (ISLE) prebreathe protocol. It combines the 4-hour protocol with exercise, overall shortening the prebreathe time required to just over 2.5 hours. Combined with the remaining work before and after EVAs, plus the typical 7-hour EVA itself, means the crew on average endures 10-12 hours without food. Since food choice is entirely dependent on personal preference, those who chose to eat a light breakfast on EVA day experience the most deprivation.

The Future of EVAs

Published in the NASA report *Evidence Report: Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System*, 2012, NASA concluded the following:

> "In addition to the nutritional risks from nutrient degradation and gaps in nutrient kinetic knowledge, space missions will have a unique nutritional risk associated with extensive extravehicular activities (EVA) and emergency contingency requiring extended crew time in pressurized suits (over 100 hours). EVAs will require no less than an additional 200 kilocalories above nominal metabolic intake, similar in nutrient composition to the rest of the diet [...] Currently, there is no effective delivery method for providing nutrition to the crew during extended time in a pressurized suit. This would be especially concerning over a multiple day event in which crewmembers are expected to be cognitively functioning and physically capable of performing tasks required for safe return. The insufficient nutritional delivery capabilities and lack of accurate nutrient data create the knowledge gap for this risk. [….] The importance of effective in-suit nutrition delivery in an emergency event, such as depressurization of the crew vehicle, becomes critical depending on the length of time."

Not much information is available at this time regarding the food delivery capabilities of the next generation space suits, as they are undergoing active development. DIDB-like in-suit feeding systems and the helmet food port remain the most popular options under consideration. One workaround that engineers are exploring is the concept of an 8-psi suit. Physiologically speaking, the human body can withstand a pressure decrease from 14.7 psi to 8 psi with little to no risk of DCS. This would eliminate the need to prebreathe O_2, meaning less preparation time prior to the EVA. The downside to an 8-psi spacesuit is the drastic decrease in suit mobility since the crewmember would have to work against the increased suit pressure. Working in the current EMU pressure of 4.3 psi is already challenging enough therefore working in 8 psi will be prohibitive without significant design changes. Additionally an 8-psi suit does not protect against a contingency scenario requiring the crew to remain in their suits for days.

CHAPTER III

METHOD

Experiment Design Overview

To test the hypotheses that 1) sustenance deprivation significantly affects EVA performance, 2) that it can be quantified, and 3) performance can be improved by feeding astronauts during an EVA, an experiment was performed with astronauts undergoing EVA training at NASA's Johnson Space Center. Astronauts' cognitive and physiological abilities were measured at the beginning and conclusion of EVA training to determine whether there was any significant change in their performance as a result of fasting. Some of the test subjects were given sustenance throughout their EVA training to see whether their performance improved over those who went without. The following sections will provide the details of the experiment.

Neutral Buoyancy Lab

The best way to gauge impacts to a spacewalking astronaut's performance would be to assess their cognitive and physical skills during an actual EVA. Unfortunately, such an ideal testing environment was beyond the scope and logistical abilities of this research however, there was a suitable Earth-bound alternative: NASA's Neutral Buoyancy Lab (NBL).

The NBL is primarily used to train astronauts for ISS spacewalks by simulating micro-gravity conditions via the effect of neutral buoyancy. It is one of the world's largest indoor pools, measuring 202 ft in length, 102 ft in width and 40 ft in depth (20 ft above ground level and 20 ft below) and holds 6.2 million gallons of water. It boasts a full-scale mockup of the US segments of the ISS (excluding the solar arrays- Figure 15). The intent of the NBL is to support the development of flight procedures, verify hardware compatibility, test model predictions, and of course train EVA skills to ensure mission success. NASA use of the NBL and its facilities in order to test the conduct this experiment, as it is an item of interest germane to current and future manned spaceflight.

Figure 13. NASA Neutral Buoyancy Lab. Photo: NASA

Astronauts training at the NBL wear modified EMUs with a combination of weights and floats to achieve neutral buoyancy, meaning the suited subject will neither sink nor float. Neutral buoyancy allows astronauts to experience and better understand the physical effects of microgravity. They learn how to move in three dimensions and how to compensate for the basic laws of physics, such as rotational forces when using tools without the aid of gravity. They experience a similar level of stress and fatigue that comes from working in a pressurized suit for several hours with little rest. Preparations begin early in the morning and, like their on-orbit counterparts, they have to endure approximately ten hours of working in a microgravity-like environment without food.

Another unique feature at the NBL is the ability to measure an astronaut's Working Metabolic Rate (WMR), the rate which they are consuming energy, via respirometry. Respirometry measures metabolism via a measurement of carbon dioxide (CO_2) production. The astronauts' suits are connected to an umbilical while in the water, which supplies them with air for breathing and suit pressure (in space they breathe pure O_2 in the EMU). The percent of O_2 they breathe is known and the CO_2 in their exhalant is measured in the outgoing line of the umbilical. The ratio of O_2 to CO_2 is used to calculate their WMR which is recorded. During an actual EVA this metabolic information is used to monitor the efficiency of the CO_2 scrubbing system in the EMU to ensure the safety of the astronaut. It can also be used to gauge the difficulty of a task. Difficult tasks increase physical exertion from a suited astronaut and more O_2 is used, thus more CO_2 is created. This creates periods of peak intensity for the WMR. Refer to Figure 16 for a sample chart of an astronaut's WMR during NBL training.

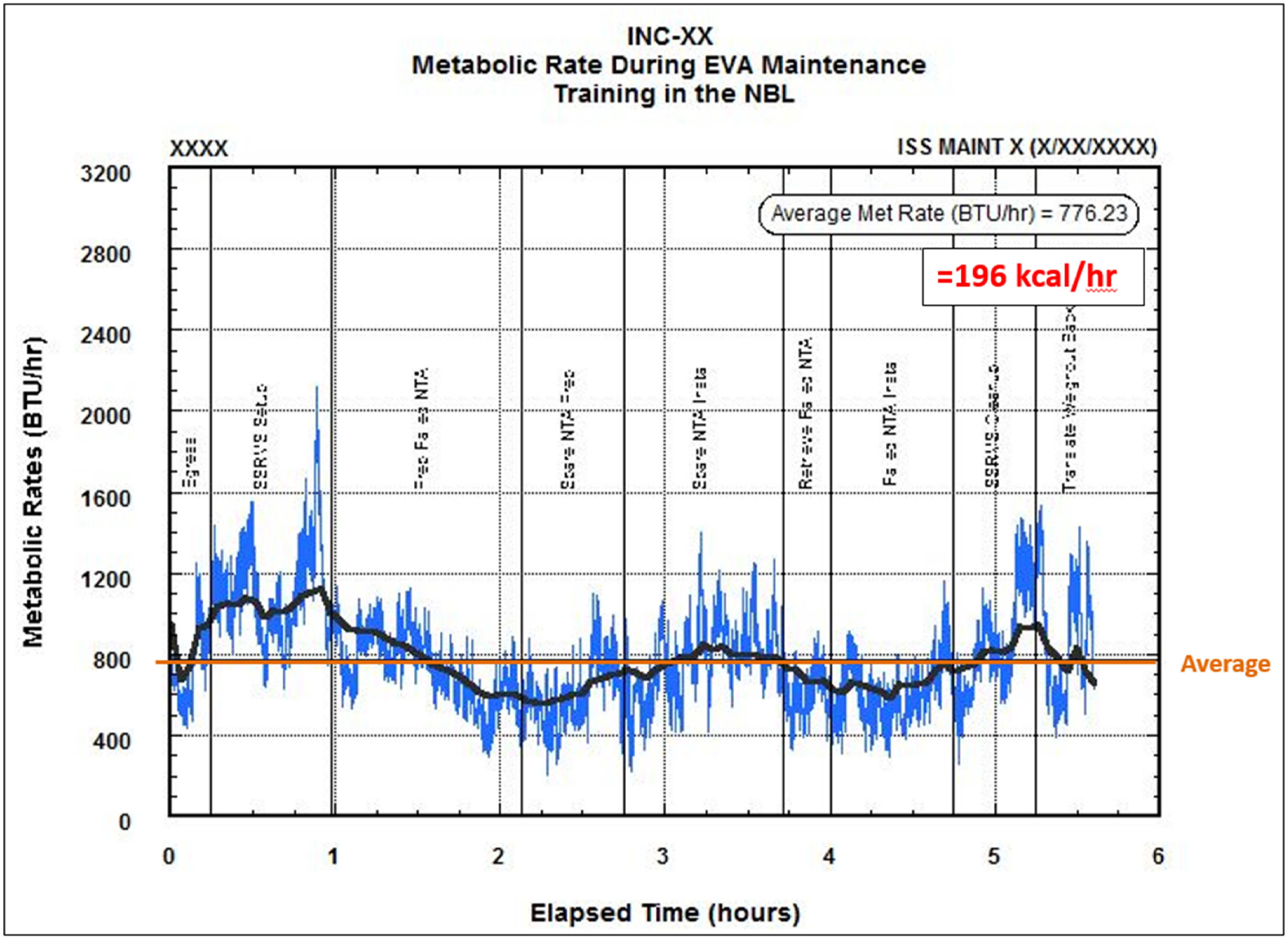


Figure 14. Example of metabolic rate during NBL training.

In-Suit Sustenance

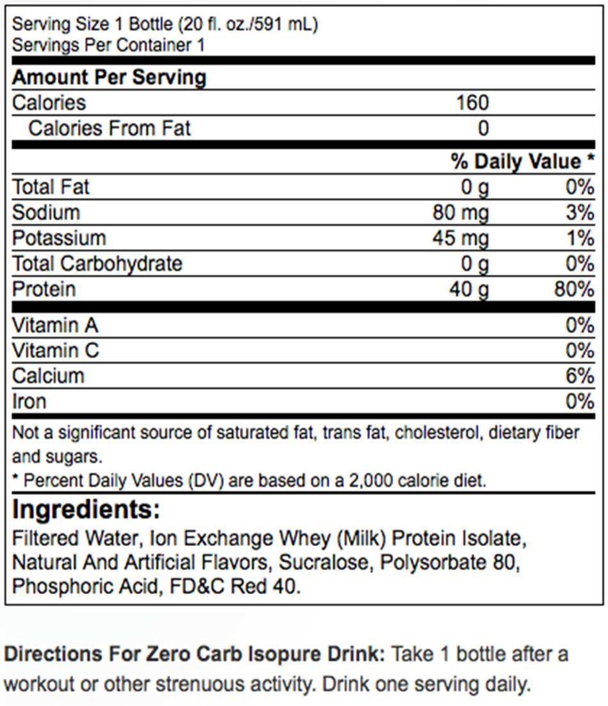
In order to consume nourishment without disturbing the tightly scheduled training agenda or requiring major modifications to the EMU, the DIDB was used similar to that of the Apollo program but instead of plain water or orange juice, the DIDBs contained a protein supplement drink.

Identifying liquid food options compatible with the DIDB delivery method was a challenge due to restrictions on substances allowed inside the spacesuit. Special permission was granted to allow for a temporary deviation from normal operating protocols in order to conduct the experiment. NASA donated 12 DIDBs to the study with the following caveats:

1. No sugary liquids due to concerns over leakage from the DIDB, which could damage sensitive internal suit components.
2. For cleaning purposes in the event of a leak, the substance could not stain the materials that comprise the EMU. This meant anything that was dark colored, such as chocolate flavored beverages, or had a strong artificial color was disqualified.
3. The drink could not be a milk-based product since it was agreed to be highly undesirable for test subjects to consume effectively warm milk during intensive physical activity.
4. Approval from a NASA medical flight surgeon to ensure the safety of the test subjects and have protocols in place for dealing with consequences from inadvertent eye contact, inhalation, or emesis.

Based on those requirements, a liquid protein drink seemed the most likely candidate for satisfying hunger and caloric replenishment, however there were limited commercially available options that were not milk-based, contained sugar, or had artificial colors. Adhering to these requirements also meant the remaining options lacked the other primary macronutrients necessary for complete nutrition: carbohydrates and fat. This was an accepted condition for the purposes of this pilot study.

