

**An Investigation of Adjustable Microgravity Workstation Anthropometrics
Through Analyses of
Neutral Body Posture and Lower Leg Muscular Fatigue Characteristics**

by

Theodore Pashley McDade

Bachelor of Science, Electrical Engineering, Clarkson University
(1985)

Submitted in partial fulfillment
of the requirements for the degree of

**Master of Science in
Aeronautics and Astronautics**

at the

**Massachusetts Institute of Technology
February 1989**

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ABSTRACT

This research investigates the use of adjustable worksurfaces for microgravity. The tasks being performed in space are becoming longer duration, stationary tasks, such as the scientific monitoring typical of Spacelab flights of the Space Shuttle. It is thus becoming more critical to have the task implements proximal to each individual's zero-g neutral posture hand positions. Performing a long duration task in a posture far from this ideal requires fatiguing isometric contractions, and indeed, a number of astronauts do complain of marked fatigue of the anterior lower leg muscles when performing tasks in foot-loop restraints. The neutral body posture is analyzed by a unique approach in this study. Anthropometric measures were obtained from a group of experimental subjects, and, in combination with the Skylab data of the zero-g posture, are used to predict the theoretical positions of each of the major joints of the body, relative to the ankle, for foot-restrained individuals in weightlessness. These analyses support a hypothesis that, the variability of hand positions in zero-g neutral posture is greater than that of the one-g overall heights, thereby suggesting the need for adjustability in microgravity workstation design. In addition, analysis of the distances of the major bodily joints from the mean values for those joints, suggests a means for understanding the degree of fatigue induced in the various skeletal muscle sets, during tasks requiring other than the neutral posture, and provide a basis for a focus on the anterior lower leg muscles for further study.

Finally, by utilizing photographic recording of posture, this study has demonstrated that the neutral posture of underwater buoyancy is a highly similar analogue to that of microgravity, and is thus an effective means of simulating long duration task conditions of orbital spaceflight, for research. This technique was utilized in a comparison of the fatigue levels at adjustable and fixed worksurfaces, for subjects performing keyboard entry tasks underwater, by the recording of electromyographic (EMG) signals from the Tibialis anterior muscle. The median frequencies of EMGs have been shown by past research to decline with fatigue, and such declines were indeed produced. Although inconclusive, the results are suggestive for future research.

Thesis supervisor: Steven R. Bussolari, Ph.D.

Title: Assistant Professor of Aeronautics and Astronautics

Acknowledgements:

This research stemmed from ideas which I developed while involved with the NASA/MIT Mental Workload and Performance Experiment (MWPE), a project investigating the use of various computer input devices at an adjustable worksurface, for weightlessness. I was primarily involved with the anthropometrics of the workstation, and became intrigued by the repeated comments of astronauts and engineers, in various meetings, that lower leg fatigue was indeed a problem, and the associated effort, a significant distraction. I hope that I've added a unique approach to these concepts, and that this research may lead to further investigation. I appreciate the development of the MWPE research by co-investigators, Byron Lichtenberg, Payload Specialist Astronaut at NASA and PSI, and Prof. S.R. Bussolari, at MIT, since it is that overall concept, from which my ideas came.

I thank Prof. Bussolari for taking the time to read and edit my thesis, and providing statistical advice, fulfilling that role of a graduate student's thesis advisor. I also thank the Man-Vehicle Laboratory at MIT, for... allowing me to pursue my ideas there. That, as well as an office, were provided. Ideally, ideas are not merely blessed with existence (preliminary funding) in an academic research laboratory, but are nurtured by mentors through the tutelage of curious and eager proteges, during the subtle process of molding a graduate student's development in an academically stimulating environment. Ideally, perhaps.

I am greatly indebted to the many individuals who assisted with the actual pool-tests of the fatigue experiments, and answered questions during later analysis. This was, from the start, a bit of a "one man show" due to the lack of any provision of support or guidance from the usual sources. Nevertheless, a number of people volunteered their time and efforts on my behalf. My experimental subjects (who I guess are officially supposed to remain anonymous) endured extended periods of cold in the water, for a simple thank you with dinner. Brad McGrath and Tom Mullen ran to get magnetic tapes prior to a shop closing. Mark Shelhamer made a switch to trigger the computer acquisition of data. Dan Merfeld literally stayed up half the night to modify his acquisition system for my purposes, seeing that I needed a back-up for data storage. As it turned out, I used that as my primary, and it saved weeks of data conversion, I'm sure. Sherry Modestino later helped me solve a computer printing difficulty. And others simply said, "Hey, if you need anything, don't be afraid to ask," as I rushed around in that amazingly desperate week which led up to the pool-tests. All this rallying to help me, suddenly stunned my weary soul that had ceased to expect even the usual formal assistance. I truly thank them for that special moment.

I am extremely thankful to C.J. De Luca, of the Boston University Neuromuscular Research Center, for being supportive of my research ideas, and allowing the inter-university exchange of ideas. I especially want to thank Prof. Serge Roy and scientist Donald Gilmore, of that lab, who showed so much enthusiasm for those ideas, and provided so much of their time and expertise. My experiences with the laboratory with which I was actually affiliated, where one might expect

such support, were so markedly different, that I found your effort truly remarkable. I would also especially like to thank Anthony Rodrigues, who spent many hours in the lab with me, modifying the electrode and preamp package for my waterproof specifications. True to your word, you provided the "magic" to make it work, and of course, your constant sense of humor, advice on women, etc., kept me in a good mood even when I might otherwise have dwelled on things annoying me at MIT. It was a true pleasure working with all of you, and I can honestly say, I could not have accomplished the fatigue portion of the research without your assistance. I only wish that my situation and support outside of your lab had been such that I could have worked even more with you, to pursue the fatigue experiments as rigorously as we discussed.

I would also very much like to thank Prof. David Akin, Mary Bowden, and the members of the MIT Space Systems Laboratory, whose experience with pool-tests helped me accomplish mine. In addition to reserving a corner of the pool for my research, you always made an effort to provide whatever equipment or assistance was necessary. This was perhaps in part due to the obvious doubts (I saw the raised eyebrows!) that I'd actually get EMG recordings from surface electrodes on submerged divers on my first attempts! I thank you, and I truly enjoyed the friendliness of your lab.

Finally, I'd like to thank all of the friends I've made while at MIT, who've helped me to keep smiling. As Dan Merfeld once said, we really have a great bunch of students at the MVL. You're certainly one with whom I've had some great times, Dan. Our trip to the arctic with Dave, was great; I know we'll stay in touch and have more fine adventures in the future ole' friend (in the arctic, winter camping with our pal Jack Daniels, in pubs, etc.)! And Braden McGrath, I must say that we've had some great times and conversations (Tuckerman's, Walden, with "Bessie" on the road, over a scotch on my b-day, etc.). Do you know how we ever got the unfair(?) reputation of being so wild and crazy, like trouble waiting to happen?! You're a great friend, with a very similar outlook on life, and I know we'll think of ways to provide more episodes for our friends' exaggerated stories! Now that this research isn't running my life, I think it's time I get back to my old tricks! Mark, my fellow night-owl (kindred spirits, or else just messed up circadian rhythms!), I was glad to see that other humans also walk the Earth after the "bewitching hour"... voluntarily... to do work! Also, you do a great Dave Letterman impression, some elements of which are so subtle, I thought they were you at first, and then I'd hear Letterman and think, "Gee, Mark does that too... oh, wait a minute...!" Dava, I'm glad I got you skiing at Tuckerman's Ravine; I knew you'd love the headwall, but I wasn't prepared to see the beauty with which you ski! Also, thanks for the great swims at Walden. And oh yes, always remember, "When I ask you how your research is going, what I really mean is... I lov..." ... well, you know! Tom, I still think of you gripping that pitcher of beer from Dan's party, saying once or twice (or a hundred times!)... "Well aaall right!" Also, thanks for the football match, and giving me a ride home (?) from Kathy's! Ilya, thanks for the good talks... I've enjoyed getting to know you that way. Also, don't forget our wagers... marksmanship,

financial success, and whether I'd finish this!! Andrew & Aude, thanks for the advice (and words of encouragement!!), friendship, and parties. You're a great couple. Divya, I enjoyed sharing the office with you. We had some great talks about MIT! Gail, I've only gotten to know you a bit, since I've been a "ghost" at the MVL since you've been here, but I'm sure I'll stop by the lab for more dart games! Cheryl, I was told by Tom and Brad that you're in lust with me, but you really must be strong about these things dear girl! Finally, Sherry, I consider you among the grad. students at heart, and you make the lab a gentler, better place.

Other people I've met while at MIT, not affiliated with the MVL, have added to the whole experience of the last couple of years. Dave Slobodin, you can be sure I'm going to call you when I go to the arctic again; it's rare to find people who get the same twinkle in the eye that I do when seeing a mountain, or glacier, or Saxifrage, or just talking about them!! Charlie Freeman, we've done some beautiful climbs, and as I've said before, we ought to get on a big Alaskan, Andean, or Himalayan peak together sometime. Say the word, and I'll tie-in to your belay! Brian Sabowitz of PSI, I appreciated your advice on many occasions, on everything from information associated with Shuttle flights, to surviving as a grad. student, to dating! I knew we'd get along well when we had the biggest grins, and loudest laughs, during our zero-g parabolic flight (and hours later!) with the MWPE equipment on the NASA KC-135. Finally, Julie, Rich, Wendy, Lucy, Yusuf, Josh, Lisa, Jo Lee, Kathy, and Brian, and any others I've shared a beer and a laugh with, you've each been part of some great times along with some of the above people. Thanks to all of you for keeping my spirits up, during some trying times!

(Please note...

Any silliness included in these acknowledgements is due to... lack of sleep... and caffeine... !!)

Dedication:

This thesis is dedicated to my parents, Harry C. McDade, M.D., and Constance McDade, R.N., who have encouraged me to follow my dreams, and have always been an inspiration to me, and to my best friend and sister, Donna Bain, whose excellence has always been my model. These individuals are very dear to me, and their support has helped me to maintain my sanity! I also dedicate this to my best pal Thor, for always lifting my spirits by greeting me with wagging tail and an old hiking sock, and to my grandfather, Bertram Pashley, whose companionship I enjoyed when I'd get home from MIT for a visit. I wanted to think they'd always be there when I'd return home, but ultimately, separation is inevitable in this strange life. I'll miss them both. I think of you Thor, when thunder crashes.

Finally, I would like to dedicate this research to the lost crewmembers of the Space Shuttle Challenger, flight 51L, 28 January, 1986, whose mutual Tsiolkovskian dream, I continue to share: Gregory Jarvis, S. Christa McAuliffe, Ronald McNair, Ellison Onizuka, Judith Resnik, Francis Scobee, and Michael Smith.

*** * *** * *** * *** * ***

The Earth is the cradle of mankind, but one cannot live in the cradle forever.

Konstantin Eduardovitch Tsiolkovsky (born 1857)

*** * *** * *** * *** * ***

If all men could float above the Earth,
to see the small round globe,
and to realize its finitude --
perhaps then, we would hesitate
to mar its magnificence.

(Ted McDade, 1981)

*** * *** * *** * *** * ***

" You know, I've always been a dreamer ..."

-the Eagles

" Ka-Ka-Ka-Ka-Ka-Ka-Katmandu ...

Up to the mountains is where I'm goin' to ...

If I ever get out of here, I'm goin' to Katmandu..."

-Bob Seger

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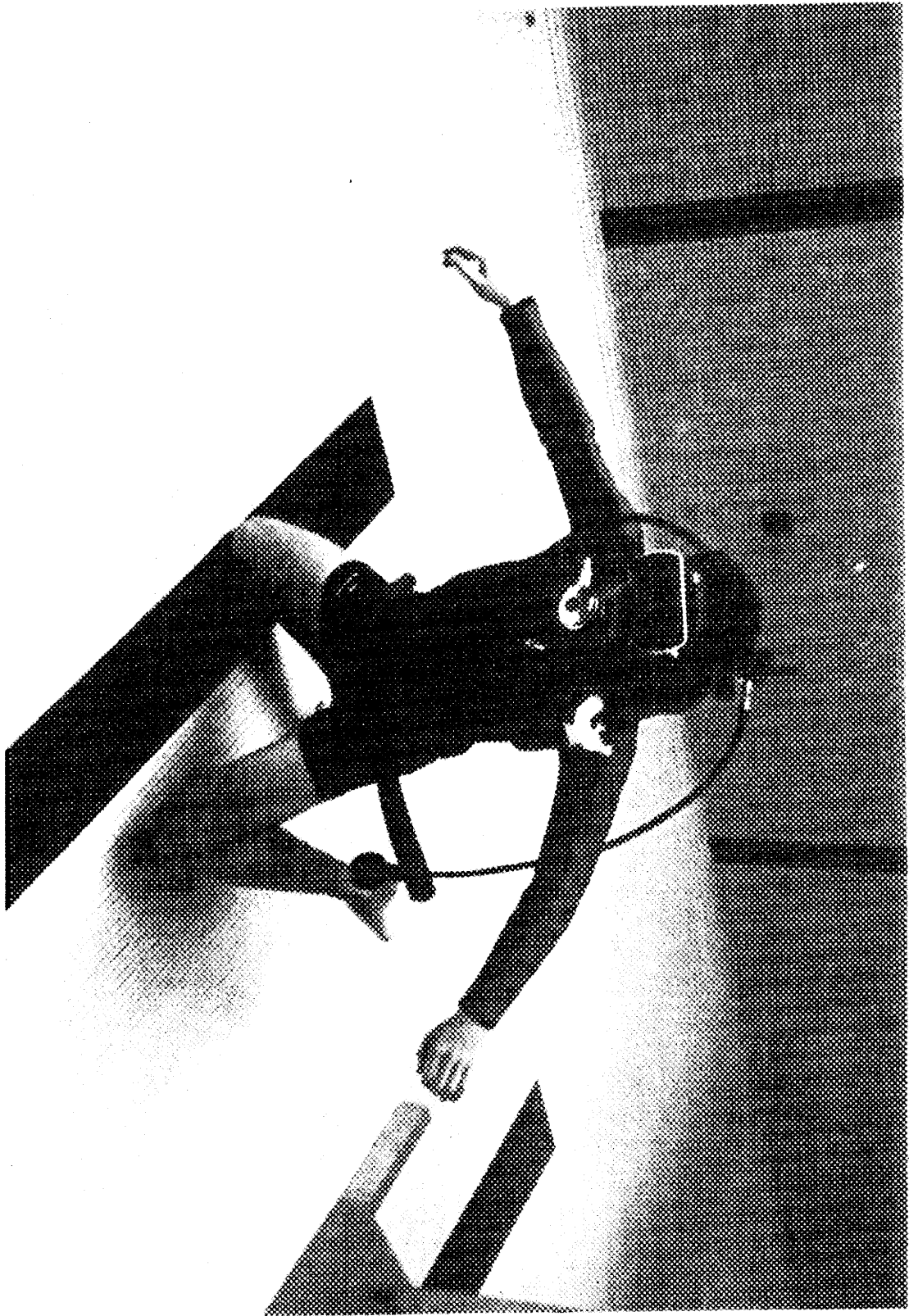
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Chapter 1

Introduction and Motivation for the Research

1.1 History and Background

Weightlessness: Early Concepts

Even long before man had acquired the knowledge and skills to leave Earth's atmosphere, scientists and philosophers were pondering the effects of such an excursion upon the human body. Assuming that such a trip was not too violent to be survivable, and that one could provide a spacecraft atmosphere with suitable temperature, pressure, and partial pressures of oxygen, carbon dioxide, and water vapor, the great reduction in the gravitational force acting upon the occupants of the craft was the remaining point of concern.

One of the first to conceptualize the situation this would produce for a human passenger, was a Russian high school teacher, named Konstantin Eduardovich Tsiolkovsky. In 1895, he wrote: "We shall not have weight, only mass. We can hold any mass in our hands without experiencing the slightest weight... Man does not press himself against anything and nothing presses against him... There is no top or bottom."¹

It was believed by some that weightlessness would not be survivable, and that our phylogenetically one-gravity bodies, could not adapt to zero-gravity. Predicted effects of weightlessness included cardiac arrhythmias, bone demineralization, inability to swallow, faulty digestion, inability to sleep, euphoria, hallucinations, disorientation, nausea, poor muscular coordination, and many others.²

As astronaut Michael Collins wrote in Carrying the Fire, the "prophets of doom and gloom" assumed that "even a few seconds of weightlessness would impair bodily functions... the heart and lungs would become confused at best, or incapacitated at worst, and the efficient human machine would quickly grind to a halt."³ Many of the predictions had theory to support them, so it was likely that even if weightlessness was survivable, physiology would be somewhat affected, and the ability to perform any useful tasks under such circumstances, was even more questionable.

Early Human Experience with Weightlessness: Direct and Indirect

The determination of the validity of any of the predicted effects of weightlessness, required the achievement of that condition by humans, or at least by a living animal. The achievement of that required a long wait for the necessary technology. Even in free-fall, the Earth's atmosphere produces sufficient drag to yield a terminal velocity for the body, so skydiving with parachutes from balloons and aircraft can not provide true weightlessness. The only way to achieve weightlessness within the Earth's atmosphere, is within a vehicle accelerating along the gravity vector at $-g$ m/sec.², which provides protection from aerodynamic drag by serving as a windbreak for the occupants. It was not until the 1940's, during World War II, that weightlessness was first achieved in that way. High performance German fighter planes were used to attack Allied bombers, by firing during sharp pull-ups from high speed dives, after which a subsequent steep

dive was made to escape Allied gun fire. Those aircraft, which were structurally capable of withstanding the high forces of pull-out from those dives, provided short periods of zero-gravity during the evasive push-overs that followed. Although the pilots reported visual disturbances, leg weakness, and reduced motor control, some of them found it quite enjoyable once they were used to it. A Dr. Hubertus Strughold attempted this after having anaesthetized his buttocks with novocaine, and found it to be much more unpleasant when tactile cues were missing. Later, in 1950, German scientists in the United States developed a technique whereby upwards of thirty seconds of subnormal gravity could be achieved by flying Keplerian trajectories (parabolic arcs). In 1951, American military test pilots Scott Crossfield and Chuck Yeager flew these profiles, reporting "befuddlement", disorientation, and a tendency to over-reach with arm movements, but noting the ability to handle it well on subsequent flights. Later, tests on animals and humans were performed aboard larger aircraft. These parabolic flights have since become a standard technique for research and astronaut training, aboard NASA's modified KC-135 aircraft, that are capable of 20 to 30 seconds of near zero-gravity.⁴

It thus appeared that man could survive and perform manual tasks in weightlessness, at least for a short time. Sub-orbital and orbital rocket flights with animals on board, were the next step, to determine long duration effects. Early tests of V-2 rockets, in America in the late 1940's and early 1950's, utilized mice and Rhesus monkeys, and demonstrated via biotelemetry that they survived the zero-g phases of flight; however, parachute and recovery failures led to accidental

death of the passengers. The first animals to be successfully recovered were monkeys Patricia and Michael, and two mice, on 21 May, 1952, and they suffered no adverse effects. The Soviet Union launched a dog, Laika, aboard Sputnik II on 03 November, 1957, and although telemetry demonstrated good health, there was no plan to recover the dog, and it was "put to sleep" by asphyxiation after a week, eventually burning up in the atmosphere when falling out of orbit. The Soviets later recovered two dogs, Strelka and Belka, as well as several mice, hundreds of fruit flies, and some plants and bacteria, after 24 hours in space, in 1960. In 1961, Americans successfully recovered chimpanzees Ham and Enos from separate flights. Not only had they shown no ill side-effects, but as trained, intelligent primates, they had been monitored performing tasks throughout the flight, and "displayed excellent psychomotor performance and physical reaction...."⁵ These flights, as well as underwater neutral buoyancy simulations, demonstrated that although some of the predicted effects of weightlessness were correct (such as mineral loss and vestibular effects), the absence of gravity was not only survivable for moderate lengths of time, but appeared to be relatively comfortable, and such that normal manual and mental tasks could be performed. There remained little reason to suspect that human space travellers would not be able to perform useful work.

