SPACESUIT: SPACE CRAFT

by

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Abstract

Often described as a "spacecraft for one," spacesuits exist as highly complex, technical systems. For the wearer of a spacesuit, it represents protection, a life-line extending into the depths of outer space, but for the public, who never see the spacesuit in person, it exists as a symbol. As such it embodies dreams and beliefs about who and what we are, and what we may become. It even goes so far as to suggest our connections to our larger environment of earth, solar system, and universe. These concepts are not just projected onto the material spacesuit, but are contained in its physical construction. Designers are themselves individuals with their own notions of what the spacesuit is and what its function should be. Consciously or subconsciously these beliefs and philosophies are made material through the spacesuit's design and construction. Once in operation, the physical object projects these philosophies onto the world around them, literally shaping the reality of the individual inside the spacesuit. The spacesuit is a highly charged, metaphysical object.

This thesis explores the concept of a spacesuit from many points along the spectrum of its existence from art, to engineering, to mathematics. Cultural explorations of the spacesuit, the body, and space have been performed, installed, written about, and documented in this thesis. These explorations have recontextualized the role of the spacesuit and the entire endeavor of human spaceflight, leading to alternative spacesuit concepts. Refining these concepts required engineering methods including mathematical modeling, model validation, and tests on the human body. In the end, a vision of a culturally invested Mechanical Counterpressure spacesuit is developed along with some of the design tools necessary for its realization. In this way, the spacesuit serves as an object of inquiry that opens up a highly technical realm to a space for exploration with the entire spectrum of human capability. By approaching even the most technically demanding, life-threatening situations in this way, we enter into "space craft," an artistic mode of investigation and realization capable of producing artifacts for the cultural advancement of humanity. Due to the embodied beliefs and philosophies, these artifacts facilitate new possibilities for the people around (and in) them.

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PREFACE

My graduate career at MIT has been framed by the terrorist attacks of September 11, 2001 and the Columbia disaster of 2003. Although both events were traumatic, separating time into before and after, both events had profound impacts on my thinking, increasing my clarity of belief. In many ways these events have pushed me further towards a personal concept of life's work.

The year between my undergraduate graduation and my MIT graduate studies was filled with travel, physical labor, fellowship applications, working at NASA, and teaching whitewater kayaking. Away from the intense focus of MIT, these activities surrounded me with people whose life visions were extremely diverse. I can clearly remember contemplating the odd transition I was undertaking as I drove from Johnson Space Center in Houston, Texas, to the rural mountains of Tuxedo, North Carolina. After spending four months intensely focussed on human space exploration and surrounded by people who did the same, how did I find myself back at the summer camp that was so vital to my personal growth? How could I transition from the intense cerebral realm of NASA to the relaxed, grounded reality of camping in the woods? I knew the summer would allow me to rediscover internal connections that had been ignored for too long.

After spending a summer with best friends from youth, people who were now dedicating their lives to whitewater kayaking and other wilderness adventures, it was hard to return to MIT to work on space exploration technology. How could the work I was to undertake connect with the people I loved outside of MIT? I did not want to forget the alienation from technology and quantification that I had grown to experience that summer, nor did I want to want to unconsciously slip back into the technological utopia of engineering research.

My year off reflected the four years of undergraduate education I spent constantly commuting between the MIT's Aerospace Engineering Department and the tattered building dedicated to lower level architecture studios and visual arts. Before moving on to graduate research and the methodologies of applied science, I felt the need to reflect, to understand where I had come from and what I stood for. It was during this reflection period that the events of September 11th took place.

I was surprised, after growing up in New York and still considering myself a New Yorker, that I had little emotion besides awe in watching the towers smoke and crumble on TV. Numbed by special effects, distance, and the surreal nature of what was happening, I could not connect in any real way. The towers were gone, I knew that, but I had no feeling of what that meant.

Before this day I had no interest in politics. I was in charge of my life and the politicians were in charge of structuring some other reality that connected to me via taxation and economy, but little else. I could not understand the urge some people felt to dedicate their lives to such a bureaucracy with its old-boy network, paperwork, and illogical regulations. I was interested in pursuing what I felt was right and good, and I could not see how the politicians affected that struggle.

As media reports started to focus on the rage of American citizens everywhere I could not relate. No one I spoke to in New York or anywhere else felt the rage that was being reported on news stations everywhere. In addition I heard the politicians make statements of retribution and the need for swift, violent action. Who were these people speaking in my name? Although I was a citizen of a democratic nation, I had no control over my nation's actions. I had no control over the way I would be represented abroad. The importance of politics suddenly became very clear.

September 11th was a powerful demonstration of the ills in the world: the unbalance and inequalities here, abroad, and worldwide. In the days after, it became harder than ever to concentrate on technology. What did space have to do with the truly important things in life? Who was I working for? What was I working towards? How did the epicenter of technology, MIT, fit into the larger context?

Although many statements of support were made by all, acknowledging the difficulties of moving forward, I found few at MIT who were using this opportunity for introspection. The juggernaut of technology had been hit by a brief gust, but beyond the customary sound and slight vibration, it kept on rolling, towards who knew where.

I did not feel anger towards the terrorists that day or any of the other days to come. I felt a sadness, a sadness that we live on a planet where these things are possible. A sadness that humanity is still so subservient to animal instincts and reactions. Where were the higher visions bringing our evolution to a better place? While so many thought about rage, revenge, survival, and protection, I thought about life.

I imagined all of those that perished that day, or in any other act of that kind. What would they want after being subjected to that horror? I could not conceive of them asking for the perpetuation of the cycle, inflicting these horrors on others; I could only imagine them asking for a difference. Their lives were lost, but it was up to the living to decide if they'd been lost in vain. We could not claim to honor their memory by subjecting other lives to violence. We had to look forward, to look higher, to a place where these things could not happen, not because of bunkers and omnipresent surveillance, but because humanity had evolved to a larger understanding of life, self, other, and universe. This was the path that would honor their memories.

Without personally knowing any of the victims, my thoughts focussed on their absence. What were they doing those last moments of life? What had they dedicated their lives to? Were they fulfilled? The biggest horror of their absence was that I would never know; *we*, as a society and world, would never know. Were we ever given the opportunity to see the universe through their eyes, or did we miss the fragile moment of opportunity to learn from their unique, once in an eternity, perspective? Their eyes have never been nor will they be again. The only life they can experience now is through the living, but only if they expressed their unique perspective and we listened.

So much in our society seems to make us ignore our inner desires and vision. Existing thought structures teach us that we have not yet learned to see. With time, and abandonment of subjectivity, they offer understanding and "truth." Instead of creating our own definitions of success, we ask society for its definition, molding ourselves to fit the box of our choosing. Who stands apart from all of these forces and gives their unique vision and reality to the world? Who truly confronts the societal reality, creating their own value system, and pushing ahead despite society's absent gaze? My past, present, and future had reached a moment of increased clarity.