The product IsoPure^{TM} was selected for its large serving of protein. Research has shown that consumption of protein reduces the level of the hunger hormone ghrelin, while also boosting the satiety hormone peptide YY and creating the sensation of feeling full (Blom et al., 2006; Latner & Schwartz, 1999). A single serving size of the IsoPure^{TM} drink contains 160 calories, no sugar, and 40 grams of whey protein; the protein equivalent of about six eggs (Figure 15).



Serving Size 1 Bottle (20 fl. oz./591 mL)
Servings Per Container 1

Amount Per Serving		
Calories	160	
Calories From Fat	0	
		% Daily Value *
Total Fat	0 g	0%
Sodium	80 mg	3%
Potassium	45 mg	1%
Total Carbohydrate	0 g	0%
Protein	40 g	80%
Vitamin A		0%
Vitamin C		0%
Calcium		6%
Iron		0%

Not a significant source of saturated fat, trans fat, cholesterol, dietary fiber and sugars.
* Percent Daily Values (DV) are based on a 2,000 calorie diet.

Ingredients:
Filtered Water, Ion Exchange Whey (Milk) Protein Isolate, Natural And Artificial Flavors, Sucralose, Polysorbate 80, Phosphoric Acid, FD&C Red 40.

Directions For Zero Carb Isopure Drink: Take 1 bottle after a workout or other strenuous activity. Drink one serving daily.

Figure 15. IsoPure flavors Coconut and Blue Raspberry and nutritional information. Photo: IsoPure^{TM}

The drink comes in a 20 oz. Ready-To-Drink (RTD) bottle or in powder form (wherein it is mixed with a liquid of ones choosing), as well as a variety of flavors. The RTD was the most compatible with the equipment used to prepare the DIDBs since the viscosity was similar to water and would not create clogs in the mixing process (though test subjects noted it required a slightly stronger sucking force through the DIDB bite valve). A taste test was conducted in order to identify flavors that would be most palatable to the most test subjects throughout the experiment. Flavors that left a strange texture in the mouth or had an unsavory aftertaste were disqualified. Ultimately, two flavors were selected for the experiment: Blue Raspberry and Coconut. Blue Raspberry was permitted, despite having conspicuous artificial color since it easily washed out in the EMU laundering process (Figure 16).

Figure 16. DIDB filled with Blue Raspberry protein drink. Photo: Author

Test Subjects

Fifteen astronauts volunteered as test subjects; 12 male and 3 female. The average age was 44 (±6) years, 53% had previous military experience, and 27% had a PhD level of education. This was a sufficient representative cross section of NASA's entire astronaut corp where historically the average age of an astronaut on their first mission is 41 (±5) years, 84% are male, 63% have previous military experience, and 33% have a PhD (*Astronaut Fact Book*, 2013).

Test subjects were randomly sorted into two groups: control group and protein group. The control group had only water in their DIDB while the protein group received the protein treatment. All participants consumed the same quantity of liquid to ensure that hydration levels were equal throughout the NBL training. Due to the nature of their training schedules, most test subjects tested only once in the experiment as either a control or protein participant. Six astronauts volunteered to repeat the tests as they were scheduled to train more frequently during the test window, completing two rounds of tests for four total data points (once in the control group and then the protein group). Of those six test subjects, two completed an additional two rounds of tests for a total of eight data points (twice in the protein group and twice in the control group).

Test subjects met with the PI upon their arrival at the NBL, prior to the required morning medical check-in. They completed their first round of measurements (detailed in next section) to set their baseline performance. Their time of breakfast was recorded, but not the details of their diet since astronauts on the ISS are free to choose their own food and have personal preferences for EVAs. After the morning assessment was complete they were advised not to consume any further food, with the exception of water, until after the post-training assessment. This ensured that all test subjects would have to withstand a similar fasting duration as the astronauts performing EVAs (approximately 10 hours). Given the obvious flavor from the protein drink, test subjects were aware as to which group they were prior to the start of their training. A placebo drink option was not included in this study but is recommended for future studies.

Institutional Review Board Considerations

This experiment required permission from the University of North Dakota's Institutional Review Board (IRB) as well as NASA's IRB since it utilized human test subjects. Volunteers were briefed on the details of the experiment and their rights as a test subject prior to agreeing to participate. Test subjects' identity and any personally identifying information is confidential and not used in the analysis. There were no complaints or withdrawals from any of the test subjects, nor were there any violations of the IRB requirements.

Data Collection

To quantify an astronaut's performance during a spacewalk, this experiment utilized standardized assessment tests for two cognitive and two physiological domains, based on criteria relevant to skills used during an EVA. The tests were modeled after the National Institute of Health (NIH) Toolbox®.

The NIH is an agency of the United States Department of Health and Human Services and is the primary agency responsible for biomedical and health-related research. They developed a set of comprehensive measures designed to quickly assess cognition, emotional, sensory, and motor function domains. Developed by more than 250 contributing scientists at 80 institutions, data were collected from 16,000+ subjects based on a nationally representative sample, aged 3-85, to enable cross-measure comparisons and designed to measure outcomes in longitudinal studies. The measures were designed for brevity and typically require minimal additional hardware beyond a laptop/tablet so that testing can be conducted in-situ.

Cognitive Testing

Astronauts are regularly expected to deal with an overwhelming amount of information in preparation for a spacewalk, however the inherent nature of manned spaceflight frequently means sudden changes are necessary with little to no advance warning. Astronauts must be able to adjust quickly and correctly execute new tasks given to them in the stressful and dynamic environment of working in space.

To gauge how cognitive skills necessary to accomplish this are possibly impacted, this research chose to investigate working memory and processing speed, as the amount of material recalled and speed of performance on tests have been shown to be correlated with blood glucose levels (Bischoff, 2007).

Working Memory

Per the NIH Toolbox's brochure:

> "Working Memory refers to the ability to store information until the amount of information to be stored exceeds one's capacity to hold that information. Working memory refers to the capacity of an individual to process information across a series of tasks and modalities, hold the information in a short-term buffer, manipulate the information, and hold the products in the same short-term buffer. This concept updates the traditional construct of "short-term memory," which refers to a passive storage buffer, to include the notion of an active computational workspace."

Working Memory is necessary for common yet complex everyday activities which require multitasking. Working Memory tests tax the limit of an individual's storage capacity and often involve multi-tasking activities such as reciting numbers while performing arithmetic tasks or remembering a string of numbers and reciting what number occurred two or three numbers back. These two-component tasks are often quite different and challenging to the examinee (Tulsky et al., 2014). To assess Working Memory skills, the NIH chose the List Sorting sequencing task because it had proven successful in the Wechsler Adult Scales of Intelligence, Third Edition.

The List Sorting test requires immediate recall and sequencing of different visually and auditorily presented stimuli. For this experiment, test subjects were quickly but smoothly presented a series of random animals on a computer screen then asked to recite the animals in order of smallest to largest. For example: images of an elephant, a mouse, and a cat would individually flash on the screen, along with audio, and the test subject was expected to recite “Mouse, cat, elephant” before proceeding to the next level (Figure 17).

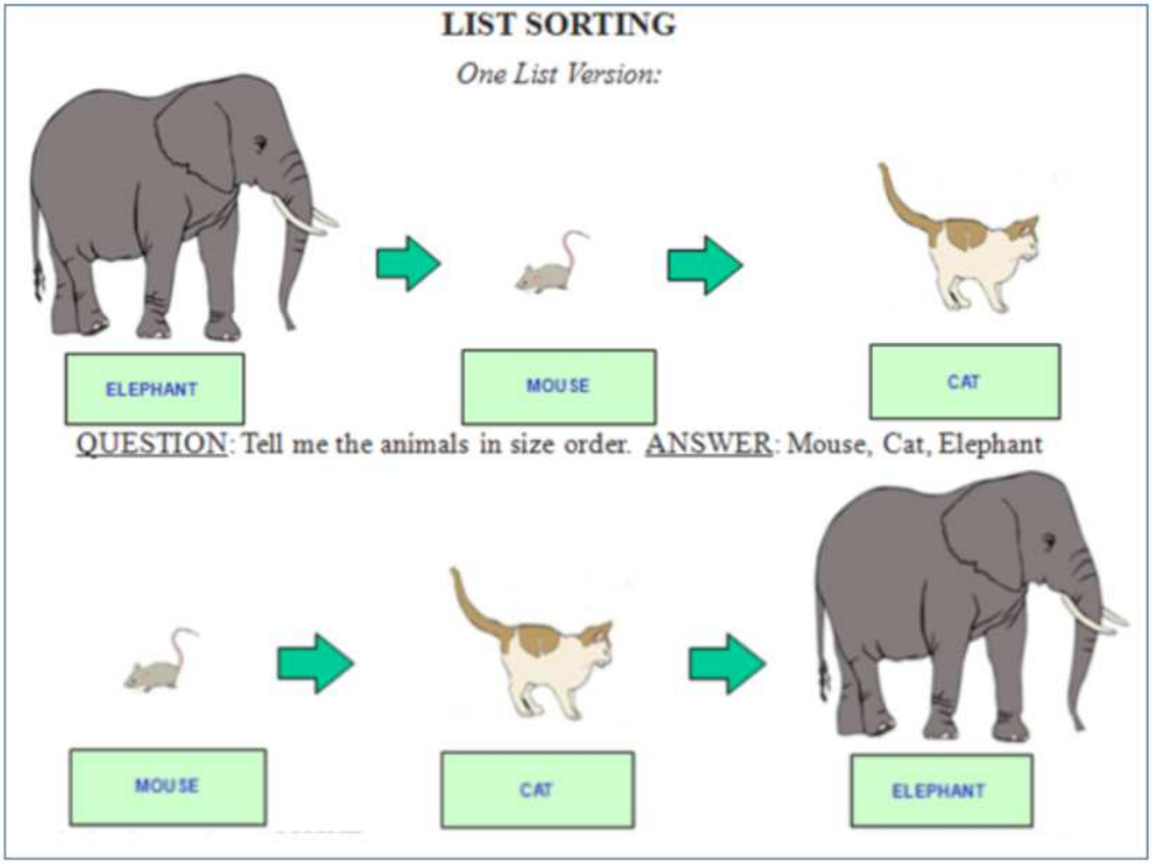


Figure 17. Working Memory List Sorting test. Photo: NIH Toolbox

Each level progressed in difficulty by increasing the number and variety of randomized animals. There were ten levels in total for this experiment, with the final round requiring eleven different animals recalled in the correct sizing sequence. Test subjects scored a point for each animal correctly recalled in order and no points were deducted for forgotten or mislabeled animals. To measure Working Memory, this experiment utilized a slightly modified version of the NIH's published List Sorting test by adding more levels and a different point system.