Working in Weightlessness: Experience from Manned Spaceflights
(Mercury, Gemini, and EVAs)

By the time of the first manned flights into space, there was sufficient evidence to rule out many of the more life-threatening effects which had been predicted for weightlessness. Although many of those concerns may seem extreme in hindsight, it was hard to predict the response of complex interacting organ systems to the removal of gravity. Indeed, many of the less extreme predictions of effects have been demonstrated to be valid, especially over long term exposure, and more complicated effects, such as those upon immune response, embryo development, and others, still require much more study. What had not yet been shown, however, was the effect of weightlessness upon the ability of a human space traveller to efficiently perform work.

On 12 April, 1961, Yuri Gagarin became the first man to reach space, when he orbited the Earth for 108 minutes, aboard the Soviet Union's Vostok I spacecraft. Shortly thereafter, on 05 May, 1961, Alan B. Shepard made a 15 minute and 22 second sub-orbital flight aboard America's Freedom 7 spacecraft, the first of the Mercury series which continued until 16 May, 1963.⁶ The astronauts and cosmonauts of these early flights returned in good health. In addition, they demonstrated that humans were capable of performing complex manual and mental tasks for extended periods in zero-gravity. Indeed, it appeared that one could accomplish almost anything that could be done on Earth, provided, of course, that the task itself did not require gravity (such as pouring fluids). Yet the Mercury spacecraft were exceedingly small, a

fact which is strongly implied by the term "insertion", which was used to describe the process by which technicians sealed the astronauts into the module. The Gemini spacecraft, were little roomier for their two passengers. Thus, knowledge of coordinated movements of the body in weightlessness was limited. The astronauts were strapped into seats among consoles and controls; only small arm movements were possible.

The first information of the ability of humans to perform the coordinated movements necessary for truly complicated manual tasks, resulted from the early excursions outside of the spacecraft. The first "spacewalks" by Soviet Alexei Leonov, on 18 March, 1965, and American Edward H. White, on 03 June, 1965, were extremely successful, and demonstrated that useful work could be accomplished while floating freely from the spacecraft during extravehicular activities (EVA). Nevertheless, there was evidence that some tasks would be more difficult as a result of the weightless condition. During his EVA from Gemini 4, White used a gun-like maneuvering unit from which he fired propellant in the opposite direction to that which he wanted to move. This worked very well, however, the fuel supply was quickly exhausted, and White soon discovered the difficulty of moving without it. Reclosing the hatch proved to be no easy task either.

White ran out of compressed oxygen for his maneuvering gun... learning the difficulties associated with tether dynamics. With no other means of attitude control, he had little alternative but to use the long, snaking line to pull himself around. In the weightless void it was an almost impossible task; like some bob-weight dancing around on the end of an elastic cord, White was going everywhere but in the actual direction he wanted to... But it was an exhilarating experience and the capsule communicator had been trying for a few minutes to get the attention of two very pre-occupied pilots.... Just 22 minutes after opening the hatch, White was back on the seat preparing to slide down into the

spacecraft. But there were problems. Reluctant to pull to, the hatch was difficult to bring down from its open position, and when it was back in place the locking mechanism refused to function. Each time White tried to apply torque to the latch, he succeeded only in lifting himself back up out of the seat. McDivitt had to hold on to White's legs to prevent him drifting up... The simple action of closing the hatch was the most strenuous part of the entire EVA. During most of his space walk, the Gemini pilot had a heart rate of between 145 and 155 beats per minute; closing the hatch down raised his heart to 180.... Inside, White was wet with perspiration, his face streaming with beads of moisture.... It certainly seemed that White became exhausted earlier than expected, only enthusiasm preventing him from recognizing the self-induced symptoms.⁷

This was the first piece of evidence, at least in the American space program, that in order to perform certain tasks in space, careful design of the implements involved, and proper techniques of using them, would be absolutely necessary. The inertia of the Gemini 4 hatch, which obediently followed the laws of physics described so many years before by Newton, resisted any force applied to close it. The theorized equal and opposite force to that which was applied, faithfully lifted the astronaut back out of the capsule, while the hatch refused to budge. Working in space requires consideration of those laws of physics with a bit more concern than is usually necessary on Earth.

As described by Michael Collins, who was at the time of Gemini 4 in charge of pressure suit development and EVAs, the problems associated with working during EVA were still not fully appreciated, since White's EVA tasks had been relatively simple.⁸ They would soon become more apparent on the next attempts. Portions of the EVA activities for Gemini's 9, 10, and 11 all had to be cancelled. On the Gemini 9 EVA, Gene Cernan's visor completely fogged up, forcing him to

return to the module. On that of Gemini 10, Michael Collins successfully removed a micrometeorite detection package from a nearby Agena target vehicle, but had found the task awkward enough without a way of restraining himself, that he chose not to attempt to put a new package in its place when the Agena began to tumble a bit. On his EVA, Dick Gordon succeeded in tethering an Agena to the Gemini 11 spacecraft, but became so exhausted that the remainder of his EVA experiments had to be cancelled.⁹ The common denominator of the problems for all of these tasks was lack of control of orientation when trying to perform them.

... without proper handholds, foot restraints, and other attaching devices, the space walker inside his pressure-suit burned up tremendous amounts of energy just trying to keep his body in proper position relative to the job at hand, with nothing left over for productive work. It became obvious that his heavy workload was a by-product or consequence of weightlessness, rather than a function of weightlessness itself... Gene's [Cernan] difficulty caused consternation among the equipment designers, and they cast a jaundiced eye on the EVA plans of later flights.¹⁰

The lessons learned through the previous EVAs were used to design some tests for the Gemini 12 EVA. On that spacewalk, Buzz Aldrin systematically tested and compared various restraining devices, while performing tasks for five and a half hours. Although his was considerably longer duration than any of the previous EVAs, Aldrin struggled little, was able to rest, and "had no difficulty whatsoever."¹¹ Proper restraining devices, and training, appeared to be the solution to the difficulties.

Working in Weightlessness: Experience from Manned Spaceflights

(Apollo, Skylab, Space Shuttle, and Spacelab)

Although the Apollo spacecraft that took astronauts to the moon and back were not particularly roomy, for they had to be small to reduce fuel requirements, there was a bit more space inside for their three man crews. Particularly for the astronauts who also had experience in the Mercury and Gemini projects, the maneuverability inside the Apollo spacecraft took some getting used to. Rather than being squeezed between console and couch, there was a little bit of room to move, which yielded entirely new insights regarding working in weightlessness. The Gemini era had demonstrated how difficult it could be to maintain a desired orientation during EVA; but that had been for short periods of time, in a bulky spacesuit, doing thrilling activities outside of the spacecraft. The ability to move about a bit in the shirt-sleeve environment of the Apollo modules meant that those same difficulties were now a constant companion, and clever techniques had to be developed to live comfortably in space.

This can't be the same command module I spent so many hours in at Downy and the Cape.... As I slide over the center couch into the lower equipment bay, my legs unexpectedly curl around into the tunnel ("up," that would be on earth), so that instead of finding my face against the navigator's panel, I discover that I'm looking the other way, back toward the side hatch and its circular window. It takes some getting used to. The tunnel on earth is simply waste space overhead, but now it turns into a pleasant little nook... I find that the corners and tunnels have a lot to recommend them because to stay in place, one must wedge himself between surfaces or else use something like a lap belt to keep from floating off and banging into equipment or compatriots.¹²

Sometimes, however, those clever tricks of wedging oneself didn't provide quite enough control for a task requiring precise and steady positioning. Aligning one's eye with a sextant during celestial navigation was one such task.

I... swing around into position at my navigator's console in the middle of the lower equipment bay. I unstow and install two eyepieces, one for the sextant, and one for the telescope, and I attach a portable handhold on either side of them. Handholds I need, and I let Neil and Buzz know it. "I'm having a hell of a time maintaining my body position down here; I keep floating up."¹³

Even with handholds, this task was difficult to accomplish. It was thus becoming evident that merely having some form of restraint available for the astronauts was not enough; instrumentation and workstations had to be designed to take full advantage of restraint devices.

What was suggested by experience in the Apollo spacecraft, became obvious aboard the Skylab, an orbiting space habitat and laboratory, with much more available room. Whereas the Mercury, Gemini, and Apollo spacecraft had only between 1-8 m.³, the large cylindrical Orbital Workshop had approximately 294 m.³ of useable space, a beneficial feature considering the fact that the three three-man Skylab crews spent 28, 59, and 84 days in residence there.¹⁴ Having all of that room to move around in certainly helped reduce the stress of being confined for such an extended period of time, however, it also made task performance a bit harder.

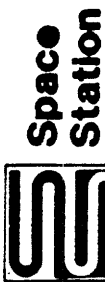
All of the Skylab astronauts experienced the sometimes pesky, sometimes pleasant aspects of living and working in zero-g. It is generally agreed that it took them about a month to get the hang of it. Even the simplest tasks had to be learned.... They learned to put on their shoes last because this was the hardest part of dressing. Without

gravity, they had to force themselves to bend and use their stomach muscles to pull their feet up. Sometimes this included a backward somersault before the shoes were tied. Their canvas-top gym shoes had aluminum soles coated with rubber to which they could fasten... cleats. Many parts of Skylab's floor had triangular metal grids to which the cleats could be attached... In order to stay put, they wedged their bodies into corners or crevasses to free their arms for working.¹⁵

The roominess of the Skylab provided the first real opportunity to observe the shape of the human body, without a confining pressure suit, when floating freely in zero-gravity. In addition to the anthropometric changes in circumferences due to fluid shifts and diuresis, a very distinctive posture was noted (Thornton, Hoffler, and Rummel, 1977), confirming what had been theorized from brief observations on parabolic flights (Simons, 1964).¹⁶ Lacking gravity to pull down, thereby providing limb weight and spinal curvature, the body tended to reach a configuration when it was relaxed, which was determined by muscle tensions. The difference between the tensions in agonist-antagonist muscle sets positioned the limbs at definite angles to the body.

This Zero-Gravity Neutral Body Posture, shown in Figure I,¹⁷ is a semi-fetal position, bent forward somewhat at the waist, with the arms flexed placing the hands forward of the shoulders, and the knees flexed with the feet in moderate plantarflexion (pointing the toe of the foot away from the lower leg). Analyses of the anthropometric data from the Skylab crews indicated that the neutral posture articulation angles at the joints of the body are relatively predictable. Since they arise from the balance of muscle tensions, it is not surprising to find that the articulation angles are similar among individuals of similar

0-g Neutral Body Posture



NASA
SP-1113

Male Angular Relationships

Profile View

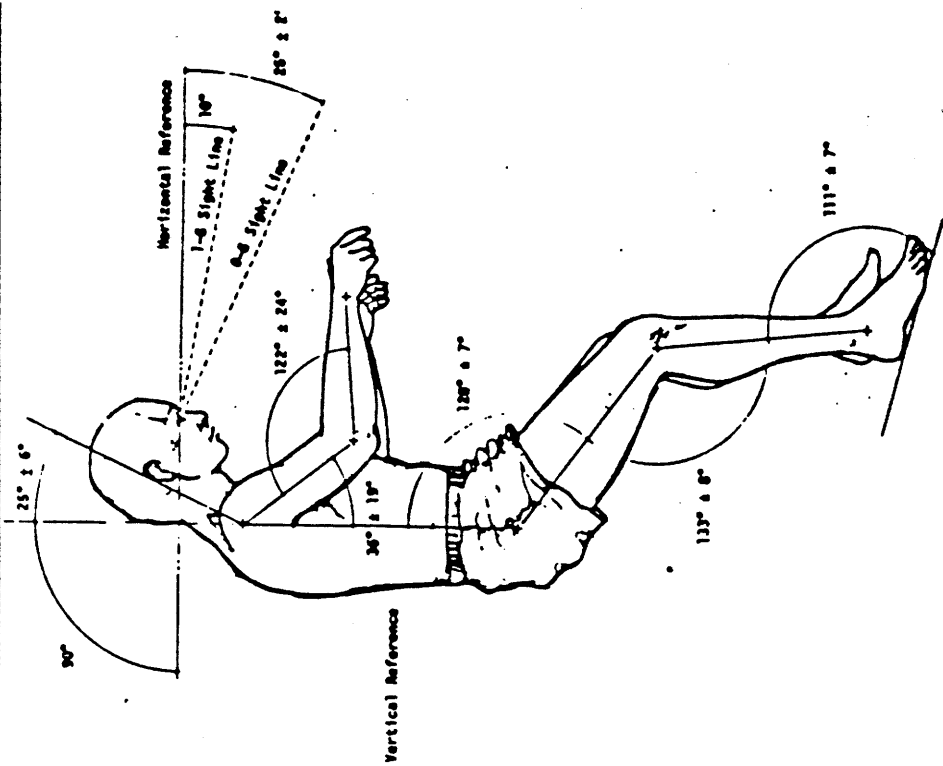


Figure I.

anatomy. Indeed, the variances of the distributions of angles at the various joints are generally quite small, five to six percent of the mean, for the ankles, knees, and hips. The shoulder and elbow variances are, however, quite a bit larger. This is perhaps due to the wider differences among individuals in upper body muscular development compared to those in lower body development. Nevertheless, the neutral posture is quite quantifiable, providing that these variances are considered, and it is therefore a valuable design tool for spacecraft crew considerations. The neutral posture angles observed in weightlessness for the Skylab crews, are included with Figure I.¹⁷

Any deviation from these articulation angles of the relaxed posture, such as bending sharply forward at the waist to tie one's shoes, required significant muscular effort. Without the presence of gravity, there is nothing to help push the upper body over to reach for the feet. For a brief task on Skylab, such as shoe lacing, that merely added challenge and a bit of sport to a typically mundane task (although with fatigue, that sporting nature of a mundane task, understandably may rapidly become tedious!). With experience, the Skylab astronauts would find that tasks were easier to perform, the less they deviated from the neutral posture.

The Space Shuttle astronauts, would soon discover the same lessons, working in the large, if somewhat less spacious surroundings, of the Shuttle flight deck, mid-deck, and the Spacelab modules that are sometimes carried aboard in the cargo bay. They've had the benefit of history to guide them, and the astronauts on their first flights often watch the veteran astronauts when they first reach orbit, thereby

speeding up their learning to move gracefully in weightlessness. Working on some things in that environment, however, still produces difficulties for everyone.

Together with the perpetual drifting, the continual need to attach every movable object lends the most menial job an aura of great deliberateness. Tasks that are virtually reflexive on earth demand careful concentration in space.¹⁸

1.2 Motivation for this Research

Posture Control and Locomotion with Earth's One-gravity

For an upright posture to be acquired and kept on Earth, whether during movement or remaining still, the skeletal muscles must maintain a certain degree of tension simply to resist the force of gravity. The rigid framework of the skeleton provides a means of support, but the existence of a variety of joints requires that muscles of agonist-antagonist sets work against each other such that a balance is reached. Intuition leads one to suspect that the presence of gravity forces the skeletal muscles to work harder than they otherwise would, and therefore contributes to fatigue. At one level, that is most certainly correct, however, the situation is not completely that simple.

Locomotion is the most straightforward situation. Obviously, any time one climbs upward on Earth, one works directly against gravity, by moving one's mass through a distance in a direction opposite to the gravity vector. Gravity strikingly hinders upward movements. Merely travelling perpendicularly to the gravity vector, however, is work as well. Mankind's bipedal form of locomotion, or for that matter

locomotion on any number of legs, is quite inefficient. Swinging arms and legs must be lifted with each and every step, and a delicate interplay of muscles must keep the body positioned over the legs. There is only so much reduction in the inefficiency of locomotion in one-gravity that can be accomplished, and what remains is the most efficient gait for an Earth-bound human. Yet, although even standing or sitting motionless require a similar interplay of muscles to maintain an upright posture, the work involved with stationary posture maintenance can be reduced, if one is clever. One can lean against a wall; the stomach and back muscles no longer need to work as much. One can lean one's head upon one's hand, the elbow propped upon a desk, and greatly reduce the muscular work involved with sitting up. Thus, to the extent that one absolutely cannot lean against something without the presence of a gravity vector, Earth's gravity actually assists our stationary posture control by allowing us to reduce the level of muscle contractions necessary to maintain a given bodily position.

Posture Control and Locomotion in Zero-gravity Conditions

Locomotion without gravity is, in terms of muscular effort, much simpler than in one-gravity. There is no up and down, except for arbitrary reference definitions for those terms. While it may require practice to learn how to move without banging clumsily into the destination point, it clearly doesn't require much muscular energy. A properly aimed, light push-off will lead to a drift which eventually will position an individual at the destination.

Posture control is a less simple matter. As described above, the astronaut does not have the ability of the Earth-bound individual to lean against a wall or worksurface. It may be argued that there is no need to do so, since the astronaut may float motionless, in any location he or she chooses. When floating so effortlessly, there is no need for strain upon the musculature. With the muscles relaxed, the neutral posture (described previously) will be achieved, and the hands may be positioned anywhere merely by floating the body to the correct position. There is no need to rest the body by leaning on something, as on Earth. It is not until one is required to perform a stationary task, requiring maintenance of hand and/or head positions for a long period of time, that this effortlessness is replaced by a complicating factor. In that situation, one must usually restrain the body in some manner, in order to avoid eventual drift away from the work area. As soon as some portion of the body has been restrained, the hands and head may no longer be positioned without regard to the rest of the body, but will be located secondarily. With no muscular effort, their positions are dependent upon the neutral posture. Positioning of the hands independently of the neutral posture must be accomplished by movements of the arms, and/or torso, and/or legs. The important concept is that at least one or more of the muscle sets controlling these sections of the body must be actively used to position the hands, and maintain that, relative to the neutral posture of the body. If foot-restraints are used, and the desired hand position is "below" that of the neutral posture, some combination of the anterior lower leg muscles, the abdominal muscles, and the muscles controlling the

position of the arms, must be used to move the hands relative to the feet. For long duration tasks, holding such a posture will produce fatigue. Past experience, and subjective reports by the astronauts, demonstrate high levels of fatigue for the anterior lower leg muscles, strongly implying that to be the primary region used for non-neutral posture alteration and maintenance. Since gravity is not present to assist to pull the hands downward, or act to pitch the body forward to move the hands forward, the muscular contractions must be sustained for as long as the posture is maintained.

Performance Deficits in Zero-gravity

Although not specifically stated, the human body must be included in the group of movable objects described in the previous quotation (p. 22), the drifting of which increases the difficulty of performance of a given task. Performance deficits attributable to zero-gravity, have been termed "operative changes" to distinguish them from physiological changes which occur.¹⁹ These operative changes may be categorized as resulting from three distinct effects of zero-gravity:

Operative Changes in Zero-g:

- I. Drift of task implements away from a desired location
- II. Drift of the body away from the task implements and/or work area, and undesirable bodily movements created by forces opposing those necessary for performance of the task (force feedback)

III. Isotonic muscular contractions necessary for movement of the body out of the Zero-g Neutral Body Posture, and sustained isometric contractions necessary for maintenance of that non-neutral posture

The first category of operative changes, has not proven to be a great problem. Implements which only need to be "put down" for brief periods of time between uses, may often be gently released in mid-space of the work area, perhaps nearby at shoulder level, such that they may float nearly motionless until needed again. Hanging objects in mid-air like that requires patience and skill, as small unwanted forces are easily applied unintentionally during release. This, in part, leads to the careful deliberateness which characterizes work in zero-g. Naturally, since it is impossible to completely null out all applied forces, implements which will not be used again quite soon must be restrained, or they will eventually drift out of reach. The restraints used for such inanimate objects are quite simple, requiring only that they be easy to operate; only the most minimal strength is required, unless forces are to be applied while the object is restrained. Simple fabric and hook type closures (eg.: VelcroTM.) have been found to work very well, even for objects of substantial mass, since they of course have no weight. Once these techniques and the use of implement restraints have been learned, task implement drift is a minor factor in performance degradation.

The second and third categories of operative change, are much more critical in their effects upon work performance in zero-g. The former

is critical for dynamic tasks, where large numbers of reaching and repositioning movements are occurring. To some extent, the force feedback phenomenon cannot be avoided, and must merely be endured. However, as was demonstrated on the Gemini 12 EVA, various forms of body restraints are effective in reduction of unwanted movements. The form of proper restraints for the astronauts, as compared to that for inanimate objects, is not a simple matter. Some are better than others, with a proper balance needing to be considered in restraint design, between adequate body fixation, and ease of getting in and out of them.