In order to give ourselves to the betterment of humanity, we have to cultivate and tune ourselves to our own inner understandings; to follow the unexplainable urges of our spirit and listen to the forces that make us feel different; to explore our differences and put them on display so that the world can use our eyes and soul to see anew. At the same time, we must expose ourselves to the vision of others so that we too can benefit from an enlarged experience of reality. As we are all prisoners of our own experience and understanding, is there any greater event or miracle than the moment of communication: the union of two or more, distinct, isolated, and trapped entities?

Looking to my education and life experience, the people that were truly exploring their unique perspective, exploring reality in their own ways, were artists. Clearly they were not motivated by money, or other societal seals of approval. Despite the outcast nature of their chosen course in life they pushed on, dedicated to their own, higher visions, and the communication of it.

September 11th renewed, in fact established, my dedication to art as the most important thing any individual can do. It is only through moments of art, of free thought, that any "progress" is made. Only through moments of personal insight do new realities immerge.

The technological feats I was to attempt in graduate school would not affect world crises such as war, famine, and disease. They would mean little to those outside MIT and the larger scientific circles. They were not the sort of things I could share with my family and friends who never studied engineering. They had no potential except for the cultural effects of fascination and inspiration: communication of a human vision, a dream: art.

My September 11th revelations made it clear that I had to follow my own interests in my work and question the justification of others. It was not enough to accept that better spacesuits were needed to walk on Mars. I needed to first consider the whole endeavor of space exploration and its goals. Not the goals of others, but the true goals, as I saw them. Could these goals be accomplished by other means? Were humans and all the expenses worth it?

With the help of others I constructed my own justifications for these actions, and moved on to consider the best methodology for the task. Of course the methods and means of engineering were clear to me, but did they truly serve my purpose: self understanding and communication? A wider perspective needed to be considered.

My conception of science, engineering and technology are often severe, in the negative sense. I do not claim to have an objective, non-biased view; I don't see how anyone can. On the contrary, I try to think and write from my own experience. As experience is shaped by one's sensibilities, the account given in this thesis is subjective and hopefully provocative. In many cases I point the reader towards further reading and references which resonate with my thoughts and beliefs. I hope they will consider reading these references as I feel they have vastly important messages to convey.

In the current culture, benefits of and praises for technology abound, therefore, I feel little impulse to argue the benefits of science. As my biography shows, I have dedicated much time and energy to learning the language and thought processes of science and engineering. I respect these fields, but do not worship them. As our society is profoundly shaped by technology I feel the need to focus attention on the ills inherent in applied science as it is currently practiced. These aspects are less discussed and are therefore more needing of attention, especially because this thesis is produced within the context of an advanced engineering degree.

In contrast, I may be accused of painting a picture of art and design that is too ideal. It could be argued that this is the "grass is greener..." effect. I have strived to be an artist and designer for many years, and have studied the two in parallel with my technical training, but as discussed above, my praise for these fields goes further than my own interest. There are many forms of art and design that I am not interested in, but my hope is that my discussions of these fields may define them in such a way that displays their true capabilities. In the case of engineering, my critique is an attempt to separate the field's strengths from its weaknesses so that a larger, revised notion of technology development might emerge.[1]

1. In its approach to these matters, this is a work of criticism. If it were literary criticism, everyone would immediately understand that the underlying purpose is positive. ... In a similar way, critics of music, theater, and the arts have a valuable, well-established role, serving as a helpful bridge between artists and audiences. Criticism of technology, however, is not yet afforded the same glad welcome. ... If any readers want to see the present work as "antitechnology," make the most of it. That is their topic, not mine.

- Langdon Winner, *The Whale and the Reactor*

As with many, the Space Shuttle Columbia disaster came as a shock. While the start of my graduate studies was framed by the irrelevance of space exploration and technology development, the end was filled with its praise. Although many of my friends and acquaintances knew little about the space station or other NASA enterprises before this disaster, the nation seemed to rally support behind space exploration. Debates over the space administration and their goals flooded the media. Was it worth the cost of human life? Was it worth any thought, time, or money at all? The overwhelming response came back, "Yes."

Why was it that after such a catastrophe, an event that sent many reeling back into the security of their friends and family, so many came forward expressing their support for *human* space exploration? Days, in fact moments, before the disaster, the ongoing exploration of space was a faded memory in the minds of most. How could such a shift be explained?

Although I haven't taken statistical poles or interviewed people across the country, or scavenged the media for documented reports, I feel I know part of the answer. No matter what politicians or bureaucrats say, the people of the earth know that the exploration of space by humans is an endeavor of the spirit, of art. Despite our personal realities of poverty, and abuse, we feel hope due to the mere fact that others are searching higher, both physically and emotionally. We appreciate that those with the resources use at least a fraction of their wealth to push for human, cultural goals no matter how illogical they may seem. In the end, we want others to play even when we cannot so that they can enlarge our realities through their communications, giving us sight where we had no time or energy to look before.

ACKNOWLEDGMENTS

The hope and vision that has kept me on my personal quest has come from inside as well as numerous outside sources. My personal development, education, and this thesis would have not been possible without them. Of course I must thank my **Mom** and **Dad**, **Yvonne Ford**, **Paula Johnson**, **Ronnie** and **Karyn Cahana**, **Sidwill Hartman**, **Ray McMillan**, **Susan Kline**, **Eva Capa**, and **Will Pitts**, my brother, for raising me and allowing me to see through their experience so that I might learn. **Camp Mondamin** and all its counselors and campers were also crucial to my development.

My primary education has included many influential instructors, but of particular note are **Mr. Hornick**, who taught me a love for physics; **Mr. Dooley**, who encouraged my artistic talents; **Ms. Bentele**, who fostered my abilities in math; **Dr. Diemente**, who allowed me to learn without "extra" work; **Coach Brian McKee**, who always demanded my all; and **Doc Johnson**, who always asked us to look in and give our whole selves to Jazz, and life.

My undergraduate education was marked by a few professors in particular: Professor **Krzysztof Wodiczko**, who taught me to think in profound new ways and continues to be one of my highest mentors; **Julia Scher**, who's body extension assignment continues to keep my busy; Professor **David Miller**, who introduced me to the joy of engineering design and the wonders of weightlessness; Professor **Andrew Scott**, who allowed me the freedom to push my design abilities in my own, unique ways; and Professor **Dava Newman**, who has supported my personal education and growth from the beginning (more thanks to come).