Processing Speed

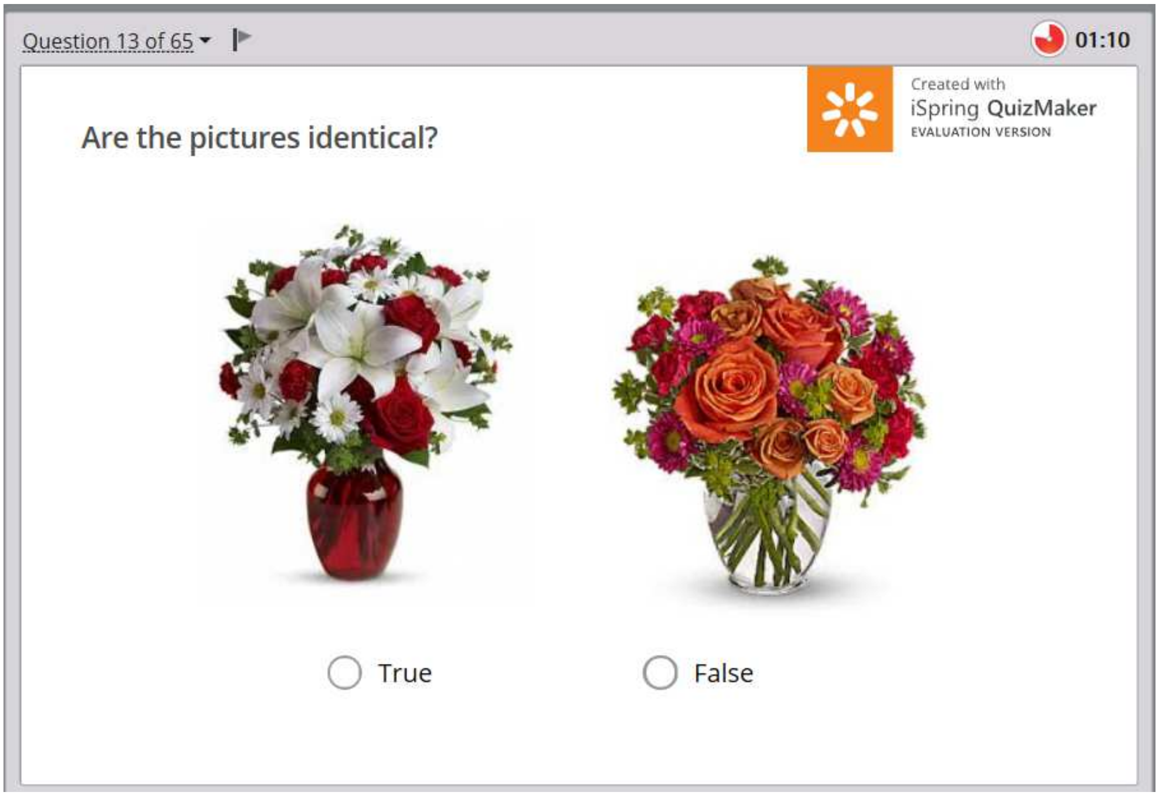
Per the NIH Toolbox's brochure:

> "Processing Speed is defined as either the amount of time it takes to process a set amount of information or conversely, the amount of information that can be processed within a certain unit of time. It is a measure that reflects mental efficiency. Processing Speed is central for many cognitive functions and domains and is sensitive to change and/ or disease."

Processing Speed plays an influential role in multiple areas of cognition and is among the most sensitive cognitive processes "to neurologically insult" (Carlozzi et al., 2015). Processing Speed is thought to serve as the foundation for other cognitive processes and deficits in this skill are associated with subsequent impacts in other cognitive domains, especially working memory (Chiaravolloti et al., 2003). Given the importance of Processing Speed as a foundation for other cognitive processes, the NIH developed a test intended to be brief but with high correlation to other well-established Processing Speed tests. In light of the relationship between Working Memory and Processing Speed, the List Sort Working Memory test was included in the original test design as a measure of divergent validity.

The Pattern Comparison Processing Speed test measures the speed of information processing by asking participants to quickly distinguish whether two side-by-side pictures are identical or not. Subjects execute their decision upon seeing the image pairs by selecting the option of "True" or "False" on a computer screen (Figure 18) to indicate their decision.

For this experiment the test was scored by the number of picture pairs correctly identified within a 90-second period. This experiment utilized a free version of the iSpring QuizMaker 8.7 software to model the test developed by the NIH.



Are the pictures identical?

○ True

○ False

Figure 18. Processing Speed Pattern Comparison test. Photo: Author

Physiological Testing

Motor-functional is indicative of neurological status, physical health, and long-term health outcomes and is integral to daily functioning and quality of life (Reuben et al., 2013). Physiological studies in the past century have established the importance of muscle glycogen on performance (Ørtenblad, 2013). Limitations on anaerobic and endurance performance, as well as muscle strength, are thought to be due to the decrease in muscle glycogen and reduced blood glucose (Shepard, 2012), which would occur during IF.

To assess how motor functions in astronauts may be impacted, this research chose to focus on hand dexterity and grip strength. Astronauts' hands are their most valuable asset. They use their hands to "walk" on the ISS by translating along a prescribed series of handrails. In essence, their hands are their feet since their actual feet are all but useless in the microgravity environment. The tasks astronauts must accomplish during an EVA require complex finger coordination and varying levels of hand strength.

Dexterity

Per the NIH Toolbox's brochure, "Dexterity is defined as an individual's ability to coordinate the fingers and manipulate objects in a timely manner." To measure dexterity the NIH recommends the 9-Hole Peg Board test. It was originally introduced in 1971 as a measure of dexterity in an official publication of the American Society for Occupational Therapy and has been frequently been included in Multiple Sclerosis research and clinical practice (Feys et al., 2017). The NIH selected it based its widespread adoption and extensive data available from medical research.

The test consists of a rectangular board with nine holes and a container with nine pegs. Subjects are timed on how quickly they can fill the nine holes, one peg at a time, then empty each hole and return the pegs to the starting point (Figure 19). For this experiment the test was performed three times in both the pre and post EVA training evaluations and averaged. For brevity, only the test subject's dominant hand was measured. The dimensions for the standardized 9-Hole Peg Board and pegs are available free online and the board used for this test was created from a 3D printer at a public library.

Figure 19. Dexterity 9-Hole Peg Board test. Photo: NIH Toolbox

Astronauts must manipulate complex tools to perform tasks for an EVA. These basic functions are complicated by working in a pressurize suit which causes additional workload on fine-finger dexterity. One of the most common feedback from astronauts is how tired and sore their hands are at the conclusion of an EVA. The ability to manipulate tools and latching mechanisms, many of which require a high degree of dexterity, could become compromised by an astronaut already weakened by hunger.

Grip Strength

Per the NIH Toolbox's brochure:

> "Strength refers to the capacity of a muscle to produce the tension and power necessary for maintaining posture, initiating movement, or controlling movement during conditions of loading the musculoskeletal system. More simply, muscle strength is the magnitude of force generated by an isolated muscle or a muscle group."

Hand-grip strength dynamometry has the advantages of reliability, ease of administration, and is well established in epidemiologic research. It is often used to characterize overall limb muscle strength (Bohannon et al., 2012). The hand-grip dynamometer test protocol was adapted from the testing protocol of the American Society of Hand Therapy. Participants sat in a chair with their feet touching the ground, elbow bent to 90 degrees and against their torso. Participants squeeze a dynamometer as hard as they can for a count of three while a gauge measures the force exerted. For this experiment the test was perform three times for both the pre and post EVA training evaluation and the scores were averaged. A donated Takei 5001 Grip-A hand-grip dynamometer (Figure 20) was used to measure grip strength, which was recorded in kilograms.

For the same reasons finger dexterity is hindered by the pressurized EMU glove, grip strength also diminishes throughout an EVA. Manipulating mechanisms that require a certain grip force becomes difficult as muscle fatigue sets in.

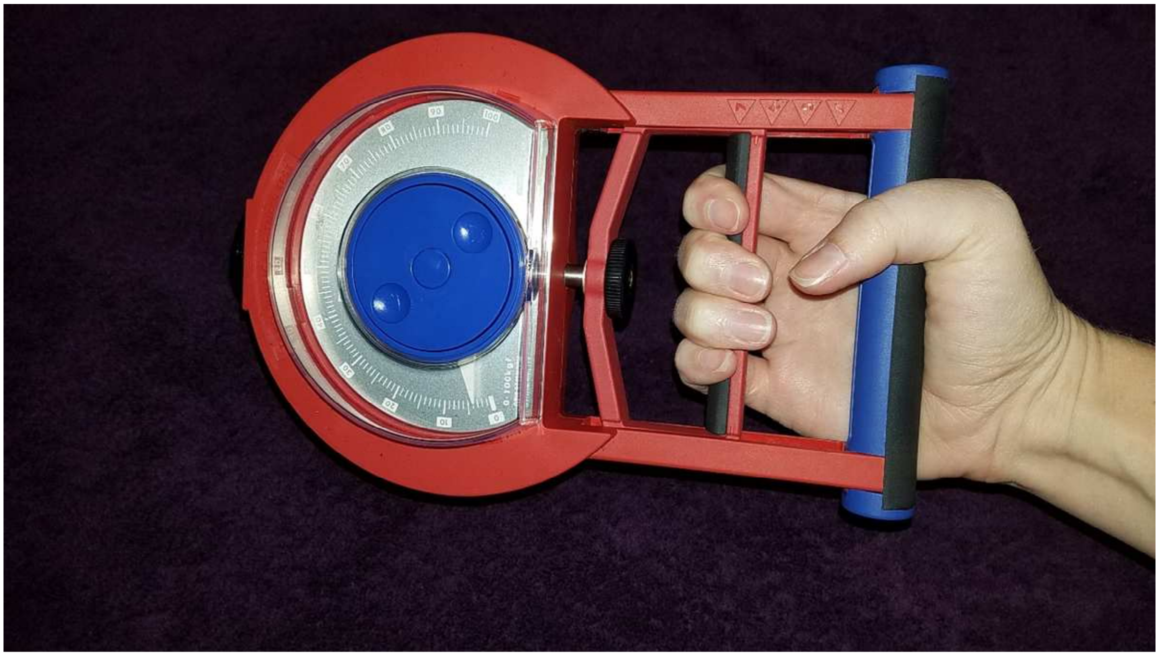


Figure 20. Hand Grip Strength Takei 5001 dynamometer. Photo: Author

Test Subject Experience

At the conclusion on their NBL training feedback was solicited from all test subjects to gauge response to the experiment. They were asked to describe their perception of hunger and fatigue and how it compared to previous NBL training. If they had the protein drink the PI asked for their opinion on the flavor, texture, use of the DIDB as a delivery system, and to describe anything unique they may have experienced throughout the training with respect to it. There was no formal questioning system and the information provided was purely subjective.

CHAPTER IV

RESULTS

Descriptive statistics (mean ± standard deviation) were calculated for the average performance scores for both test groups. A linear mixed effects regression model was used to predict future outcomes based on these test conditions. The model incorporated a random intercept term, which accommodated random heterogeneity in astronauts that persisted throughout the study. Sex, education, and military training were treated as continuous covariates and treatment (control or protein) as a categorical covariate, using indicator variables for each. Data modeling was performed with STATA v.14.2 statistical analyses software. Detailed STATA analysis output is in Appendix C: Data Analysis. Eq. 2 is the mixed effects model used for this analysis.

$$Score_{ij}=\beta_0+\beta_1\times(Time)_{ij} + \beta_2\times(Treatment)_j + \beta_3\times(Sex)_j$$
$$+ \beta_4\times(PhD)_j + \beta_5\times(Training)_j + \beta_6(Treatment\times Time)_{ij}+ b_{0i} + \varepsilon_{ij}$$

Equation 2. Linear regression model

where

$$b_{0i} \sim N(0, \sigma_{Astro}^2) \text{ and } \varepsilon_{ij} \sim N(0, \sigma^2)$$

Eq. 2 models the response $Score_{ij}$ at the j^{th} measurement for the i^{th} astronaut, where β_0 is the overall population intercept, $\beta_1, .., \beta_6$ are the fixed effects for each covariate, ε_{ij} is an independent error term, and b_{0i} is the random intercept that allows for deviation from the population intercept for astronaut i.

The first null hypothesis was that EVA skills in the tested domain did not change at the conclusion of EVA training. The second null hypothesis was that the tested domain scores would not improve if astronauts consumed sustenance during EVA training. Significance was determined at the 0.05 α-level. Any outliers detected in the model that were more than 1.5 standard deviations (SD) from the edge of the box in a boxplot were inspected for accuracy of data collection kept in the analysis if no error was found. Normality of the data, residuals, and random effects was assessed by the Shapiro-Wilk's test ($p > 0.05$) and visual inspection of scatter plots.

Working Memory: List Sorting test

Table 3 shows the means and SD for the empirical scores of each group taken at pre and post EVA training and Figure 21 provides a visual assessment. The protein group improved their overall average List Sorting score with a mean delta of 2 points and the control group's average score decreased by 0.62 points. At first glance it would appear that there is positive effect of the protein drink on the astronauts' Working Memory.