Each time the astronauts move to a new location they must free themselves from the restraints holding them in one area and attach themselves in the new area. Experience in Skylab indicates that of the devices used so far, the ones that keep an individual securely in place are difficult to engage and disengage, whereas those that are easy to slip into and out of are virtually useless.²⁰

An ideal restraint system, has probably not yet been found, and indeed, what is ideal for one task, may not be for another. Thus, a fair amount of research remains to be done in the area of restraint design. How important an area is it? That again is very task dependent. For short duration dynamic tasks which involve low levels of force, perhaps such as activating an experiment package by flipping a number of toggle switches, no restraints at all may be necessary. For somewhat more complicated tasks, loose foot-loops are often used. The problem with these, however, is that since they are simple to slip the toes beneath, one's feet slide out of them just as easily. One must "hook the feet" upwards, in sharp dorsiflexion, to remain in the foot-loops. Discussions with a number of astronauts has confirmed this

to be a common complaint.²¹ For long duration tasks, more adequate restraining devices, such as body harnesses or foot restraints providing more fixation, are probably necessary.

For both passive and dynamic tasks, the muscular work of non-neutral posture acquisition and maintenance is a very important operative change (the third category listed previously). For long duration passive tasks, it is the chief effect of weightlessness upon work performance. Those sorts of tasks which require long term maintenance of a relatively passive posture throughout the task, will be highly affected by the similarity, or lack thereof, between the neutral and task postures. Examples of such long duration, passive tasks are: writing (daily planning, recording of experimental observations, etc.), computer interaction, and experimental monitoring. The fatigue induced by maintaining a non-neutral posture for extended lengths of time, has been noted by astronauts, particularly those first involved with the long duration tasks typical of the Spacelab flights.²² Research on the importance of these factors on workstation design, has been quite limited. With the high probability that such long duration tasks will become more and more typical in space flight, with a high percentage of tasks on the proposed Space Station mimicking the computer interactive and experimental situation present at Earth based laboratories, there is a strong need to research these areas. In fact, current guidelines for Space Station design specify that the zero-gravity posture must be accommodated.²³

Research Goals

The research described in this thesis seeks to investigate the use of adjustable worksurfaces in microgravity, and to investigate the relationship of their use to the lower leg muscular fatigue associated with long duration manual and visual tasks performed by astronauts. During the accomplishment of such tasks in weightlessness, an astronaut must perform isometric contractions of the skeletal musculature, in order to maintain any position deviating from that of zero-gravity neutral body posture. Ultimately, these contractions can be expected to lead to muscular fatigue, if the combination of their degree and duration are great enough. It is reasonable to expect, that the least fatigue-producing work environment, for long duration, manual and visual tasks in microgravity, is one that positions the task apparatus nearest to the astronaut's neutral body posture hand position, and which orients the visual field along his or her neutral body posture gaze line, thereby minimizing the degree of contraction necessary to maintain task posture. Zero-gravity neutral body posture hand positions and gaze lines are dependent upon the combination of individual human body dimensions, with angles of articulation arising from the balanced, relaxed tonus, of the agonist-antagonist muscle sets. Two individuals with identical one-gravity stature (overall height) may nevertheless have very different limb and torso lengths. Thus, when these two equal heighted individuals are in zero-g, their neutral posture hand positions may be markedly different. It is therefore probable that the distribution of neutral hand positions has

a substantially wider variance than that of the statures of Earth-bound individuals. Traditional one-gravity design techniques to fit a workstation to a range of individuals, may not be adequate for the anthropometrics involved in weightlessness. The preliminary portions of this thesis examine the underlying factors of these anthropometrics, relating them to the use of adjustable workstations. These results are then used to develop fatigue experiments comparing adjustable and fixed worksurface configurations during underwater simulation of zero-gravity.

Footnotes:

- 1 Eloise Engle, and Arnold Lott, Man In Flight: Biomedical Achievements in Aerospace (Annapolis, Maryland: Leeward Publications, Inc., 1979), p.269.
- 2 Arnauld Nicogossian, M.D., and James F. Parker, Jr., Space Physiology and Medicine (Washington, D.C.: U.S. Government Printing Office, NASA SP-447, 1982), pp.4-5.
- 3 Michael Collins, Carrying the Fire (New York: Bantam Books, 1983), pp.62-63.
- 4 Engle and Lott, pp. 269-270.
- 5 Ibid, pp. 81-105.
- 6 Ibid, pp. 369&372.
- 7 David Baker, The History of Manned Space Flight (New York: Crown Publishers, Inc., 1982), pp. 206-207.
- 8 Collins, p. 129.
- 9 Ibid, pp. 187-263.
- 10 Ibid, p. 188.
- 11 Ibid, p. 263.
- 12 Ibid, pp. 389-390.
- 13 Ibid, pp. 372-373.
- 14 Nicogossian and Parker, p. 11.
- 15 Engle and Lott, pp. 288-289.
- 16 Mary M. Connors, Albert A. Harrison, and Faren R. Akins, Living Aloft: Human Requirements for Extended Spaceflight (Washington, D.C.: U.S. Government Printing Office, NASA SP-483, 1985), p. 121.
- 17 Marc M. Cohen, and Erika Rosenberg, Proceedings of the Seminar on Space Station Human Productivity (Washington, D.C.: U.S. Government Printing Office, NASA TM-86673, 1985), p. 4-114.
- 18 Joseph P. Allen, with Russell Martin, Entering Space: An Astronaut's Odyssey (New York: Stewart, Tabori & Chang, Publishers, 1984), p. 75.

- 19 Bioastronautics Data Book (Washington, D.C.: U.S. Government Printing Office, NASA SP-3006, 19), pp. 400-401.
- 20 Connors, Harrison, and Akins, pp. 62-63.
- 21 Discussions with astronauts Owen Garriott, Vance Brandt, Claude Nicollier, et al, at NASA LBJ on 14 January, 1986.
- 22 M.W.P.E. proposals, NASA/MIT, Bussolari and Lichtenberg.
- 23 Ivan Bekey and Daniel Herman, Space Stations and Space Platforms - Concepts, Design, Infrastructure, and Uses (New York: American Institute of Aeronautics and Astronautics, Inc., 1985), pp.299-301.

Chapter 2

An Analysis of the Skeletal Joint Locations Resulting from the Zero-g Neutral Posture, Related to the Use of Adjustable Microgravity Workstations

2.1 Introduction: Hypotheses Regarding the Need for Adjustability in Microgravity Workstation Design

As has been discussed, fatigue associated with long duration posture dependent tasks, is a result of the necessity for sustained isometric contractions of the musculature, in order to maintain a task posture deviating from the neutral posture. The use of adjustable worksurfaces, allows the matching of the task implements to the neutral posture. It also, however, produces additional tasks of the setting of the worksurface to the neutral posture hand location, as well as the setting of the worksurface angle. Although these additional tasks may be minimized by appropriate design which includes set up and operating aids (These concepts are developed in depth in Chapter 6.), those that remain are acceptable only if the fatigue reduction resulting from the adjustability cannot be accomplished as well in another way. Thus, this research must examine the question: Is the adjustability necessary, or can the neutral posture hand positions of most individuals be adequately matched with some standard fixed configuration for zero-gravity?

It is reasonable to hypothesize that the use of a standard fixed workstation configuration, is not appropriate for zero-g conditions. Earth-based workstation envelope design, often utilizes principles based upon suiting a given percentile range of statures, usually a

minimum size to be large enough for the 95th percentile male, and a maximum to be small enough for controls to be reachable by the 5th percentile female. For example, a control panel may be found to be best positioned somewhere between ten and twenty inches away from a seat, in order that all but the largest 5 percent of men will have room for their extended arms, but all but the smallest 5 percent of women will still be able to reach the panel. Tables of anthropometric data such as arm lengths, are used to perform such designs. This is a sensible and useful design criterion, provided, however, that the variance of that anthropometric parameter is not too large. If the anthropometric measure being used as a guideline, of the 95th percentile male, is huge in comparison to that of the 5th percentile female, it is clear that the minimum envelope permissible can eventually become larger than the maximum; to even barely fit, the big people need an envelope simply too big for the small people to reach anything. This problem may be solved by using less stringent requirements, such as 10th and 90th percentiles. The problem is that the resulting envelope design is no longer functional for as large a number of individuals. Thus, if a variance is large enough, a fixed design will be functional for only a small percentage of the population of individuals.

If the arithmetic mean, of the hand positions that result from the zero-g neutral body posture, is used as the appropriate positioning dimension for a fixed worksurface, then the variance of the neutral posture hand positions is the most relevant parameter for investigating the range of individuals that such a fixed design can accommodate. A

larger variance than for the one-g stature of the same individuals provides strong evidence that fixed designs in zero-g may be inappropriate, since they accommodate a smaller range of user's body types. It is reasonable to predict a larger variance. The neutral posture hand position results from individual limb and torso lengths, each with a variance of its own, in combination with multiple geometric deviations within the left-right sagittal plane, occurring at each joint. The results of an investigation of this are presented in Section 2.4.

In addition to the hand position, the locations of all of the major skeletal joints of the body may be utilized to investigate the importance of the various muscle sets in acquiring, and maintaining, a non-neutral posture in zero-g. A simple example is that if a foot-restrained individual's knee, hip, shoulder, and elbow joint locations coincide with those predicted for the neutral posture, then the biceps and triceps muscles of the arm are virtually the only muscles being used to acquire/maintain a non-neutral hand position. If the shoulder and elbow positions do not coincide, but the hips do, then the abdominal musculature is required. The predicted neutral posture joint locations, for a group of experimental subjects, are calculated based upon their unique anthropometric measurements, in Section 2.2. The results are related to the use and fatigue of the various muscle sets, in Section 2.5.

2.2 Analysis of the Predicted Major Skeletal Joint Locations of Zero-g Neutral Posture

An anthropometric questionnaire was distributed among MIT graduate students in their middle to late twenties in age, of moderate to high physical fitness, and of both genders. These individuals, though used primarily due to their convenient accessibility, may be considered to be representative examples of potential future astronaut candidates. Thus, their anthropometric measurements should be representative of those likely among a typical mixed gender Space Shuttle crew. Eight individuals responded to the questionnaire, which is reproduced in Appendix I. The anthropometric data obtained from the questionnaire is provided in Table I.

Number of respondents: 8
 Gender of respondents: 6 male, 2 female
 Unit of measure: centimeters

Subject: A Gender: male Overall height (OH): 182.9 Interjoint lengths: -ankle//knee (A//K): 38.7 -knee//hip (K//H): 46.4 -hip//shoulder (H//S): 55.9 -shoulder//elbow (S//E): 30.5 -elbow//wrist (E//W): 25.4	Subject: B Gender: male OH: 182.0 Interjoint lengths: -A//K: 38.0 -K//H: 48.0 -H//S: 61.5 -S//E: 34.0 -E//W: 27.0
Subject: C Gender: male OH: 175.0 Interjoint lengths: -A//K: 35.5 -K//H: 43.0 -H//S: 55.0 -S//E: 30.5 -E//W: 24.0	Subject: D Gender: male OH: 170.2 Interjoint lengths: -A//K: 39.4 -K//H: 40.6 -H//S: 50.8 -S//E: 29.2 -E//W: 23.5
Subject: E Gender: female OH: 154.9 Interjoint lengths: -A//K: 31.8 -K//H: 49.5 -H//S: 47.0 -S//E: 30.5 -E//W: 24.1	Subject: F Gender: male OH: 167.6 Interjoint lengths: -A//K: 30.5 -K//H: 43.2 -H//S: 36.8 -S//E: 25.4 -E//W: 21.6
Subject: G Gender: male OH: 183.0 Interjoint lengths: -A//K: 35.5 -K//H: 46.0 -H//S: 64.0 -S//E: 34.5 -E//W: 26.0	Subject: H Gender: female OH: 167.6 Interjoint lengths: -A//K: 35.6 -K//H: 44.5 -H//S: 50.8 -S//E: 29.2 -E//W: 24.8

Table I: Anthropometric Questionnaire Data

For these analyses, the locations of the six major joints (on one side of the body) were chosen to mark the neutral posture, relative to some fixed point. The joints chosen are at the obvious points of flexion which constitute the neutral posture: the ankle, knee, hip, shoulder, elbow, and wrist. To ensure that the five interjoint lengths measured between these points could be confidently compared among subjects, the precise anatomical point upon which the measurements were to be based had to be specifically defined within the relatively broad regions covered by the common terms for the joints. The following anatomical locations were chosen to define the measurement points for each joint, partially for their anthropometrically useful lateral nature, and partially for their ease of discovery (with certainty) both visually and with palpation. A means for properly locating them was developed for this research, and is provided in Appendix I.

Ankle: fibular lateral malleolus
Knee: lateral head of the fibula
Hip: femoral greater trochanter
Shoulder: humeral greater tubercle
Elbow: humeral lateral epicondyle
Wrist: lateral head of the ulna

The predicted zero-g neutral posture joint locations for each experimental subject were then calculated from the measured anthropometric interjoint lengths, combined with the known articulation angles of the posture. As described in Chapter 1, these articulation angles for the neutral posture were observed and measured from the Skylab crews, and found to fall within a relatively small range. For these

analyses, the arithmetic means of the Skylab data for these angles (values obtained from NASA TM-86673) were used. Those mean values are:

<-ankle = 111.0 degrees
<-knee = 133.0 degrees
<-hip = 128.0 degrees
<-shldr = 36.0 degrees
<-elbow = 122.0 degrees

The horizontal and vertical locations of the six joints that bound the five anthropometric measures, relative to the ankle joint, were calculated as follows. The definition of location as being relative to the ankle joint is arbitrary, but has a logical basis when analyzed in terms of an astronaut using foot-restraints (still the most common fixation device).

Let:

KPH = horizontal knee position (relative to ankle)
KPV = vertical knee position (relative to ankle)
HPH & HPV = horizontal & vertical hip positions (relative to ankle)
SPH & SPV = horizontal & vertical shoulder positions (relative to ankle)
EPH & EPV = horizontal & vertical elbow positions (relative to ankle)
WPH & WPV = horizontal & vertical wrist positions (relative to ankle)

And:

(A//K) = ankle//knee interjoint distance
(K//H) = knee//hip interjoint distance
(H//S) = hip//shoulder interjoint distance
(S//E) = shoulder//elbow interjoint distance
(E//W) = elbow//wrist interjoint distance

Then, the predicted zero-g neutral posture joint positions, relative to the ankle, may be calculated as:

$$KPH = -(A/K) \times \sin (\underline{\langle\text{-ankle}} - 90)$$

$$KPV = -(A/K) \times \cos (\underline{\langle\text{-ankle}} - 90)$$

$$HPH = KPH - ((K/H) \times \cos (\underline{\langle\text{-knee}} - \underline{\langle\text{-ankle}}))$$

$$HPV = KPV + ((K/H) \times \sin (\underline{\langle\text{-knee}} - \underline{\langle\text{-ankle}}))$$

$$SPH = HPH - ((H/S) \times \sin (\underline{\langle\text{-ankle}} + \underline{\langle\text{-hip}} - \underline{\langle\text{-knee}} - 90))$$

$$SPV = HPV + ((H/S) \times \cos (\underline{\langle\text{-ankle}} + \underline{\langle\text{-hip}} - \underline{\langle\text{-knee}} - 90))$$

$$EPH = SPH + ((S/E) \times \sin (\underline{\langle\text{-ankle}} + \underline{\langle\text{-shldr}} + \underline{\langle\text{-hip}} - \underline{\langle\text{-knee}} - 90))$$

$$EPV = SPV - ((S/E) \times \cos (\underline{\langle\text{-ankle}} + \underline{\langle\text{-shldr}} + \underline{\langle\text{-hip}} - \underline{\langle\text{-knee}} - 90))$$

$$WPH = EPH + ((E/W) \times \sin (\underline{\langle\text{-knee}} + \underline{\langle\text{-elbow}} - \underline{\langle\text{-ankle}} - \underline{\langle\text{-hip}} - \underline{\langle\text{-shldr}} + 90))$$

$$WPV = EPV + ((E/W) \times \cos (\underline{\langle\text{-knee}} + \underline{\langle\text{-elbow}} - \underline{\langle\text{-ankle}} - \underline{\langle\text{-hip}} - \underline{\langle\text{-shldr}} + 90))$$

The predicted joint locations obtained from these calculations, for the eight experimental subjects, are listed in Table II. It is important to note that positive numbers denote locations above, and to the right of, the ankle, while negative numbers denote locations below, and to the left of, the ankle. For example, $KPV = 31.0$ and $KPH = -12.0$ means that a given experimental subject's knee may be predicted to be vertically located 31 cm. above, and horizontally 12 cm. to the left of, the ankle, when in zero gravity, with skeletal muscles relaxed (if one assumes the standard (mean) joint articulations obtained from Skylab astronaut crews).

units: centimeters

EXPERIMENTAL SUBJECT (A to H)								
	A	B	C	D	E	F	G	H
KPH	-13.9	-13.6	-12.7	-14.1	-11.4	-10.9	-12.7	-12.8
KPV	36.1	35.5	33.1	36.8	29.7	28.5	33.1	33.2
HPH	-56.9	-58.1	-52.6	-51.7	-57.3	-51.0	-55.4	-54.1
HPV	53.5	53.5	49.2	52.0	48.2	44.7	50.3	49.9
SPH	-72.3	-75.1	-67.8	-65.7	-70.3	-61.1	-73.0	-68.1
SPV	107.2	112.6	102.1	100.8	93.4	80.1	111.8	98.7
EPH	-48.3	-48.3	-43.8	-42.7	-46.3	-41.1	-45.8	-45.1
EPV	88.4	91.7	83.3	82.8	74.6	64.5	90.6	80.7
WPH	-24.4	-22.9	-21.2	-20.6	-23.7	-20.8	-21.4	-21.8
WPV	97.1	100.9	91.5	90.8	82.8	71.9	99.5	89.2

Note:

KPH & KPV = horizontal & vertical knee position
 HPH & HPV = " & " hip "
 SPH & SPV = " & " shoulder "
 EPH & EPV = " & " elbow "
 WPH & WPV = " & " wrist "

Table II: Predicted Zero-g Neutral Posture Joint Positions
Relative to the Ankle, for a Subject in Foot-restraints

2.3 Research Requirements for Use of the Predicted Major Skeletal Joint Locations of Zero-g Neutral Posture

The mean values for each predicted joint position (See Section 2.4.), may be used as design guidelines for the proper dimensions for fixed zero-g designs. The neutral wrist positions are the most important parameters for the primary focus of this research, adjustable worksurfaces. However, other joint positions are also important. For instance, for high force-feedback producing tasks, where foot-restraints do not provide sufficient fixation, various other forms of bodily restraints are sometimes used. One of the more successful of these devices, though somewhat more difficult to get into and out of, is the thigh-cuff restraint mechanism. The mean of the predicted neutral posture vertical and horizontal hip positions, provide a potential location to be reached with a fixed length thigh-cuff restraint, for a range of individual bodily sizes. Just as for the worksurface design, the variance of the hip location should be examined to determine if a fixed length will be adequate for a wide enough range. If not, then adjustment of the straps could be made possible, about that mean length.

Other design uses for the joint predictions, are for any device which demands passive or dynamic physical interaction by a person in the zero-g neutral posture. Currently, astronauts either sleep by free-floating, or are loosely restrained in a sort of sleeping bag rest area. It has been suggested, however, that to counteract some of the long-term physiological degradations of weightlessness, such as bone demineralization, immunosuppression, etc., full body centrifugation

sleep-stations could be used. Potentially, the centrifugation could provide head to foot forces comparable to that produced by some fraction of gravity, while allowing normal sleep. In addition, it avoids some of the difficulties inherent in the continuous provision of artificial gravity (such as Coriolis forces), while being substantially less expensive and complicated than rotating space vehicles and habitats. This is currently under active investigation by Peter H. Diamandis, at MIT and the Harvard Medical School, and could prove to be highly important for future manned Mars missions and space colonization. It may prove to be necessary, and indeed seems logical, that to allow for the most comfortable restrained sleep in space, the centrifuge bed should be shaped to match the neutral posture. If a full one-g centrifuge is used, the neutral posture will, of course, no longer be a factor. It is probable, however, that a lesser g-level will be used (for reasons too complicated to detail here), and thus, some intermediate reduced-g neutral posture will occur. Once the preferred g-level for centrifuge sleep stations has been determined, the joint articulations matching that neutral posture can be empirically quantified, as was done for zero-g on Skylab, and using the techniques outlined in this research, the predicted joint positions determined. A sleep couch could then either be customized to each astronaut's knee, hip, and shoulder positions relative to the ankle, or else shaped to a generic design based on the arithmetic means of those joint positions, if the variances were determined to be acceptably small.