Beyond their role in my formal education, particular people are especially deserving of thanks. First I'd like to thank my best friend **Bruce Engle** for his love, dedication, and never ending inspiration. You have always pushed me personally, emotionally, and intellectually and will forever continue to do so. I look forward to our future collaborations and growing old together. **Seth Riskin**, **Donna Marcantonio**, **Sophia Sarafina Riskin,** and **Noah Riskin** are more recently found friends, but are deserving of great thanks. You inspired and helped me in so many ways since our meeting. I hope to develop a long lasting, deep friendship with each of you as we pursue the vision of an art-technology hybrid. **Krzysztof Wodizcko**, although mentioned above, deserves special thanks. It was through your work and instruction that my eyes were opened to a much larger reality and a powerful force of change. If I ever teach it will be in large part due to your impact on me.

Of course, this means of expression would not have been possible without the support of **Dava Newman**. From my freshman year at MIT until today you have always supported my interests and shown great faith in my abilities. In my graduate years you have been trusting enough to allow me great freedom and independence, always asking me to do things in my own way. It is because of you that I am allowed to express myself so freely in this thesis, without being limited by the standard formats. Although you have expressed your disagreement with my thoughts many times, you have never once suggested that I censor them. Thank you.

Jeff Hoffman also deserves special thanks for his guidance on my thesis. Your experience and insights have helped greatly. I look forward to working with you in the future.

The following people also deserve mention: everyone at **MIT's Man-Vehicle Lab**, (especially **Annie Fraser**, **Chris Carr**, **Philip Ferguson**, and **Alan Natapov**) **Cam Brensinger**, **Otto Piene**, **Michael Light**, **Stelarc**, **Phil Spampando**, **Leroy Garey**, **Dave Graziosi**, **David Zetune**, **Dave Robertson**, **JC Calhoun**, **Casey Gething**, **Mat Carey**, **Marthinus Van Schoor**, **Dick Perdichizzi**, **Don Wiener**, **Mariel John**, **Quoc Trong**, **Brian Corner**, **Rob Doyle**, **Kristen**

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As I'm sure I have been unable to mention all the people who have made this work possible, I would like to apologize and offer my grateful thanks for all my instructors, past, present, and future, in all their forms.

-

BIOGRAPHY

May 17, 1978	Born in New York Hospital, New York, NY.
1981 - 1982	Attended 68th St. YMCA nursery school, NY, NY.
1983	Attended Christ Church Kindergarten, NY, NY.
1984 - 1992	Attended Collegiate School, NY, NY.
Summers of 1989 - 1995	Attended Camp Mondamin, Tuxedo, NC.
1992 - 1996	Attended Trinity School, NY, NY.
June - August, 1996	Instructed whitewater kayaking at Cascade Recreation, Horseshoe Bent, ID.
August, 1996	Attended MIT studying Aeronautical and Astronautical Engineering, Architecture, and Visual Arts, Cambridge, MA.
June - August, 1997	Studied graphic design at the School of the Museum of Fine Arts, and drafting at the Boston Architectural Center, Boston, MA.
January, 1998	Interned at Baxt Architects, NY, NY.
June - August, 1998	Studied industrial design, and abstract painting at Rhode Island School of Design, Providence, RI.
January, 1999	Interned at Robert Stern Architects, NY, NY.
June - August, 1999	Traveled throughout Europe with Bruce Engel, studying architecture.
June, 2001	Graduated from MIT with a B.S. in Aeronautical and Astronautical Engineering, and a minor in Architecture, Cambridge, MA.
June - July, 2001	Traveled through Turkey, France, and Italy.
August - November, 2001	Worked as a physical laborer on a housing development construction sight in Danbury, CT.
January - May, 2002	Worked at Johnson Space Center with their space architecture division, Houston, TX.
May - August, 2002	Instructed whitewater canoeing at Camp Mondamin, Tuxedo, NC.
August, 2002	Returned to MIT to pursue a Masters of Science in Aeronautical and Astronautical Engineering, Cambridge, MA.

"There is a vitality, a life force, a quickening, that is translated through you into action and because there is only one of you in all time, this expression is unique and if you block it, it will never exist in any other medium and will be lost. The world will not have it. It is not your business to determine how good it is, nor how valuable it is, nor how it compares with other expressions. It's your business to keep it yours, clearly and directly, and to keep the channel open. You do not even have to believe in yourself or your work; you have to keep open and aware directly to the urges that motivate you. Keep the channel open.

"No artist is pleased. There is no satisfaction whatever at any time. There is only a queer, divine dissatisfaction, a blessed unrest that keeps us marching and more alive than the rest."

- Martha Graham to Agnes de Mille

1 INTRODUCTION

In the summer of 2001, I had a personal revelation brought on by Michael Light's work, Full Moon,[1] using the Apollo mission film negatives. While standing in front of his prints at the Rose Center for Earth and Space in New York City, I described my fascination with them to a friend. Their sheer beauty was astounding. So crisp, tight, black, and brilliant. So alien. And yet, so human and personal. Here were the astronauts' documentations of their experiences in a medium that far exceeded the power of numbers or analysis.

1. Light, Michael, *Full Moon*, Johnathan Cape, London, 1999. (http://www.projectfullmoon.com/)

So much lies behind these images -- technology, individuals, and the universe. Literally behind the camera is the astronaut, who, in order to survive long enough to take these pictures, must wear a spacesuit. The story behind that spacesuit, the one-man spacecraft, has a history and development process that connected with many peoples' lives. There are hundreds of human stories of triumph and failure, vision and sweat.

Inside the spacesuit stands the astronaut. Apollo photographs provide us with a glimpse of what they saw with their own eyes, what they themselves experienced, and allow us to stand with them on the alien, yet familiar, landscape. Here too, captured behind these images, are hundreds of lives and stories behind each astronaut, their training, and their lives before the instant of shutter release.

Of course, to get to this moment in space and time, the astronauts and suits had to make the journey from earth to moon. Behind the travel lay advanced technology, spacecraft, hundreds of thousands of workers and engineers, a nation, a world, and millions of spectators. As with any other action, there is an entire planet, an entire history of civilization, an entire universe, behind these photos.

Figure 1.1: (This and opposite page) Photographic composite of the Taurus-Littrow valley. On the horizon, from left to right, we see the Sculptured Hills, the East Massif rising over geologist-astronaut Dr. Harrison Schmitt, Bear Mountain, the 2,286 meter-high (7,500-foot-high) South Massif, and finally the North Massif rising almost 2,134 meters (7,000 feet) over Camelot Creator, itself 610 meters (2,000 feet) in diameter. Hasselblad 70mm transparency by James Irwin, Apollo 15, July 26-August 7, 1971. Image and text from the book ***FULL MOON*** by Michael Light, copyright 1999/2002.

