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EFFECTS OF FRACTIONAL GRAVITY ON HUMAN GAIT

by

Elizabeth Nicole Smith

Bachelor of Science in Kinesiology, University of North Dakota, 2018

A Thesis
Submitted to the Graduate Faculty

of the

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for the degree of

Master of Science

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Title	Effects of Fractional Gravity on Human Gait
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Chris Nelson
Dean of the School of Graduate Studies

4/29/2022

Date

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Abstract

Only twelve humans have stepped on the Moon, and for a mere 80 hours. Further, none of that Lunar exposure has been within the last 50 years. NASA's Artemis Program recently announced that the next manned missions to the Moon will be scheduled for 2024 and 2025. With only a few years to prepare, it is pertinent that training for prospective astronauts reflects current scientific knowledge to ensure safety. In this study, the coordinative gait structures under 1.0g (Earth), as well as simulated 0.38g (Martian) and 0.17g (Lunar) were analyzed to discover critical changes in gait that may occur in these environments. In the current study, participants walked and ran on a treadmill while being supported by ARGOS (Active Response Gravity Offload System) which simulates fractional gravity conditions. The Vicon motion capture system was utilized and coupled with MatLab's PManalyzer to capture and analyze participants' coordinative gait structures. Results show that there are significant changes ($p<0.05$) in the coordinative structures under simulated Lunar and Martian gravity. Changes were found when the speed on the treadmill increased. A skipping component was expressed during Lunar and Martian running trials. Findings suggest that if astronauts are trained how to skip bilaterally under these conditions, learning time would be reduced with fractional gravity ambulation.

Introduction

Artemis 3 launches to the Moon in 2025. Astronauts will be expected to spend a week exploring the moon's surface and performing a variety of scientific activities ("Artemis Program: What you need to know," 2022). Only twelve humans, consisting of a single gender, race, and nationality, have stepped on the Moon at this point in our history. This group's combined duration of stay on the moon represents a mere 80 hours and 32 minutes. Additionally, it has been fifty years since humans have stood on the moon.

According to the Marshall Space Flight Center, it costs around US$10,000 to send a 1-pound mass into Earth orbit ("Advanced Space Transportation Program," 2008). Even something as small as a standard pack of bandages weighing 3.2 ounces may cost around US$2,000. It is costly to send supplies on missions, and it is nearly impossible to return to Earth for supplies. These costs highlight how important it is for astronauts to understand and be prepared for how fractional gravity will affect their health and wellbeing. If an astronaut were injured and required to have reduced duties, the other crew members would have to work harder to complete all operational tasks. Over time, this additional burden could adversely affect their physical performance, health, and wellbeing.

With only a few more years to prepare for Artemis 2 and Artemis 3 - the subsequent human-crewed missions to the Moon - it is essential to look further into concerns such as astronaut health and performance. Artemis 3 plans to launch in the year 2025. There is much information on performance in microgravity since there have been astronauts on the International

Space Station for the past two decades. What seems to be missing is information on bipedal locomotion in fractional gravity. Examining astronauts' gait under different levels of fractional gravity could help identify potential movements that increase injury risk.

Many studies have examined aspects of astronaut health and performance under simulated Lunar or Martian gravity, such as muscle activation (Orr, 2019), biomechanical and cardiopulmonary responses (Richter et al., 2017); and human posture (Mukadam et al., 2017). However, it is still unclear how the segmental coordination of the human gait changes under fractional gravity. Numerous studies have reported changes in gait under different levels of gravity, yet very few have studied the coordinative structures that change the motion. In this unique study, a principal component analysis (PCA) was conducted on the captured motions of participants walking and running under simulated Earth, Martian, and Lunar gravity. This study aims to analyze the changes in gait coordinative structures under fractional gravity.

This thesis will review the literature on essential tools for gait analysis, such as Vicon Motion capture, the Active Response Gravity Offload System (ARGOS), and PCA for the deconstruction of movements. These tools collectively assist in analyzing gait and locomotion. These methods will allow for a constant comparison between participants’ movements within this thesis. The results will show the coordinative structures that change a participant's gait under different levels of fractional gravity and will enhance the current understanding of space exploration's impact on human gait.

Literature Review

Human gait has evolved over the past three million years on Earth within terrestrial gravity constraints (Sylos-Labini et al., 2014). Due to this, gait analysis is typically studied under terrestrial gravity (-9.807 m/s^2) (Williams, 2016). The ability to ambulate defines living organisms in their daily life activities, work habits, and ability to survive. Thus, gait is a primary concern in all aspects of human life. However, astronauts will continually be exposed to varying gravitational constants. It is challenging to assess how subjecting an organism to environmental conditions under which it has not evolved will affect various bodily systems. Therefore, studying the phenomenon of human gait within different gravitational constants has only been done within the limited amount of time that astronauts have physically spent on the Moon and within our various simulations of non-terrestrial gravity.

Several studies such as Rader et al. (2007), and de Winkel et al. (2012), have examined human gait and kinematics under lunar gravity; however, technological limitations of the time hindered thorough examination of gait in this environment. Shifts in space policy and new commercial ventures have spurred the announcement of the Artemis program, NASA's multi-phase path from the Moon to Mars (Orr, 2019). It is pertinent to reconnect with the lessons learned from Apollo and how training needs to be updated to reflect the current scientific knowledge.

Simulation

Only twelve people have ever stepped on the Moon. Those 80 hours and 32 minutes of lunar exposure are the only direct experience any human has had with locomotion in a non-terrestrial gravitational constant. Neither instrumentation nor protocols were available for adequate assessment of human gait on the Moon at that time. Therefore, simulation is critical for examining non-terrestrial gravity on human gait. Two primary methods of gravitational simulation have been mechanical apparatus and aerial freefall simulation. Aerial freefall, also known as the ‘vomit comet,’ allows prospective astronauts to experience various gravitational constants through parabolic flight patterns, enabling varied freefall and simulated gravitational constants (Dempsey et al., 2007). The major drawback of areal freefall is that simulated gravity is only possible for 30 seconds or less and is very expensive.

Mechanical apparatus for gravity simulation includes NASA's ARGOS, which is a steel frame that is 12.5 m x 7.3 m x 7.6 m tall with electric motors that are computer-driven, and in-line sensors to accurately simulate any gravitational constant that is less massive than the Earth (Cowley et al., 2014).

Figure 1 *ARGOS Johnson's Space Center (Chambers, 2013).*

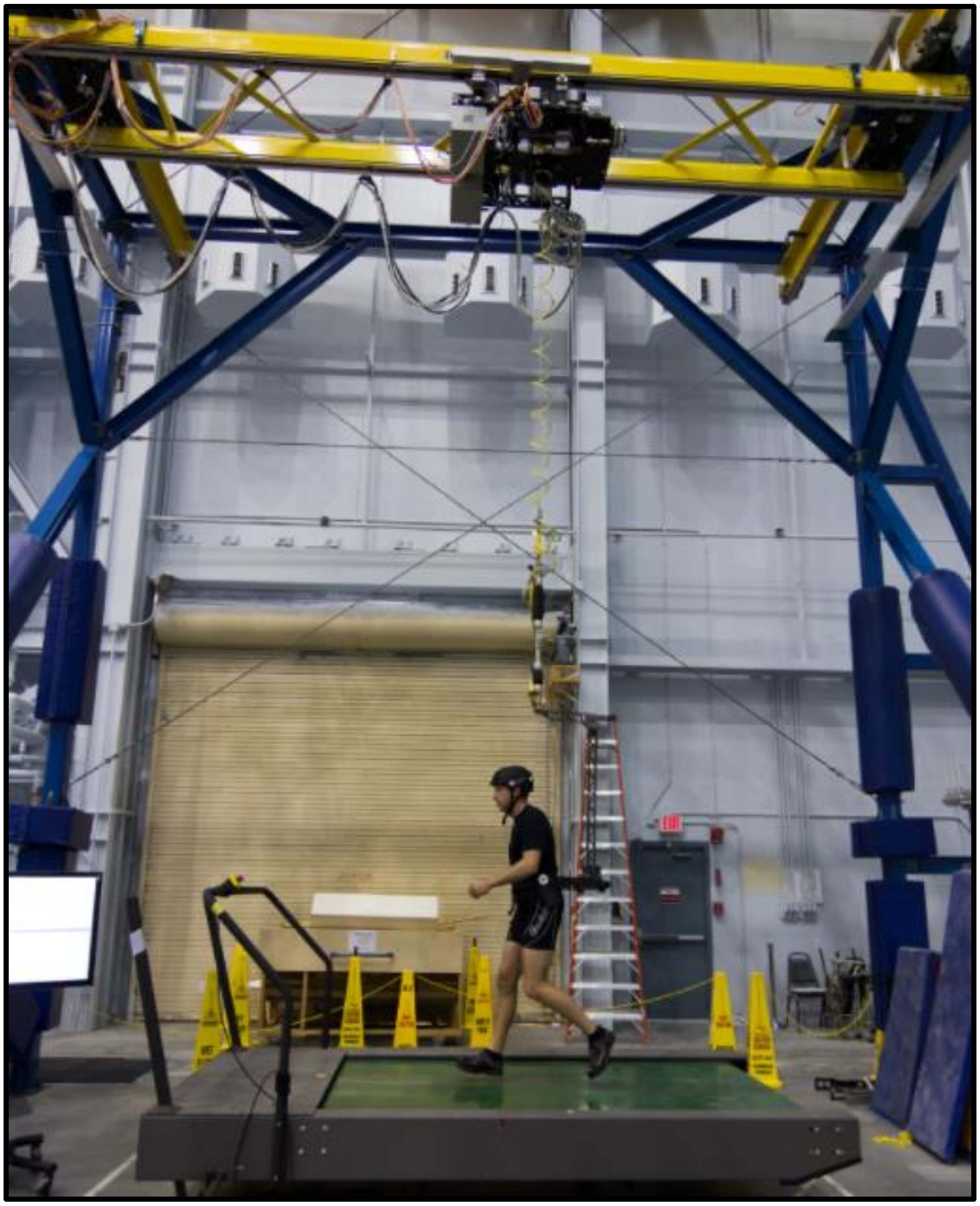


Figure 1 shows the ARGOS when fully assembled at the Johnson Space Center.

ARGOS provides the ability to simulate the gravity effect of planets, moons, comets, asteroids, and microgravity (Valle et al., 2011). Unlike aerial freefall, simulated time is nearly limitless, allowing long-duration gait analysis. Typically, ARGOS is utilized for training purposes, and not much research has been done on this device. The fact that there has not been much research using ARGOS makes this study on gait coordinative structures even more unique.

A study conducted at the Johnson Space Center in Houston, Texas, in 2014, looked to help NASA design new spacesuits capable of working in deep space and on Mars (Cowley et al., 2014). They utilized ARGOS to simulate reduced gravity conditions, and all data were collected using an optical motion capture camera system known as Vicon NEXUS. Gait analysis of the participants showed differences in joint kinematics and temporal-spatial parameters between fractional and terrestrial gravity. The analysis also showed a change in ambulation in an offloaded environment. The ambulation modification indicated that the relative kinetic energy of the subject was increased per unit of static body weight compared to the terrestrial gravity (Cowley et al., 2014). With ARGOS giving us the ability to simulate fractional gravity, it is also essential to have a tool that will simultaneously capture motion of the participants. For these reasons, the Vicon NEXUS software and motion capture system were utilized for this study.

Vicon NEXUS

Vicon is an apparatus that captures the motion of objects and people through infrared optical tracking. It was the first commercially developed motion capture system established in the mid-1980s. Since then, it has innovated immensely. Vicon NEXUS software has been used in life sciences, biomechanics, sports science, object tracking, and entertainment. According to Vicon’s official website, Vicon's software and systems have won an Academy Award for developing accessible motion capture technology that delivers the most reliable data in any movement analysis application. The movement of both live and inanimate objects can be captured and analyzed for various motion capture applications. Optical, digital, and analog capture are all contained in a single, easy-to-use platform that gives users an advantage in their gait analysis and rehabilitation; biomechanical research; posture, balance, and motor control; sports performance; and animal science (Vicon Motion Systems Ltd., 2017).

Plug-in Gait is the Vicon implementation of the Conventional Gait Model (CGM) widely used in the gait analysis community (Vicon Motion Systems Ltd., 2017). Plug-in Gait has been validated through criterion testing with representative anthropomorphic models. This software enables users to produce gait analysis reports that conform to established clinical practices.