After running the linear mixed effects regression model it can be concluded that a typical astronaut performing an EVA without food is anticipated to show a mean decrease of 0.62 points, 95% CI [-2.38, 1.15]. With a 0.05 α-level and $p=0.49$, this is a non-significant degradation and fails to reject the first null hypothesis.

Holding all else constant, the astronaut can expect to improve their Working Memory when imbibing the protein drink by a mean difference of 2.61 points, 95% CI

[0.07, 5.16). The mean difference was significantly different from zero at the 0.05 α-level with a p=0.04. Therefore we can reject the second null hypothesis.

Table 3. Results of List Sorting Test

Group	List Sorting Scores (pts)		
	Pre	Post	Delta
	M (SD)	M (SD)	M (SD)
Control (N=13)	44.1 (±5.0)	43.5 (±5.8)	-0.62 (±2.6)
Protein (N=12)	43.3 (±3.4)	45.3 (±4.5)	+2.0 (±3.5)

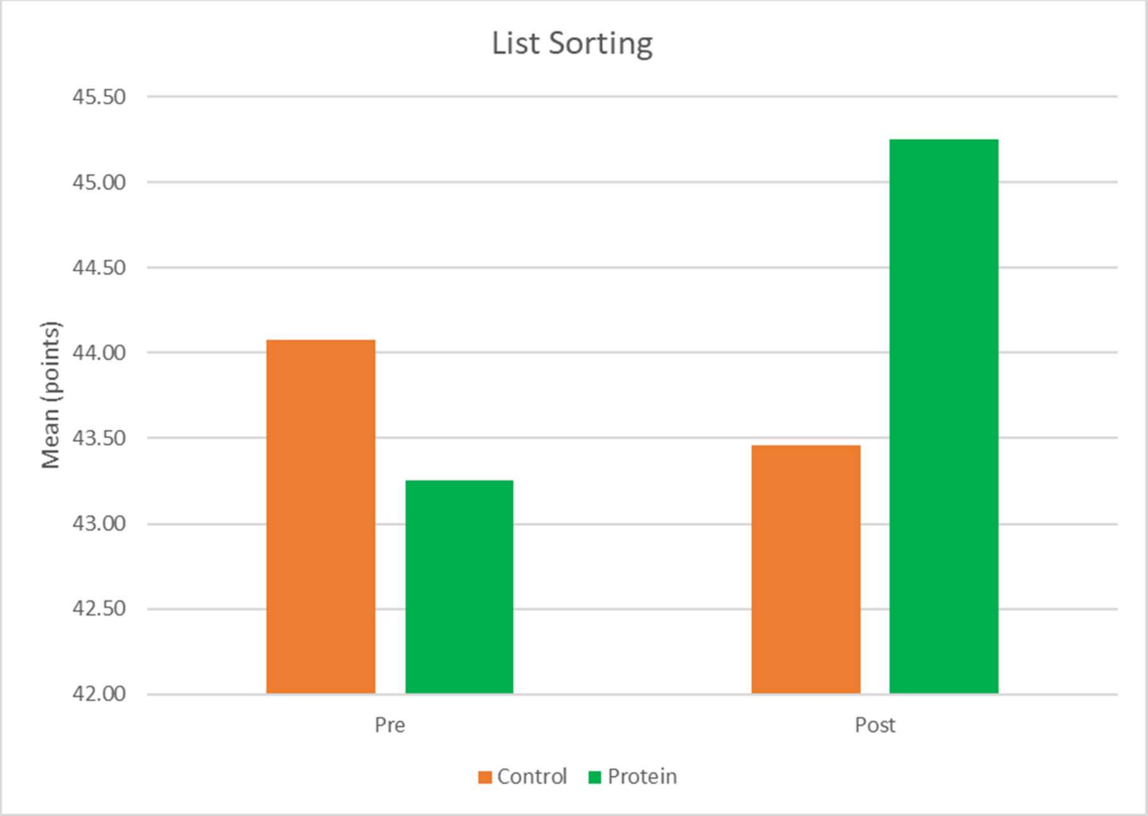


Figure 21. List Sorting group empirical scores.

Processing Speed: Pattern Comparison test

Table 4 shows the means and SD for the empirical scores of each group taken at pre and post EVA training and Figure 22 provides a visual assessment. The protein group's average improved by 3.5 points however the control group's average also improved by 1.77 points.

The model indicated that a typical astronaut performing an EVA without food is anticipated to show a non-significant score decrease in the Pattern Comparison test, with a mean decrease of 0.385 points, 95% CI [-2.49, 3.25]. This fails to reject the first null hypothesis at the 0.05 α-level with a p=0.79.

An astronaut can expect to improve their Processing Speed when imbibing the protein drink by a mean difference of 3.12 points, 95% CI [-1.03, 7.26) however the mean difference was not significantly different from zero at the 0.05 α-level with a p=0.14. T herefore it fails to reject the second null hypothesis.

Table 4. Results of Pattern Comparison Test

Group	Processing Speed Scores (pts)		
	Pre	Post	Delta
	M (SD)	M (SD)	M (SD)
Control (N=13)	43.8 (±7.6)	45.6 (±6.9)	+1.77 (±5.6)
Protein (N=12)	40.4 (±6.0)	43.9 (±5.9)	+3.50 (±4.6)

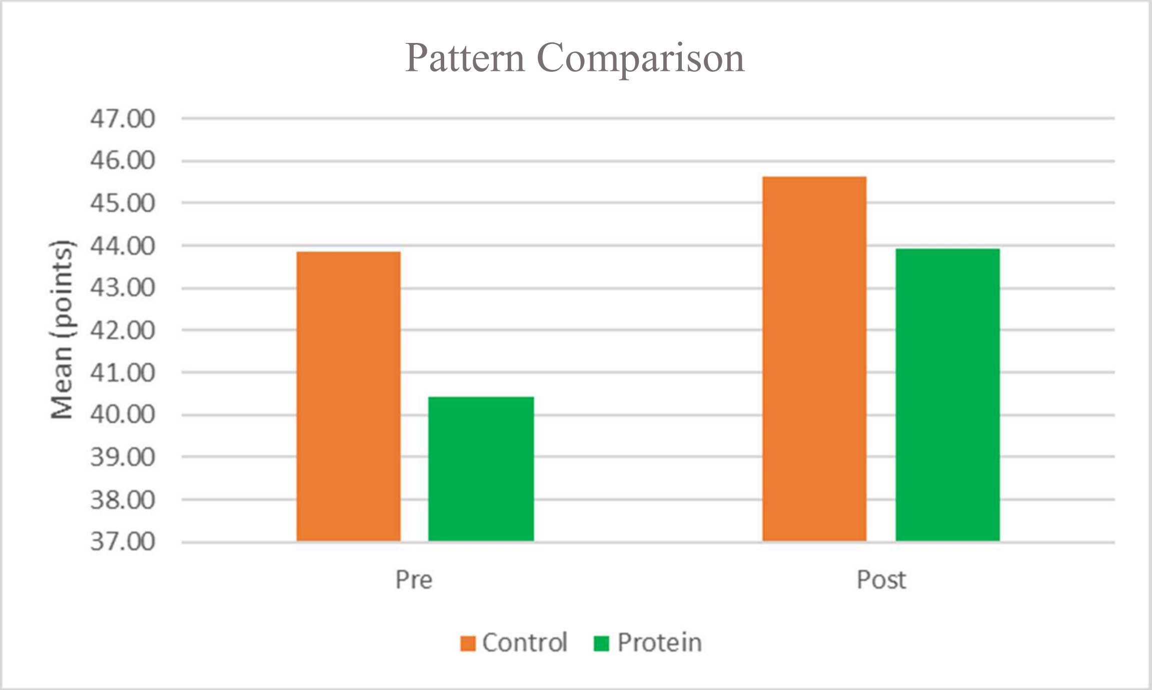


Figure 22. Processing Speed Pattern Comparison empirical scores.

Dexterity: 9-Hole Peg Board test

Table 5 shows the means and SD for the empirical scores of each group taken at pre and post EVA training and Figure 23 provides a visual assessment. The protein group's average improved (faster) by 0.4 seconds and the control group's average slowed by 0.01 seconds.

The model indicated that a typical astronaut performing an EVA without food is anticipated to show a non-significant reduction in speed in the Pattern Comparison test, with a mean decrease of 0.11 seconds, 95% CI [-1.32, 0.33]. This fails to reject the first null hypothesis at the 0.05 α-level with a p=0.70.

An astronaut can expect to improve their Dexterity when imbibing the protein drink by a mean difference of 0.50 seconds, 95% CI [-1.32, 0.33). However the mean difference was not significantly different from zero at the 0.05 α-level with a p=0.24 therefore it fails to reject the second null hypothesis.

Table 5. Results of 9-Hole Peg Board Test

Group	9-Hole Peg Board Scores (s)		
	Pre	Post	Delta
	M (SD)	M (SD)	M (SD)
Control (N=13)	15.5 (±1.8)	15.6 (±1.6)	+0.01 (±0.7)
Protein (N=12)	16.3 (±1.8)	15.9 (±1.8)	-0.4 (±1.0)

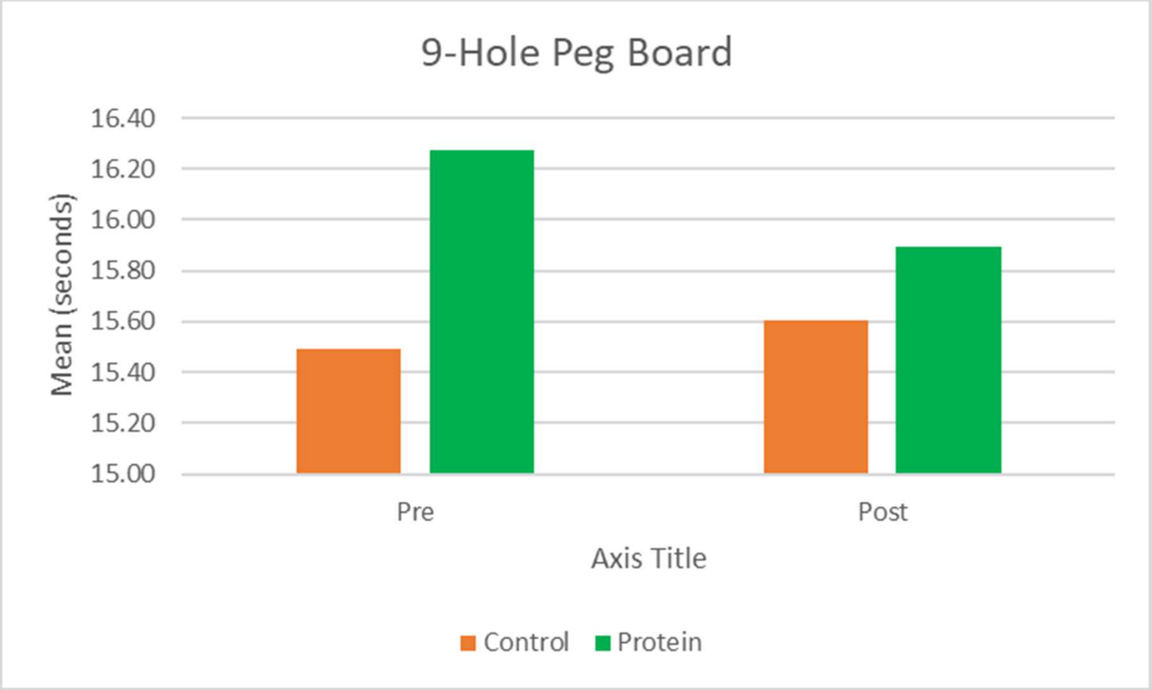


Figure 23. Dexterity 9-Hole Peg Board empirical scores.

Grip Strength: Hand Grip Dynamometer test

Table 6 shows the means and SD for the empirical scores of each group taken at pre and post EVA training and Figure 24 provides a visual assessment. The protein group's average decreased by 1.9 kilograms but the control group's average decreased by 2.6 kilograms.