2.4 Comparison of the Distribution of Neutral Body Posture Hand Positions to that of Overall Stature

As described in Section 2.1, the variance of the zero-g neutral posture hand position is a useful parameter for the investigation of the applicability of adjustability in microgravity workstation design. The predicted zero-g neutral posture horizontal and vertical wrist positions, WPH and WPV, are ideal for such analyses. If a fixed worksurface is located at the arithmetic means of WPH and WPV, then the variances about those mean values serve as a measure of the range of individuals for whom it is functional, without unacceptably high levels of fatigue.

It is necessary to use some objective means for the determination of how broad a distribution of hand positions constitutes an unacceptable basis for fixed worksurface design. A logical means for the interpretation of this, is to utilize a comparison of the variance of the zero-g neutral wrist joint locations to that of some similar one-g parameter. Clearly, if the former is markedly larger than the latter, than the range of individuals for which a fixed workstation will be functional in zero-g, will be markedly less than that of fixed designs in one-g. The anthropometric design concepts for one-g are well defined, and utilizing percentile envelope techniques, one may quantify the range of statures fitted to such a design. Thus, by utilizing a one-g parameter which describes the breadth of the distribution of the population of users of the workstation, one has an objective basis for comparison. The one-g stature (overall height) of the experimental subjects, is an ideal parameter for the purpose.

The variances of all of the predicted neutral posture joint positions, as well as the one-g overall height, were calculated, and are listed in Table III. This is done for both the general group of experimental subjects, as well as separated in terms of gender. Before interpretation, however, it must be considered that a variance for a distribution with a small arithmetic mean, implies a higher variability than does an equivalent variance for that with a large mean. Thus, the coefficient of variation has been used for these analyses.

$$\text{coefficient of variation} = \text{CV} = 100\% \times \frac{(\text{variance})^{0.5}}{(\text{arithmetic mean})}$$

The normalized variances obtained by calculating the CV's for each anthropometric parameter, are listed in Table IV. The results support the hypothesis described in Section 2.1.

units: centimeters

	arith- metic mean (grand)	arith- metic mean (male)	arith- metic mean (female)	variance (grand)	variance (male)	variance (female)
OH	172.9	176.8	161.3	95.54	46.83	80.65
WPV	90.5	92.0	86.0	90.06	113.43	20.48
WPH	-22.1	-21.9	-22.8	1.95	2.18	1.81
EPV	82.1	83.6	77.7	80.77	100.64	18.61
EPH	-45.2	-45.0	-45.7	6.54	8.87	0.72
SPV	100.8	102.4	96.1	111.36	143.07	14.05
SPH	-69.2	-69.2	-69.2	19.97	27.73	2.42
HPV	50.2	50.5	49.1	8.62	11.12	1.45
HPH	-54.6	-54.3	-55.7	7.30	8.59	5.12
KPV	33.3	33.9	31.5	8.71	9.25	6.13
KPH	-12.8	-13.0	-12.1	1.30	1.39	0.98

Note:

KPH & KPV = horizontal & vertical knee position
 HPH & HPV = " & " hip "
 SPH & SPV = " & " shoulder "
 EPH & EPV = " & " elbow "
 WPH & WPV = " & " wrist "
 OH = overall height in normal one-g

Table III: Statistical Summary of Zero-g Neutral Posture
 Joint Positions and Overall Height

units: centimeters

	CV (grand)	CV (male)	CV (female)
OH	5.65	3.88	5.57
WPV	10.49	11.58	5.26
WPH	6.32	6.75	5.91
EPV	10.95	12.01	5.56
EPH	5.66	6.62	1.86
SPV	10.46	11.68	3.90
SPH	6.46	7.61	2.25
HPV	5.85	6.60	2.45
HPH	4.94	5.40	4.06
KPV	8.88	8.98	7.87
KPH	8.94	9.08	8.18

Note:

KPH & KPV = horizontal & vertical knee position

HPH & HPV = " & " hip "

SPH & SPV = " & " shoulder "

EPH & EPV = " & " elbow "

WPH & WPV = " & " wrist "

OH = overall height in normal one-g

CV = coefficient of variation = 100% x $\frac{(\text{variance})^{0.5}}$

(arithmetic mean)

Table IV: Normalized Variances (Coef. of Var.) for
Predicted Zero-g Neutral Joint Positions
and Overall Height

The first important observation from Tables II and III is that the vertical component of the neutral joint positions, is much more critical in terms of the need for adjustability, than is the horizontal component. Thus, if it is determined that adjustability should be included in zero-g workstation design, it may be possible to fix the horizontal location of the worksurface relative to the foot-restraints, with only vertical adjustability necessary. This would considerably simplify the implementation of adjustable worksurfaces, with just the need for vertical and angle adjustments. In contrast to the multi-jointed support arms of a fully adjustable worksurface (See Ch. 4), a single dimensionally adjustable worksurface could merely be mounted in vertical tracks allowing for up-down adjustment, a set distance fore-aft from the foot-restraints. This might be easier and faster to adjust than a fully adjustable workstation, while allowing sufficient customization to neutral posture hand positions for reduced user fatigue.

The coefficients of variance in Table IV demonstrate that, for the experimental subject population used for this research, the zero-g neutral posture joint locations are markedly more widely variant than the overall heights of the same individuals in one-g. Indeed, the CV's for the vertical locations of the upper body joints are nearly twice that of the overall height. The variance at the hip is greater than, but quite close to the overall height, and that at the knee, is again substantially higher. Apparently, the deviation from the mean due to the lower leg, is somewhat cancelled out by that due to the upper leg. No such cancellation appears to occur above the hip joint, however.

Thus, the upper body neutral posture joint locations appear to have an exceedingly wide distribution. If the CV of the overall height is indeed a useful parameter for one-g design comparison, it appears critical to have some form of vertical worksurface position customization, most likely through the use of adjustability. The criticality of horizontal adjustability is a bit less apparent, however, the horizontal variances are not insubstantial enough to rule out its use.

In terms of gender-specific differences, the data is insufficient for a direct male versus female comparison, due to the failure of some female subjects to respond to the questionnaire. Thus, not enough female respondents are available for a useful measure of the variance of a female-only subject pool. Nevertheless, the statistical parameters are calculated in terms of gender, since by separating the insufficient female data from the male data, it can be determined if, for just one gender (male), the conclusions drawn from the variances are significantly altered, or the same. As can be seen in Table IV, the CV's for the male subject joint locations are even more markedly greater than the overall height, than those of the total subject group. This results since the variance of overall height is greater for both genders together, than for each separately. This makes sense since the distribution of that of both genders is bimodal, a reflection of the means from each gender. Thus, looking at the CV's for just one gender (male), is perhaps the most reflective of the actual variances. As can be seen, this is even more demonstrative of the hypotheses of this research. It is likely that a sufficiently large female population,

would demonstrate similar results. In the end, since our astronaut populations have begun to more naturally represent both genders, all zero-g designs should, of course, be based upon the anthropometrics of both genders.

2.5 Trends in the Deviations from the Mean of the Predicted Neutral Posture Joint Locations

Analysis of the deviations of the neutral joint positions, from their arithmetic means, has yielded some striking results. Table V lists the calculated values for these deviations from the mean. For each subject, the deviations of each component of the wrist, elbow, and shoulder positions are markedly similar. In addition, they are substantially larger than those of the hip and knee joints. The significance of these results become apparent when considered in terms of the acquisition of the mean wrist position as a representative non-neutral worksurface location. Any other fixed non-neutral locations, would merely be shifted from this known value.

The fact that the upper body deviations from the mean are so comparable is a rather surprising coincidence. What this means is that if the upper body configuration remains unchanged from that of the neutral posture, the mean values for all of the upper body joint

units: centimeter

	EXPERIMENTAL SUBJECT (A to H)							
	A	B	C	D	E	F	G	H
WPV-WPV _{mean}	6.64	10.44	1.04	0.34	-7.66	-18.56	9.04	-1.26
WPH-WPH _{mean}	-2.30	-0.80	0.90	1.50	-1.60	1.30	0.70	0.30
EPV-EPV _{mean}	6.32	9.62	1.22	0.72	-7.48	-17.58	8.52	-1.38
EPH-EPH _{mean}	-3.12	-3.12	1.38	2.48	-1.12	4.08	-0.62	0.08
SPV-SPV _{mean}	6.36	11.76	1.26	-0.04	-7.44	-20.74	10.96	-2.14
SPH-SPH _{mean}	-3.12	-5.92	1.38	3.48	-1.12	8.08	-3.82	1.08
HPV-HPV _{mean}	3.34	3.34	-0.96	1.84	-1.96	-5.46	0.14	-0.26
HPH-HPH _{mean}	-2.26	-3.46	2.04	2.94	-2.66	3.64	-0.76	0.54
KPV-KPV _{mean}	2.85	2.25	-0.15	3.55	-3.55	-4.75	-0.15	-0.05
KPH-KPH _{mean}	-1.14	-0.84	0.06	-1.34	1.36	1.86	0.06	-0.04

Note:

KPH & KPV = horizontal & vertical knee position
 HPH & HPV = " & " hip "
 SPH & SPV = " & " shoulder "
 EPH & EPV = " & " elbow "
 WPH & WPV = " & " wrist "

Table V: Deviations from the Mean of the Predicted Neutral Posture Joint Locations

positions will be virtually obtained by simply acquiring the mean wrist position. The importance of this is obvious when one considers that the acquisition and maintenance of any non-neutral wrist position, while in foot-restraints, is dependent upon contractions of the skeletal muscle sets, starting at the ankles and continuing to each joint to the wrists. Thus, the fact that the neutral posture for the upper body is coincident with the mean joint values for the upper body, demonstrates that to acquire and maintain the mean wrist position as a fixed non-neutral worksurface location, one merely needs to use the lower body musculature to shift the upper body as a unit. The musculature of the upper body virtually need not be used.

Subjects G and H serve as good representatives of these concepts, although the data for all subjects demonstrate the same trend. Subject G's predicted vertical neutral wrist position is approximately 9 cm. above the mean value. That of his elbow is merely half a centimeter less above its mean. Therefore, if the elbow is aligned with its mean position, the biceps and triceps need not be used at all in order for the wrist to be almost precisely at the mean for that joint. Similarly, subject G's neutral shoulder position is about 11 cm. above its mean. Thus, setting the shoulder to the mean with just spinal and leg adjustments still provides quite reasonable alignment of the wrist with the mean value, being merely a centimeter and a half too high. Such small deviations from a worksurface may be compensated for simply via slight finger movements. In contrast, the hip and knee deviations from the mean for subject G are quite markedly different from those of the upper body. The neutral posture must therefore be departed from,

in the lower body, to acquire the mean vertical wrist position, a non-neutral value for subject G. Subject H is a female whose neutral joint positions lie on the other side of the mean from those of subject G, however, they demonstrate precisely the same points. The vertical deviation from the mean for subject H's elbow and shoulder are only a few millimeters different than the deviation from the mean of the wrist. Again, the lower body deviations from the mean are an order of magnitude different. The data for all of the subjects follow strikingly similar trends.

Of course, any of the muscles may be used to position the wrist (ie.: locate the hand at a worksurface in a non-neutral location), however, for the purposes of energy conservation, the above results serve as a strong incentive for use primarily of the lower body. There are two fatigue reducing strategies. One is to spread the muscular work out among as many muscles as possible, thereby minimizing the level of contraction necessary from each one. The other is to minimize the number of muscle sets utilized, selecting the region to be relied upon as that requiring the minimum level of contraction among the various choices, although still requiring a higher level than if the task was evenly shared. Lacking the trends in the upper body anthropometrics of zero-g, as described above, it would be a close draw between the two strategies. Even so, however, some muscle sets fatigue differently due to differences in fiber type (See Appendix II), and the reliance upon the best suited muscles rather than the tensing of the entire skeletal musculature, is logical. The leg musculature, used in one-g for both posture and locomotion, is a logical region for reliance

upon sustained contractions when compared to the less used arms, and especially the back and abdominal muscles. In a similar way, all rock climbers learn that the legs should be used primarily, even when that means relying upon tiny foot-holds, and pull-ups with the arms should be performed only when there's nothing there for the feet; the more precarious finesse demanded by this technique is justified based upon the fact that the arms simply fatigue much more rapidly than the legs. (It should be noted here, that although the majority of the leg musculature is indeed less prone to fatigue than that of the upper body, there are, in addition to the one-g posture control muscles, non-posture muscles in the legs (anterior lower leg). Thus, although reasons are suggested here for the reliance upon the legs for primary posture maintenance in foot-loops, it must be remembered that the non-one-g-posture muscles will still fatigue rapidly, which is why astronauts develop the anterior lower leg fatigue studied in this thesis.)

With the presence of the trends that result from these analyses, the fact that the lower body appears to be the most depended upon for zero-g non-neutral posture maintenance is even more reasonable. Firstly, even ignoring the tendencies of the upper body to fatigue more rapidly, the fact that the upper body may be positioned at the mean values while remaining in the neutral configuration, thus calling upon little to no upper body contractions, is strong incentive to use the strategy of regional posture control, rather than the full body approach. Secondly, with the exception of subject D who lies very close to the mean anyway, the deviations from the mean of the knee and

hip are consistently considerably less than those for the upper body. Thus, the level of contraction necessary to approach the mean, for the lower body, is less than that for the upper body.

It is likely that non-neutral zero-g posture control is performed subconsciously, just as is usually the case in one-g. Thus, while there may be very little decision-making between strategies, the regional approach probably results naturally. Effectively what probably occurs is a reliance upon the slowly fatiguing upper leg musculature first, which with quite reasonable levels of contraction brings the upper body near the desired fixed location. Next, recruitment of the lower leg musculature, controlling ankle flexion, as well as the back and abdominal musculature, to curve the spine, results in appropriate positioning of the shoulder. Finding that the wrist position is correct without the need for upper body contraction, the upper body is left in the relaxed neutral configuration. Perhaps as fatigue begins to strike the lower body musculature, other regions are recruited. It is known that the astronauts first develop fatigue in the anterior lower leg muscles (further support of the results of these analyses), and it is possible that for very long duration tasks, other regions are eventually recruited. The analyses of the deviations from the mean identify the important muscle groups for that fatigue research. Most importantly, the anterior lower leg muscles (Tib. ant.) should be studied during long duration tasks, followed by the chief posterior lower leg muscles (Gastroc.), the anterior and posterior upper leg muscles, and the lower back and abdominal muscles. There

appears to be little reason to perform electromyographic measurements from the upper body.

2.6 Summary

The results of the analyses, of the collected anthropometric data which is relevant to the zero-g posture, have been striking. Firstly, the existence of the extremely large variances of predicted neutral posture joint positions, supports the need for adjustability in zero-g design, particularly for manual workstations. Secondly, the criticality of the vertical component in adjustability, has been demonstrated. Furthermore, it has been suggested that the horizontal component is more open to question. It has been demonstrated that the deviations from the mean of the lower body, are substantially less than those for the upper body, thus requiring lower levels of contraction to perform zero-g posture control with the musculature of that region. Perhaps most strikingly, a consistent trend in the upper body deviations of the mean has led to the discovery that the neutral configuration of the upper body may be maintained even during the acquisition and maintenance of non-neutral postures. This fact, combined with the previous result, sheds light on zero-g non-neutral posture control. It should be noted that the arithmetic mean of the wrist position has been used as a basis for the above analyses, although that is not a restriction to the conclusions drawn. That parameter is an arbitrary, though logical, example of a potential fixed worksurface location calling for a minimized non-neutral posture. Any

other choice for a fixed location would merely be an addition or subtraction from the mean value. Thus, for example, the trends in the upper body deviations from the mean are still present, merely being shifted by the same addition or subtraction.

These analyses further clarify the anthropometrics of the neutral posture beyond what has been done before, and provide a hypothesis for non-neutral posture control. They also fully support the need for adjustability in microgravity workstation design, providing evidence that it should be implemented in any Space Station or later spaceflight designs.

Chapter 3

An Investigation of the Neutrally Buoyant Posture, as a Research Analogue of the Zero-g Neutral Posture

3.1 Introduction: Neutrally Buoyant Posture

The neutral buoyancy of water immersion is one method which has been successfully used to simulate the weightless conditions associated with spaceflight. With proper loading of an individual, using lead weights, the buoyancy of the water may be used to exactly cancel out the downward force of the gravity vector which acts upon the center of mass. Such tests have been, and are, very useful for the practicing of various tasks to be performed in space, or the analysis of the performability of tasks not yet previously attempted. Few such studies, however, require careful consideration of the neutral posture, since the tasks under study may not be highly posture dependent. A common example of such research involves EVAs ("spacewalks"), where the posture is essentially defined by the pressure suit.

It so happens, however, that the relaxed posture achieved in submersion, is very similar to that of zero-gravity. As discussed previously, the zero-g neutral posture arises from the differences in relaxed tensions of antagonistic muscle sets, when there are no limb weights present. The neutrally buoyant posture arises from the differences between the buoyancy of the limbs, and their weights. The postures resulting from these separate phenomena are highly similar, as this research demonstrates, sufficiently so to justify utilizing neutral buoyancy simulations of weightlessness for posture dependent

task research. The similarity occurs since the density of the tissues is very close to that of water making the buoyancy/weight difference exceedingly small, and thus the neutrally buoyant posture dependent upon the same relaxed muscle set points as the zero-g posture. The following sections of this chapter detail an investigation of the neutrally buoyant posture, and its results. This neutral buoyancy study, in combination with the results of the anthropometric studies of the previous chapter, provides important information about the neutral postures of zero-g and submersion, and their relationship to the use of adjustable workstations. In the next chapter, a technique is proposed for the analysis of fatigue at adjustable versus fixed workstations, using the neutrally buoyant posture as a research technique.

3.2 Neutral Buoyancy Study

The following experiment was designed to address the issue of the validity of underwater simulation for posture-dependent tasks. A neutrally buoyant (about the center of mass), submerged test subject was photographed during repeated episodes of full voluntary relaxation of the skeletal musculature. This was performed both in and out of foot-restraints. The resulting joint articulation angles were then later measured from the photographic records. The means and standard deviations of the neutrally buoyant posture angles, were then compared to those of the zero-g neutral posture. It should be noted that only

one experimental subject was used for this simple study (a young adult male, of average build and leanness). There is certainly an intersubject variation of the neutrally buoyant posture, caused by differences in limb buoyancy, which ultimately depends upon the percentage of body fat and muscular tonus. The effects of gender differences in body fat distribution, individual differences in percentage within individuals of the same gender, and muscular conditioning differences, upon the neutrally buoyant posture, would be interesting to study in their own right. This study, however, is less interested in the factors effecting the neutrally buoyant posture, than whether or not that posture for an average individual bears some reasonable similarity to that of zero-gravity. Thus, this study merely examines the intrasubject mean and variance of the neutrally buoyant posture, thereby answering if, at least for some representative individuals, the underwater simulation of weightlessness is appropriate for posture-dependent tasks. Any intersubject differences which cause a given individual's neutrally buoyant posture joint articulations to be markedly different from those of the zero-g neutral posture may be observed during any preliminary neutral buoyancy study. Thus, an individual whose neutrally buoyant posture is not an acceptable analogue of the zero-g posture is merely not a candidate for use in submersion simulations. The scope of this project is not to investigate these factors, but merely to identify that there are indeed some candidates for such studies in existence.