Vicon uses non-wearable sensors (NWS) and wearable sensors (WS) that can study human gait. NWS uses image processing and floor sensors (i.e., force plates), while WS uses sensors placed on several body parts. The placement of these sensors can be predetermined. Different sensors capture the various signals that characterize the human gait. These include accelerometers, gyroscopic sensors, magnetometers, force sensors, extensometers, goniometers, active markers, electromyography, etc. (Muro-de-la-Herran, 2014).

A study conducted in Malaysia investigated the Vicon motion capture system and how it compares to the traditional anthropometric method of body measurement (Zainuddin et al., 2017). This information would then be used to expand the national anthropometric database. However, Malaysia is behind in comparison to other countries because they still rely on traditional or direct measurement, which has several factors that can contribute to problems such as accuracy, time, posture, identification of landmarks, instrument position, and pressure due to measuring equipment (Zainuddin et al., 2017). There is no documentation with specific methods such as motion cameras, 3D scanners, or other computer mechanisms used for Malaysian human measurement. It was concluded that the overall results depict that 50 out of 50 measurements chosen for the motion capture camera method (Vicon) had passed a bias, test-retest reliability, and accuracy test. Test-retest reliability of motion capture camera measurement was excellent and comparable to traditional anthropometric measurement. Motion capture cameras were shown to be as precise as conventional anthropometric measurements. Thus, Vicon is the premier motion capture system for analyzing gait.

Human Gait

Human gait depends on the complex interplay of the nervous, musculoskeletal, and cardiorespiratory systems (Walter & Katzenschlager, 2016). The technology supporting human motion analysis has advanced dramatically in the past thirty years. Past decades of locomotion research have provided significant knowledge about the accuracy of tests performed and understanding of human locomotion (Simon, 2004).

Figure 2 Human Gait Phases (Walter & Katzenschlager, 2016).

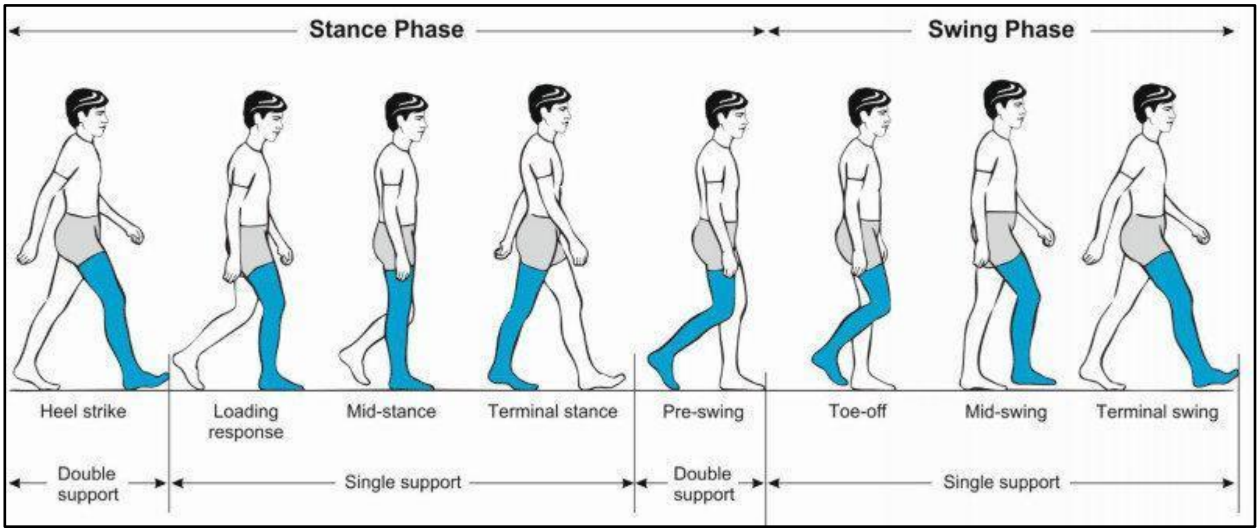


Figure 2 illustrates the complete bipedal human gait cycle. It visually explains how the human gait changes between the stance and the swing phase during walking. During the stance and swing phase, the body has double support from both feet touching the ground (bipedal locomotion) and periods where the body only has single support from one lower extremity (unipedal stance).

Through gait research, six key determinants of gait have been developed. These determinants of gait described by Saunders et al. (1953) are pelvic rotation, pelvic tilt, knee, and hip flexion, knee and ankle interaction, and lateral pelvic displacement. Locomotion translates the center of gravity through space along a pathway requiring the least energy to be expended. It shows the unifying principle, which permits the qualitative analysis of gait into the essential determinants. If someone were to lose the ability of one of these determinants, compensation would be adequate. If they were to lose the ability of two or more determinants, fair compensation would be impossible.

The six critical determinants of gait are essential, but they only look at specific movements and are typically used during specific gait analysis. It is essential to understand that gait is a highly dynamic series of movements. Gait can be difficult even under terrestrial gravity, so it is difficult to predict what variables are crucial when adding gravitational constants to a variable. Traditional gait analysis prescribes essential variables to examine, such as the six determinants. While this deductive analysis makes sense on Earth, it is very limiting when gravity becomes a variable. A more inductive approach will allow for the capturing of emergent coordinative structures. Therefore, this study aims to analyze the coordinative structures of gait under different levels of fractional gravity using a principal component analysis. PCA is more inductive and descriptive than typical gait analysis and gives us more details about a person's gait changes.

Coordinative Structures

Gait analysis is typically a deductive process that aims to test an existing theory. The present study on gait coordinative structures requires an inductive analysis to look deeper into gait and to examine how its coordinative structures work together. Human locomotion is highly complex, so it is easy to understand that transitioning from one level of gravity to the next will significantly impact how the body adapts. Principal component analysis is a mathematical method that can decompose a complex movement pattern into its main components (Federolf et al., 2012).

Human movement is too difficult to describe in simple terms, so a principal component analysis allows movements to be broken down into discrete components that can be examined separately. Human upright posture is maintained by postural movements, which can be quantified by "principal movements" (PMs) obtained through a principal component analysis of kinematic marker data (Federolf et al., 2016). The deconstruction of the whole movement into principal movements through a PCA assists in the determination of the extent of change. In the current study, PCA will help compare the coordinative structures under various fractional gravity levels and allow for an inductive analysis that can help us identify the most critical variables for human gait under fractional gravity conditions.

Principal Component Analysis

A principal component analysis aims to extract the vital information and represent this information as a new set of orthogonal variables or principal components and display similar observations and variables as data points. A study was done with 29 subjects on the analysis of postural movement strategies quantified by a principal component decomposition that employed a normalization technique that allowed combining the posture vectors of different subjects to calculate universal principal movements (PMs) (Federolf et al., 2013). The movement vectors need to be normalized and then centered, which allows all posture vectors for the subjects to be assembled into one input matrix for the PCA. This then yields orthogonal eigenvectors that indicate the direction of the most significant variance of the posture vectors. Principal component analysis has been utilized in many biological, physical, and engineering fields. PCA can quantify techniques in sports, classify gait, analyze movement patterns using full-body kinematics, analyze posture and posture control, and assist in creating athletic attire and equipment (Federolf et al., 2012).

Principal component analysis is one of the newer methods to analyze human movement. In the past, there have been other tools utilized within the realm of kinesiology to describe human movement qualitatively. For example, the usage of wearable sensors is an inexpensive and efficient way to analyze and provide helpful information about human gait. The gait analysis method based on wearable sensors is divided into gait kinematics, gait kinetics, and electromyography (Tao, 2012). Kinematic measurement collects gait data using various sensors. Based on these collected gait data, a kinematic analysis can be performed to recognize the gait phases and obtain the general gait parameters and movement information on each body segment. As a basis of gait kinematics, kinematic measurement is an essential principle that can significantly affect the selection of the kinematic analysis method (Tao, 2012).

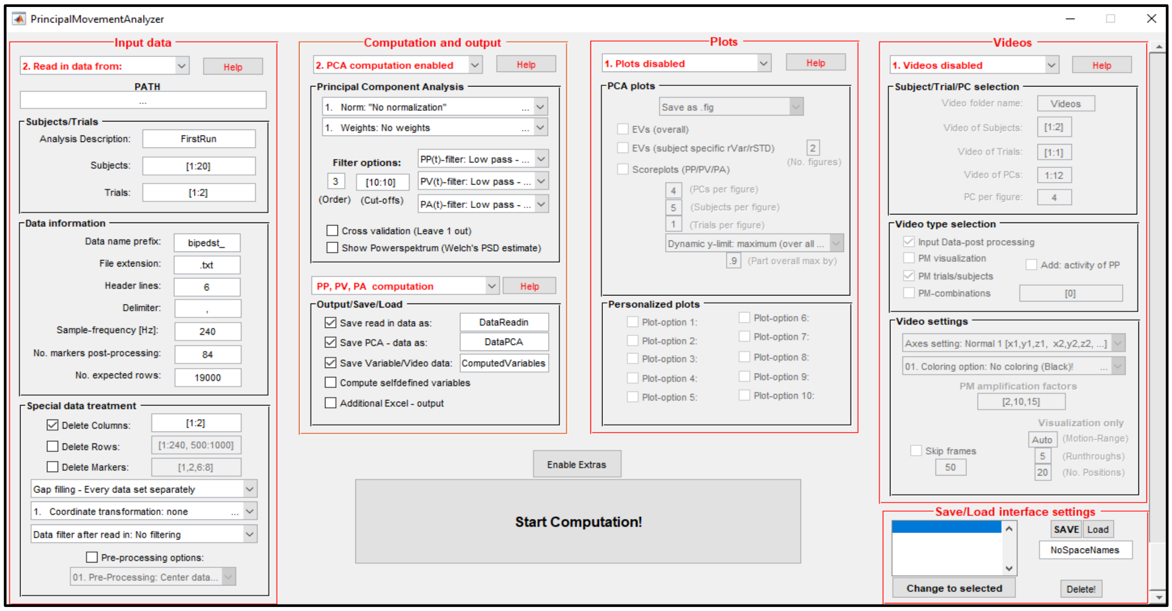
To address the validity and reliability of the principal component analysis, a study was conducted on leg dominance effects on postural control while balancing applied PCA to assess bilateral asymmetry on the coordinative structure or the control characteristics of specific movement components (Promsri et al., 2020). This study used leave-one-out cross-validation to evaluate the vulnerability of the PM. This process is closely related to the statistical method of jack-knife estimation (Efron, 1982).

PManalyzer

Biomechanics' principal components analysis has advanced the field in new and exciting ways. Specifically, by processing kinematic data through a principal component framework, complex movements can be broken down into their essential elements or coordinative structures. PCA essentially allows for the isolation of individual coordinative structures, which may not be noticeable to a person simply watching a movement. Further, PCA allows researchers to determine rank-identified coordinative structures based on their overall explained movement variance. This has two key advantages. First, identifying dominant coordinative structures allows for a better description of movements and provides coaches or trainers to identify critical elements of training. Second, this ranking system filters out components representing such a small percentage of the explained variance. In many cases, they can be discarded in explaining the movement. For instance, an identified component that only represents .02% of the variance cannot significantly contribute to the completion of the movement task and thus can be excluded from the explanation of movement components.

An issue with kinematic PCA is the technical aspect of conducting the process. Conducting a PCA on kinematic data is highly technical, involving several vital steps. However, PCA only provides a numeric representation of the coordinative structures. Further processing is required to produce a visual representation of the coordinative structures. Even some specialists within the field may not possess the necessary skills to conduct this analysis. To address these critical issues, a group of researchers at the University of Innsbruck developed a program called PManalyzer which runs within the MatLab framework. Figure 3 illustrates the graphical user interface for this application.

Figure 3 *PManalyzer Interface.*



This program allows for the automated computation of principal kinematic components, derivatives of principal components, and a video representation of these principal components.