The model indicated that a typical astronaut performing an EVA without food is anticipated to show a non-significant reduction in hand grip strength by 3.2 kilograms, 95% CI [-7.43, 1.02]. This fails to reject the first null hypothesis at the 0.05 α-level with a p=0.14.

An astronaut can expect to improve their grip strength when imbibing the protein drink by a mean difference of 2.05 kilograms, 95% CI [-4.05, 8.15). However the mean difference was not significantly different from zero at the 0.05 α-level with a p=0.51. Therefore it fails to reject the second null hypothesis.

Table 6. Results of Hand Dynamometer Test

	Hand Grip Scores (kg)		
Group	**Pre**	**Post**	**Delta**
	M (SD)	**M (SD)**	**M (SD)**
Control (N=13)	44.7 (±9.7)	42.3 (±9.5)	-2.6 (±3.1)
Protein (N=12)	45.1 (±7.9)	43.2 (±7.8)	-1.9 (±4.3)

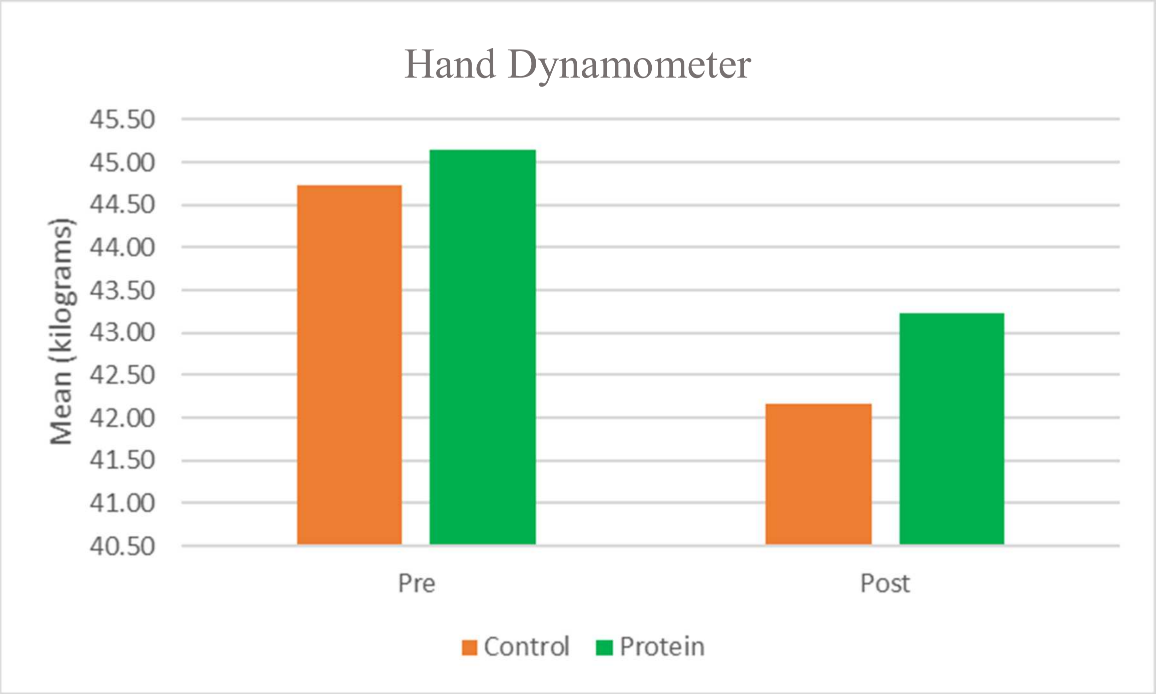


Figure 24. Grip Strength Hand Grip empirical scores.

CHAPTER V

DISCUSSION

The astronauts in the control group, who were anticipated to have significant performance degradation due to IF, showed only minor changes across all tested domains. The empirical scores from each test generally decreased from the morning baseline evaluation, as was expected, but analysis of this change did not reveal this delta to be statistically significant. In the Processing Speed domain the control group average actually improved, if only ever so slightly. While still an insignificant improvement, some research indicates certain domains may actually improve as a result of IF and this may have been an indication of that. Ultimately the null hypothesis could not be rejected in any of the tested domains. There was not enough evidence in these data to claim there is a significant degradation in these domains as a result of sustenance deprivation.

Astronauts consuming the protein drink throughout EVA training showed an increase in empirical test scores, indicating a performance improvement over the control group, however it was not a statistically significant change except for one domain. The Working Memory-List Sorting test showed a significant score improvement for those with the protein drink. An improvement in this domain, under these conditions, supports the idea that astronauts should perform technically complex tasks more accurately as compared to astronauts experiencing IF during the EVA. An increase in task-execution accuracy would decrease the risk of harm to the astronaut.

NBL training objectives varied in lesson content and difficulty, unique to each crewmember, and could not be controlled in the analysis. The WMR of each test subject was averaged into a group total. The mean WMR of both test groups was within ±10 kcal/hr, so it was assumed that both groups as a whole performed approximately the same level of work.

This experiment successfully demonstrated an in-suit feeding system using the DIDB with a substance other than water. Other alternative food system designs should be explored which could allow for a broader range of food types available for a spacewalk.

Test Subject Experience

After the post training assessments each test subject was briefly interviewed for feedback. They were asked to comment on topics such as personal performance assessment on the test domains, perceived hunger levels post evaluation, and reactions to the protein supplement. There was no formal scoring criteria so the feedback was purely subjective, based on their personal experiences and observations from the PI.

Of those that tested with only water, their response was as expected. They seemed less happy and energetic, as compared to their morning evaluation, and reported feeling extremely hungry and physically exhausted. Mental clarity and concentration appeared diminished and their hands felt especially fatigued, with a weakened grip and an increased frequency of fumbles during the 9-Hole Peg Board dexterity test.

Unexpected was the overwhelmingly positive and enthusiastic reaction from the participants who had the protein supplement. Their perceived hunger ranged from noticeably lessened, as compared to their previous NBL experiences, to nonexistent with reasonably high energy levels. Some reported they felt they recovered faster than usual the following day, feeling less sore and tired than normal.

The consensus was that it was generally pleasant to have something other than plain water throughout the training, as it helped by distracting them from focusing on the fatigue that was setting in. They did notice it required a stronger sucking force on the DIDB bite valve (due to the increased viscosity of the protein drink over water) but it was tolerable. The response to initial flavor, after-taste, and texture ranged from acceptable to very enjoyable. A few of the test subjects even inquired if it would continue to be an option for training at the NBL after the experiment was concluded, with a couple of enthusiastic participants wanting to know how soon it would be available onboard the ISS.

CHAPTER VI

FUTURE RESEARCH

This experiment was conducted over a 4-month period, with data collection occurring approximately one to two times per week. The number of available astronaut test subjects, and their ability to repeat the experiment, was subjective to the NBL training schedule. As such, the sample size was not dictated by an a priori power analysis; this was a pilot, exploratory study. A future study design is enabled by the data collected in this pilot study. Longer-term observations with repeated testing on a larger sample size may elicit different results and reduce the large within- and between-subject variability.

The observed metrics may not have been sensitive enough to sustenance deprivation, which could explain why the data did not support the expected results. Other domains and higher fidelity data collection methods should be considered to determine whether a significant performance impact stills presents in some state.

Future studies should include a placebo for comparison, with respect to the test subject feedback. Additionally, different nutritional compositions of in-suit sustenance may alter performance in the EVA environment.

CHAPTER VII

CONCLUSION

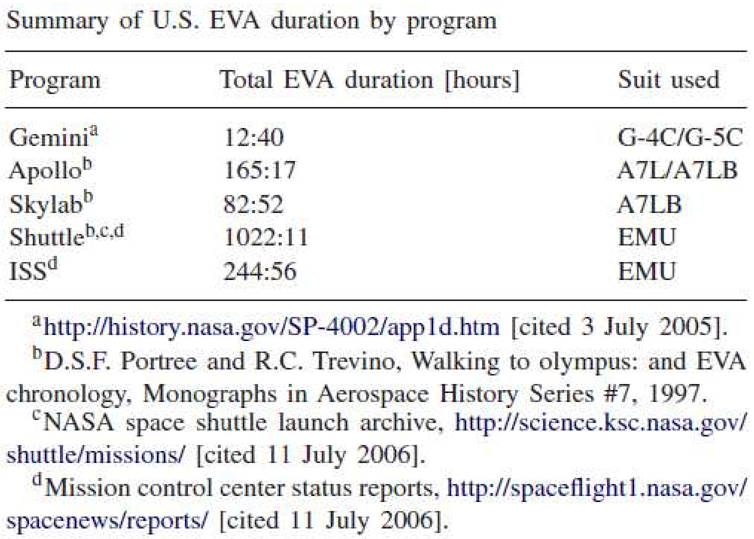
In conclusion, astronauts were not significantly impacted in the domains measured in this study due to acute sustenance deprivation and those who were given the protein supplement throughout their training demonstrated only minor performance improvement. Further research is necessary to determine whether there is still an impact to astronaut performance due to sustenance deprivation during EVA. There remains substantial support from NASA's astronaut corps for some type of in-suit sustenance option, which is required per NASA Space Flight Human-System Standards. Considerations for this human factor should be given for future spacesuit designs and EVA protocols to mitigate risk to the crewmember and enhance the spacewalking experience by improving morale and productivity.

APPENDICES

Appendix A: Acronyms

Basal Metabolic Rate	BMR
Carbon Dioxide	CO_2
Central Intelligence Agency	CIA
David Clark Company	DCC
Decompression Sickness	DCS
Disposable In-Suit Drink Bag	DIDB
Extravehicular Mobility Unit	EMU
Intermittent Fasting	IF
International Latex Corporation	ILC
National Advisory Committee for Aeronautics	NACA
National Aeronautics and Space Administration	NASA
Neutral Buoyancy Lab	NBL
Nitrogen	N_2
Oxygen	O_2
Primary Life Support System	PLSS
Request For Proposal	RFP
Standard Deviation	SD
Union of Soviet Socialist Republics	USSR
United States	U.S.
United States Air Force	USAF
Working Metabolic Rate	WMR