"Imagine if the sole reason for the Apollo missions were to take these photos," I remarked. "Think of everything that had to happen just so these astronauts, with cameras mounted to their chests, could capture these images." And then I realized my true fascination with these images and everything they captured: these images *were* the sole reason for these missions, for the technology, for the hope and dreams of an entire planet that was put behind the Apollo program. The photos: what else was there?[a]

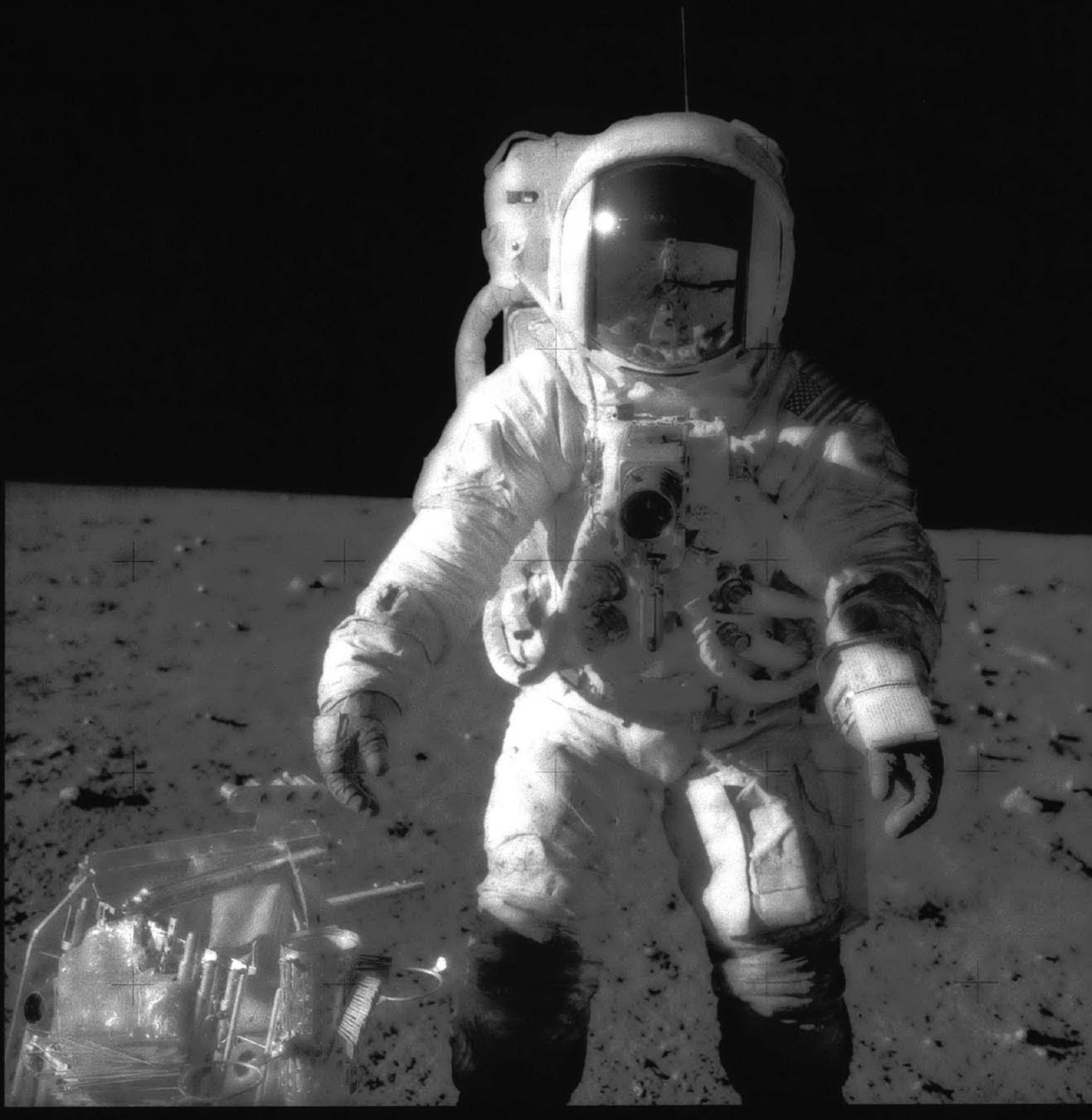
Many would be disappointed with this conclusion and point to the wealth of scientific evidence that was gathered while on the moon's surface; the spin-off technologies that impacted people's lives (and continue to do so); the political objectives fulfilled during the cold war era. But think, for a moment, about the beauty of a simple goal: a picture, that's

a. Some would be quick to point out that humans did not need to be on the moon surface to take pictures. Plenty of robotic probes send back impressive images. Humans, however, need to be on the surface to take human photographs. Without humans there would be no powerful images of humans on the surface, or their worn, tired faces. There would be no humor and little identification.

all. A simple human expression of an individual located in a specific place and time. An act of savoring a moment so that it can be shared with others. That act of sharing was the sole reason for the Apollo missions.

Are there any other relics from these missions with the ability to cut across all language, education, religious, or other barriers in such an immediate and direct way? The person gazing over the surface of these photos does not need to know about the extreme environment of space, the challenges of orbital mechanics, guidance systems, propulsion, or life support. In many ways they don't even need to know that these images were taken on the surface of the moon, although that certainly adds to the experience. Everything is there to be experienced directly, as if one's own feet were standing in the moon boots on the soft, powder-grey surface. The bizarre brilliance and luminescence of the terrain against the blackest of black skies; the odd, unearthly crispness that surrounds everything; the black and white landscape behind the color figures; the marks on the terrain with their odd permanence. Nothing needs to be stated; we can look with our own eyes and soul. What greater reason to go to the moon?

Figure 1.2: (Opposite page) Alan Bean at Sharp Creator with the handtool carrier near his right hand. On the carrier are visible the cuplike sample bags and the large sample collection bag that fills its center. Hasselblad 70mm transparency by Buzz Aldrin, Apollo 11, July 16-24, 1969. Image and text from the book ***FULL MOON*** by Michael Light, copyright 1999/2002.