Figure 4 *Video Output for Five High-Order Coordinative Structures.*

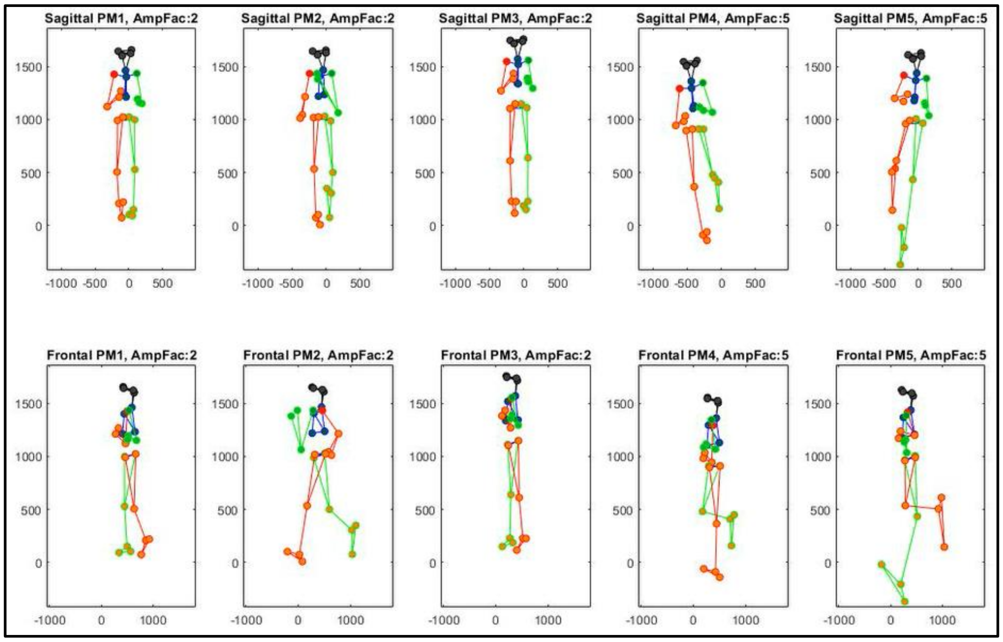
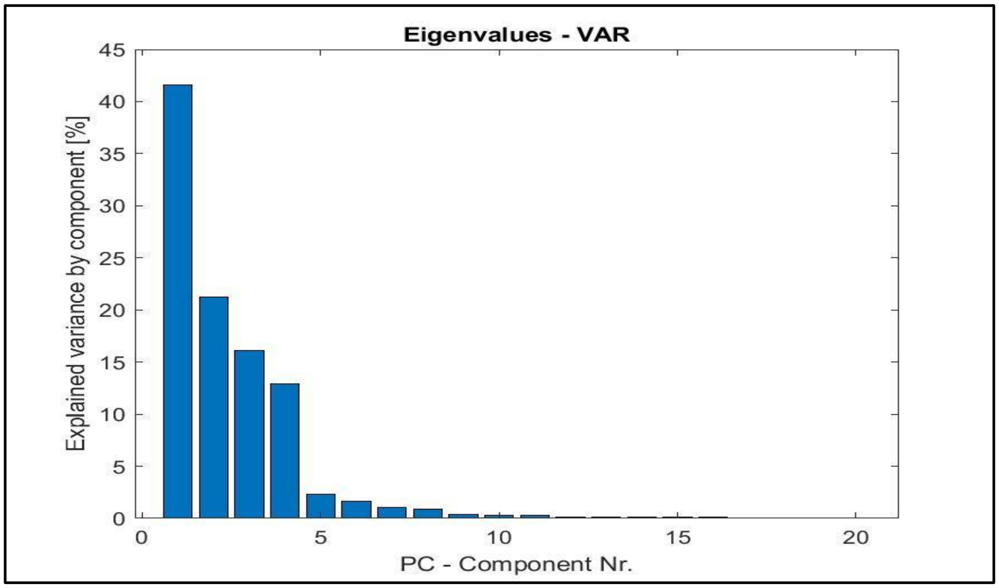


Figure 4 illustrates a video output for five high-order principal components/principal movements/coordinative structures.

Figure 5 *Quantitative Assessment of Coordinative Structures.*



Finally, Figure 5 illustrates the quantitative assessment of these principal components/ movements/coordinative structures. Essentially, these show how dominant each of these components is in the observed movement.

Methods

Data Collection

This exploratory study was derived from previous research conducted by Sophie Orr and colleagues from the John D. Odegard School of Aerospace Sciences at the University of North Dakota (Orr, 2019). They used motion capture data and electromyography to explore muscle activation and ankle joint angles during walking, running, and skipping under fractional gravity. These motion conditions were collected at a range of speeds in 1g (Earth gravity) and simulated reduced gravity conditions equal to Mars and the Moon. The simulated gravitational conditions were made possible through the ARGOS at NASA's Johnson Space Center in Houston, Texas.

Sample

The sample size (n) for this study is six adult participants (n = 3 women, n = 3 men). Three of the participants were civilians, and three were candidate astronauts. This sample size is consistent with other NASA studies (e.g., Abercromby et al., 2006; Jaramillo et al., 2008).

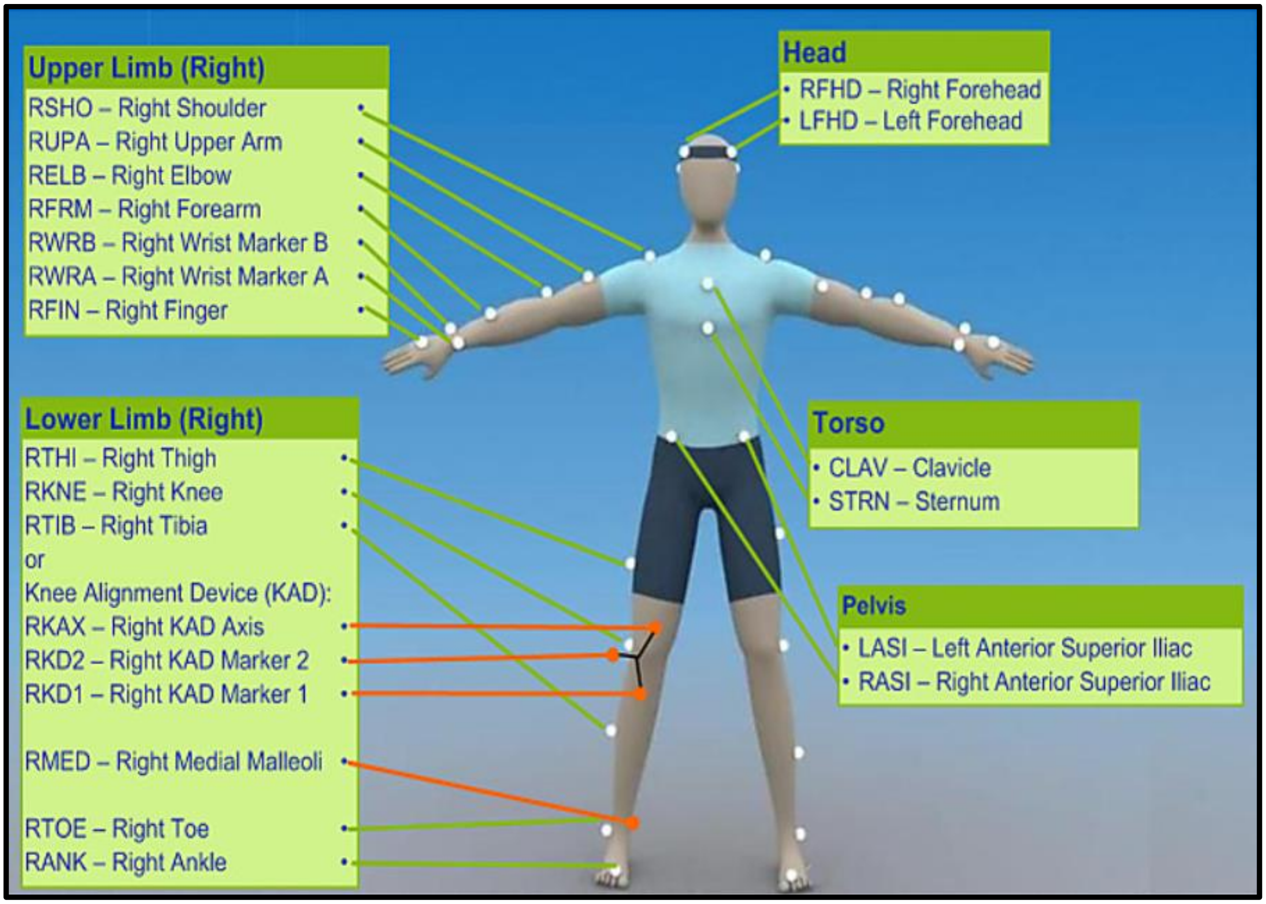
Participants

Participants were selected by convenience based on their ability to perform the required physical tasks with minimal risk. To minimize potential health risks, NASA's Institutional Review Board recommended that participants: a) have a BMI between 19 and 30 kg/m^2, b) be non-smokers, c) have no history of lower back pain, d) have no history of Achilles tendinopathy, and e) be able to complete the physical tasks as described in the consent form. Additionally, The Institutional Review Board of the University of North Dakota approved this study (IRB-201710-080).

Procedures

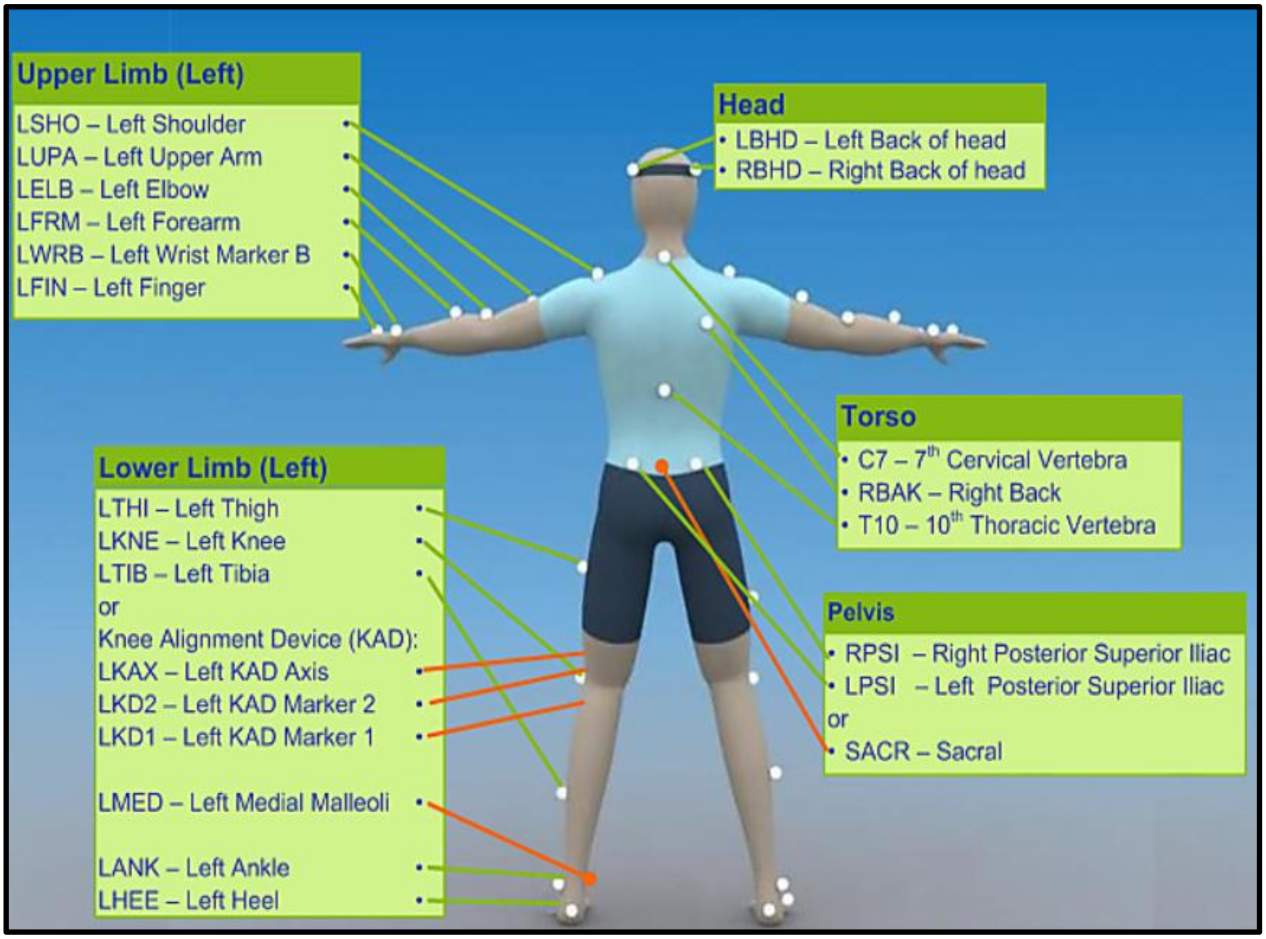
Participants walked, ran, and skipped on a treadmill at one mph (1.6 km/h) increments from two to six mph (3.2 to 9.6 km/h). The tests were repeated for the simulated gravity levels of Lunar and Martian gravity by connecting the participants to the ARGOS via a gimbal system. The duration of testing was one minute per speed of gait. The pre-test allowed participants to get used to the speed of the system setup to reduce data noise. Skipping data was deleted as the participants' gait was too uncoordinated to be compatible with a principal component analysis. Speeds and gravitational constants were verified through the Vicon system. A single experienced biomechanist identified twenty-eight body landmarks through palpation and placed reflective markers on those landmarks (Figure 6 and Figure 7).