3.3 Experimental Protocols

This neutral buoyancy experiment was performed at the M.I.T. swimming pool, with the assistance of the Space Systems Laboratory. The experimenter served as the test subject, and was assisted by an undergraduate who performed the photography. The experiment was performed as follows:

Procedure:

- (1) Foot-restraints were set up and weighted down at the bottom of the deep end of the pool.
- (2) A SCUBA tank of compressed air was placed on the bottom of the pool, near the foot-restraints. A long extension hose (about 15 feet) connecting the first stage regulator to the second stage and mouthpiece, was used to provide air from the tank, while allowing the test subject to free-float or stand in foot-restraints without the need of wearing the tank. The tank would alter the neutral posture if worn on the body.
- (3) The test subject, wearing a swim suit, and SCUBA mask of low volume, entered the pool and adjusted lead weights on a belt to achieve neutral buoyancy. No wet suit was worn, as these would alter the neutral posture. The low volume mask was used to minimize the buoyant effect of the air pocket upon the head.
- (4) The photographic assistant entered the pool wearing his own compressed air supply, and positioned himself at a right angle relative to the foot-restraints. In such a position, a right-side profile view

of the subject was obtained, providing the proper perspective for the recording of the angles of the joints within the left-right sagittal plane of the body.

(5) The test subject positioned himself in the foot-restraints.

(a) Upon a hand signal to the photographic assistant, the test subject fully relaxed his skeletal muscles.

(b) The subject maintained the relaxed posture for a count of approximately 15 seconds, while breath-holding. This breath-hold was necessary to keep pulmonary volume changes from causing upper body movement relative to the restrained feet, with each breath, thus varying the joint articulations. Since the depth of the subject was modest (about ten feet at the head), and the foot-restraints ensured a constant pressure-depth, the breath-hold procedure was completely safe, as compared to normal dive conditions, when it would be considered an unsafe practice on SCUBA (due to the possibility of pulmonary expansion injury).

(c) During the relaxed posture and breath-hold, the photographic assistant took 35mm. camera exposures of the test subject, obtaining a head-to-toe field of view.

(d) At the end of the 15 second count, the test subject signalled the photographic assistant that the relaxation task was being ended, and thus subsequent photos would no longer represent neutral posture. The subject began breathing normally again.

(e) Normal breathing was continued until the respiration rate returned to normal (minimizing the risk of sudden black-out associated with respiratory acidosis).

(6) Step 5 was repeated nine more times.

(7) The subject then removed his feet from the restraints, attempting not to push off from the location in doing so. Step 5 was then repeated ten times in free-float without the foot-restraints. The subject did not breath-hold during this portion of the experiment, as there was no way to ensure constant depth, and therefore safety. Since the feet were not restrained, however, the joint articulations were not effected by respiration, since in that situation, the entire body moves due to changes in lung volume (and therefore buoyancy), rather than the upper body moving relative to the feet, as occurs when they are fixed.

3.4 Results

Tables I and II list the results of the neutral buoyancy study. Table I provides the neutrally buoyant posture joint articulations for a submerged subject in foot-restraints (illustrated in Figure V of Chapter 5, where the adjustable worksurface configuration is in use), while Table II provides those for a free-floating submerged individual (illustrated in Figure II, on the following page). This data may be compared with the zero-g data from Skylab, presented in Chapter 1. For convenience, the zero-g articulation values will be listed here again.

Figure II.



units: degrees

Neutral Buoyancy Posture Joint Articulation Angles (in foot-restraints)						
	ankle	knee	hip	shoulder	elbow	head tilt
Trial #1	130	147	117	57	131	24
Trial #2	128	146	122	56	135	27
Trial #3	124	149	128	43	125	30
Trial #4	128	149	119	42	130	30
Trial #5	129	150	118	46	131	25
Trial #6	126	144	125	38	127	40
Trial #7	127	149	127	40	128	40
Trial #8	120	151	140	32	122	42
Trial #9	119	149	137	30	119	47
Trial #10	123	144	133	37	127	44
arith. mean	125.4	147.8	126.6	42.1	127.5	34.9
stnd. dev.	3.8	2.4	8.0	9.0	4.7	8.6
range	11	7	23	27	16	23

Note:

The head tilt angle is based upon the angle between the torso line (a line joining hip to shoulder) and a line running through the shoulder and forming a tangent to the back of the ear. This definition was chosen to correspond with that used in the Skylab zero-g neutral posture anthropometric data.

Table I: Neutrally Buoyant Posture Joint Articulation Angles
(in foot-restraints)

units: degrees

Neutral Buoyancy Posture Joint Articulation Angles (out of foot-restraints)						
	ankle	knee	hip	shoulder	elbow	head tilt
Trial #1	112	123	113	66	143	46
Trial #2	118	123	113	56	132	47
Trial #3	118	153	117	81	140	51
Trial #4	118	130	114	68	132	42
Trial #5	119	154	126	78	137	50
Trial #6	107	128	125	47	137	48
Trial #7	126	127	115	63	136	42
Trial #8	118	126	119	65	140	45
arith. mean	117.0	133.0	117.8	65.5	137.1	46.4
stnd. dev.	5.5	12.9	5.2	11.0	3.9	3.3
range	19	31	13	34	11	9

Note:

The head tilt angle is based upon the angle between the torso line (a line joining hip to shoulder) and a line running through the shoulder and forming a tangent to the back of the ear. This definition was chosen to correspond with that used in the Skylab zero-g neutral posture anthropometric data.

Table II: Neutrally Buoyant Posture Joint Articulation Angles
(out of foot-restraints)

Zero-g Neutral Posture Articulation Angles:

ankle: 111, + or - 7 degrees
knee: 133, + or - 8 degrees
hip: 128, + or - 7 degrees
shoulder: 36, + or - 19 degrees
elbow: 122, + or - 24 degrees
head tilt: 25, + or - 6 degrees

Analysis of the neutral buoyancy data shows some unexpected results, however, in general, the neutral buoyancy data does simulate most aspects of the zero-g neutral posture quite well. As was expected, the foot-restraints did alter the ankle and knee articulations from those found in the zero-g case. In my opinion, this is not due to any significant differences in the agonist-antagonist muscle set points between the two environments. Rather, it is likely that the primary influence on the leg articulations while in foot-restraints in the underwater setting, is the variation in pulmonary volume, and therefore, upper body buoyancy. To ensure that the subject did not "bob up and down" with each breath, it was necessary to breath-hold at as nearly the same point during the respiratory cycle as possible during each trial. This was necessary to maintain some fixed position, however, it is clear that the foot-restraints still acted as a pivot point, at some angle to which the subject was referenced, the value depending upon where the breath-hold began. While in foot-restraints, there is no way to circumvent this problem, which is unique to the underwater environment. When in space, of course, the lung volume has no effect on one's position, since there is no buoyancy. By examining both the in and out of the foot-restraint trials, however, one can more effectively approach the model of the zero-g neutral

posture. When free-floating, the pulmonary volume still causes buoyancy changes. However, since there is no pivot point to fix one end of a limb (the ankle), the entire body rises and falls, remaining in a consistent neutral posture throughout the breath cycle. As can be seen, the values of the mean ankle and knee articulations for the out of foot-restraints trials are very close to those of the zero-g neutral posture. This tends to support the hypothesis that the neutral postures of zero-g and submersion are quite similar due to approaching the unweighted muscle set point tensions.

The upper body joint articulations, on the other hand, more closely approach the zero-g values for the in-foot-restraint trials. Curiously, the out-of-foot-restraint trials yield a markedly larger shoulder angle. There should be no variations in the forces on that limb to cause such a marked change, except simply for a new orientation. A larger data sample is required to confirm if this is a statistically significant deviation.

The head tilt angle is the one parameter which was in the greatest error from the zero-g values in all cases. Upon careful examination of the films, it is apparent that the second stage SCUBA regulator, and the mouthpiece, represented a significant loading factor on the head, although this was not particularly noticeable during the experiments. When in foot-restraints, the effect on the neck angle is not as great, because one tends to have the feet oriented to the horizontal, therefore tilting the body back, and thus causing a larger component of the regulator/mouthpiece weight to be directed toward the torso. When out of foot-restraints, however, one tends to slowly pitch forward,

thus causing the greater component of the weighting to be in a chin down direction. This explains the extreme head tilt for the out-of-foot-restraints trials of the neutral buoyancy study.

The results of this study give encouraging evidence that given the proper test subject placement in the underwater environment, extensive limb weighting and floating does not have to be employed to reasonably simulate the neutral posture of weightlessness, for long duration task research. It may, however, be advisable to attach a float to the head (or regulator second stage/mouthpiece) if head angle for a particular task being studied is important. This would include any task where it is desired for the visual field to be positioned near the neutral posture gaze-line.

Finally, it should again be noted that this study utilized a male test subject of average build. Future studies should observe the neutrally buoyant postures of individuals with different body types, and particularly that of females. Since females have a visibly different percentage and distribution of body fat than males, the effects of this on their neutrally buoyant posture should be considered when utilizing underwater simulations to make decisions which effect astronauts of both genders regarding workstation design, and zero-g task performance.

Chapter 4

An Electromyographic Fatigue Study Comparing Adjustable and Fixed Worksurfaces During Neutral Buoyancy Simulation of Weightlessness

4.1 Introduction

To further investigate the preliminary findings of this research, an experimental protocol was developed to examine the fatigue associated with the performance of posture dependent tasks, and in particular to compare that of a fixed workstation configuration to that of an adjustable one set to the neutral hand position. Since the accomplishment of this research in actual zero-g may not be practical for a number of years, the principles of underwater neutral posture simulation, as developed in the previous chapter, are a useful alternative. Thus, this experiment was developed to be performed during underwater simulation of weightlessness.

For the reasons previously outlined, the anterior lower leg muscles are the most logical choice for primary study. Electromyographic recordings from the Tibialis anterior muscle are, therefore, the focus of this research. Ultimately, it may be desirable to compare the fatiguing of many muscle sets to clarify the degree of use of each region for zero-g posture control. This may be done for various task durations, thus demonstrating not only what workstation configurations are least fatigue producing, but also what dynamics occur in long duration recruitment of other muscles as primary regions fatigue. That, however, must await future research, as such broad analysis goes

beyond the scope of this thesis. It is eagerly hoped, however, that such follow-up studies may be sparked by this research.

4.2 General Guidelines for the Research

This neutral buoyancy study of the neutral posture, and the use of adjustable worksurfaces, has one primary goal. The fatigue of the anterior, lower leg skeletal muscles, produced during long duration posture dependent tasks, is to be compared for a fixed worksurface and a fully adjustable worksurface. The hypothesis is that the fatigue will be markedly higher for the fixed configuration, since the hand position at the worksurface, to be maintained throughout the task, will deviate too greatly from the hand position of the neutral posture. A positive result supports the hypothesis. A negative result implies one of two things. Either the hypothesis is incorrect, and the fixed configurations currently used in space architecture demand very little fatiguing active posture control, or else the design of the experiment is merely insufficient to discern a significant difference (buoyancy simulation ineffective, insufficiently fatiguing task duration, etc.).

To avoid a false negative result, the task to be performed must be highly posture dependent. This demands that it require the experimental subjects to maintain a relatively static posture with the hands remaining over the work area. The nature of this task should ideally be as representative of posture dependent tasks typical of current Space Shuttle and Spacelab, and future Space Station, tasks. For this research, a 20 minute keyboard entry task and intermittent

recording of data on a writing surface, were used. Both the character of the task itself, and the duration, may be considered reasonable simulations of typical computer-interactive astronaut activities. The duration is also considered likely to begin to lead to observable fatigue. The particular nature of the keyboard entry task is not highly important, provided that the task requires sustained maintenance of task posture. However, regardless of the task involved, a subject might attempt to rest momentarily between keyboard operations. This may be avoided by careful instructions to the test subjects, and monitoring of their continuous close attention to the task. However, it is perhaps most effectively accomplished by simply keeping the test subjects self-motivated, and this was done for this research by keeping them entertained with the challenge of a computerized keyboard game (blackjack), mounted on the worksurface in a waterproof bag. Scores were then intermittently noted on a SCUBA diver's writing slate, also mounted on the worksurface.

The comparison of the fatigue producing task, between both configurations, is made via spectral analysis of the electromyographic signals recorded from the Tibialis anterior muscle. The principles behind this analysis technique are outlined in Appendix II, and performed in detail for the data of this research in Chapter 5. The approach used in Chapter 5 is briefly described in Section 4.5. Since the spectral analysis techniques being used require a constant force level of contraction, for reliability in interpretation, the EMG cannot be analyzed during the task itself, during which the level of contraction varies. For this reason, it was recorded prior to, halfway

through, and immediately following, the posture dependent task, during 45 second static tests. The static tests are constant and known force-level contractions, between which is sandwiched the posture dependent task. These were accomplished using lead weights, which were held up via dorsiflexion of the Tibialis anterior. It is the downward shift of the median frequency of the EMG during these static tests, and the increased rate of its decline from the first static test to the second, that is analyzed to compare metabolic fatigue produced (Again, please refer to Chapter 5 and Appendix II.).

It must be remembered that the EMG signals for this research were recorded from the muscle of individuals who were fully submerged underwater. This represented a substantial logistical problem, however, a bit of experimentation, with the aid of researchers at the Boston University Neuromuscular Research Center, led to a very effective experimental set-up which included modified surface electrodes. This is described in Section 4.4. Naturally, due to the low impedance interface to the experimental subject that is created by electrodes, they were connected to the instrumentation via a biomedical isolation amplifier.

The posture dependent task was performed at two different types of worksurface configurations, which were alternated for each session. One configuration was a standard fixed worksurface position. This configuration was preset by the experimenter to a position, relative to the foot-restraints, matching that of the ESA Spacelab workbench racks (This was interpolated from dimensions of diagrams in the NASA/ESA Spacelab Accommodation Handbook (ESA Ref. no. SLP/2104) to be such that

the center of the work surface be 40.8 inches above, and 9 inches beyond, the toe area of the foot-restraints.). The other configuration was individually set by the test subjects to match, as closely as possible, their own unique neutral (buoyancy) posture hand position while in foot-restraints.

4.3 Experimental Protocols

This experiment used three test subjects, one of whom was female, and the other two male. There were four neutral buoyancy test sessions per subject, during which the keyboard tasks were performed at a microgravity workstation mock-up set up on the bottom of the pool. Although a larger sample space, of both subjects and sessions, would have been preferable, this was not possible due to time constraints that included the logistics of performing each session, the inflexible nature of scheduling neutral buoyancy tests at MIT's recreational swimming pool, and the limited tolerance to water temperature that could be endured by the subjects. The subjects were not allowed to wear full body coverage for warmth, since both wet and dry suit styles of thermal protection alter the neutral posture by changing limb buoyancy, as well as their freedom of movement. The possibility of having the standard pool temperature raised (from approximately 81 degrees Fahrenheit) was not available for these experiments, but is a solution. Therefore, duration of immersion had to be limited. In addition, a hooded neoprene wet suit vest (commonly called a chicken vest by divers) was provided for the subjects. This provided some

thermal insulation for the head and thorax, while not altering the neutral posture. An added buoyancy about the center of mass was the only effect, and this was cancelled with a weight belt. The use of this vest allowed subjects to remain immersed for approximately half an hour before chilling became too extreme (It should perhaps be noted for readers familiar with happily swimming in colder water temperatures than that of this pool, that the test subjects of these experiments were essentially motionless, except for minor hand movements. Under such circumstances, the first stages of hypothermia occur rapidly in water more than 15 degrees Fahrenheit below normal body temperature.).

The standard protocol for a given test subject, during a given session, was as follows:

- I. The test subject began preparation for the experimental session. The subject donned a hooded wet suit type vest, and a weight-belt, and entered the pool. The subject began breathing on SCUBA (surface supplied via extension hose to second stage regulator), checked/adjusted the amount of weight on the belt to achieve neutral buoyancy about the center of mass, and familiarized him or herself with the research set-up. Once this was accomplished, the subject returned to the edge of the pool. The experimenter prepared the right lower leg of the subject (shave, and abrade superficial epithelia), and attached a small surface electrode and waterproof pre-amp package to the region above the Tibialis anterior muscle. While performing these tasks, the experimenter verbally reviewed the experimental and safety

procedures, and provided the subject the opportunity to ask any questions.

II. The test subject entered the pool, rechecked neutral buoyancy, and slipped the feet into the foot-restraints of the workstation, relaxing in neutral posture. The experimenter, who also served as the safety diver for the subject, assisted with this, and then took a nearby position for observation.

III. Long Duration Keyboard Entry Task:

Two types of configurations (see below) were used for the long duration tasks. Each subject saw each configuration during half of the sessions. Each configuration was encountered by subsequent subjects in an alternating reverse fashion from that of the previous subject, thus balancing the experiments for order effects, compounded fatigue effects, etc..

A. Fixed Standard Configuration

During half of the test sessions, the experimenter set the worksurface to a standard configuration, matching as closely as possible, that currently used for the E.S.A./NASA Spacelab workbench racks. Each subject then performed a long duration task at the worksurface in that fixed configuration, for twenty minutes. The task, the primary purpose of which

was to require the subject to maintain a task posture necessary for the given configuration, consisted of a series of keyboard entries at a calculator-sized game in a waterproof container. Immediately prior to, halfway through, and following the task, a 45 second static test was performed, in which the subject applied a known, constant force isometric contraction to hold the weighted assembly for the right foot (see Section 4.4) in dorsiflexion. During the static tests, the EMG signal from the right Tibialis anterior, was sampled at 1000 Hz. and recorded digitally. A raw, unsampled analog signal was simultaneously recorded on magnetic tape with an FM recorder.

B. Individual Unstowed Configurations (adjustable)

During the remaining test sessions, the test subjects performed the long duration task at the workstation in an unstowed configuration, as adjusted by them to their neutral hand position. The static tests were performed as above, and the same data was recorded.

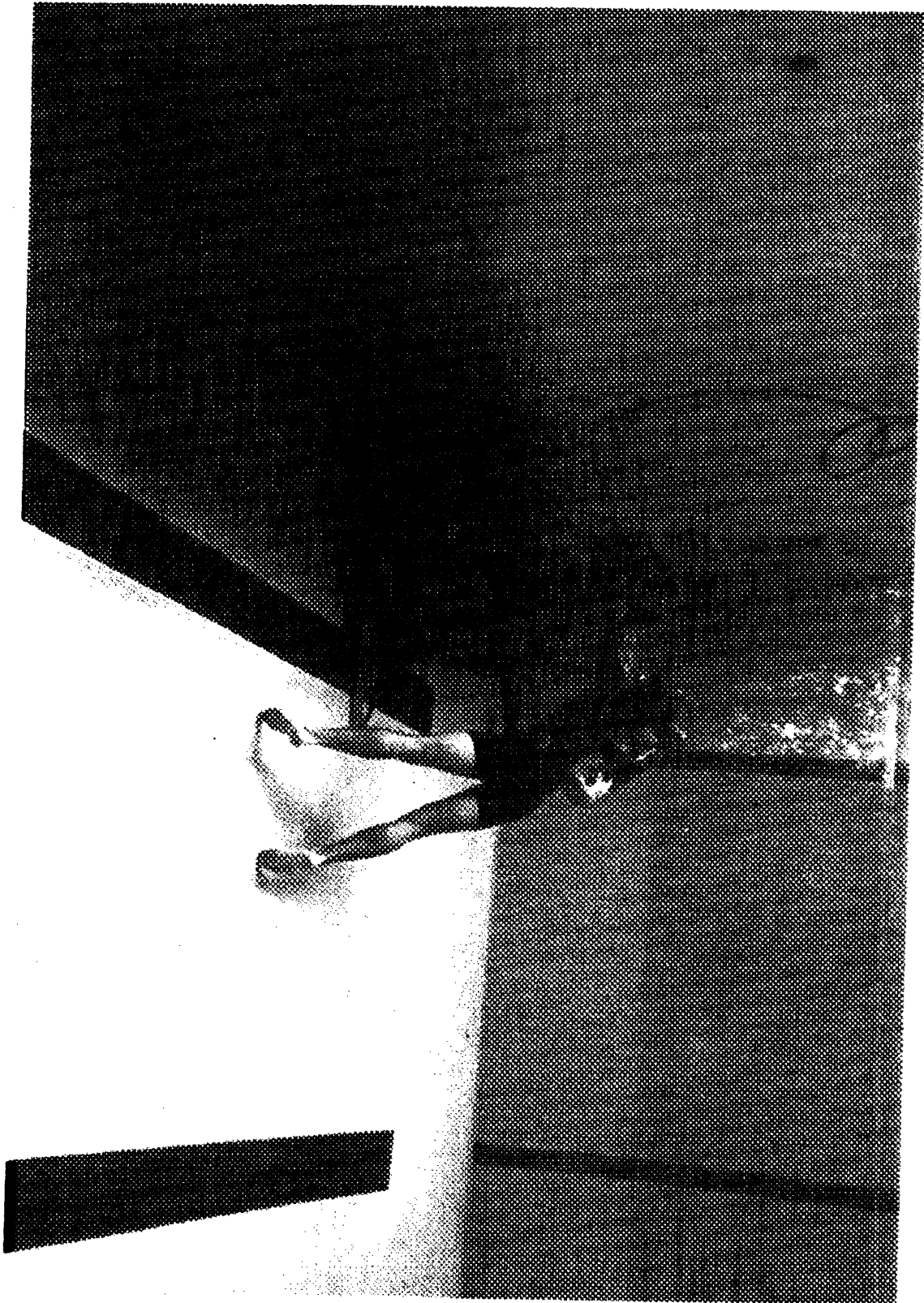
The adjustment of the worksurface, to the neutral hand position of the individual, was accomplished as follows. The subjects were instructed to, once in the foot-restraints, close the eyes while completely relaxing their musculature, simply letting the body drift into the neutral posture. At this point, the experimenter

assisted the subject to adjust the worksurface, relative to the restraints, to the resultant location of the hands. This was then repeated (at least once) until the subject was content with the adjustment. A subject being assisted in this manner is illustrated in the photo of Figure III.