This moment of revelation confirmed a long-felt belief about space exploration: that it is an endeavor dedicated to art; an art so technically demanding that the technical devices and their quantified outputs are mistaken for the goal. These artifacts are not the reason we do these things, nor will they ever be. In 1962, President John F. Kennedy stated, "We choose to go to the moon ... and do the other things - *not* because they are easy, but because they are *hard*,"[2] but in choosing to do the hard things we make a human statement about their importance. We step outside the realm of instinct and survival and into the realm of creative, free, thought: art.[3]

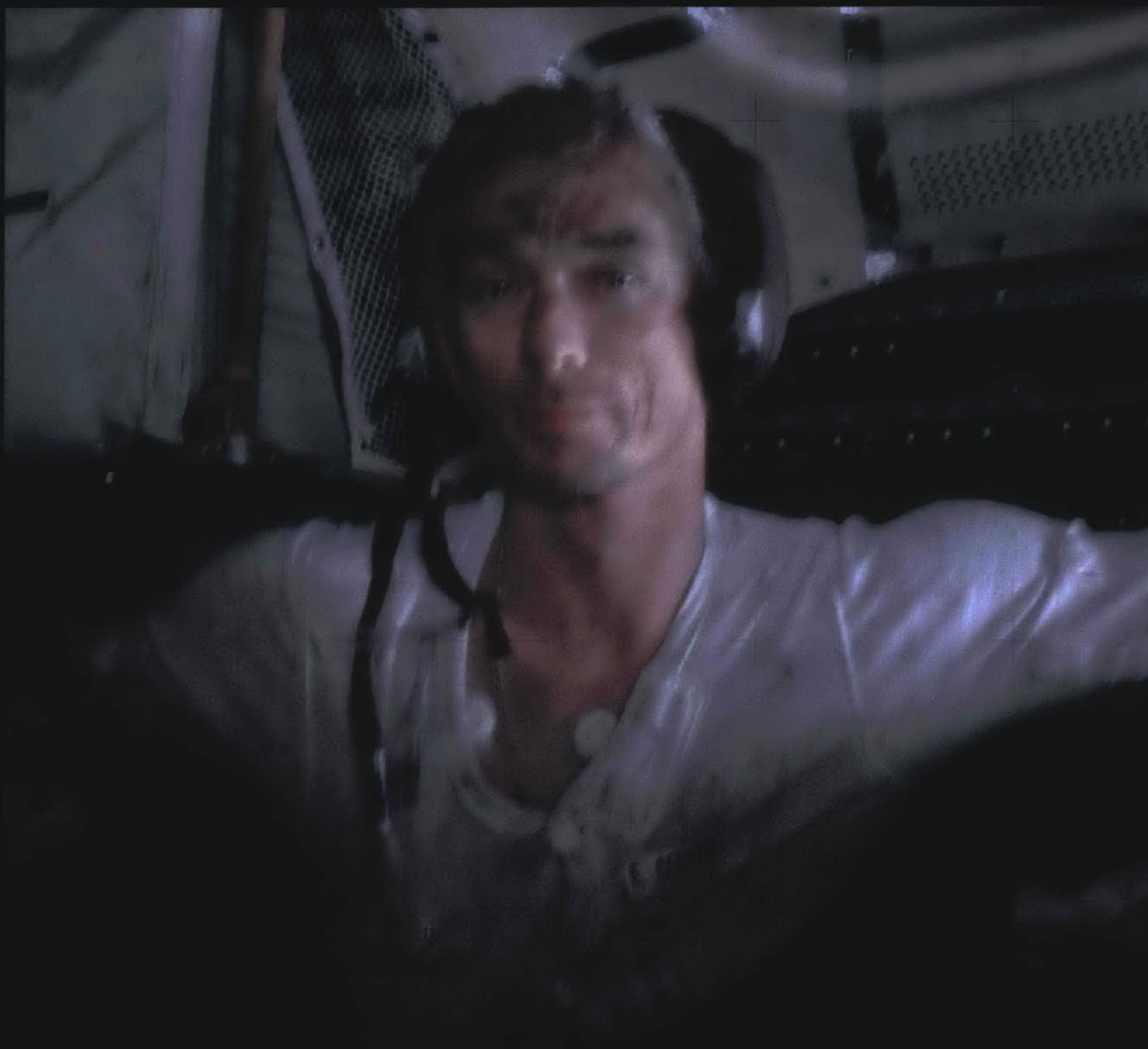
2. Rice University, Houston, Texas, September 12, 1962.

3. **Art**, as I see it, is any human activity which **doesn't** grow out of **either** of our species' two basic instincts: **survival** and **reproduction**!
- Scott McCloud, *Understanding Comics*.

Those who have always been excited by the space program know this; this is why they are excited. The technology may give them a thrill, but this is only because that technology holds the inherent potential for the act. Would we marvel over these artifacts in the same way if they were Hollywood props with no ability to physically achieve these feats?

Technology spin-offs are not the goal of the engineers or creative minds, nor are they the government's, for all acts produce unforeseen spin-offs, be they technological, intellectual, or inspirational. There is no unique need to go to space

Figure 1.3: (Opposite page) A tired mission commander Eugene Cernan, grimy with lunar soil from three days of exploring the Moon's Taurus-Littrow valley. On his chest, underneath his longjohns, are two of the sensors that relayed biomedical data to mission control. Hasselblad 70mm transparency by Harrison Schmitt, Apollo 17, December 7-19, 1972. Image and text from the book ***FULL MOON*** by Michael Light, copyright 1999/2002.



for spin-offs. Space exploration, like any exploration, is about a spiritual, artistic quest.

Exploration is an artistic act, for in its purest form it embodies a goal-less quest, or search. True explorers are open to all modes of understanding that their surroundings present them with. They constantly operate with many intelligences, receiving information on all channels of experience, subconscious and conscious. Although exploration usually gets institutionalized and pursued for specific reasons, the broadest exploration must remain goal-free, for it is these goals that inevitably narrow vision and prohibit the view of the periphery.

These notions of exploration and value are impossible without suspended disbelief. The idea of sending humans so far away so that they could take photographs is such an illogical, irrational concept that it could quickly be erased by societal forces. The fact is, however, that logic and reason confine our vision preventing suspension of disbelief: the primary gateway to discovery.

When visiting art museums with friends or family I am continually questioned as to what makes a certain work a piece of art. The question is usually posed as if I were the bearer of some special knowledge, some trick to unlock the puzzle. Although I am happy to talk about these issues, the question drives me mad; it represents a lack of investment on the part of the observer. No reality, art or other, will ever be greater than the sum of its parts without suspended-disbelief, for it is this suspension that makes reality possible.

As an example, consider a painting, your favorite painting or image, that you consider to be a fine example of art. Consider all the ways you have mentally and emotionally connected with this piece of art and what it means to you. Meditate on your excitement about the piece and its resonance with your sensibilities. Now I'll ask, "Why is *that* art?"

The nonbeliever sees the work as a collection of pigments on a surface. If the image is representational, they look behind the canvass and see no depth to the two dimensional image. There is no light, emotion, space, or movement in this piece of matter. It is a collection of molecules amounting to nothing more. Why is *that* art?

The key to unlocking the secrets of the work as art is a suspension of the initial disbelief.[d] This represents an active engagement process by the observer. Children and adults

d. Typically, I feel that people are threatened by "suspension-of-disbelief." They fear that they are reacting without standards, without a voice, if they approach reality with such a suspension. After all, their believes have been built up over their lifetime. What would they be without them?