Figure 6 *Ventral View Plug-in-Gait Marker Set (Vicon Motion Systems Ltd, 2005).*



The marker set selected for this study was the Plug-in-Gait (PiG) Vicon developed marker set. Figure 6 illustrates ventral marker placements for the PiG, and Figure 7 illustrates the dorsal marker placement for PiG.

Figure 7 *Dorsal View Plug-in-Gait Marker Set* (Vicon Motion Systems Ltd, 2005).



Research Question

This study aimed to better analyze the coordinative gait structures under fractional gravity changes to better understand the coordinative structures necessary for space exploration. Additionally, this study aimed to answer the specific research question: how does Lunar and Martian gravity affect coordinative gait structures for humans?

Data Processing

Raw Vicon data were processed through several steps. These data consist of simple point vectors projected into 3D space. The 35 markers of the PiG model were tracked and saved in 2D format. During data processing, the 2D format was transformed into 3D point data. Due to these points moving through 3D space, they were referred to as trajectories. These trajectories were then filtered with a high-low band second-order Butterworth filter at 7 Hz (Winters, 2009).

Filtering was conducted to correct camera pixelization errors. Once trajectories were filtered, each trajectory X, Y, and Z, plus time-series data, were exported as a comma-separated file using ASCII protocols. These comma-separated files were imported into the PManalyser within MatLab R2021a (The MathWorks Inc., Natick, MA, USA). Principal component analysis requires symmetrical marker placements. Thus, several PiG markers were eliminated from the PManalyser processing. Specifically, the RBAK, LTHI, RTHI, LTIB, RTIM RUPA, LUPA, RFRM, LFRM, RFIN, and LFIN (see Figure 7) were eliminated within the processing. These exclusion criteria are the same preprocessing PiG data carried out in previous studies (Federolf et al., 2013).

PManalyzer ran several data normalization steps before data processing. First, the data from each trial were gap-filled, centered by subtracting the mean, and normalized to the mean Euclidean distance (Federolf et al., 2013). After normalizing the data, the PCA was calculated using eigenvectors to describe the decomposed movement between the trials. RSTD, or relative standard deviation, was used to compare the movement between the different levels of simulated gravity. RSTD better scales to actual movements than does the relative variance (Federolf et al., 2013).

Data Analysis

This study utilized a mixed methodology approach in that it employed qualitative and quantitative data analysis techniques. First, AVI video files produced by PManalyzer were qualitatively coded by two researchers. Constant comparative measures were used between the two researchers to identify and classify coordinative structures. The two researchers observed the emergent coordinative structures during the constant comparative process. Only structures that represented 95% of the explained variance were coded. Once each researcher coded the coordinative structures independently, they met to compare their coding. After this initial meeting, with notes of their discussion, each researcher conducted a second independent examination of the coordinative structures. Subsequently, a final meeting to compare results was conducted when agreements were solidified, and disagreements were adjusted to create a uniform description of coordinative structures.

Tables were made for each speed, mode of locomotion, and gravitational condition. From these tables, condensed versions were made to illustrate all emergent coordinative structures across all the speeds within the study. Constant comparison was used to identify coordinative structural themes within each mode/gravitational constant data.

Quantitative analysis in this study utilized PCA at the individual level where through a specific derivative of PCA, individual elements and contributions of each condition could be teased out. Using the RSTD, the contributions of individual participants, or the contributions of individual conditions to an overall PCA, were determined. Essentially, the RSTD allowed the identification of differences between experimental conditions by comparing the variance explained by each condition to the overall described components. For example, when walking on Earth and Mars were compared, an overall PCA was conducted on all walking trials collected on both planets. This analysis provided combined or common coordinative structures between the two planets. With RSTD, it is possible to delineate how much each planet contributed to the common coordinative walking structures. This delineation is quantified through the amount of shared variance explained.

Therefore, paired t-tests were used to quantify differences between two planets' contributions to the common coordinative structures, illustrating key differences in emergent coordinative structures for walking on either planet. Paired sample t-tests were run to compare the relative percentage of the variance between the common coordinative structures of each gravitational condition for the top five components. Additionally, Cohen's d effect sizes were computed for each of the t-tests. Cohen’s d effect sizes use the following criteria to interpret the effect size: Cohen’s thresholds of 0.2, 0.5, 0.8 for small, medium, and large. 0.2 is insignificant (Cohen, 1988).

Results

The qualitative results of this study are presented first, followed by the quantitative results, with emergent themes resulting from the qualitative and quantitative results subsequently presented.

Qualitative Results

The following six tables describe the coordinative structures found while participants walked and ran under Earth, Lunar, and Martian simulated gravity conditions. The following tables explain the coordinative structures found given the sagittal and frontal planes and express the percentage of the trials in which these components emerged within our participant population. A constant comparative qualitative data analysis was conducted on the emergent visualized components. Charts describing the unique codes for each speed and gravitational condition were constructed (see Appendix A). For convenience, the below charts are presented as condensed versions.

Additionally, a percentage of emergence was calculated to illustrate how each of these components emerged. The percentage indicates how often each of the listed coordinated structures emerged out of the five speeds observed. For example, twisting of the upper torso and foot shuffle stepping action had a percent of the emergence of 100% in Lunar walking, so these coordinative structures emerged at all five speeds; concordantly, skipping action had a percent of the emergence of 40% in Lunar walking so that coordinative structure emerged at two of the tested speeds.

Table 1 *Emergent Coordinative Structures of Earth Walking.*

Sagittal Plane	Frontal Plane	Percent of Emergence
Traditional walking gait, arms opposite legs	Traditional walking gait, arms opposite legs	100%
Twisting of the upper torso	Foot shuffle stepping action	100%
Upper body pendulum action	Flexion and extension of the knee, no arm or hip motion	100%
Bouncing motion, arms in conjunction	Bouncing motion, arms in conjunction	100%
Unified kicking action, arms in conjunction	Broad jump action with leg and arm kicking	40%

Table 2 *Emergent Coordinative Structures of Earth Running.*

Sagittal Plane	Frontal Plane	Percent of Emergence
Traditional running gait, opposition movement	Traditional running gait, opposition movement	100%
Twisting of the upper torso	Foot shuffle stepping action	80%
Bouncing motion, arms in conjunction	Bouncing motion, arms in conjunction	80%
Upper body pendulum action	Flexion and extension of the knee, no arm or hip motion	80%
Lower body pendulum action	Flexion and extension of the knees slight arm and slight hip motion	100%

Table 3 *Emergent Coordinative Structures of Lunar Walking.*

Sagittal	Frontal	Percent of Emergence
Traditional walking gait, arms opposite legs	Traditional walking gait, arms opposite legs	100%
Twisting of the upper torso	Foot shuffle stepping action	100%
Lateral stepping	Stepping in place, arms in opposition	100%
Lower body pendulum	Classic opposition, with heavy backward lean	100%
Twisting dance arm opposition	Upper body arm opposition, lower body nearly still	80%
Bouncing motion, arms in conjunction	Bouncing motion, arms in conjunction.	60%
Skipping action	Skipping action	40%

Table 4 *Emergent Coordinative Structures of Lunar Running.*

Sagittal	Frontal	Percent of Emergence
Traditional running gait, arms opposite legs	Traditional running gait, arms opposite legs	100%
Upper body pendulum with central stepping	Arms and legs in opposition, dramatic backward lean	100%
Skipping action	Skipping action	80%
Rotation around central axis	Asymmetric foot kicking action	60%
Slight twisting	Foot shuffle stepping action	60%
Asymmetric stepping down	Landing from the skipping action	40%
Asymmetric sliding sideways	Single footstep forward, dramatic backward lean	40%

Table 5 *Emergent Coordinative Structures of Martian Walking.*

Sagittal	Frontal	Percent of Emergence
Traditional walking gait, arms opposite legs	Traditional walking gait, arms opposite legs	100%
Twisting of the upper torso	Foot shuffle stepping action	100%
Bouncing motion, arms in conjunction	Bouncing motion, arms in conjunction	100%
Lower body pendulum	Legs in opposition, arm slight opposition	100%
Body moving laterally	Flexion and extension of the knee, arm opposition	60%
Twisting dance move with asynchronous lower leg	Asynchronous leg kicking action	60%
Upper body pendulum action	Flexion and extension of the knee, arm opposition and hip flexion-extension	40%

Table 6 *Emergent Coordinative Structures of Martian Running.*

Sagittal	Frontal	Percent of Emergence
Traditional running gait, arms opposite legs	Traditional running gait, arms opposite legs	100%
Lower body pendulum	Traditional running gait with opposition	100%
Dramatic rotation upper body around central axis	Arms in opposition, twist dance action	100%
Twisting of the upper torso	Foot shuffle stepping action	80%
Bouncing motion arms in conjunction	Bouncing motion, arms in conjunction	60%
Leg scissoring action	Landing from the skipping action	40%
Initiating skipping action	Initiating skipping action	40%

Table 7 *Average Emergent Components At 95% of Variance.*

Mode	Avg Emergent Components
Earth Walking	4.5
Earth Running	5.4
Lunar Walking	6.8
Lunar Running	7.0
Mars Walking	6.0
Mars Running	6.0

Illustrated in table 7 are the average number of principal components or coordinative structures that emerged. The average number of components at 95% of variance ranged from 4.5 to 7.0. It should be noted that there is a slight upward trend from fewer emergent components on Earth to higher emergence in lunar gravity.

The traditional running gait coordinative structure surfaced within all six conditions. We also see that all conditions above the "normal" Earth walking have an overall higher average of coordinative structures that emerge. Essentially, the instability of emerged coordinative structures increases as the gravity level decreases. Another important emergent variable that surfaced was the amount of asymmetry in the participants' gait as the gravity level decreased.

During data collection, the participants were instructed during walking trials to exclusively walk. During running trials, they were instructed to exclusively run. A skipping coordinative structure was identified throughout the qualitative analysis while participants were walking around 4–5 mph. Figure 10 illustrates the emergent skipping component during Lunar running at 5 mph. The overall data from the qualitative analysis can be seen in the Appendix A.

Quantitative Results

Paired sample t-tests were run to compare the relative percentage of variance between the common coordinative structures of each gravitational condition. Additionally, Cohen's d effect sizes were computed for each of the t-tests. This allowed for a determination of the confidence in the differences in emergent coordinative structures within each of the gravitational conditions for each of the five speeds tested. The top five components were selected due to the lowest number of emergent components to achieve 95% of the explained variance.

A couple of crucial points found within the following tables expressing the results of the paired t-tests of the walking and running trials show that most of the changes in walking are during the primary components. In the running, the changes are primarily spread out. The findings were found to have a large effect size, which is also expressed in Table 8 and Table 9. See Appendix B for Cohen’s d calculations.