Appendix B: U.S. Spacewalks



Summary of U.S. EVA duration by program

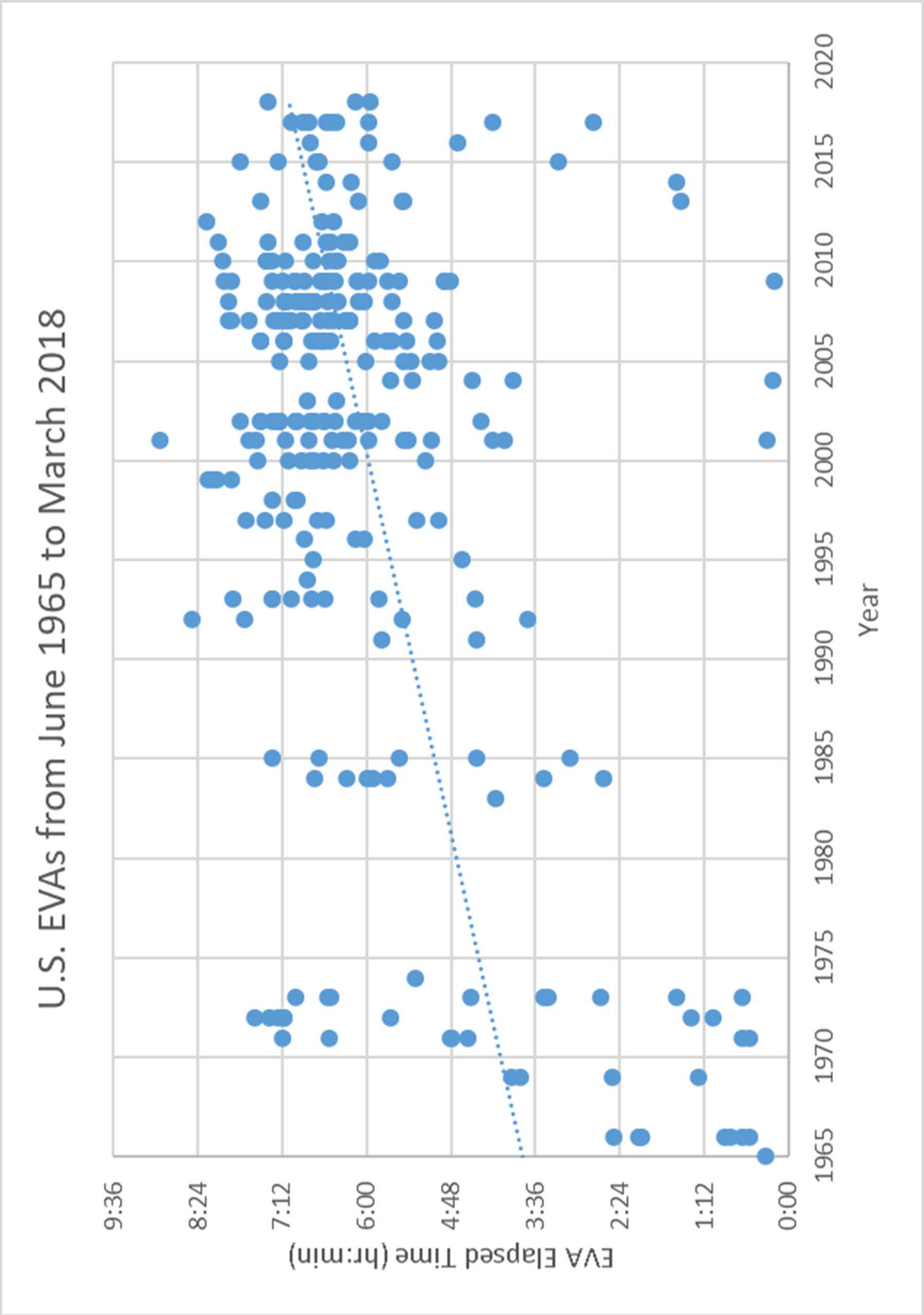
Program	Total EVA duration [hours]	Suit used
Gemini[a]	12:40	G-4C/G-5C
Apollo[b]	165:17	A7L/A7LB
Skylab[b]	82:52	A7LB
Shuttle[b,c,d]	1022:11	EMU
ISS[d]	244:56	EMU

[a] http://history.nasa.gov/SP-4002/app1d.htm [cited 3 July 2005].

[b] D.S.F. Portree and R.C. Trevino, Walking to olympus: and EVA chronology, Monographs in Aerospace History Series #7, 1997.

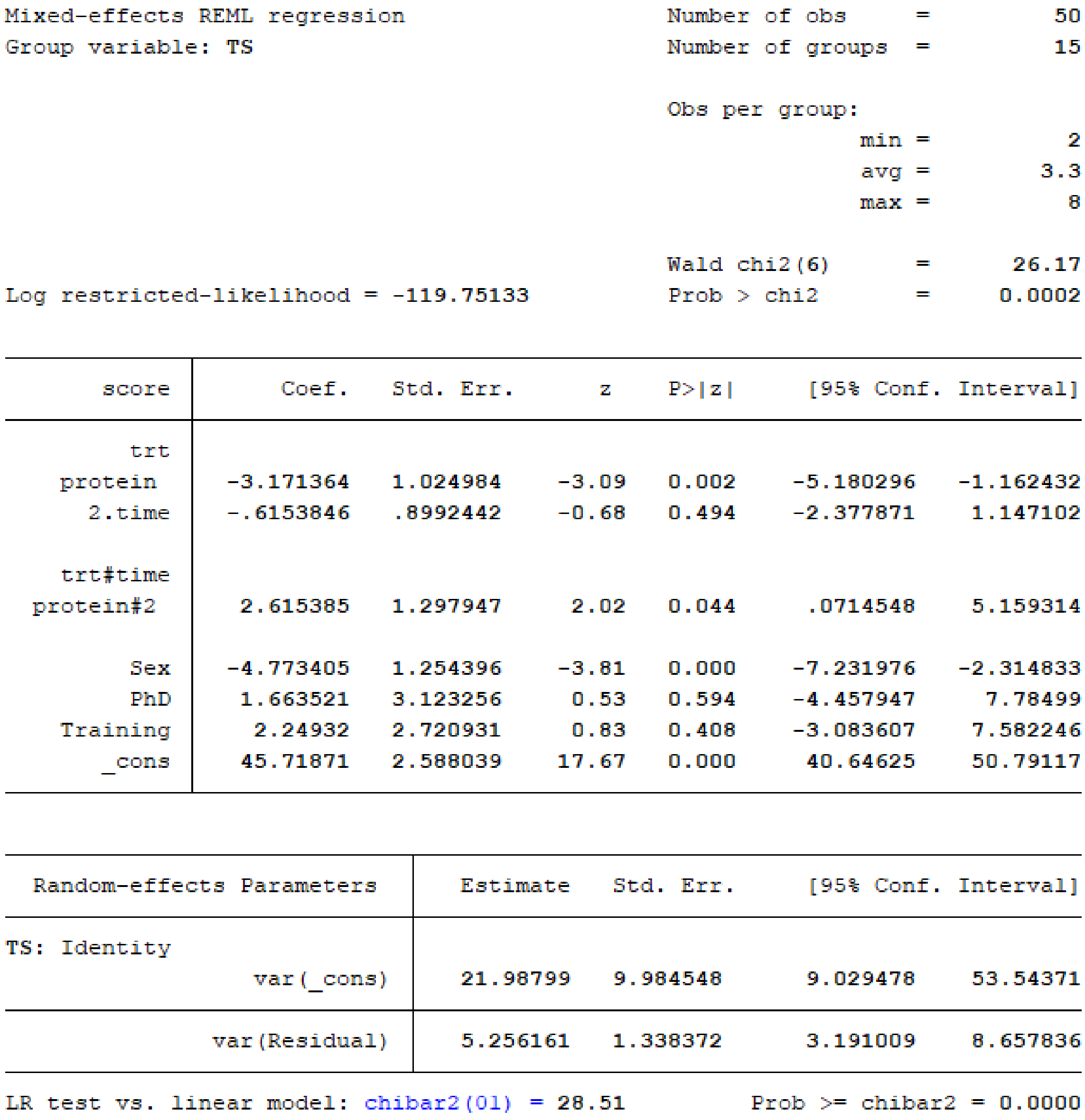
[c] NASA space shuttle launch archive, http://science.ksc.nasa.gov/shuttle/missions/ [cited 11 July 2006].

[d] Mission control center status reports, http://spaceflight1.nasa.gov/spacenews/reports/ [cited 11 July 2006].


U.S. EVAs from June 1965 to March 2018
EVA Elapsed Time (hr:min)
0:00
1:12
2:24
3:36
4:48
6:00
7:12
8:24
9:36
Year
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020

Appendix C: Data Analysis

Table 7. Working Memory List Sorting Repeated Measures Mixed Effects Linear Regression Model



```
Mixed-effects REML regression                   Number of obs     =         50
Group variable: TS                              Number of groups  =         15

                                                Obs per group:
                                                              min =          2
                                                              avg =        3.3
                                                              max =          8

                                                Wald chi2(6)      =      26.17
Log restricted-likelihood = -119.75133          Prob > chi2       =     0.0002

------------------------------------------------------------------------------
       score |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
         trt |
     protein |  -3.171364   1.024984    -3.09   0.002    -5.180296   -1.162432
      2.time |  -.6153846   .8992442    -0.68   0.494    -2.377871    1.147102
             |
    trt#time |
   protein#2 |   2.615385   1.297947     2.02   0.044     .0714548    5.159314
             |
         Sex |  -4.773405   1.254396    -3.81   0.000    -7.231976   -2.314833
         PhD |   1.663521   3.123256     0.53   0.594    -4.457947     7.78499
    Training |    2.24932   2.720931     0.83   0.408    -3.083607    7.582246
       _cons |   45.71871   2.588039    17.67   0.000     40.64625    50.79117
------------------------------------------------------------------------------

------------------------------------------------------------------------------
  Random-effects Parameters  |   Estimate   Std. Err.     [95% Conf. Interval]
-----------------------------+------------------------------------------------
TS: Identity                 |
                  var(_cons) |   21.98799   9.984548      9.029478    53.54371
-----------------------------+------------------------------------------------
               var(Residual) |   5.256161   1.338372      3.191009    8.657836
------------------------------------------------------------------------------
LR test vs. linear model: chibar2(01) = 28.51         Prob >= chibar2 = 0.0000
```

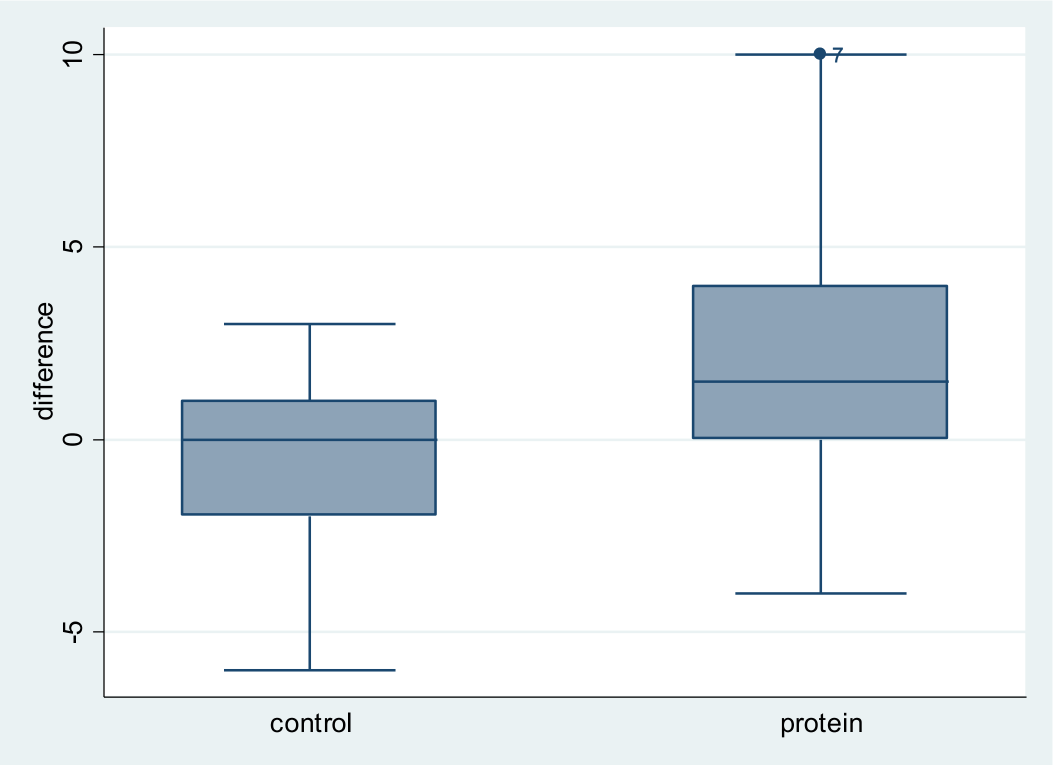
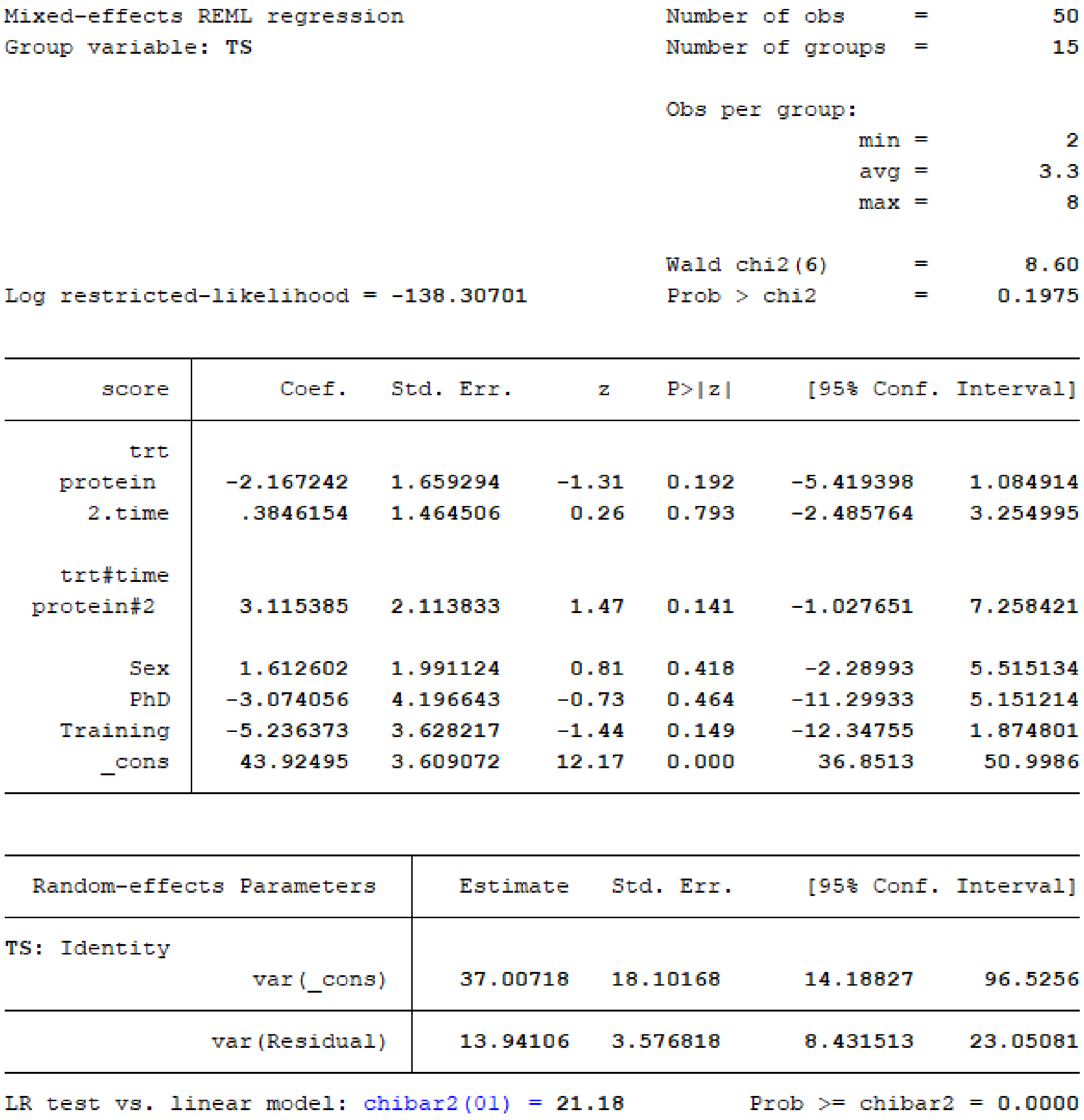