4.4 Experimental Equipment and Data Acquisition

The equipment necessary for this research was kept as minimal and simple as possible, due to a limited budget. The underwater zero-g workstation mock-up, is a non-enclosed apparatus, consisting of an adjustable worksurface, and a foot-restraint assembly. It was designed to serve in both the fixed standard and fully adjustable configurations. Two microphone boom stands were mounted in parallel on a sturdy base. A light plexiglass worksurface was mounted on the end of the booms, in such a manner as to allow for tilt adjustment. This can be seen in use in Figures V and VI of Chapter Five. With the booms slid back to the stops, in a fully retracted position, and the height adjustment set at the minimum, the worksurface was positioned to the fixed standard configuration. This was ensured due to the location on the base to which the foot-restraints were mounted, relative to the boom stands. One knob controlled fore-aft adjustment of each boom, while a second controlled the angle of the boom, allowing height adjustment. These were used during the sessions using the adjustable configuration. The foot-restraints were also fixed to the base, and

Figure III.



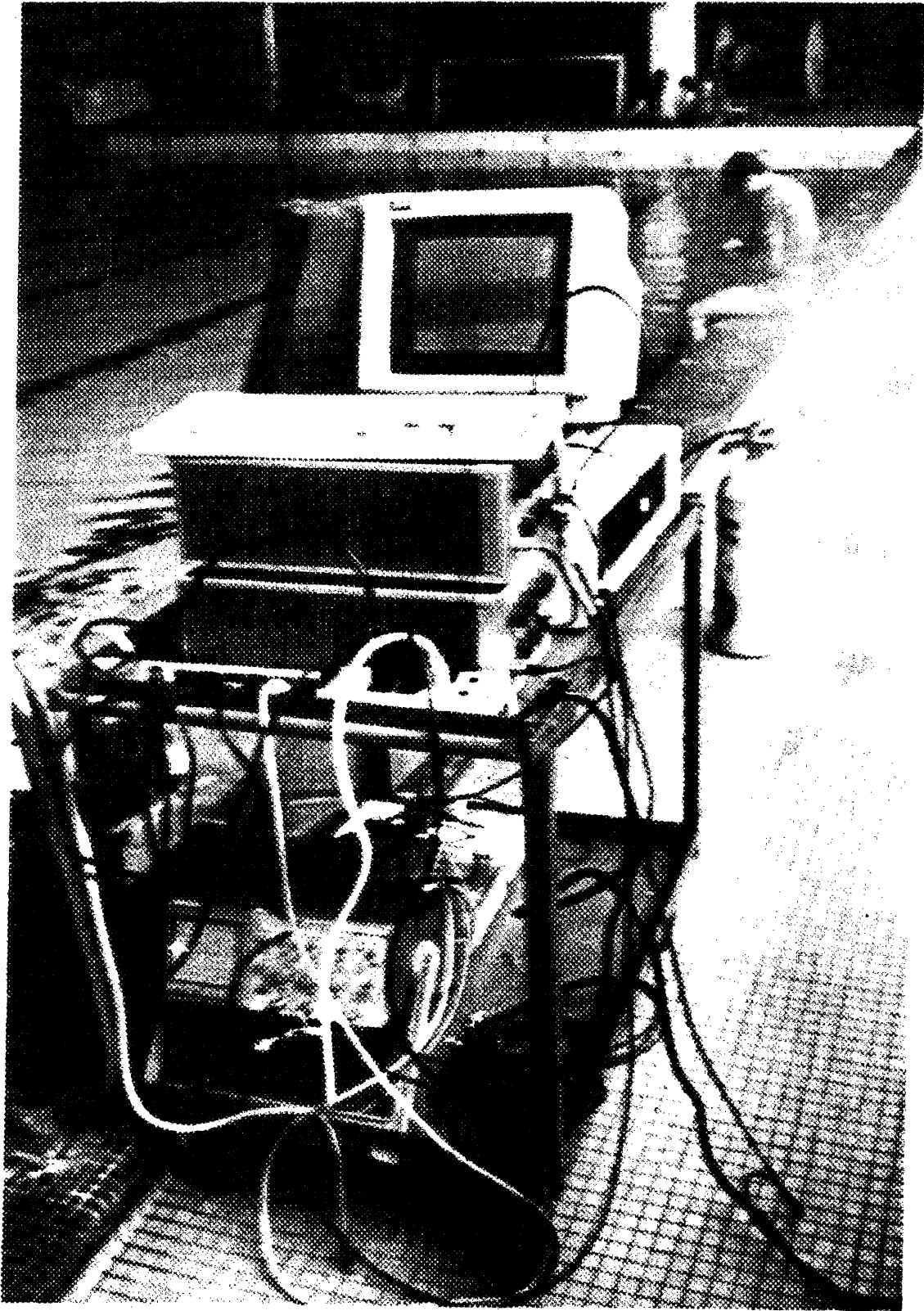
consisted of modified water-skiing bindings. These allowed the feet to be slid easily into them, with firm attachment once that was done. In addition, a lead weight assembly, to be placed on the right foot during static tests, was positioned in a location relative to the foot-restraints. This could be slipped over the right foot by the subject, the heel placed in a precise location, and the base assembly held with the hands while the subject was seated for the static tests.

The electromyographic (EMG) signal from the Tibialis anterior muscle of the right leg, was acquired with a modified surface electrode and pre-amp package. The modification, necessary due to the underwater environment, consisted of potting the entire assembly of a bar electrode pair and preamp circuit, in a small rectangular cube of epoxy. The entire assembly, was thus waterproofed, with the upper surfaces of the silver electrode bars being the only exposed components. This final design (please refer to the Acknowledgements) was tested in the underwater environment, and proved to be quite effective. The problem that a short would be created by the presence of water, thus nulling the potential difference between the electrodes, was avoided by ensuring a minimal water layer in that region. The epoxy layer between those electrode bars, was purposely brought right up to virtually the level of their surface. Finally, a firm pressure on the skin, sufficient to leave impressions of the electrode bars on the leg following their removal, served to evacuate any remaining water in the region being discussed. This was accomplished by taping and covering with an elasticized knee brace slid over the lower leg, and

the electrode/pre-amp package can be seen beneath this wrapping in Figure V of the next chapter.

Cabling ran from the electrode/pre-amp package to the surface of the pool. Here, it was amplified (x1000) with a fully isolated biomedical amplifier (Analog Devices 284J). The raw signal was then recorded on a multichannel F.M. recorder, which was used as a back-up for data storage. The same signal was acquired digitally with a Compaq Deskpro 386/20 computer, and a Metrabyte DASH-16G data acquisition board. Using the software package Labtech Notebook, the EMG signals during the static tests were sampled at 1000 Hz., for 55 seconds, with a +/- 10 volt A/D range. In addition, there was a five second recursive pre-trigger sample. Thus, with a hand signal from the safety diver to the surface, marking the point at which the static test was initiated, the sampling was triggered, grabbing five seconds prior to the signal and the following 55 seconds. This ensured recording of the entire static test. The entire instrumentation set-up, on a cart with a splash-guard, is shown near the pool in Figure IV.

Figure IV.



4.5 Data Analysis

Signal processing and spectral analysis of the digitally recorded data was performed using the MATLAB software package. The data files were transformed such that they were in matrix (vector) format, as required for MATLAB operations. These files were plotted, so that the precise instant of initiation of contraction for the static tests, could be observed. A macro file was then written to perform the following. Three seconds beyond the point of contraction initiation was chosen as the point at which transients (motion artifact) disappeared, and elements of the matrices below this time instant were removed. These data files were then divided into 18 intervals of two second duration, with the elements beyond this point also being removed. The resultant 36 seconds of data, from each file, were clean EMG signals, free from transients, with the time instants representing a common duration of fatiguing contraction from the point of initiation. These two second files were transformed into the frequency domain via Fast Fourier Transformation (FFT). The lower frequency components were removed, yielding high-pass filtering with a cut-off of 80 Hz.. This value was chosen to match the approach used by researchers at the Neuromuscular Research Center at Boston University, the fundamental research of whom formed the basis of the fatigue analysis of this study. Frequency components below 80 Hz. are sufficiently long in wavelength to produce significant distortion when travelling along muscle fibers, and are therefore better filtered from a signal than included in analysis (Broman, Bilotto, and De Luca,

Journal of Applied Physiology, 1985). Conveniently, this value also served to remove 60 Hz. noise, a problem which had been minimized, but was present, for the recordings from the pool. Finally, spectral analysis was performed on the high-pass filtered data files to determine median frequencies for each two second interval. This was accomplished within the macro file, using the definition of median frequency whereby the energy content of the signal power spectrum is equally divided on both sides of the median frequency value.

The resultant eighteen median frequencies, for each two second interval per session, were fitted with a linear regression. The slope, intercept, and standard deviation of the slope, were calculated. Since the rate of negative slope increase (rate of increase of median frequency decline), for pre- to post- static tests, was hypothesized to be greater for the fixed configurations, statistical T tests were performed between the slopes of the two configurations. This is performed on the data of this research, in the next chapter.

Chapter 5

Results of the Neutral Buoyancy Electromyographic Fatigue Analysis

5.1 Presentation of the Results

The neutral buoyancy experiments described in Chapter 4, were performed during the summer of 1988. Figure V shows one of the experimental subjects performing the keyboard entry task at the adjustable worksurface configuration. Thus, before the photo had been taken, the workstation mock-up had previously been set by the subject to match the neutral posture, as defined in the protocols. Also visible in the photo, is the electrode and pre-amp package, held beneath an outer elastic band, over the right Tibialis anterior muscle. Figure VI shows the same subject at the fixed configuration, designed to match the position, relative to foot-restraints, of the worksurface of the NASA/ESA Spacelab general workracks. This configuration was pre-set by the experimenter.

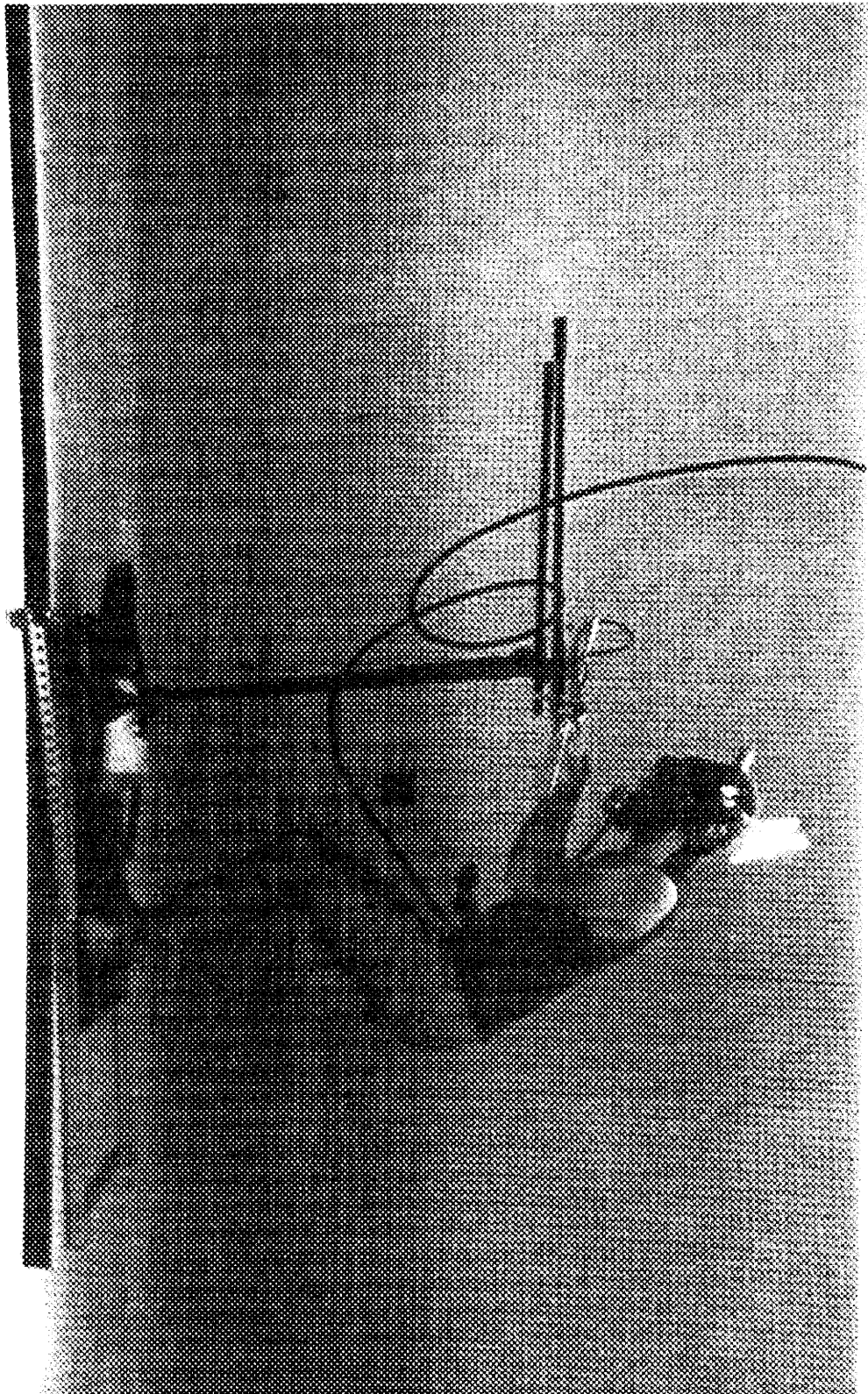
A comparison of Figures V and VI shows that the subject is more upright at the fixed configuration. Since the upper body is unfixed, this deviation from the neutral posture must stem from the muscular action of the lower body. It was interesting to note that one of the subjects (Subject B), stated an obvious and marked difference in effort required to perform the task at the two configurations, with the use of the adjustable worksurface being pleasantly easier.

The EMG data was recorded and analyzed, as described in Sections 4.3 through 4.5. The results, for each session of each subject, are

Figure V.



Figure VI.



listed at the end of this chapter, and will be discussed in the next section.

5.2 Discussion of the Results

In over 80% of the static tests performed, anterior lower leg muscular fatigue was successfully produced, and could be observed in a steady decline of the median frequency during each static test. In the remaining tests, the slope of the linear fit was either virtually flat, or slightly positive. Since the latter situation is not logical in terms of the theory (fatigue recovery can not occur during a contraction), this data was grouped with the flat linear fits, all implying that the static test was not sufficiently fatiguing. This may have been due to either insufficient percentage of the maximal voluntary contraction for that muscle making the test border-line in fatigue production, or simply imprecise task performance. Nevertheless, since the vast majority of cases agree with the theoretical negative slope that signifies fatigue, it can be confidently stated that the analysis was performed upon clean EMG data, recorded during effectively fatiguing tasks.

The following plots (Figures VII through IX) show the median frequency declines during three successive static tests performed during the long duration keyboard task at the adjustable worksurface. The slopes of the linear regression lines may be compared to show that, for this session as an example, the slopes are indeed becoming

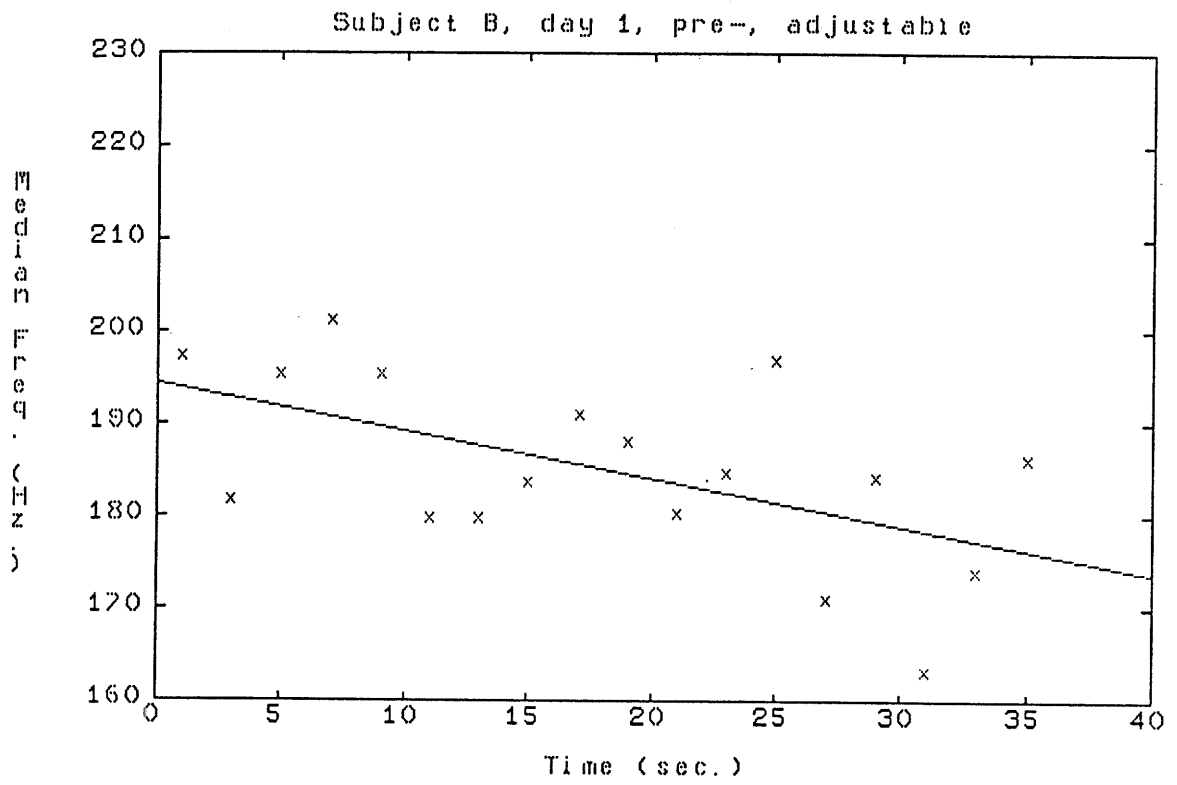


Figure VII.