Table 8 *Walking Comparisons.*

Mode	Comparison	CS1	CS2	CS3	CS4	CS5
2 mph	Earth Vs. Moon	0.86	0.00*↟	0.01*↟	0.00*	0.12
3 mph	Earth Vs. Moon	0.00*↟	0.85	0.05	0.39	0.19
4 mph	Earth Vs. Moon	0.00*↟	0.40	0.36	0.80	0.02*
5 mph	Earth Vs. Moon	0.00*↟	0.85	0.61	0.04	0.17
6 mph	Earth Vs. Moon	0.01*↟	0.95	0.69	0.01	0.75
2 mph	Earth Vs. Mars	0.00*↟	0.99	0.38	0.00	0.05
3 mph	Earth Vs. Mars	0.00*↟	0.30	0.05*↑	0.04	0.00*
4 mph	Earth Vs. Mars	0.00*↟	0.36	0.13	0.01	0.81
5 mph	Earth Vs. Mars	0.00*↟	0.74	0.78	0.00*↟	0.00*↟
6 mph	Earth Vs. Mars	0.03*↟	0.95	0.04	0.72	0.59
2 mph	Moon Vs. Mars	0.50	0.03*	0.07	0.44	0.12
3 mph	Moon Vs. Mars	0.18	0.04*	0.61	0.18	0.00*↟
4 mph	Moon Vs. Mars	0.78	0.06	0.11	0.64	0.14
5 mph	Moon Vs. Mars	0.07	0.67	0.75	0.19	0.95
6 mph	Moon Vs. Mars	0.48	0.60	0.30	0.33	0.25

*= P<0.05 (for p values <0.05 ↑= Cohens'd > 0.50 and ↟= Cohens'd >0.80)

Table 9 *Running Comparisons.*

Mode	Comparison	CS1	CS2	CS3	CS4	CS5
2 mph	Earth Vs. Moon	0.40	0.41	0.59	0.05*↑	0.06*↑
3 mph	Earth Vs. Moon	0.08	0.00*⤒	0.36	0.03*⤒	0.01*⤒
4 mph	Earth Vs. Moon	0.00*⤒	0.06	0.20	0.02*⤒	0.02*⤒
5 mph	Earth Vs. Moon	0.03*⤒	0.09	0.19	0.01*⤒	0.25
6 mph	Earth Vs. Moon	0.00*⤒	0.29	0.00*⤒	0.20	0.57
2 mph	Earth Vs. Mars	0.33	0.41	0.70	0.87	0.08
3 mph	Earth Vs. Mars	0.98	0.02*⤒	0.02*↑	0.18	0.15
4 mph	Earth Vs. Mars	0.20	0.03*↑	0.01*⤒	0.05*↑	0.92
5 mph	Earth Vs. Mars	0.01*⤒	0.82	0.00*⤒	0.01*⤒	0.89
6 mph	Earth Vs. Mars	0.01*⤒	0.89	0.00*⤒	0.33	0.71
2 mph	Moon Vs. Mars	0.71	0.99	0.53	0.00*⤒	0.64
3 mph	Moon Vs. Mars	0.22	0.01*⤒	0.02*⤒	0.01*⤒	0.02*⤒
4 mph	Moon Vs. Mars	0.00*⤒	0.87	0.02	0.43	0.00*⤒
5 mph	Moon Vs. Mars	0.38	0.24	0.01*⤒	0.04*↑	0.26
6 mph	Moon Vs. Mars	0.01*⤒	0.59	0.13	0.64	0.57

*= P<0.05 (for p values <0.05 ↑= Cohens'd > 0.50 and ⤒= Cohens'd >0.80)

Emergent Analysis

One concept that emerged through data analysis was a lack of bilateral symmetry in some of the derived components. Emergence is defined as the process of becoming into being. The concept of asymmetry was applied to gait to examine the opposition between limbs and planes of the body. The lack of opposition during gait is an indication of asymmetry.

Asymmetry

Bodily asymmetry emerged from the qualitative analysis with increasing speed under Lunar and Martian gravity. Asymmetry is defined as the absence of symmetry and lack of equality between aspects of something; in this case, the bilateral symmetric nature of human gait was used as a quality of symmetry.

Quantitative Asymmetry Comparison

To determine if the observed asymmetry was anecdotal or had a statistical basis, the coordinative structures (see Appendix A) were coded as either symmetric or asymmetric characteristics. These codes were again subjected to constant comparative measures. The coordinative structures were coded for all five speeds across all the gravitational conditions. As with all principal component analyses, emergent components, or coordinative structures, are weighted based upon their percentage of variance explained. The percentages of variance explained by asymmetric and symmetric coordinative structures were summed to assess significant differences in the emergence of asymmetric coordinative structures.

This process allowed for the overall percentages of variances explained by asymmetric coordinative structures to be quantified. Paired t-tests were then used to determine the confidence in the differences of the emergence of asymmetric coordinative structures between the gravitational conditions. This allowed for significant differences in asymmetric coordinative structure emergence between the various gravitational conditions to be determined.

Table 10 *Descriptive Statistics for Average Asymmetric Variance Percentages.*

Mode	Mean	Std. Dev
Earth Walking	2.4%	2.0
Mars Walking	1.9%	2.2
Moon Walking	7.7%	5.1
Earth Running	1.0%	0.3
Mars Running	12.9%	16.2
Moon Running	38.1%	20.4

Shown in table 10 are descriptive statistics for the asymmetric coordinative structures. Moon walking has the highest average of asymmetric coordinative structures within all walking speeds, and Moon running has the highest average within all running speeds. The largest percent difference of mean average asymmetric coordinative structures was found between Earth running and Lunar running.

Table 11 *Comparisons of Average Asymmetric Variance Percentages (no speed delineation).*

Comparisons	Mean	Std. Dev	Sig
Earth Walking Vs. Mars Walking	0.5	2.7	0.72
Mars Walking Vs. Moon Walking	-5.8	6.6	0.12
Earth Walking Vs. Moon Walking	-5.3	3.9	0.04*↟
Earth Running Vs. Mars Running	-11.9	16.3	0.18
Earth Running Vs. Moon Running	-37.1	20.6	0.02*↟
Mars Running Vs. Moon Running	-25.2	16.9	0.03*↟

*= P<0.05 (for p values <0.05 ↑= Cohens'd >0.50 and ↟= Cohens'd >0.80)

Shown in Table 11 are the comparisons of the average asymmetric variance percentages with Cohen's d effect sizes identified. See Appendix B for Cohen's d calculations.

Figure 8 *Average Asymmetrical Component Percentage of Variance for Walking.*

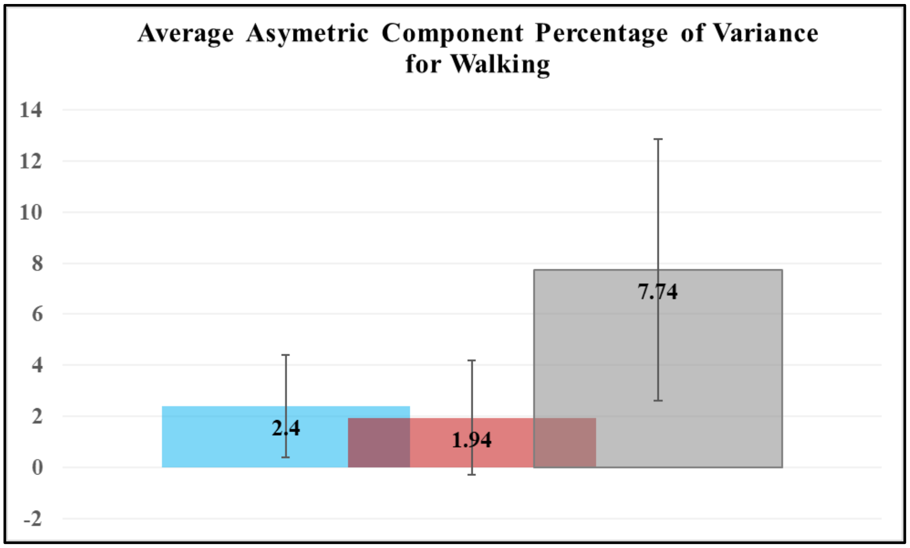


Figure 8 visually expresses the average asymmetrical component percentage of variance for walking from Table 10.

Figure 9 *Average Asymmetrical Component Percentage of Variance for Running.*

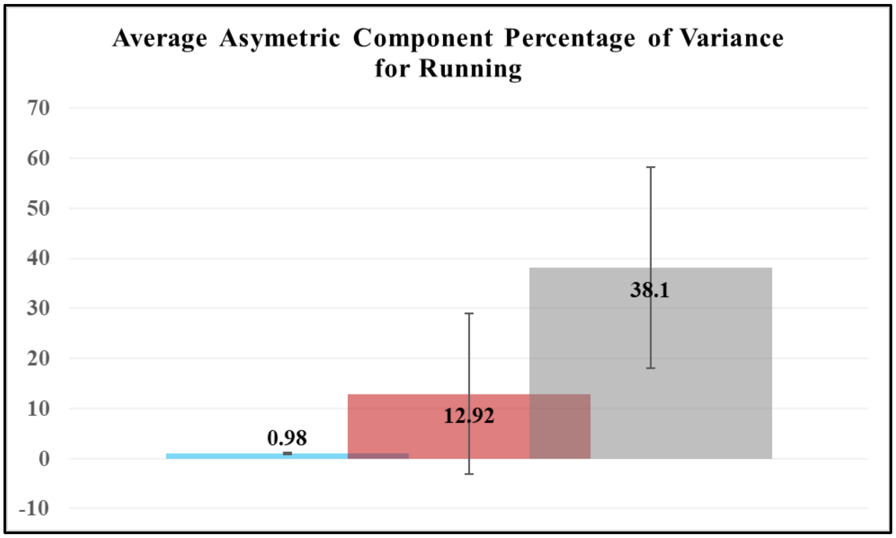


Figure 9 visually expresses the average asymmetrical component percentage of variance for running from Table 10.

Skipping

Skipping emerged during the coding of asymmetric components, and an individual coordinative structure emerged 80% of the time during Lunar running and 40% of trials during Lunar walking. It should be noted that skipping repeatedly emerged within specific gravitational conditions and represented a fundamental motor pattern. Skipping is a complete motor pattern, not simply a component of a motor pattern.

Figure 10 *Emergent Skipping Action During Lunar Running at 5 mph.*

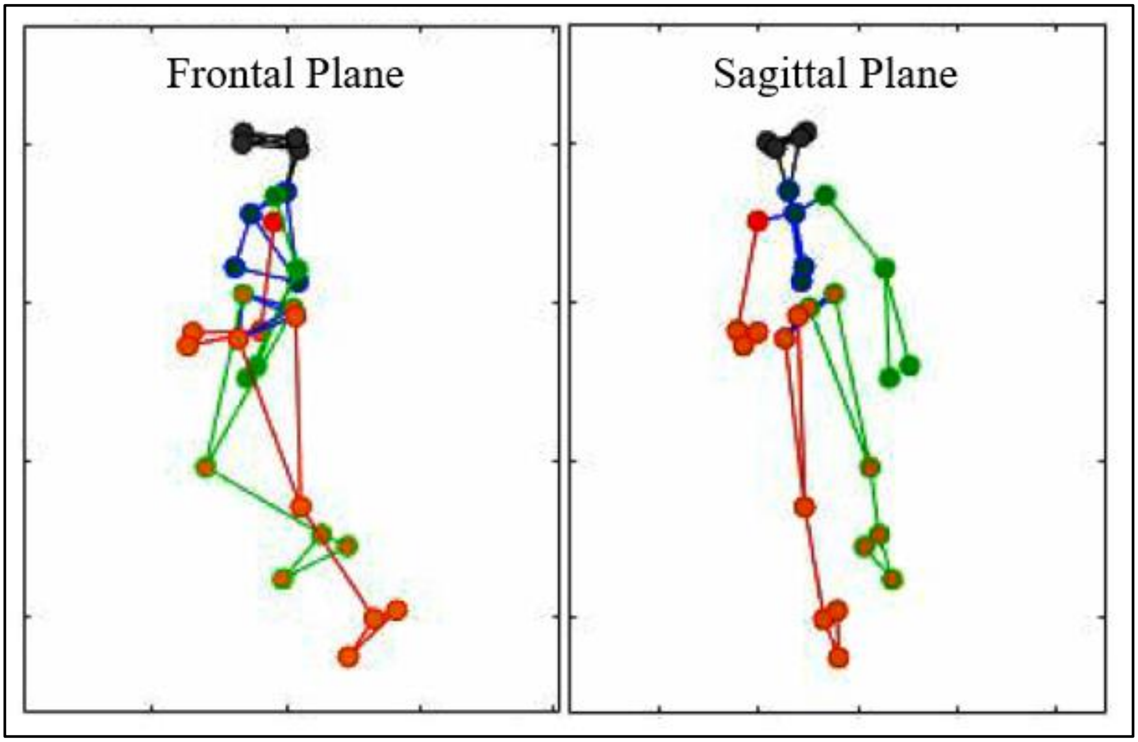


Figure 10 shows the coordinative structure of skipping found within PManalyzer analysis which is illustrated from the frontal and sagittal planes.

Discussion

Coordinative Structural Change

One of the most notable findings in the present study was the change in coordinative structures. The change in coordinative structures was typically seen when participants' speed increased on the treadmill and when the gravity level decreased. The traditional walking and running gait emerged 100% on all six conditions. However, a dominant trend of the coordinative structures of lateral bending, twisting, rotation, and skipping was observed as the gravity level decreased. With the added pressure of the low gravity environment, the participants' gait changes more asymmetrically.