Of course this perceived threat is no threat at all. The only was to explore something new is to allow yourself to be exposed to it. Once exposed there is no reason why you can't apply all your reason, beliefs, and past experience to probe and understand. But without exposure, without allowing the new experience to enter in, unguarded, you can never see it. We must be conscious of our assumptions and beliefs as they always try to lock things out of our reality.

watch puppet shows in which the puppeteers are clearly visible and never question the individuality and life of the puppets. The whole scenario is reliant on the audience's collaboration.[e] Although they may not be aware of it, they are actively engaging and interacting with the work of art.

e. Thanks to Aya Kanai for explaining her love of puppetry to me and the notion of suspended disbelief.

This process is no less descriptive of other art work or our everyday interactions with reality. When approaching a representational painting we must suspend the cynicism that causes us to reason that the canvas is flat and there is no depth to the image. We must ignore the fact that the image is merely an optical illusion, the trick of an artist's brush. In a similar way we must constantly suspend the disbelief in the reality of the universe. There is no way to disprove that all of existence is a dream, a play of the mind, a halucination. As hard as one might try, there is no experiment to be performed that lies outside one's experience. Despite this missing cornerstone of existence, we carry on, suspending our disbelief, assuming that an external reality exists and that we can effect it. Without suspension, life would be merely a matter of physics.

To relinquish oneself to the disbelief is to be passive, expecting to be hand-fed the delicacies of life. Instead of peering through the cracks in the wall of cynicism, skepticism, and isolation, the disbeliever builds the wall up, rejecting all that does not fit their notion of "truth." Unless we can both see the bricks and the cracks in our walls, we will never be able to expand their confines, let alone tear them down. I truly believe that the grass is greener on the other side of the wall.

In this thesis, it is my interest to try to expand the notion of engineering design beyond technology development.[6] Beyond the technical challenge of creating a new capability in the realm of the possible, I am interested in the motivations behind the creation of that capability and its possible implications, be they further capabilities or cultural, spiritual, or paradigmatic alterations. Indeed, I am more interested in such cultural implications and possibilities, as these are what truly define us as human. It is only by addressing the entire human reality (capabilities as well as dreams, philosophies, emotions, etc.) that truly meaningful differences can be made.

Much like Joseph Beuys, I am seeking a mode of creation that allows for the full possibilities of the human existence.[7] This mode of creation allows the full realities of humans to

6. I mean merely that if the thesis is not in fact [the greatest scientific work a person has ever done and perhaps ever will do], it should at least be in intention the gateway to vigorous creative study. ... What sometimes enrages me and always disappoints and grieves me is the preference of great schools of learning for the derivative as opposed to the original, for the conventional and thin which can be duplicated in many copies rather than the new and powerful, and for arid correctness and limitation of scope and method rather than for universal newness and beauty, wherever it may be seen.

- Norbert Wiener, *Cybernetics and Society*

7. "[Beuys] was interested in the new art, i.e., an art in which hierarchical barriers between the various artistic disciplines, on the one hand, and the barriers between art and the different areas of human creativity, on the other, were broken down in a vision of free work and fraternal collaboration."

-Lucrezia De Domizio Durini, *The Felt Hat: Joseph Beuys, A Life Told* be addressed by expanding realms of thought. Of course, at certain moments in the creation/thought process, it might become necessary or advantageous to take on a reductionist strategy, but this is not the starting point. As the Beuysian paradigm encompasses notions of the individual and their place in society, it becomes highly political.

No one would argue against the profound cultural and political affects/effects[8, 9] (aeffects[j]) of technology, but to address them within the field of science or engineering is rare. Considered on a larger scale, politics concerns the structuring of relationships between people, therefore technology (indeed any physical reality) is inherently political. Technology not only allows one to alter reality, but also demands that individuals shape themselves in order to use the technology.

The structure of this thesis is designed so that primary importance is given to the personal and cultural understanding of the technology discussed. It is impossible to predict all the future impacts of an action or thought, but my desire is to consider, from the outset, the human and technical goals from a broad perspective.

j. I define the word "aeffect" to remind the reader that events produce both physical and human results. In technology we usually think of cause and *effect* relationships. In this case, the ambiguity of language facilitates a narrow view of technology and its role in society and culture. It therefore seems necessary to alter the language so that it can remind audiences that these two effects of technology are both real and important.

8. Main Entry: **af·fect**
Pronunciation: 'a-"fekt
Function: noun
Etymology: Middle English, from Latin affectus, from afficere
Date: 14th century
1 obsolete : FEELING, AFFECTION
2: **the conscious subjective aspect of an emotion considered apart from bodily changes**
Function: transitive verb
: to produce an effect upon: as a: to produce a material influence upon or alteration in <paralysis affected his limbs> b: **to act upon (as a person or a person's mind or feelings) so as to effect a response**: INFLUENCE
synonyms AFFECT, INFLUENCE, TOUCH, IMPRESS, STRIKE, SWAY mean to produce or have an effect upon. **AFFECT implies the action of a stimulus that can produce a response or reaction <the sight affected her to tears>...**

9. Main Entry: **ef·fect**
Pronunciation: i-'fekt, e-, E-
Function: noun
Etymology: Middle English, from Middle French & Latin; Middle French, from Latin effectus, from efficere to bring about, from ex- + facere to make, do -- more at DO
Date: 14th century
1 a: PURPORT, INTENT b: basic meaning: ESSENCE
2: **something that inevitably follows an antecedent (as a cause or agent) ...**
Function: transitive verb
Date: 1533
1: **to cause to come into being ...**
-Merriam-Webster OnLine (www.m-w.com) (Emphasis added)

Before outlining the sections of the thesis I should comment on the layout, which was inspired by the ancient Jewish text The Talmud.[11] This thesis tries to inhabit a moment in time rather than create a permanent, immalleable existence. Much like The Talmud, original, preexisting references are presented to the inside of the main text; these references are numbered and appear near the binding.[12] Notes, referenced by letter, are presented to the side of the text further from the binding.[m] These notes comment on the main text. Where possible, both references and notes are presented adjacent to their cross-reference. It is my hope that this structure will allow a reading of the thesis, with or without note/reference inspection, that is clear and fluid.

11. The Talmud = [Talmud Bavli] : the Steinsaltz edition / New York : Random House, c1989-<c1992>

12. Cited references always appear close to the binding.

m. Notes, like this one, comment on the main text and always appear away from the binding.

'Part I: The Art in Exploration' contains the conceptual core of the thesis. Chapter 2: 'Meditations on a Spacesuit' explores the symbolism and meaning of the spacesuit in order to gain insight. This chapter allows for personal connection with the spacesuit and the technology it represents. It is here that larger lessons from the spacesuit are suggested.