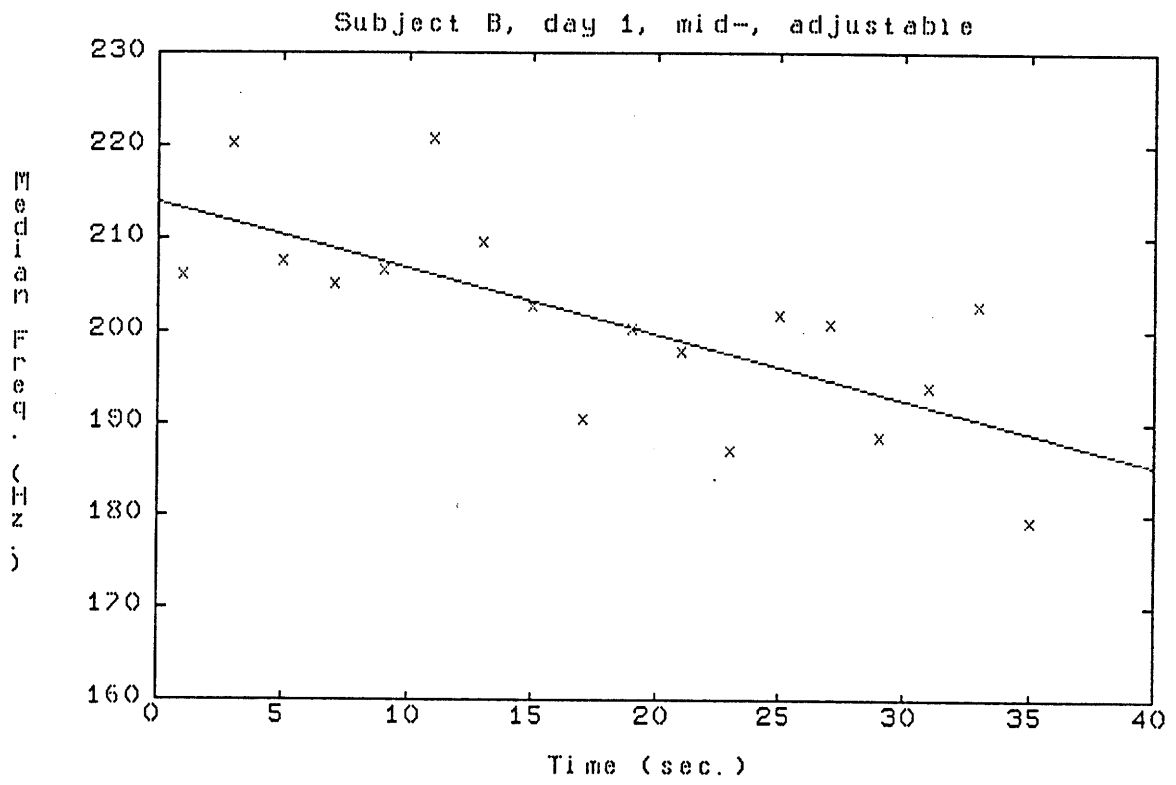


Figure VIII.

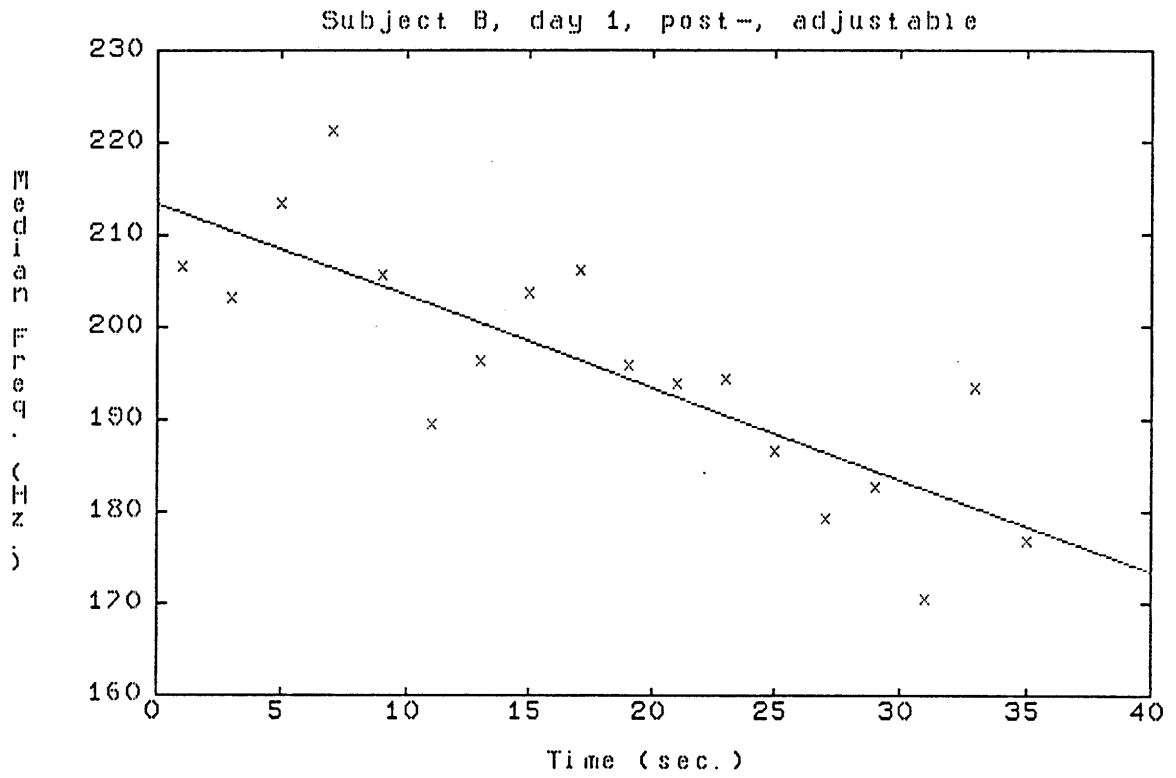


Figure IX.

increasingly negative throughout the posture dependent task. The mid-task static test was performed ten minutes after the pre-task static test, and the post-task test was performed ten minutes after that. These plots demonstrate that Subject B fatigued the Tibialis anterior during the pre-task static test (median frequency decline), and ten minutes later, a static test of precisely the same type produced more rapid fatigue, while the final static test after a total of twenty minutes led to yet more rapid fatigue. The conclusion is that the posture dependent keyboard task between the static tests, has fatigued the muscle, such that the static tests become increasingly more difficult for the muscle. Metabolites and waste products produced by the contraction begin to build up during this process, and as they alter the conduction velocity within the muscle, their effect may be seen upon the median frequency (De Luca, Sabbahi, Stulen, and Bilotto, 1983).

It is that increase in median frequency decline which is to be compared between the two configurations. Naturally, the adjustable configuration matching the neutral posture, is expected to lead to a lesser increase than for the fixed configuration. Unfortunately, not all of the data was as ideal when plotted, as that shown in Figures VII, VIII, and IX. In some cases, slopes became flatter as the task progressed. Thus, the data does not demonstrate the desired effect in all cases. Nevertheless, the hypothesis may still be valid. As a non-biased test of the hypothesis, a T test was performed on the data. This is presented in combination with the data as a whole, in the following table.

Summary of Results:

Subject	A				B			
	1		2		1		2	
Session	1	2	1	2	1	2	1	2
Configuration f=fixed a=adjustable	f	a	a	f	a	f	f	a
Slope of linear fit (+/-std.dev.) (pre-)	-0.11 (0.09)	0.80 (0.17)	-0.52 (0.15)	0.44 (0.16)	-0.52 (0.18)	0.24 (0.13)	-0.34 (0.17)	-0.10 (0.10)
(post-)	-0.05 (0.11)	-1.28 (0.22)	-0.75 (0.12)	-0.60 (0.19)	-1.00 (0.17)	-0.48 (0.11)	-0.34 (0.13)	-0.40 (0.10)
T test shows fatigue * (for p<0.01)	no	yes	yes	yes	yes	yes	no	yes
Day	1		2		1		2	
Day's Sessions show hypoth. effect **	no		yes		yes		no	

* as determined by increasingly negative slope

** (post-)slope minus (pre-)slope greater (negatively) for fixed than adjustable

Summary of Results (continued):

Subject	C			
	1		2	
Day				
Session	1	2	1	2
Configuration f=fixed a=adjustable	f	a	a	f
Slope of linear fit (+/-std.dev.) (pre-)	-0.03 (0.11)	0.63 (0.28)	-0.09 (0.14)	-0.26 (0.11)
(post-)	0.10 (0.17)	0.17 (0.09)	-0.24 (0.13)	-0.11 (0.07)
T test shows fatigue * (for p<0.01)	no	yes	yes	no
Day	1		2	
Day's Sessions show hypoth. effect **	no		no	

* as determined by increasingly negative slope

** (post-)slope minus (pre-)slope greater (negatively) for fixed than adjustable

As can be seen from the table of the summary of experimental results, two thirds of the sessions showed fatigue produced by the posture dependent task, with statistical significance ($p < 0.01$). The demonstration of the hypothesized effect, however, was more equivocal. Only in one third of the cases was the effect apparent, and even this could not be demonstrated with significance, due to the very small sample size. This was despite verbal commentary by the subjects that the hypothesized ease of task performance at the adjustable configuration was apparent. It is probable that the level of fatigue produced was simply not high enough to be born out in the small sample space. Thus, the posture dependent task, should probably have been longer, and this could be done in future work with warmer water temperatures. This research cannot prove the hypothesis, however, that is very likely due to a border-line degree of fatigue. It does demonstrate trends which deserve more research effort, and what has been seen (see the T test results*) to be a useful experimental design.

Chapter 6

Other Future Workstation Research and Design Considerations

6.1 Foot-restraint Design

The theoretical aspects of this research, developed in Chapter 2, suggest both the reliance upon the lower body musculature for non-neutral posture control, and the usefulness of adjustability in reducing this, and thereby the resultant fatigue. Nevertheless, it is likely that even when using adjustable worksurfaces to allow matching with the neutral hand positions, there will remain lower leg fatigue. Why? In theory, if the neutral posture is exactly obtained for task performance, there should be no contractions necessary. In practice, however, drift and task-reaction force phenomena do lead to some minimum amount of contraction, which will always be necessary. Yet the situation is far from hopeless. There is one final way in which fatigue may be reduced; foot-restraint design must be improved, perhaps to a body-restraint system.

In the conversations with astronauts referred to in Chapter 1, their comments regarding task performance in foot-loops were remarkably similar reflecting their dissatisfaction with the level of performance possible with the current foot-loop design. Most striking was a comment stating that it seemed half of the task time and concentration were wasted trying to hold position in the foot-loops. This is not surprising, since foot-loops (especially the current loosely fitting ones) require sharp dorsiflexion just to keep the toes underneath them.

The anterior lower leg muscles are not capable of sustaining the force required for us to go about hooking our feet and toes upward. Thus, foot-loops are not the optimum form of foot-restraint. Although any complication added to foot-loops makes entry and exit from them more difficult, proper design can minimize this problem, while still providing restraints which do not demand dorsiflexion. I suggest the use of VelcroTM to allow rapid snugging of the foot-loop over the arch of the foot, with another strap wrapping around the heel from that, also attaching with VelcroTM, the foot being held like in a snowshoe binding. The resulting foot-restraint would allow rapid entry/exit, yet serve as a useful restraint. In addition, with the heel strap left open, and the loop unsnugged, this design would still be useable as a standard foot-loop, for brief tasks requiring repeated entry/exits.

6.2 Routine Worksurface Angle Selection Indicators

This research has demonstrated the requirement for adjustability in microgravity workstation design, for effective fatigue reduction. The addition of adjustability in design, however, complicates user implementation. Rather than merely going to work at a fixed worksurface (which although simpler, will be fatiguing), the user must first set the vertical and horizontal position of that worksurface to his neutral hand position, and then set the desired working angle of that worksurface. It is difficult to do much to reduce the work

involved with setting the position. At best, the knobs, etc., that tighten the supports once the position is set, may be made as easy to use as possible. As has been suggested, perhaps only vertical adjustability is necessary, which is one possible simplification. Nevertheless, the setting of the worksurface to neutral hand position shouldn't be too bothersome; one must merely relax the skeletal musculature to find that location, and then tighten the supports there. There is no convenient way to set the angle, however, and therefore some means should be provided to easily accomplish that.

Optimum worksurface angle depends upon the nature of the task being performed. The visual field should approach being perpendicular to the line-of-sight, within personal preference. Thus, for reading a checklist on the worksurface, the worksurface itself should be nearly perpendicular to the zero-g line-of-sight (LOS). For a computer task, the worksurface angle should be that which allows the computer screen to be perpendicular to the zero-g LOS. For example, the standard workstation computer might have a screen tilted 60 degrees relative to the worksurface upon which it is mounted. The worksurface should then be set at 30 degrees to the zero-g LOS. The keyboard should probably be separate from the computer screen, so that the angle of that may be adjusted separately.

It is likely that there will be several such "routine" angle settings for adjustable microgravity workstations. The problem is that the zero-g LOS is more difficult to determine than the neutral hand position. The eyes can be opened when in neutral posture, for a reasonable approximation, however, that is time consuming. In

addition, the further judgement of right angles to the zero-g LOS is another source of difficulty and error. Thus, for "routine" tasks of known optimum angle setting, there should be some means of rapidly acquiring that setting. Simple markings will not work with the multi-jointed support arms of a fully adjustable worksurface. Therefore, a more elegant design must be developed. One possibility is to provide an array of LED lights, some shielded at certain angles, others at other angles. Thus, when the worksurface is correctly aligned to some desired "routine" angle, certain LED's of certain colors would be visible, while others would not. Each "routine" angle would have its own LED pattern, similar in design to the VASI glideslope indicators used for aircraft instrument landings. Whether or not such an adjustment indexing scheme is necessary is debatable, and may be determined once adjustable worksurfaces are put into use. They do, however, have the potential benefit of reducing the time associated with the individual adjustment necessary of such worksurfaces. With every moment of astronaut in-orbit time being economically valuable, this question warrants consideration.

6.3 Fatigue Analyses in Space

This research provides new insights to the anthropometrics of the neutral posture, and the use of adjustable worksurfaces. However, to fully investigate these concepts, it would be extremely useful to

perform experiments in actual microgravity conditions. Although the logistics would be more difficult than a neutral buoyancy simulation, the fatigue studies of the previous chapter could be done in spaceflight without too much problem. The instrumentation required for the recording of EMGs is quite simple, and the lack of the water present in the buoyancy studies, would actually make the zero-g measurements easier. EMGs could be recorded during actual on-orbit Spacelab tasks of long duration. Perhaps future research will lead to such exciting studies.

Appendix I:

EXPERIMENTAL SUBJECT QUESTIONNAIRE

An Investigation of Adjustable Microgravity Worksurfaces,
Through Analyses of
Neutral Body Posture and Lower Leg Muscular Fatigue Characteristics

Subject name: _____

Thank you for your interest in, and assistance with, my research. I'd appreciate your assistance in providing me with some important information. Please return this to me as soon as conveniently possible, in the envelope I have provided. Although this questionnaire may appear quite lengthy, there are only a few questions. The majority of this verbiage is merely a description of the precise information I'm looking for regarding the anthropometric measurements. So, hopefully this should not be nearly as tedious to complete as it may appear, and should take only a few minutes of your time. Really! Your answering the anthropometric and physical endeavor questions (#'s 4 and 5) are completely voluntary, and your answers to all questions will be kept confidential. All experimental subjects will remain anonymous. Please provide all applicable information, if you choose to answer a given question. Otherwise, it is better to state your wish not to answer, either at all, or in part.

After reading the instructions which follow, please fill in the blank spaces in the chart below, regarding a few of your unique anthropometric measurements. PLEASE, be certain to read through my instructions BEFORE taking any measurements. It should only take a moment, and will ensure that we're all making the same assumptions, of which there are a number of valid ones, but only specific ones in which I'm interested. The instructions may appear complicated, but they're really not. It's merely the result of trying to explain something quite simple on paper. You should be able to read them very quickly. You'll be amazed!

Anthropometric measurements:

(Please specify your units of measure; inches or centimeters are acceptable, while parsecs or Angstrom units are somewhat inconvenient!)

INSTRUCTIONS BEGIN ON THE NEXT PAGE.

- a. units of measure: _____
- b. overall height: _____
- c. distances between anatomic locations (Please fill in the five missing values to the chart.):

[Right Side of the Body]	ankle/knee/hip/shoulder/elbow/wrist					
fibular lateral malleolus (ankle)	zero		X	X	X	X
fibular lateral head (knee)	X	zero		X	X	X
femoral greater trochanter (hip)	X	X	zero		X	X
humeral greater tubercle (shoulder)	X	X	X	zero		X
humeral lateral epicondyle (elbow)	X	X	X	X	zero	
ulnar lateral head (wrist)	X	X	X	X	X	X

A FEW BRIEF COMMENTS ABOUT THESE MEASUREMENTS (optional reading):

These particular measurements are important when analyzed in combination with the articulation angles (degree of bending at the joints) of the neutral body posture of microgravity. Facilities on Earth, for use while standing, may be appropriate for use by people of a specific range of statures. The flexed posture assumed in microgravity ("weightlessness") divides overall height into a number of measures within the sagittal plane, which separates the body into left and right sides. One individual with a given overall height, may have a long torso and short legs, while another of equivalent stature, may have a short torso and long legs. Once the body is flexed, these differences may lead to significantly different bodily positions (eg: hands, head) within the sagittal plane.

That is why these measurements are important for this research. Some anthropometric measurements may be considered by some individuals to be personal, private, or embarrassing. One's bodily weight, as well as tape measure type circumferences (eg: waist, legs, bust, biceps muscle, etc.), are sometimes utilized as methods to describe one's figure or shape, and some individuals are therefore uncomfortable with quantifying those things. I am not requesting any such measures, since I have no experimental need for them. I cannot imagine any meaning applicable to those measurements which I am requesting, besides the non-personal purposes of this sort of research. Nevertheless, all anthropometric information will be kept completely confidential and anonymous, and is completely voluntary.

INSTRUCTIONS FOR MAKING THESE ANTHROPOMETRIC MEASUREMENTS (please read):

!!!!IMPORTANT!!!!

As can be seen from the blank spaces in the chart to be filled in by you, I am requesting only your overall height, and five other anthropometric measurements, which shouldn't take too long to perform. In order for those measurements to have any usefulness to my research, we must both be assuming precisely the same thing about between what locations I want you to base your measurements. For your overall height, this is very easy; merely measure the distance from the floor to the top of your scalp, while standing up straight with your feet flat, without shoes, and while looking straight ahead. Standing with one's back up against a wall (a metaphorical description of the situation of working on thesis research?!), one can make a small mark with a pencil, and then turn around and measure the height of the mark. If you already have a value for your height, which you know is current and accurate (eg: doctor's check-up, driver's license), you may use that. For the other five measurements, there are a few other likely assumptions, and I'd like you to use mine. Please locate the six specific anatomic locations, as described below, and then take the measurements between them, and fill in the chart. For the measurement

between the hip and shoulder points, please be sure that you obtain and keep a straight spine. Regardless of what hand dominance, etc. you have (I'm partially ambidextrous, so I'm not trying to be discriminatory!), please be sure to make all measurements from the right side of your body. To find the anatomic locations described, you may find it easiest if you do so in minimal or thin clothing, such as underwear, a close fitting bathing suit, or other clothing of light material. Once you have found the six locations, the measurements between them may be made with a tape measure. What ... you're not a tailor or carpenter, and have no tape measure? No need to panic, a ruler and a length of string (unstretchable!!) will allow you to do the job admirably. If you have someone assist you, the measurements may be easier that way.

LOCATING PARTS OF YOUR ANATOMY:

(Perhaps you never knew they needed locating, let alone that they were lost in the first place!)

A. greater trochanter of the femur (hip):

This is one of the key locations I don't want you to make any wrong assumptions about. One's definition of the general term, hip, depends upon the situation. Commonly, the "hip" is considered the firm, bony area directly below one's waist, referred to when describing the posture of "placing one's hands on top of the hips", where the hands rest above the belt-line of an average pair of pants. That's a valid definition, but not useful for my research. That's anatomically considered the top of the iliac crest. What I wish you to measure from is the lateral side of the top of the femur (upper leg bone), where it joins the hip socket, well below the iliac crest. The greater trochanter is, for our purposes, a big bump which marks that location. Please refer to Figures A-I and A-II. To find it, palpate (feel around with the tips of your fingers) your right side, in the vicinity shown in the figures, while standing normally (This is where having on, at most, thin clothing, will be found helpful. You probably won't find the spot through heavy jeans.). If you think you've found the spot, slide your fingertips backwards, to double-check; if they're at the top or bottom end of your gluteal region (buttock), you've found the wrong bump (The bump forward of the top of the buttock is part of the iliac crest.). While allowance must be given for the natural differences in individual anatomies, the greater trochanter should be forward of the area somewhere about halfway along the length of the buttock. Once you've found the bump, wiggle your thigh back and forth a couple times. You should feel the movement of the hip joint. Base your measurements from the radial center of this bump.