The quantitative results indicate statistical changes in the coordinative structures, meaning that some of the coordinative structures change in dominance. It is not possible to identify specific components that changed, but it is possible to identify general changes in the coordinative structures.

Emergent Coordinative Structures

The mean number of coordinative structures changed throughout the study. There was an average of 4.5 coordinative structures at 95% variance found within walking on Earth, while there were 5.4 coordinative structures found within running on Earth. As the simulated gravity level changed to Lunar gravity, an average of 6.8 coordinative structures were. In contrast, 7 coordinative structures were found running on the Moon. Finally, an average of 6 coordinative structures emerged within walking and running on Mars. An increase in the average number of coordinative structures emerged as gait changed from walking to running and the simulated gravity decreased. These increased coordinative structures were highly dissipative. Although the charting of the coordinative structures (see Appendix A) illustrates several new coordinative structures arise, they do not become consistent.

The change in the number of inconsistent emergent coordinative structures could be explained by the innate human capabilities of learning and trial and error. Walking and running on Earth have the least amount of emergent coordinative structures because humans are already assimilated to and have evolved within this gravitational environment. As the gravity level changes, the way that the body manipulates itself to move forward changes. Think of when a young child learns to walk compared to a mature adult who has a confident gait. There are more dissipative movements within a young child's gait than a grown adult's because the child must learn to use their balance and trial and error until they have practiced enough. Gait maturation is typically seen around the ages of 7-13, depending on the parameters considered (Malloggi et al., 2021). In the present study, there were higher average emergent coordinative structures during walking gait and running gait on Mars and Moon gravity which could be explained by participants not being accustomed to engaging in gait under those levels of simulated gravity and needing to learn how to safely.

In humans and other bipeds, the preferred transition speed (PTS) is the speed at which a subject chooses to change from a walking to a running gait. The hypothesis for locomotion suggests that animals of different sizes will move similarly at similar Froude numbers. The Froude number for legged locomotion relates the centripetal force to the gravitational force acting on the body and measures efficiency. The Froude number is a dimensionless parameter that can be found by:

$$Fr = V^2/gl^2$$

Where v is the locomotion velocity, l is the leg length, and g is the acceleration due to Earth's gravity (i.e., 9.81m/s^2). The PTS values during simulated and actual Lunar gravity were greater than predicted using the Froude number equation set to 0.5 (De Witt et al., 2014). Comparing this notion to the present study, the Froude number set at 0.5 would agree with the results of the transition velocity.

Table 12 *Walking to Running Transition Based on Froude Quotient.*

Fr	Gravity	Transition Velocity (mph)
0.5	Moon	2.4
0.5	Mercury	2.9
0.5	Mars	2.9
0.5	Venus	4.25
0.5	Uranus	4.36
0.5	Earth	4.47
0.5	Saturn	4.58
0.5	Neptune	4.69
0.5	Jupiter	6.71

Shown in table 12 are the results from De Witt et al. 2014 and the preferred transition speed with a set Froude number of 0.5. This is an example showing the PTS using the calculated average leg length from their participants. Within the present study, participants transitioned from walking to running at about 3 mph in Lunar gravity, 3-4 mph in Earth gravity, and 4 mph in Martian gravity. These results agree with De Witt et al. 2014 as our actual transition velocity rates were greater than what was predicted, aside from the PTS on Earth gravity. It is suggested that by increasing the gravity level, the walk-run transition speed occurred at faster speeds whereas corresponding Froude numbers remained constant. The most significant effect of gravity level on the Froude number can be observed in planets with gravity that is lower than the Earth (Hossien, Kani, Gulstan, Nzar, 2014).

Figure 11 *Walking to Running Transition Based on Gravity Level (Hossien, Kani, Gulstan, Nazar, 2014).*

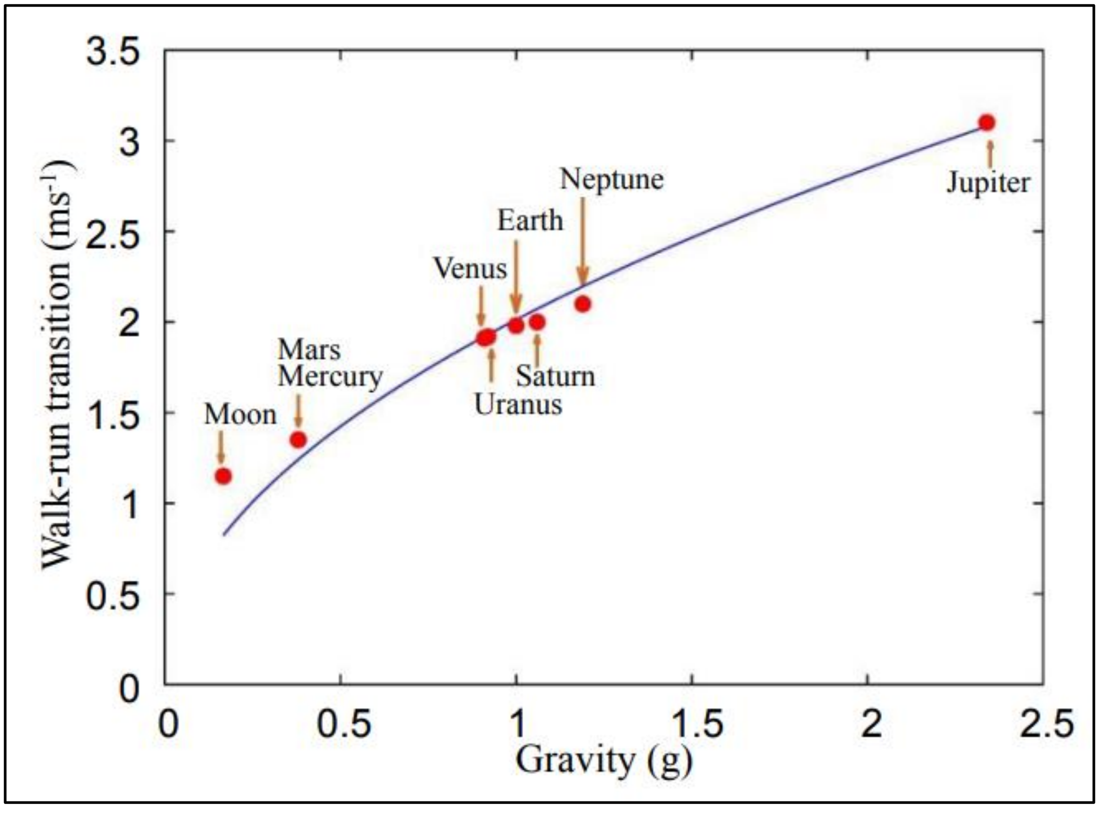


Figure 11 illustrates the walk to run transition speed with a Froude number of 0.5 at different gravitational force for the planets of the solar system. By reducing the gravity level, the walk-to-run transition occurs at a slower speed.

Asymmetry

Asymmetry is an interesting variable that came to be throughout data analysis. When this study was designed, asymmetry was not originally planned to be discussed. A significant amount of asymmetry, however, arose within the observed coordinative structures. A coordinative structure was coded as asymmetrical if there was an absence of symmetry and lack of equality between the planes of the body. Asymmetrical coordinative structures were found more often in non-terrestrial simulated gravity conditions during both walking and running.

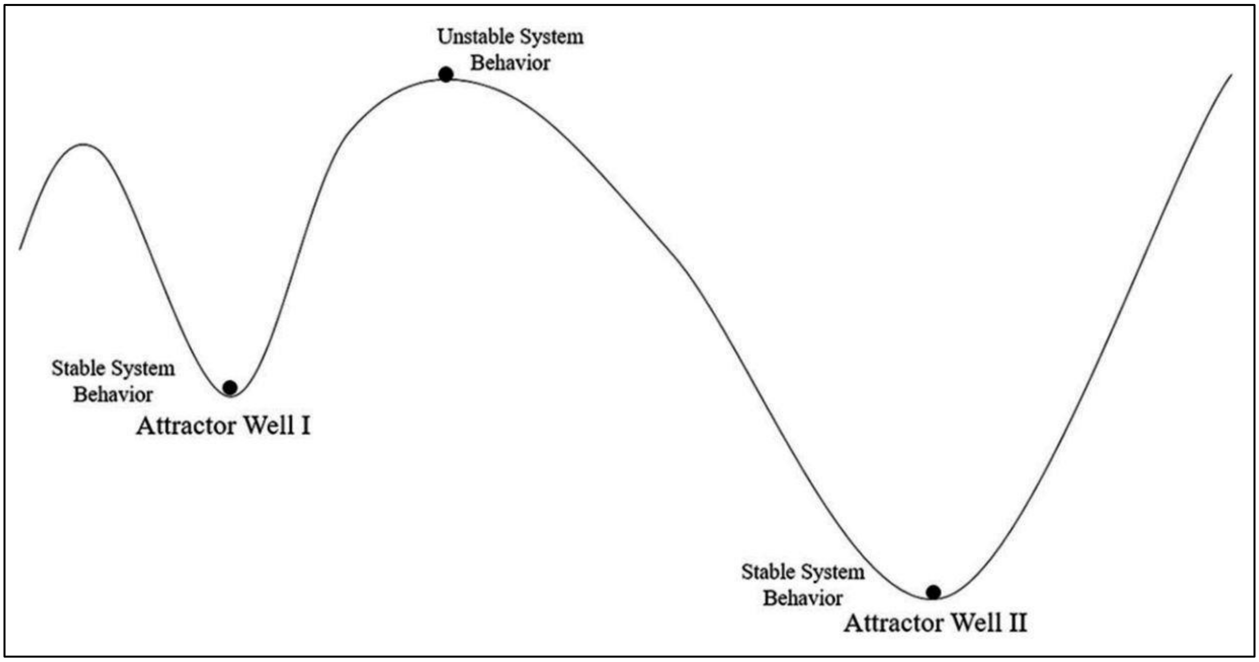
Additionally, there is a higher mean average of asymmetrical coordinative structures within comparisons of Moon walking, Mars running, and Moon running. In conjunction with the distribution of 95% of explained variance over more components with running and walking in lower gravitational conditions, these findings suggest a high degree of instability in the emergence of coordinative structures within these lower gravitational conditions. Interestingly, this notion of instability during motor performance, especially during a novel, is represented in current motor learning literature (Newell, 1986; Rhoades & Hopper, 2017;2020).

Dynamic Learning

Human beings can be conceptualized as complex adaptive systems (Renshaw, Chow, Davids, & Hammond, 2010). This means humans will adapt to their environment in the most basic sense. Essentially, if something changes in their environment, they will adapt to those changes; this adaptation can be considered learning (Morrison, 2008). If we think of motor learning as moving from one stable state to another stable state, then the adaptive process is simply the body learning and employing a new stable motor pattern; this motor pattern is crafted to be the best suited for the altered environmental constraint (Morrison, 2008).

Interestingly, during adaptation, systems must go through a time of instability; this messy time of instability is the system actively adapting to the new environmental constraint. This learning period is often called a phase transition; during the phase transition, the system will be volatile, exhibiting much unpredictability in its functioning. Stable states are sometimes referred to as attractors; these are predictable states that a system will adapt to within certain environmental constraints (Newell, 1986; Rhoades & Hopper, 2017;2020). If we conceptualize a system rolling down a hill, an attractor state can be thought of as a divot that the ball is stuck in for a time. If the system is perturbed sufficiently, it will dislodge from its divot and move downhill to the next divot. The ball is very stable when it is in the divot; however, during the transitional time, it is volatile (Newell, 1986; Rhoades & Hopper, 2017;2020). Essentially, motor learning is moving from one stable attractor state to another can be conceptualized as illustrated in Figure 12.

Figure 12 *Attractor Wells (Rhoades & Hopper, 2017).*



The instability of systems during phase transitions is very similar to what has been observed within this study. In this study, non-terrestrial gravitational constraints exhibited high instability in coordinative structures. In contrast, walking and running within earth gravity exhibited a highly stable set of coordinative structures. Essentially, what is observed in this experiment is a learning process. However, the observations were not long enough to observe the final stable form of these emergent motor patterns.