Figure 25. List Sorting outliers.

Table 8. Processing Speed Pattern Comparison Repeated Measures Mixed Effects Linear Regression Model



```
Mixed-effects REML regression                   Number of obs     =         50
Group variable: TS                              Number of groups  =         15

                                                Obs per group:
                                                              min =          2
                                                              avg =        3.3
                                                              max =          8

                                                Wald chi2(6)      =       8.60
Log restricted-likelihood = -138.30701          Prob > chi2       =     0.1975

-------------------------------------------------------------------------------
       score |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+-----------------------------------------------------------------
         trt |
     protein |  -2.167242   1.659294    -1.31   0.192    -5.419398    1.084914
      2.time |   .3846154   1.464506     0.26   0.793    -2.485764    3.254995
             |
    trt#time |
   protein#2 |   3.115385   2.113833     1.47   0.141    -1.027651    7.258421
             |
         Sex |   1.612602   1.991124     0.81   0.418     -2.28993    5.515134
         PhD |  -3.074056   4.196643    -0.73   0.464    -11.29933    5.151214
    Training |  -5.236373   3.628217    -1.44   0.149    -12.34755    1.874801
       _cons |   43.92495   3.609072    12.17   0.000      36.8513    50.9986
-------------------------------------------------------------------------------

-------------------------------------------------------------------------------
  Random-effects Parameters  |   Estimate   Std. Err.     [95% Conf. Interval]
-----------------------------+-------------------------------------------------
TS: Identity                 |
                  var(_cons) |   37.00718   18.10168      14.18827     96.5256
-----------------------------+-------------------------------------------------
               var(Residual) |   13.94106   3.576818      8.431513    23.05081
-------------------------------------------------------------------------------
LR test vs. linear model: chibar2(01) = 21.18         Prob >= chibar2 = 0.0000
```

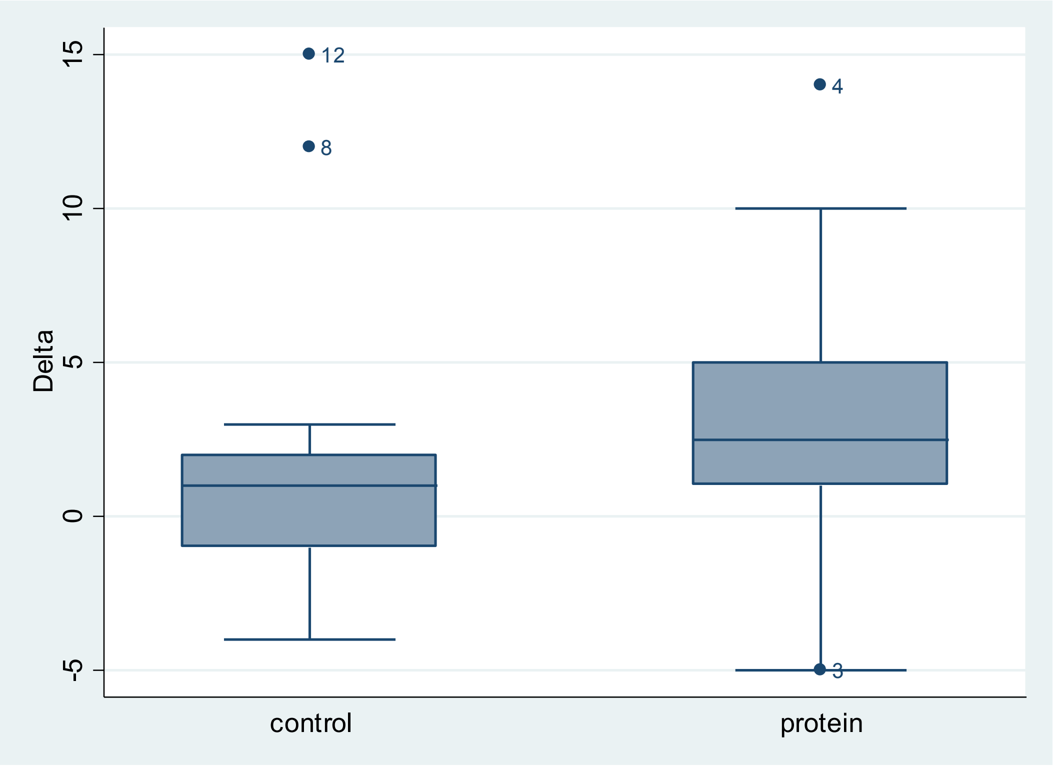
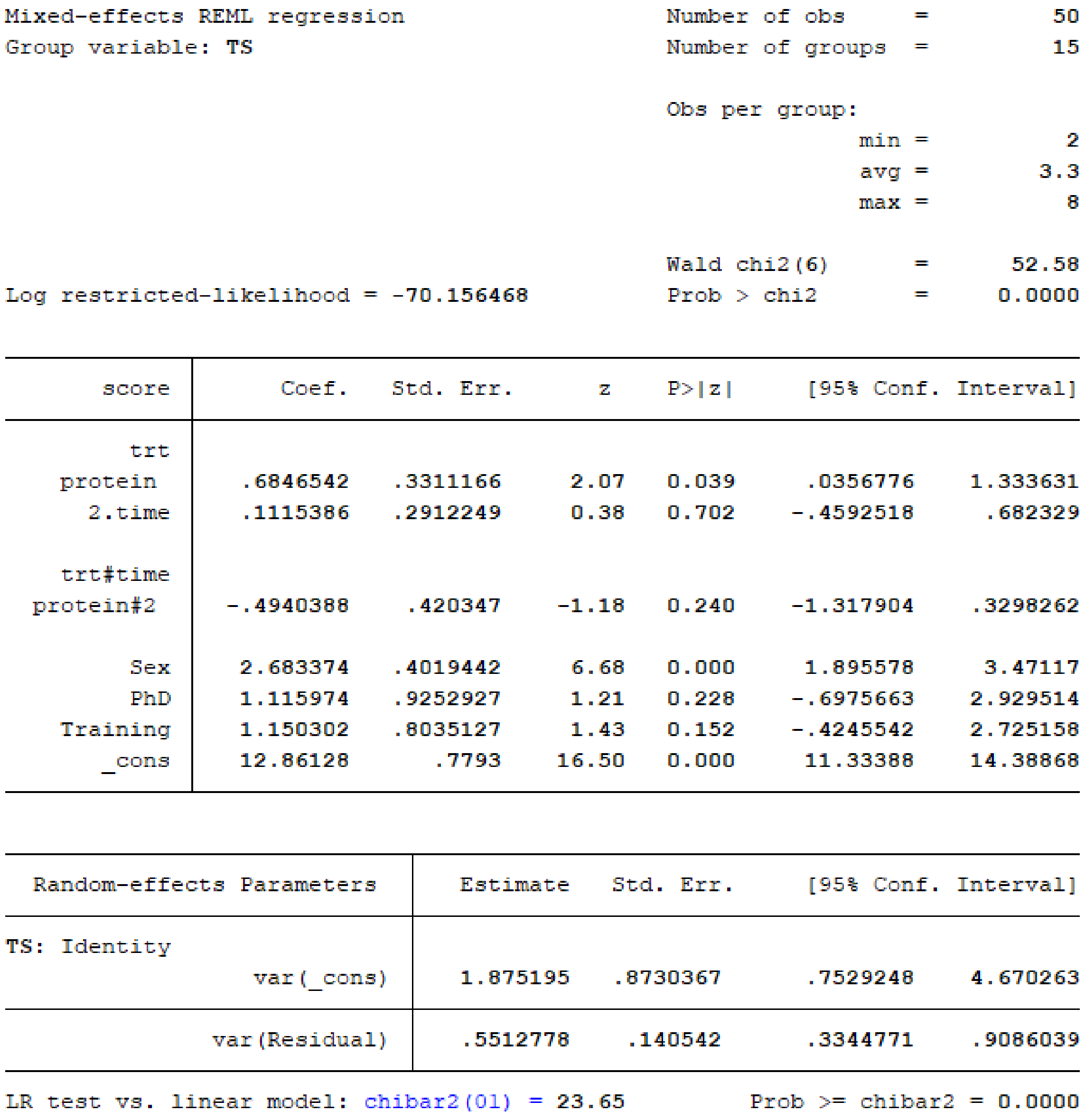


Figure 26. Pattern Comparison outliers.