Chapter 3: “Works” on page 73 presents artistic exploration of spacesuit themes. It is where some of the thoughts presented in Chapter 2 are brought into action. As Joseph Beuys once stated, "the intellectual, ... as a human being, ... is in a position of extremism and is basically ill. From this point of view, the action is totally therapeutic."[14] Thus, thought without action is not enough and Chapter 3 documents actions that explore issues of space exploration including the body, space, perception, and architecture among others. Most of these explorations are pursued within the context of art for it is the only field open enough to truly embrace a transdisciplinary[15] perspective.

14. De Domizio Durini, Lucrezia, *A Felt Hat: Joseph Beuys, A Life Told*, 'Conversation between Joseph Beuys and Achille Bonito Oliva, 1972' pages 160-163, Charta, Milano, 1997.

15. "The true innovations ... are going to be produced by agents, that is 'users,' who move freely across the range of disciplines and take from them what they need to solve the problems at hand. ... it is through their performative appropriation and improvised re-combination of existing forms of knowledge in specific situations that the 'users' produce new forms of knowledge through 'transdiciplinarity.' [Transdiciplinary knowledge production] does not seek to legitimize itself through a recourse to the legitimatory framework of disciplines. Conversely, by moving outside and across this disciplinary framework it calls its very legitimacy into question. In contrast, I understand the term 'inter-disciplinary' as uncritical of the legitimatory function of the disciplinary apparatus."

- Jan Verwoert, *Transdisciplinary Moves*

Chapter 4, "The Tx Suit," on page 93, discusses the larger conceptual, philosophical, and poetic issues of concern when pursuing spacesuit design. Here a highly poetic vision of a spacesuit is presented, leading to a metaphysical garment. It is this vision that guides the technical work described in the next section of the thesis.

"Part II: Technical Development of the Tx Pressure Garment" on page 113 addresses several technical investigations required in order to move towards realizing the T^x pressure garment. The motivation for this section is both formal, in terms of engineering practice, and informational, in order to give a complete picture of the exploration process. Although I consider the term 'functional art' to be an oxymoron in many ways, the T^X suit only gains its meaning through use/ performance and in order to be used, it must meet certain functional requirements.

"Part III: Humane Performance in Extreme Environments" on page 235 expands the scope of this thesis beyond spacesuit design into "Space Craft." To start, a larger view of humanity and technology is presented, leading to the term "humane factors engineering," which frames the transdicipinary approach taken in this thesis. This chapter is followed by 'Space Craft' which considers cultural motivations behind space exploration.

In an age of world crisis where fundamental, practical needs require much attention, the justification for any pursuit cannot be taken for granted. There are many in the world that feel no connection to the current space administrations and their goals. As the sole funders of space programs the citizens of the world demand and require an explanation for the great monetary, temporal, and mental cost of such endeavors. In addition, rationale for the increased cost of human missions must be given. Chapter 12 examines this rational and points toward poetic possibilities in future space exploration. It is hoped that future explorations will respond to a more complete conception of the human being.

Introduction References

[1] Light, Michael, ***Full Moon***, Johnathan Cape, London, 1999.

[2] De Domizio Durini, Lucrezia. *The felt hat: Joseph Beuys, a life told*, Milano : Charta, c1997.

[3] Mirriam Webster Online Dictionary; http://www.m-w.com

[4] McCloud, Scott, *Understanding comics: the invisible art*, Northampton, MA : Kitchen Sink Press, c1993.

[5] *The Talmud = [Talmud Bavli] : the Steinsaltz edition*, New York : Random House, c1989-<c1992>

[6] Verwoert, Jan, "Transdisciplinary Moves"

[7] Wiener, Norbert, *The human use of human beings: cybernetics and society*, New York, N.Y. : Da Capo Press, 1988, c1954.

[8] Winner, Langdon. *The whale and the reactor: a search for limits in an age of high technology*, Chicago : University of Chicago Press, 1986.

Part I: The Art in Exploration

2 MEDITATIONS ON A SPACESUIT

> The Buddha, the Godhead, resides quite as comfortably in the circuits of a digital computer or the gears of a cycle transmission as he does at the top of a mountain or in the petals of a flower. To think otherwise is to demean the Buddha - which is to demean oneself.
>
> - Robert M. Pirsig
>
> *Zen and the Art of Motorcycle Maintenance*

The spacesuit is a highly technical, specialized piece of hardware. For the public, beyond the images on TV and the occasional published photo, the spacesuit both literally and figuratively inhabits an unknown, alien realm. But, as with every fragment of the universe, larger secrets and insights exist within the notion, and artifact, of the spacesuit.

In eastern religions, rock gardens create a microcosm for meditation; by meditating on the garden, individuals are able to explore deeper meanings of the universe. In this way the specific stands for the general and by focussing on a fraction of existence, one is able to pass through a keyhole into larger realities. The spacesuit is a similar microcosm for meditation.

In a literal sense it is constructed to be a pocket of earth's atmosphere that the individual inhabits in order to sustain life. As it records human needs, desires, and dreams, it is also a spiritual microcosm. Meditation on the spacesuit reveals connections between internal and external, self and humanity, life and universe.

CONCEIVING THE BODY

> Man is called by the ancients a world in miniature and certainly this name is well applied ...
>
> \- Leonardo da Vinci[1]

> He who realizes the truth of the body can then come to know the truth of the universe.
>
> \- from *Ratnasara*, Tantric text, India[1]

Before design can take place, there must be an understanding of the problem; therefore, if the design is to inhabit physical reality, the possibilities inherent in reality must be understood. When designing an artifact that intimately connects with the body, as a spacesuit does, a conception of the body holds central importance. It is around this conception that designing takes place.

1. Taken from "Mapping the Body" by Mark Kidel and Susan Rowe-Leete as published in Fragments for a History of the Human Body, Zone Books, 1989.