Injury

Even though the data in this study suggest that the instability and asymmetric coordinative structure will dissipate with exposure, injury is still a possibility. There is a clear possibility for many motor issues for astronauts that could arise while being exposed to different gravitational environments. Environment characteristics may influence running asymmetries and are related to irregularities requiring compensatory movements changing the workload on joints and bones (Carpes, Mota, Faria, 2010). The average percentage of asymmetrical coordinative gait structures during walking and running gait is significantly higher in Lunar and Martian gravity when compared to Earth gravity.

The body could be more vulnerable when a higher percentage of asymmetrical coordinative gait structures are seen, which means the body could be at higher risk of injury. Testing before, after, and during a physical loading, protocol is recommended to consider the influence of exercise-induced fatigue on specific tasks and identify the possible mechanisms underlying load-dependent inter-limb asymmetries because inter-limb asymmetries are associated with higher injury risk (Heil, Loffing, Busch, 2020). Suppose there was a program to train astronauts to alternate these asymmetrical body movements to symmetrically sound coordinative structures or add strength and conditioning regimes to strengthen specific muscle groups. In that case, the risk of injury then could be reduced.

If the observed asymmetric coordinative structures result from the participants in this study going through an everyday learning process as described above. This would indicate that people exposed to these gravitational constraints will stabilize in a stable motor pattern. The assumption would be that the asymmetric coordinative structures are part of the observed instability.

Skipping

Skipping was observed as a coordinative structure emerging during lunar running. This emergent coordinative structure requires a bit more exploration as, unlike many of the asymmetric emergent components observed in this study, skipping is a fundamental motor pattern. This motor pattern is itself a complete locomotor motor skill (Rhoades, 2017). Its emergence suggests that skipping was in its early stages of becoming a stable motor pattern for this environmental constraint. This suggests that skipping may be a naturally occurring attractor state for lunar locomotion. In and of itself, skipping would not necessarily be of major concern; however, in this study, skipping was observed as unilateral. Unilateral skipping is an independent complete motor pattern, not simply a coordinative structure. The issue with this is that if univariant skipping is an attractor for this gravitational constant, the injury potential with the asymmetric loading may be a permanent trait of locomotor learning in these environments.

Skipping was a vital motor pattern that was observed. This was predicted, as skipping is the preferred means of gait of humans experiencing Lunar gravity (Pavei, Biancardi, Minetti, 2015). It was typically found when participants were suspended under Lunar and Martian gravity levels. Skipping occurred during Lunar walking at 40% of the five-speed rates, and it was also found in Lunar running at 80% of the five-speed rates. During Martian running, an initiating skipping action and a landing from the skipping action were found at 40% of the speeds.

Moon walking, Moon running, and Martian running had a higher mean percentage of asymmetric components when compared to all other constraints. Skipping is coded as an asymmetrical coordinative structure, so that these skipping components could play a role in the high mean percentage of asymmetric components. These skipping components are typically coupled with a dramatic backward lean under simulated Lunar gravity.

Training Recommendations

Even though skipping is a specific motor pattern considered an asymmetrical coordinative structure, it might be a positive gait characteristic. If the preferred gait method on the Moon is skipping, as considered by (Pavei, Biancardi, Minetti, 2015), this could be used to NASA's advantage. Pre-flight training on skipping under Lunar and Martian gravity could reduce the possible risk of injury. Assuming Wolff's Law ("Wolff's Law," 2022), if the bones were to be subjected to these conditions beforehand, they could have time to adapt and remold to endure the stresses of fractional gravity. Increased pre-flight fractional gravity training on skipping bilaterally while giving participants an extended time of exposure to the gravity constraints could benefit present and future astronauts. This increased exposure could strengthen that motor pattern and reduce the learning time for ambulation when physically experiencing fractional gravity environments.

Future Studies

One of this study's most notable findings was the significant change between walking and running coordinative gait structures and between the various simulated gravity conditions. It would be interesting for future studies to examine how pre-flight training regimes - aside from the programs already in place - that specifically targeted the vulnerable muscle groups would affect their coordinative gait structures. Additionally, it would also be interesting to study if training programs could mediate the amount of asymmetrical coordinative gait structures and create a more fluid gait while experiencing fractional gravity.

Another element that future studies could examine would be how long it would take participants to become accustomed to skipping bilaterally within the gravity constraints. The present study burdened participants for one day, which was not enough time for them to strengthen the motor pattern. The acute bouts of testing may not reflect the final solutions. It would be interesting to see how long it would take to strengthen that motor pattern under fractional gravity and assumingly alter the amount of unilateral and asymmetrical movements.

These recommendations are directly related to the present study, but the motion analysis techniques and technologies utilized in this study could have many other purposes.

Limitations

A limitation of this exploratory study was the power being small because the sample size is 6 participants. This small sample size is consistent with other NASA studies (e.g., Abercromby et al., 2006; Jaramillo et al., 2008). A study published in 2019 investigated how peak breaking forces could be decreased following an 8-session gait retraining program among females (Napier et al., 2019). This study was an exploratory research study that only had 12 participants. Most exploratory research has smaller sample sizes due to exploring the research questions and does not intend to offer final solutions to problems.

Another limitation of this study is that participants were studied using a treadmill while being suspended in simulated gravity conditions. With this being a simulation, it gives a good idea about what the fractional gravity environments will be like for astronauts, but physically being in that environment would be different. Gait on land compared to gait on a treadmill could be different, but the degree is uncertain. This study gives researchers a good idea as to what astronauts may experience as the simulation is as close to being in that environment as possible preflight, but there are going to be differences between the simulated environment compared to the physical environment.

Conclusions

This study observed that coordinative gait structures changed under fractional gravity conditions. As the simulated gravity level decreased, there was an increase in the average amount of coordinative structures. The increase in coordinative structures is due to participants being unfamiliar with the environment and needing to modify their gait to ambulate in the different gravity constraints comfortably and safely. With the changes in gravitational constraints, this study observed a high amount of asymmetrical coordinative gait structures including the motor pattern of skipping. If the observed asymmetric coordinative structures are a result of the participants in this study going through a normal learning process, injury in the short term may be a concern. It should be expected that people subjected to these environments should learn how to adapt to the environmental constraints and stabilize in those environments beforehand to reduce learning time with fractional gravity ambulation.

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Appendix A

Cumulative Sagittal Coding Earth Walking

CS	2MPH	3MPH	4MPH	5MPH	6MPH
1	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs
2	Twisting of the upper torso	Twisting of the upper torso	Twisting of the upper torso	Twisting of the upper torso	Twisting of the upper torso
3	Upper body pendulum action	Upper body pendulum action	Upper body pendulum action	Upper body pendulum action	Upper body pendulum action
4	Bouncing motion arms in conjunction	Bouncing motion arms in conjunction	Bouncing motion arms in conjunction	Bouncing motion arms in conjunction	Bouncing motion arms in conjunction
5	Lower Body Pendulum	Unified Kicking Action, with arm conjunction			Asymmetric leg kicking with arm bouncing
6	Unified Kicking Action, with arm conjunction				

Cumulative Frontal Coding Earth Walking

CS	2MPH	3MPH	4MPH	5MPH	6MPH
1	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs
2	Foot S huffle stepping action	Foot Shuffle stepping action	Foot Shuffle stepping action	Foot Shuffle stepping action	Foot Shuffle stepping action
3	Flexion and extension of the knee, no arm or hip motion	Flexion and extension of the knee, no arm or hip motion	Flexion and extension of the knee, no arm or hip motion	Flexion and extension of the knee, no arm or hip motion	Flexion and extension of the knee, no arm or hip motion
4	Bouncing motion arms in conjunction.	Bouncing motion arms in conjunction.	Bouncing motion arms in conjunction.	Bouncing motion arms in conjunction.	Bouncing motion arms in conjunction.
5	Hyper extending legs and arm opposition	Broad jump type action with leg and arm kicking			Crazy hyper extension leg kicking , arms in conjunction
6	Broad jump type action with leg and arm kicking				

Cumulative Sagittal Earth Running

	2MPH	3MPH	4MPH	5MPH	6MPH
1	Slight Twisting	Traditional gait opposition movement	Traditional gait opposition movement	Traditional gait opposition movement	Traditional gait opposition movement
2	Lateral Stepping	Twisting of the upper torso	Twisting of the upper torso	Twisting of the upper torso	Twisting of the upper torso
3	Bouncing, arms in conjunction and Aligned	Bouncing motion arms in conjunction	Bouncing motion arms in conjunction	Bouncing motion arms in conjunction	Bouncing motion arms in conjunction
4	Traditional Running Gait, arms opposite legs	Upper body pendulum action	Upper body pendulum action	Upper body pendulum action	Upper body pendulum action
5	Lower body lateral pendulum action	Lower body Pendulum action	Lower body Pendulum action	Lower body Pendulum action	Lower body Pendulum action
6	Asymmetric twisting at the waist				
7	Asymmetric twisting with leg conjunction				

Cumulative Frontal Earth Running

	2MPH	3MPH	4MPH	5MPH	6MPH
1	Shuffle Stepping	Traditional gait opposition movement	Traditional gait opposition movement	Traditional gait opposition movement	Traditional gait opposition movement
2	Stepping in place, arms in opposition	Foot Shuffle stepping action	Foot Shuffle stepping action	Foot Shuffle stepping action	Foot Shuffle stepping action
3	Bouncing motion, Slight asymmetric movement of arms and legs	Bouncing motion arms in conjunction.	Bouncing motion arms in conjunction.	Bouncing motion arms in conjunction.	Bouncing motion arms in conjunction.
4	Traditional Running Gait, arms opposite legs	Flexion and extension of the knee, no arm or hip motion	Flexion and extension of the knee, no arm or hip motion	Flexion and extension of the knee, no arm or hip motion	Flexion and extension of the knee, no arm or hip motion
5	Knees flexion and extension, no arm or hip movement	Flexion and extension of the knees slight arm and slight hip motion	Flexion and extension of the knees slight arm and slight hip motion	Flexion and extension of the knees slight arm and slight hip motion	Flexion and extension of the knees slight arm and slight hip motion
6	Bunny hopping action with asymmetric arm twisting				
7	Torso flexion with asymmetric arm and leg twisting				

Cumulative Sagittal Lunar Walking

	2MPH	3MPH	4MPH	5MPH	6MPH
1	Twisting of the upper torso	Traditional Running Gait, arms opposite legs	Twisting of the upper torso	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs
2	Traditional Running Gait, arms opposite legs	Twisting of the upper torso	Traditional Running Gait, arms opposite legs	Slight Twisting	Slight Twisting
3	Lateral Stepping	Lateral Stepping	Lateral Stepping	Lateral Stepping	Lateral Stepping
4	Bouncing motion arms in conjunction	Bouncing motion arms in conjunction	Initiating Skipping Action	Initiating Skipping Action	Bouncing motion arms in conjunction
5	Twisting dance arm opposition	Twisting dance arm opposition	Lower body Pendulum	Lower body Pendulum	Lower body Pendulum
6	Lower Body Pendulum	Lower body Pendulum	Twisting dance arm opposition	Twisting dance arm opposition	Pelvic Thrusting
7		Twisting of the shoulders		Total Body Rotation	
8		Lower leg opposition flexion extension		Pelvic Thrusting	

Cumulative Frontal Lunar Walking

	2MPH	3MPH	4MPH	5MPH	6MPH
1	Foot Shuffle stepping action	Traditional Running Gait, arms opposite legs	Foot Shuffle stepping action	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs
2	Traditional Running Gait, arms opposite legs (Backward Lean)	Foot Shuffle stepping action	Traditional Running Gait, arms opposite legs	Shuffle Stepping	Shuffle Stepping
3	Stepping in place, arms in opposition	Stepping in place, arms in opposition	Stepping in place, arms in opposition	Stepping in place, arms in opposition	Stepping in place, arms in opposition
4	Bouncing motion arms in conjunction.	Bouncing motion arms in conjunction.	Initiating Skipping Action	Initiating Skipping Action	Bouncing motion arms in conjunction.
5	Upper body arm opposition, lower body nearly still	Upper body arm opposition, lower body nearly still	Classic opposition, with heavy backward lean	Classic opposition, with heavy backward lean	Classic opposition, with heavy backward lean
6	Classic opposition, with heavy backward lean	Classic opposition, with heavy backward lean	Upper body arm opposition, lower body nearly still	Asymmetric flexion extension of legs arm opposition	Lower body Dramatic backward lean
7		Lower body Dramatic backward lean		Shuffle Stepping	
8		Lower Leg opposition Arms opposition		Lower body Dramatic backward lean	