B. lateral head of the upper fibula (outer, lower side of the knee):

The knee joint itself is covered anteriorly by the patella ("knee cap"). That might well be assumed to be a region from which to make a

measurement from the knee, however, it is not the location I am interested in for this research. Instead, I would like your anthropometric measurements to be based on the head of the upper fibula (one of the lower leg bones). That spot happens to be another easy bump to find. Please refer to Figures A-I and A-III. To find it, sit on the front edge of a convenient chair, and bend your right leg at the knee to an angle of about 90 degrees. With a bare leg, you probably will be able to see a bump, as marked on Figure A-III. Palpating your bare knee should confirm the location. To double-check your finding, slide your fingertips forward; they should be a finger's width or two below the lower edge of the patella.

C. lateral malleolus of the lower fibula (outer "ankle bone"):

This one's pretty easy to find. Please refer to Figure A-I. The big, bony, bump on the outside of your ankle, is the spot I'm interested in you finding. One can hardly miss this bump; it's the area one somehow always seems to bang, when walking briskly past chair-legs, etc., especially when not wearing socks! If you find a scar or two, that's probably the spot!

D. greater tubercle of the humerus (tip of the shoulder):

The particular shoulder location I'd like you to use for your measurements, is at the head of the humerus (upper arm bone). The greater tubercle marks that spot, but this bump is overlain by the deltoid muscles, so it is somewhat more difficult to locate than the previous bumps we've used. To find it, please refer to Figures A-I and A-IV, and then palpate that region, at the tip of the shoulder. It should be well off to your side, rather than to the front or back. Moving your arm up and down may allow you to feel around the musculature to locate the bone below.

E. lateral epicondyle of the humerus (side of the elbow):

The lateral epicondyle of the humerus forms another handy bump to use to locate a specific spot, which in this case, is on the side of the elbow. To find it, please refer to Figures A-I and A-V. As shown in Figure A-V, flex your right arm as far as it goes, and then place your left index and middle fingers on the side of your right elbow, such that the lower edge of your middle finger is near the end of your elbow. Lessen the flex of your right elbow until it forms an angle of about 90 degrees. You should now feel the bump we're looking for under your index finger. If not, move it around a bit; you should be close. This may sound complicated, but should only take a couple of seconds. The figures should make the location clear.

F. lateral head of the ulna (outer side of the wrist):

The ulna is the lower arm bone which attaches on the opposite side of the wrist from the thumb, and the lateral head of it is an easy bump

to find. You should be able to see it, and then palpate to confirm what you've found. Please see Figures A-I and A-VI.

Thank you very much for your time. If you have any questions, about any portion of this questionnaire, or the experiments in general, or would like assistance with the anthropometric measurements, please feel free to see or phone me. I may be reached at M.I.T. 37-371, (617)253-0017, or messages may be left at (617)253-7805. Thank you again.

Appendix II: Muscular Metabolic Fatigue and its Relationship to
Electromyographic (EMG) Spectral Analysis

A.1 Introduction

Muscles may be considered to be an organ system, since they are made up of specialized cells grouped together to provide a specific function: the production of force and/or movement within, or of, a living organism. The observation of the outward appearance of a lean human figure provides an indirect look at the variety of skeletal muscle sizes and shapes. It is often stated that form follows function, and that is surely true regarding the skeletal musculature. The spindle shaped fusiform muscles of the upper arm, the Biceps and Triceps brachii, have a large number of cells in parallel, and thus are well designed for providing large forces, but narrow down at their ends to tendons of smaller diameter to allow such muscles to connect to the small attachments at the elbow and shoulder. In contrast, the parallel bands of muscles seen beneath the skin of a well-toned abdomen are the Rectus abdominis muscles; these are strap muscles well designed for the task of drawing the chest down toward the hips, and don't have the small attachment requirements present for the upper arm.¹ There are, however, even more subtle differences among muscles. Comparison of the musculature of humans and that of other creatures, demonstrates differences in musculature among species. The flight muscles of a chicken which merely needs a burst of energy to reach the top of the coop when avoiding a hungry fox, are designed far differently from

those of a Canada Goose or Snow Goose, which may migrate hundreds of miles to and from the arctic. The flight muscles of a Luna Moth are different in yet other ways. Later, it will be shown that many of those differences stem from fiber types, which not only differ between the same muscles of different species, but also between those of different individuals, and even among muscles of a given individual. Finally, there is variation which goes beyond geometric form and fiber type; the muscles of the heart, digestive organs, blood vessels, and other organs, are all quite different in character from the skeletal musculature, and each other.

Nevertheless, muscles are all made up of cells which are functionally very distinct, demonstrating an ultimate molecular similarity, despite diversity. In order to draw any useful conclusions regarding the fatigue associated with using certain muscles during a given task in weightlessness, both the similarities and differences of muscle cells must be understood. The commonalities of their metabolism, as well as the unique properties of fiber types, must be appreciated prior to any analysis or interpretation. Different muscles will fatigue differently.

Muscle is a remarkable tissue.... the same muscles in one case can lift enormous weights and in another can produce the delicate movements required for dancing or music making. Muscle can either move the massive bulk of elephants or give rise to the intricate flutter of the gossamer wings of insects. In some muscles contraction is extremely fast, but fatigue is rapid. In others, like the adductor muscles of bivalves such as mussels and oysters, very large forces are developed relatively slowly... and these forces can be sustained for hours on end with little fatigue.²

A.2 Muscles: Classification, Structure, Contractile Mechanism, and Differentiation into Fiber Types

Muscular Classification, Structure, and Contraction

There are three distinct classes of vertebrate muscle which may be distinguished according to, their appearance under light microscopy, and the forms of their innervation. These classes are the striated skeletal and cardiac muscles, and the non-striated vertebrate smooth muscle of the blood vessels, alimentary canal, respiratory tract, urinary bladder, uterus, vas deferens, and elsewhere.³ Despite their differences, however, all of these classes have the same molecular functional units for contraction. This research investigates fatigue associated with the skeletal musculature.

Muscle tissues are almost entirely made up of water and protein, and some seventy percent of that protein is accounted for by two structural proteins, myosin and actin. The latter protein contains two smaller proteins, tropomyosin and troponin. The actin and myosin molecules form filaments, grouped together into cylindrical myofibrils. A muscle cell is made up of hundreds of myofibrils packed in parallel.⁴

A repeating pattern within myofibrils is referred to as a sarcomere, and these are known to shorten during contractions. The early Greek physician, Galen (ca.: 130-200 AD), theorized that "animal spirits" flowed into the muscles from the nerves, thereby inflating the muscles to make them bulge and shorten.⁵ Little changed until Robert Hooke's microscope of 1665 led the way to cell theory, by Schleiden and Schwann in 1838 and 1839.⁶ From the 1840's to the 1920's, muscular

contraction was explained by the "viscoelastic theory", which essentially assumed that the actin and myosin filaments themselves shortened, the energy necessary for contraction being stored by coiling the molecules like a spring. In 1969, the "sliding filament theory" was proposed by H.E. Huxley, and is now the recognized model for muscular contraction. In this theory, the sarcomeres shorten as the actin and myosin filaments slide along each other, the filaments themselves, however, remaining the same length. This is now known to occur via ratcheting of the globular myosin heads along the actin filament, during repeated cross-bridging of the two filaments, activated by the presence of ATP and stimulated by action potentials.⁷ While the individual filament lengths are on the order of only a micron, they are organized into extensive three-dimensional groups, which when sliding and ratcheting in unison, lead to the macroscopic contractions which are observed.⁸

Myogenesis and Fiber Type Distribution

In section 4.1, the variety of muscle types were discussed at the functional, species, and muscle classification levels. The development of a living organism must somehow lead to these eventual differences. Within a given class of muscle, such as vertebrate skeletal muscle, there can be found "quite distinct sarcomere ultrastructures and physiological properties. These differences are usually discussed in terms of different skeletal muscle fiber types. A single muscle can contain several distinct fiber types, and it is the nature of these

fiber types and their relative abundance and distribution in a particular muscle that gives the muscle its unique functional properties."⁹ These distinct fiber types arise during myogenesis, the formation of muscles before and after birth.

-(a) Ontogenetic Muscular Cell Differentiation

During the early phases of ontogeny, the cells of an embryo begin the processes of differentiation and morphogenesis. By a mechanism not yet well understood, the zygote (fertilized egg) eventually divides to form a spherical morula, which is later organized into a hollow blastocyst that undergoes gastrulation. Vertebrate muscle cells arise from the mesoderm, the middle germ layer of the three-layered gastrula. Differentiation of the muscle cells from other mesodermal cells occurs with the synthesis of the appropriate proteins, and such early muscle cells are termed myoblasts. These fuse into myotubes, which eventually form myofibrils. This is all somehow governed by the genetics controlling cellular differentiation. All of these muscle fibers are essentially the same at this point.¹⁰

-(b) Post-natal Muscular Differentiation into Fiber Types

Although some differences among the muscle cells of a newborn are present, the dramatic differences in fiber types, and their distribution within and among muscles, develop primarily after birth. Fiber type differentiation has been demonstrated experimentally to

occur as the result of the character of the nervous input present.¹¹
Fast- and slow-twitch types of fibers are innervated by fast and slow motor units, respectively.

Clearly, all muscle fibers in a given animal contain the same genetic information. But, once the fiber stage has been reached in myogenesis, it is the action of motor units of different character that modulates the synthesis of the contractile and other proteins. This causes the transformation of the rather uniform population of fibers in early postnatal muscles into the various fiber types...¹²

...impulse activity of a motor nerve in some way modulates gene expression, so that... some genes are suppressed and others are switched on.¹³

There appear to be at least three levels at which this genetic control of muscle fiber types occurs. The first level has already been mentioned in section 4.1. Encoded within the chromosomes is a species-dependent fiber type distribution. The flight muscles of chicken and geese are anatomically very similar, however, the flesh of the breast of a goose is clearly of a dark meat, while that of a chicken is white meat. The long flights of migrating geese require fibers which favor endurance, and those happen to yield a dark color. Chickens do not have a distribution of many of those fiber types in the flight musculature, performing comparatively much shorter flights. The second level of genetic control is a muscle-specific distribution of those fibers for a given species. In the human, for example, the Soleus muscle of the lower leg is involved in posture and locomotion, and it therefore requires a high distribution of the so-called "slow-twitch" fibers, which favor endurance. The muscles of the hands, such as the Flexor and Extensor digitorum longus muscles, are generally used for much shorter periods of time, with relatively high levels of force, and

are often given as key representatives of "fast-twitch" muscle types.¹⁴ Thus, genetics has developed a distribution of fiber types appropriate for the tasks a given muscle is commonly called upon to accomplish. Finally, there may be an individual-dependent level of genetic control. Some individuals have a genetic design suiting them particularly well for some endeavors. The Olympic runner who breaks world records in distance and/or time may be referred to as "a natural", and may indeed have more endurance or be faster than another individual who has practiced and trained to an equal degree. The unique genetics of that individual may yield, among many other things, a muscle fiber distribution extremely well suited for running a given style of race. This level of genetic control may, however, be somewhat compensated for by environmental effects. The "natural" who does not train properly, may not fulfill the potential to become a champion. The less fortunate individuals, who may lack an ideal genetic distribution of fiber types for their chosen physical endeavors, can train in specific ways to favor fibers for speed, endurance, or strength, over others. The cyclist who trains for the approximately 1500 mile Tour de France bicycle stage race, is likely to develop many more endurance types of fibers in the legs, than a sprinter who may run less than a minute at a time, although very quickly.¹⁵

All of these factors control the distribution of types of fibers within a given muscle, of a given individual, of a given species. To study fatigue objectively, those factors must be considered.

A.3 Metabolic Fatigue and the Role of Fiber Types

In the previous two sections of this chapter, muscle fiber types have been referred to rather loosely, as "favoring endurance", or speed, or being "fast-twitch", or slow. An understanding of those differences is critical for an investigation of fatigue; clearly, failure to account for the normal distribution of fiber types in the particular muscle being investigated, as well as any species or individual differences, could invalidate conclusions resulting from the analysis. In addition, however, the fiber types' dependence upon the underlying metabolic processes, must be understood in detail, since it is ultimately the metabolism which lies at the basis of fatigue, and may be used as a guideline to objectively analyze it.

Muscular Metabolism

The metabolic processes providing the sources of energy for muscular contraction, involve biochemical reactions ultimately yielding ATP. While a detailed study of these reactions is neither appropriate, nor necessary here, the information required as background for this research will be presented. A more detailed description may be found in a good physiology text.

In a relaxed, unfatigued muscle, there is only enough ATP for about eight myofibril "twitches", and to sustain a contraction, more must be rapidly synthesized.¹⁶ When the amount of ATP present within myofibrils is exhausted, it is replaced via a series of reactions

involving the breakdown of foodstuffs which have been consumed by the animal bearing the contracting muscle. There are two primary pathways through which this mechanism may take place, which one depending upon the presence of oxygen and mitochondria. The first pathway to be utilized has glycogen as the fuel source, providing energy (ATP) without any consumption of oxygen, even if it is present. This glycolytic pathway yields three ATP molecules for each glucose molecule in the glycogen. There is also an oxidative pathway, and this is not directly involved with contraction, but is referred to as recovery metabolism. Recovery metabolism, however, may take place in parallel with contractions.¹⁷ If oxygen is available (bound with myoglobin), the oxidative pathway will take place in recovery of ATP. Pyruvic acid from the glycolytic pathway, or products from fatty acid oxidation, are used to form acetyl coenzyme A, which is used in Krebs's Cycle to generate hydrogens as protons. These are used in the electron transport chain to create a charge gradient across the mitochondrial membrane, which drives ATP synthesis via oxidative phosphorylation.¹⁸ Under anaerobic conditions, however, the glycolytic pathway will continue on instead, yielding lactic acid as an end product.

Specific Fiber Types

The key concepts in the previous section, for this research, are that two pathways lead to the production of the energy source for muscular contraction, pathways which are associated with the presence, or lack thereof, of oxygen, and mitochondria organelles. Fibers which

are rich in mitochondria, will clearly favor the oxidative pathway, and appear reddish due to the plentiful myoglobin supply of oxygen. These are termed Type I or oxidative fibers, and are relatively slow twitching fibers (sluggish contractile response). They favor endurance, in the presence of oxygen, rather than speed. Fibers lacking many mitochondria, favor the glycolytic pathway, are whitish, and are termed Type IIB fibers. They are relatively fast twitching, favor speed, and do not depend upon oxygen being available. They will lead to lactic acid build-up if the so-called oxygen debt occurs, when the glycolytic pathway continues in anaerobic conditions. Finally, there are also intermediate fiber types, termed Type IIA.¹⁹

Metabolic Fatigue

It is largely the formation of lactic acid, when an oxygen debt occurs, that gives a tired feeling to musculature after sustained and/or repeated contractions. If an excessive amount is allowed to accumulate, pain will develop and may require days to dissipate.²⁰ The oxygen debt will occur when respiration and circulation are not sufficient to replenish oxygen stores being depleted by oxidative metabolic pathways during muscle use. This build-up of metabolites, may be used as an objective means of quantifying and comparing various levels of fatigue, rather than relying on subjective feelings of "tiredness" or discomfort. Thus, metabolic fatigue is a specific physiological condition, rather than the broad general term fatigue, which may be related to alertness, sleepiness, etc..

A.4 Means of Objectively Quantifying Metabolic Muscular Fatigue with Electromyography

To separate confounding subjective factors from physiological factors involved in fatigue, it is desirable to have a means of observing, directly or indirectly, the effects of the metabolic processes taking place. Electromyography has long been a valuable tool in muscular research. It is based upon the electrical activity which takes place within the muscles. A single motor neuron will generally innervate a group of many fibers, and together, this constitutes a motor unit, the smallest portion of a muscle which can independently contract.²¹ The twitch triggered in a fiber creates a small electrical potential which is dissipated through the surrounding muscle, and this may be recorded via electrodes.

There are various clinical uses for electromyography. The use for fatigue studies is possible because one can observe that the electromyographic signal is compressed toward lower frequencies as a muscular contraction is sustained. This was theorized by Lindstrom (1970) and Stulen & De Luca (1981) to be a direct result of the metabolic processes associated with muscular fatigue.²² Amplitude was first used as the parameter upon which to base analysis of fatigue, however, it is very affected by surface electrode placement, and the time varying properties of the boundary layer of those electrodes. Also, since low frequency component increases tend to cancel high frequency decreases, the total spectral power is not a sensitive measure of the overall shift. Since then, other parameters have been

examined and used, including rms ratios, zero-crossing number, mean frequency, and median frequency. Stulen and De Luca have demonstrated that, for various reasons, the median frequency is superior to the other parameters.²³

Subsequent research has validated the relationship between decline in the median frequency and various metabolic processes. By producing reduced circulation to and from muscles under study, it has been shown that ischemia greatly reduces the initial median frequency of a contraction. Thus, hindered clearance of end-products of metabolism known to produce fatigue, may be observed via the EMG median frequency.²⁴ In addition, intramuscular pH has been monitored during sustained contractions, showing high correlation to median frequency decline.²⁵ This matches the known fatiguing effects of lactic acid build-up. For these reasons, EMG median frequency shift has been chosen as a measure of fatigue for this microgravity workstation research. Figure X shows example plots of median frequency versus time, obtained by Broman, Bilotto, and De Luca for 80% maximal sustained contractions of the Tibialis anterior muscle (the same muscle utilized for this research).²⁶ The scale of the ordinate parameter is zero to 150 Hertz, while that of the abscissa is 75 seconds. The decline in median frequency is quite apparent.

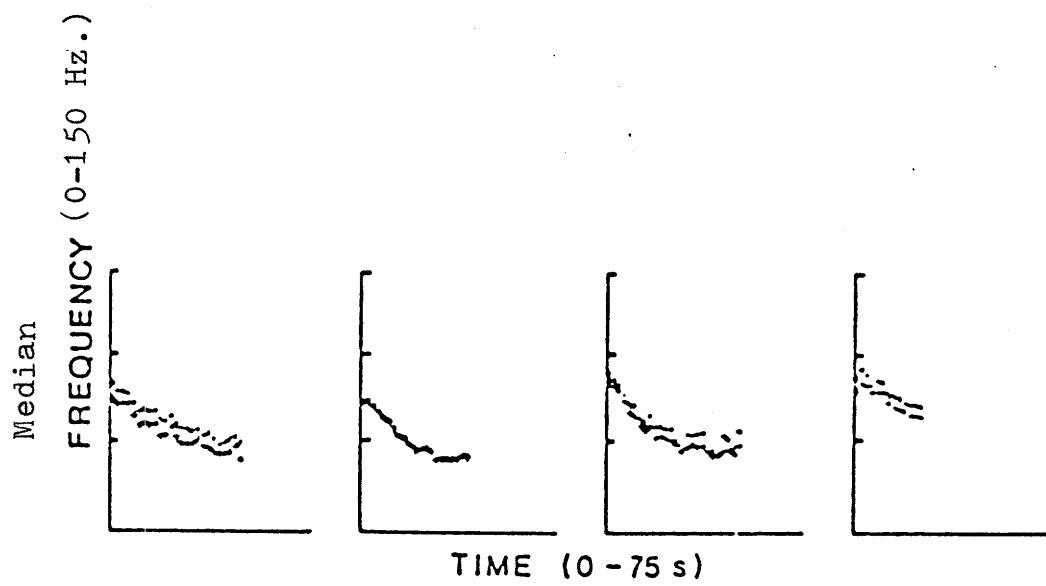


Figure X.

Footnotes:

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- 9 Ibid, pp. 36-38.
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- 17 J.B. West, Best & Taylor, pp. 86-87.
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