Table 9. Dexterity 9-Hole Peg Board Repeated Measures Mixed Effects Linear Regression Model



```
Mixed-effects REML regression                   Number of obs     =         50
Group variable: TS                              Number of groups  =         15

                                                Obs per group:
                                                              min =          2
                                                              avg =        3.3
                                                              max =          8

                                                Wald chi2(6)      =      52.58
Log restricted-likelihood = -70.156468          Prob > chi2       =     0.0000

------------------------------------------------------------------------------
       score |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
         trt |
     protein |   .6846542   .3311166     2.07   0.039      .0356776    1.333631
      2.time |   .1115386   .2912249     0.38   0.702     -.4592518     .682329
             |
    trt#time |
   protein#2 |  -.4940388    .420347    -1.18   0.240     -1.317904    .3298262
             |
         Sex |   2.683374   .4019442     6.68   0.000      1.895578     3.47117
         PhD |   1.115974   .9252927     1.21   0.228     -.6975663    2.929514
    Training |   1.150302   .8035127     1.43   0.152     -.4245542    2.725158
       _cons |   12.86128      .7793    16.50   0.000      11.33388    14.38868
------------------------------------------------------------------------------

------------------------------------------------------------------------------
  Random-effects Parameters  |   Estimate   Std. Err.     [95% Conf. Interval]
-----------------------------+------------------------------------------------
TS: Identity                 |
                  var(_cons) |   1.875195   .8730367      .7529248    4.670263
-----------------------------+------------------------------------------------
               var(Residual) |   .5512778    .140542      .3344771    .9086039
------------------------------------------------------------------------------
LR test vs. linear model: chibar2(01) = 23.65         Prob >= chibar2 = 0.0000
```

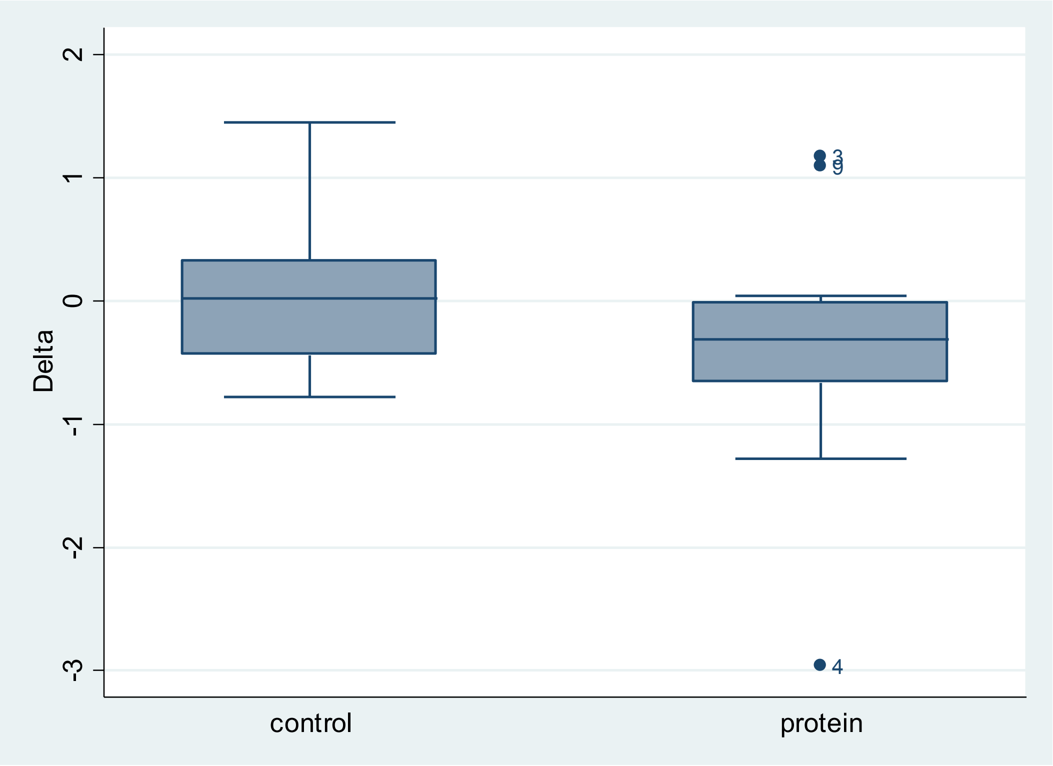
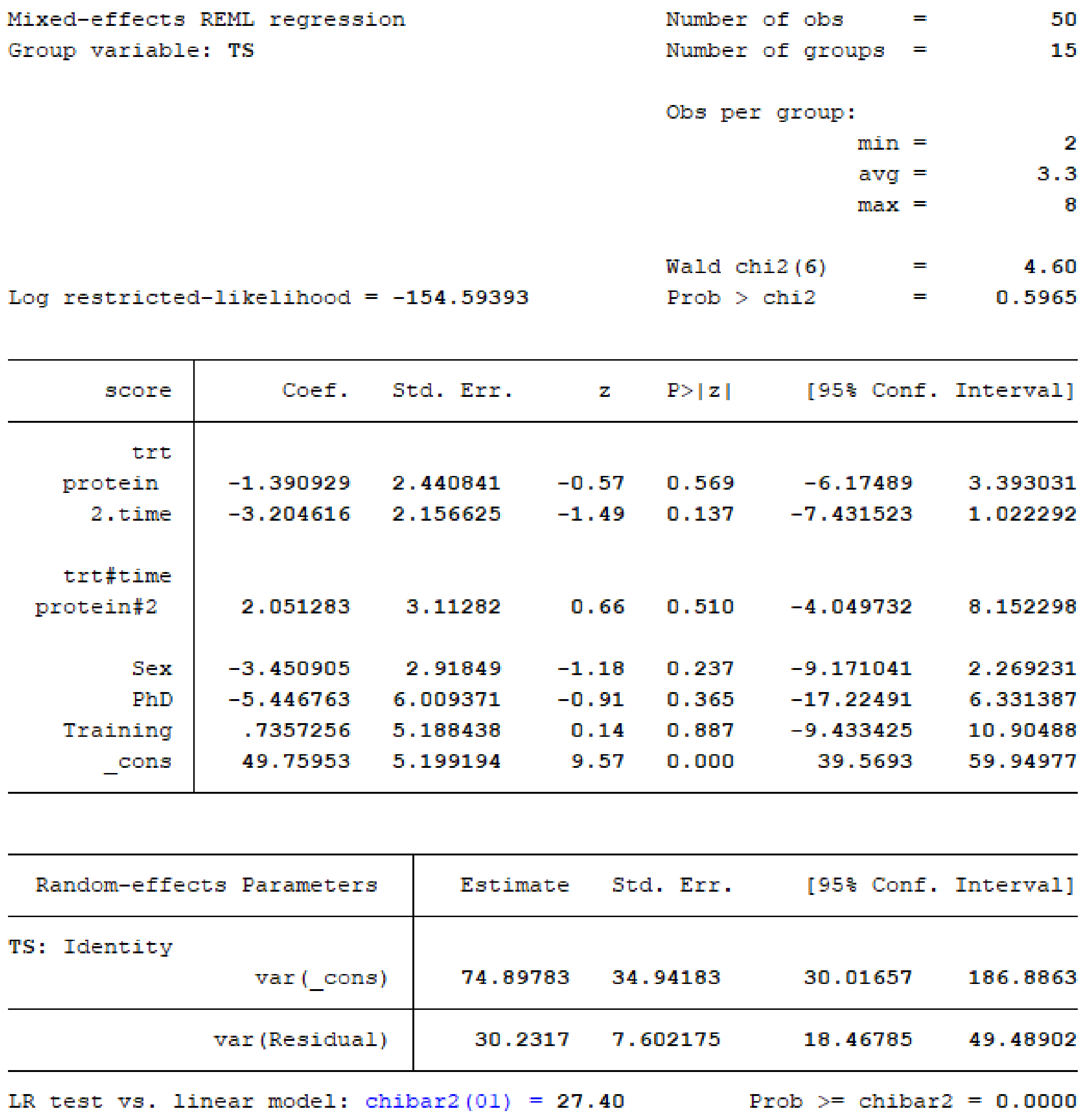


Figure 27. 9-Hole Peg Board outliers.

Table 10. Grip Strength Hand Grip Repeated Measures Mixed Effects Linear Regression Model



```
Mixed-effects REML regression                   Number of obs     =         50
Group variable: TS                              Number of groups  =         15

                                                Obs per group:
                                                              min =          2
                                                              avg =        3.3
                                                              max =          8

                                                Wald chi2(6)      =       4.60
Log restricted-likelihood = -154.59393          Prob > chi2       =     0.5965

------------------------------------------------------------------------------
       score |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
         trt |
    protein  |  -1.390929   2.440841    -0.57   0.569     -6.17489    3.393031
      2.time |  -3.204616   2.156625    -1.49   0.137    -7.431523    1.022292
             |
    trt#time |
  protein#2  |   2.051283    3.11282     0.66   0.510    -4.049732    8.152298
             |
         Sex |  -3.450905    2.91849    -1.18   0.237    -9.171041    2.269231
         PhD |  -5.446763   6.009371    -0.91   0.365    -17.22491    6.331387
    Training |   .7357256   5.188438     0.14   0.887    -9.433425    10.90488
       _cons |   49.75953   5.199194     9.57   0.000      39.5693    59.94977
------------------------------------------------------------------------------

------------------------------------------------------------------------------
  Random-effects Parameters  |   Estimate   Std. Err.     [95% Conf. Interval]
-----------------------------+------------------------------------------------
TS: Identity                 |
                  var(_cons) |   74.89783   34.94183      30.01657    186.8863
-----------------------------+------------------------------------------------
               var(Residual) |    30.2317   7.602175      18.46785    49.48902
------------------------------------------------------------------------------
LR test vs. linear model: chibar2(01) = 27.40         Prob >= chibar2 = 0.0000
```

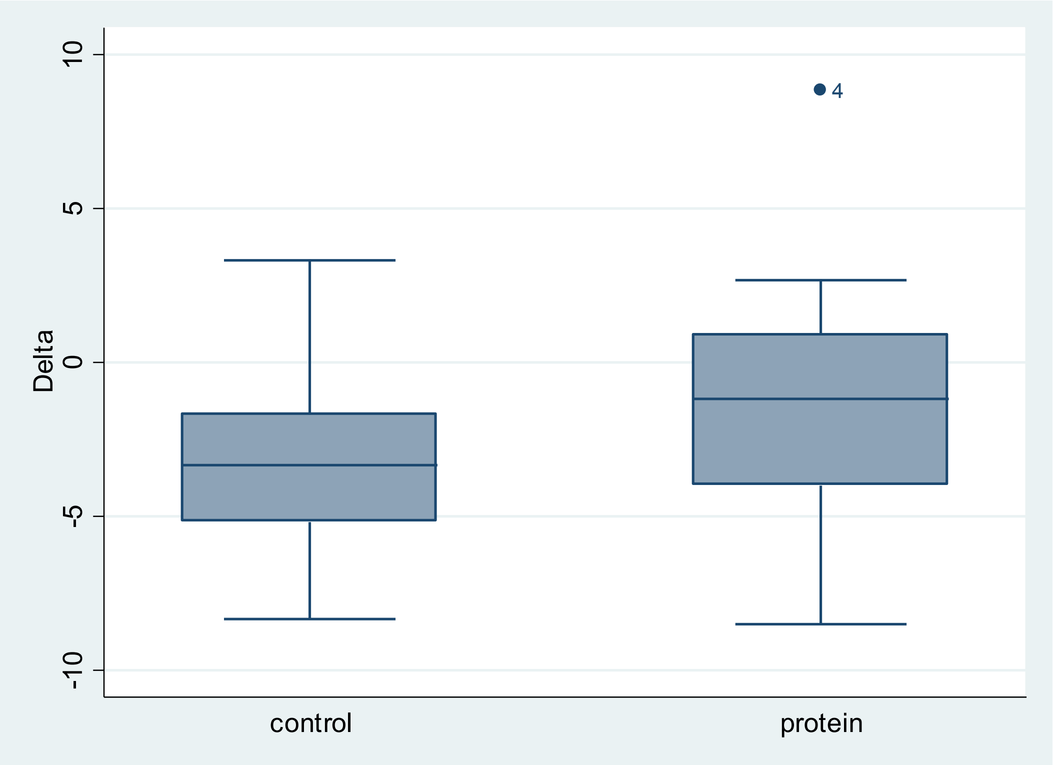


Figure 28. Dynamometer outliers.

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