Cumulative Sagittal Lunar Running

	2MPH	3MPH	4MPH	5MPH	6MPH
1	Slight Twisting	Shuffle Stepping	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs
2	Upper body pendulum with central stepping	Slight Twisting	Leg Scissoring action	Asymmetric Stepping Down	Asymmetric Stepping Down
3	Bouncing motion arms in conjunction	Skipping Action	Slight Twisting	Asymmetric hopping	Skipping Action
4	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs	Skipping Action	Skipping Action	Bouncing with arms in conjunction
5	Lower pendulum with total body rotation	Twisting upper total body pendulum	Asymmetric sliding sideways	Asymmetric sliding sideways	Twisting upper total body pendulum
6	Asymmetrical rotation with no arm motion	Asymmetric rotation, toes in concert pull side	Twisting upper total body pendulum	Twisting upper total body pendulum	Rotation around central axis
7	Asymmetric sliding action	Sideways gliding	Rotation around central axis	Rotation around central axis	Asymmetric foot stepping

Cumulative Frontal Lunar Running

	2MPH	3MPH	4MPH	5MPH	6MPH
1	Shuffle Stepping	Stepping down action end of skip	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs
2	Stepping in place, arms in opposition	Shuffle Stepping	Symmetric scissoring	Landing from the Skipping action	Landing from the Skipping action
3	Bouncing motion arms in conjunction.	Skipping Action	Shuffle Stepping	Hopping Action	Skipping Action
4	Traditional Running Gait, arms opposite legs (Backward lean)	Traditional Running Gait, arms opposite legs	Skipping Action	Skipping Action	Bounding with twisting of lower body
5	Leg flexion and extension no arm motion with heavy rotation	Arms Legs opposition, dramatic backward lean	Single foot step forward, dramatic lean back	Single foot step forward, dramatic lean back	Stepping Traditional with arm opposition
6	Asymmetric rotation with foot shuffle	Asymmetric stepping with left leg, upper body rotation	Arms Legs opposition, dramatic backward lean	Arms Legs opposition, dramatic backward lean	Arm Leg opposition
7	Sliding action	Dramatic Backward lean and rotation	Asymmetric foot kicking action	Asymmetric foot kicking action	Asymmetric foot kicking action

Cumulative Sagittal Martian Walking

	2MPH	3MPH	4MPH	5MPH	6MPH
1	Twisting of the upper torso	Twisting of the upper torso	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs
2	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs	Twisting of the upper torso	Twisting of the upper torso	Twisting of the upper torso
3	Upper body pendulum action	Upper body pendulum action	Body moving laterally	Body moving laterally	Body moving laterally
4	Bouncing motion arms in conjunction	Bouncing motion arms in conjunction	Bouncing motion arms in conjunction	Bouncing motion arms in conjunction	Initiating Skipping Action
5	Lower Body Pendulum	Lower Body Pendulum	Lower Body Pendulum	Lower Body Pendulum	Lower Body Pendulum
6	Twisting dance move with asynchronous lower leg		Twisting of the upper torso	Arm Flexion and Bouncing action	Twisting of the upper torso
7					Upper Twisting no arms

Cumulative Frontal Martian Walking

	2MPH	3MPH	4MPH	5MPH	6MPH
1	Foot Shuffle stepping action	Foot Shuffle stepping action	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs
2	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs	Foot Shuffle stepping action	Foot Shuffle stepping action	Foot Shuffle stepping action
3	Flexion and extension of the knee, arm opposition and Hip flexion extension	Flexion and extension of the knee, arm opposition	Flexion and extension of the knee, arm opposition	Flexion and extension of the knee, arm opposition	Flexion and extension of the knee, arm opposition
4	Bouncing motion arms in conjunction.	Bouncing motion arms in conjunction.	Bouncing motion arms in conjunction.	Bouncing motion arms in conjunction.	Initiating Skipping Action
5	Legs opposition arm slight opposition	Legs opposition arm slight opposition	Legs opposition arm slight opposition	Legs opposition arm slight opposition	Legs opposition arm slight opposition
6	Asynchronous leg kicking action		Asynchronous Leg kicking action	Lower body bouncing action	Asynchronous Leg kicking action
7					Shuffles step with arm opposition

Cumulative Sagittal Martian Running

	2MPH	3MPH	4MPH	5MPH	6MPH
1	Twisting of the upper torso	Twisting of the upper torso	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs
2	Running in place side to side	Traditional Running Gait, arms opposite legs	Twisting of the upper torso		Twisting of the upper torso
3	Bouncing motion arms in conjunction	Leg Scissoring action	Bouncing motion arms in conjunction	Leg Scissoring action	Bouncing motion arms in conjunction
4	Traditional Running Gait, arms opposite legs	Initiating Skipping Action	Upper body pendulum	Initiating Skipping Action	Upper body pendulum
5	Lower body Pendulum	Lower body Pendulum	Lower body Pendulum	Lower body Pendulum	Lower body Pendulum
6	Dramatic rotation upper body around central axis	Dramatic rotation upper body around central axis	Dramatic rotation upper body around central axis	Rotation upper body around central axis	Rotation upper body around central axis

Cumulative Frontal Martian Running

	2MPH	3MPH	4MPH	5MPH	6MPH
1	Foot Shuffle stepping action	Foot Shuffle stepping action	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs	Traditional Running Gait, arms opposite legs
2	Asymmetric stepping action	Traditional Running Gait, arms opposite legs	Foot Shuffle stepping action	Traditional Running Gait, arms opposite legs	Foot Shuffle stepping action
3	Bouncing motion arms in conjunction.	Landing from the Skipping action	Bouncing motion arms in conjunction.	Initiating Skipping Action	Bouncing motion arms in conjunction.
4	Traditional Running Gait, arms opposite legs	Initiating Skipping Action	Lower legs knee flexion and extension hip action with no arm movement	Initiating Skipping Action	Lower legs knee flexion and extension hip action with no arm movement
5	Traditional Running gait with opposition	Traditional Running gait with opposition	Traditional Running gait with opposition	Traditional Running gait with opposition	Traditional Running gait with opposition
6	Arms opposition Twist dance action	Arms opposition Twist dance action	Arms opposition Twist dance action	Arms opposition Twist dance action	Arms opposition Twist dance action

Appendix B

Walking Effect Sizes ES=Point Estimate (95% CI: Lower - Upper)

Mode	Comparison	CS1	CS2	CS3	CS4	CS5
2 MPH	Earth Vs. Lunar	-.050 (-.616-.517)	3.268 (1.798-4.717)	.900 (.209-1.562)	-1.224 (-1.967--.450)	-.485 (-1.076-.125)
3 MPH	Earth Vs. Lunar	1.836 (.877-2.767)	.056 (-.512-.621)	.631 (-.004-1.242)	-.260 (-.830-.322)	-.400 (-.981-.198)
4 MPH	Earth Vs. Lunar	3.231 (1.775-4.666)	-.255 (-.825-.326)	-.278 (-.849-.306)	-.077 (-.642-.492)	.802 (.133-1.444)
5 MPH	Earth Vs. Lunar	1.409 (.583-2.205)	.055 (-.512-.620)	-.151 (-.717-.421)	.683 (.039-1.303)	-.425 (-1.009-.176)
6 MPH	Earth Vs. Lunar	1.155 (.325-1.950)	-.021 (-.640-.600)	-.132 (-.751-.494)	-.981 (-1.728--.200)	-.103 (-.722-.522)
2 MPH	Earth Vs. Mars	2.143 (1.081-3.179)	.001 (-.565-.567)	-.264 (-.834-.318)	-1.309 (-2.076--.512)	-.623 (-1.233-.010)
3 MPH	Earth Vs. Mars	1.272 (.485-2.028)	-.313 (-.887-.274)	.635 (.000-1.247)	-.661 (-1.277--.021)	1.416 (.587-2.214)
4 MPH	Earth Vs. Mars	1.850 (.886-2.785)	-.278 (-.849-.305)	.473 (-.135-1.062)	.978 (.268-1.658)	.070 (-.498-.635)
5 MPH	Earth Vs. Mars	1.259 (.476-2.012)	-.098 (-.663-.471)	-.084 (-.649-.484)	2.423 (1.263-3.558)	-1.660 (-2.534--.757)
6 MPH	Earth Vs. Mars	.804 (.068-1.508)	-.019 (-.638-.602)	-.772 (-1.468--.043)	.119 (-.506-.738)	-.178 (-.798-.452)
2 MPH	Lunar Vs. Mars	.201 (-.375-.769)	-.728 (-1.356--.074)	-.585 (-1.189-.041)	.231 (-.348-.799)	-.486 (-1.077-.124)
3 MPH	Lunar Vs. Mars	-.409 (-.991-.190)	-.682 -1.302--.038)	-.152 (-.718-.421)	-.414 (-.997-.185)	1.717 (.796-2.608)
4 MPH	Lunar Vs. Mars	-.083 (-.648-.486)	-.606 (-1.213-.024)	.499 (-.113-1.091)	-.140 (-.706-.432)	.456 (-.149-1.044)
5 MPH	Lunar Vs. Mars	-.593 (-1.198-.035)	-.126 (-.691-.445)	.094 (-.475-.659)	.399 (-.198-.980)	.019 (-.547-.585)
6 MPH	Lunar Vs. Mars	-.210 (-.778-.367)	.158 (-.415-.724)	-.315 (-.889-.272)	.292 (-.293-.864)	.355 (-.237-.932)

Running Effect Sizes ES Point Estimate (95% CI: Lower - Upper)

Mode	Comparison	CS1	CS2	CS3	CS4	CS5
2 MPH	Earth Vs. Lunar	.280 (-.360-.905)	-.271 (-.896-.368)	-.177 (-.798-.452)	.731 (.012-1.419)	.678 (-.029-1.356)
3 MPH	Earth Vs. Lunar	.622 (-.074-1.289)	2.722 (1.326-4.090)	-.308 (-.935-.336)	-.830 (-1.539--.088)	.976 (.196-1.722)
4 MPH	Earth Vs. Lunar	2.106 (.950-3.229)	.679 (-.028-1.357)	-.435 (-1.075-.227)	-.869 (-1.587--.117)	.892 (.134-1.616)
5 MPH	Earth Vs. Lunar	.848 (.101-1.561)	.611 (-.082-1.277)	.448 (-.215-1.089)	-1.035 (-1.796--.239)	.391 (-.263-1.026)
6 MPH	Earth Vs. Lunar	1.270 (.404-2.098)	.359 (-.292-.990)	1.515 (.570-2.423)	-.440 (-1.081-.222)	.186 (-.445-.807)
2 MPH	Earth Vs. Mars	.293 (-.292-.866)	-.248 (-.817-.333)	.113 (-.458-.678)	.050 (-.517-.615)	.555 (-.066-1.155)
3 MPH	Earth Vs. Mars	-.009 (-.575-.557)	.816 (.144-1.461)	.771 (.109-1.407)	-.418 (-1.001-.182)	.444 (-.160-1.029)
4 MPH	Earth Vs. Mars	.394 (-.203-.974)	.712 (.062-1.337)	.838 (.161-1.487)	-.647 (-1.261--.010)	.031 (-.536-.596)
5 MPH	Earth Vs. Mars	.862 (.180-1.516)	.067 (-.501-.632)	1.307 (.510-2.074)	-.852 (-1.505--.172)	-.042 (-.607-.525)
6 MPH	Earth Vs. Mars	.973 (.265-1.653)	.042 (-.525-.607)	2.476 (1.297-3.630)	-.294 (-.867-.291)	.111 (-.459-.677)
2 MPH	Lunar Vs. Mars	.120 (-.506-.739)	.003 (-.617-.623)	.205 (-.427-.826)	-1.355 (-2.210--.463)	-.152 (-.772-.475)
3 MPH	Lunar Vs. Mars	-.419 (-1.057-.240)	1.048 (.248-1.812)	-.877 (-1.598--.123)	1.142 (.288-1.767)	-.930 (-1.664--.163)
4 MPH	Lunar Vs. Mars	-1.225 (-2.040--.374)	-.052 (-.671-.569)	.866 (.115-1.584)	.261 (-.377-.885)	-1.242 (-2.063--.385)
5 MPH	Lunar Vs. Mars	-.294 (-.921-.348)	-.402 (-1.039-.254)	1.173 (.337-1.973)	.743 (.021-1.434)	-.380 (-1.014-.273)
6 MPH	Lunar Vs. Mars	-1.144 (-1.935--.317)	-.177 (-.797-.453)	.525 (-.152-1.177)	.154 (-.474-.773)	-.189 (-.809-.442)