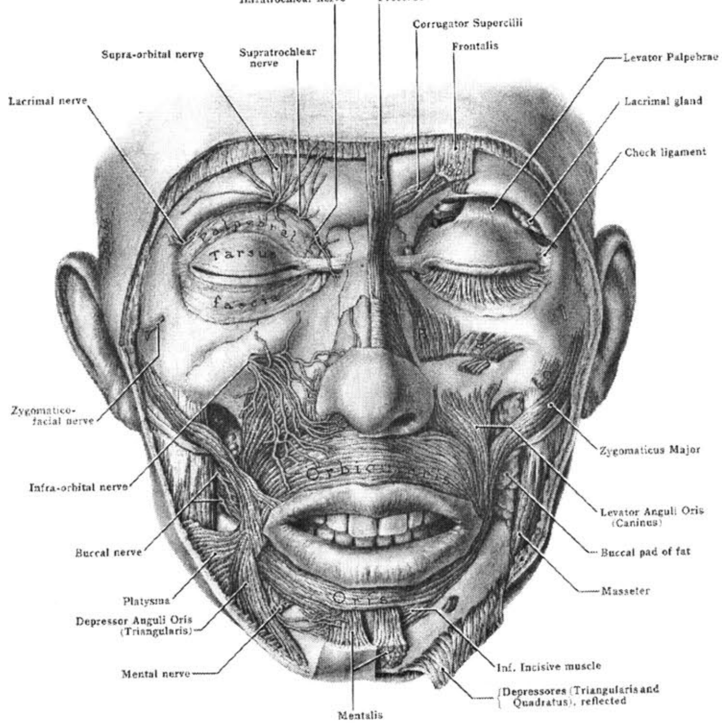
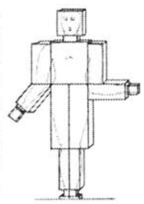
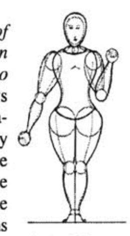


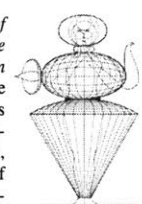
Figure 2.1: (Top Center) The depiction of the body offered by western science. From *Grant's Atlas of Anatomy.*



The laws of the surrounding cubical space. Here the cubical forms are transferred to the human shape: head, torso, arms, legs are transformed into spacial-cubical constructions.
Result: *ambulant architecture.*



The functional laws of the human body in their relationship to space. These laws bring about a typification of the bodily forms: the egg shape of the head, the vase shape of the torso, the club shape of the arms and legs, the ball shape of the joints.
Result: *the marionette.*



The laws of motion of the human body in space. Here we have the various aspects of rotation, direction, and intersection of space: the spinning top, snail, spiral, disk.
Result: *a technical organism.*

The metaphysical forms of expression symbolizing various members of the human body: the star shape of the spread hand, the ∞ sign of the folded arms, the cross shape of the backbone and shoulders; the double head, multiple limbs, division and suppression of forms.
Result: *dematerialization.*

Figure 2.2: Oscar Schlemmer's study of stage costume, from "Man and Art Figure."

Our conception of the realities of the body reflects our notions of truth. In western science, notions of chi or body auras are hard to accept due to the fact that western science's notion of reality is grounded on the observable or measurable (see Fig. 2.1). Because of this, the body, and reality as a whole, takes on a highly mechanistic framework. As an artifact of western science and an artifact for the body, NASA's spacesuit is conceived of, designed, and tested for the body mechanism, or "the marrionette."(Fig. 2.2)

Alternative depictions of the universe and body are not wedded to observation and measurement and are therefore

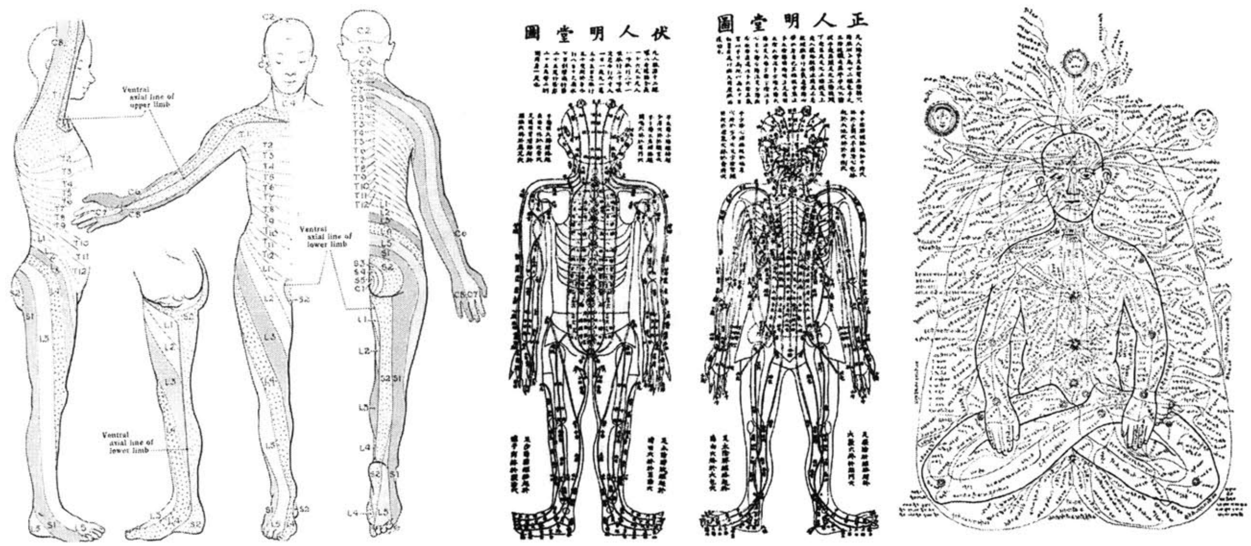


Figure 2.3: A map of the dermatomes on the body (right) from *Grant's Atlas of Anatomy*, acupuncture diagram (center), and the Subtle Body (right) both taken from "Mapping the Body."

allowed to explore the body in a more spiritual way. These issues seem clearest when considering body mappings/topologies for it is in these mappings that the cartographers impression of the body is made visually apparent. Consider western versus eastern depictions of the body. While muscles have been a central focus of the western body since the renaissance, Chinese descriptions of the body around that did not even have a specific word for "muscle."[2]

Mappings such as Langer lines,[a] the flow of dermatomes, or the lines of nonextension[b] suggest the possibility of other invisible lines, landmarks, or flows such as chi, acupuncture/pressure points, or, in general, "the subtle body." (Fig. 2.3) Once again, these topologies reveal our understanding of the body on physiological as well as spiritual levels. What does a

a. Langer lines describe lines of minimum in vivo skin tension. They are used by various sergions to minimize scaring.

b. See "Body Restraint" on page 141.

2. Kuriyama, Shigehisa The Expressiveness of the Body and the Divergence of Greek and Chinese Medicine, Zone Books, MIT press, Cambridge, Massachusetts, 1999.

spacesuit become when it is designed to house these conceptions of the body? Which body(ies) do we want to bring with us to outer space?

The art instillation *Body Flux*, presented in the "Works" chapter, explores bodily connections by examining the passage of matter and information between the body and the surrounding environment. In the 1996 realization of this piece, the "inputs" considered were food/fluid, air, sound, and light. Collected "outputs" were breath, urine, feces, detritus (hair, finger nails, skin), sweat, sound, and light. These material outputs were displayed at the end of tubes extending from the body thereby establishing the intimate link between the body and its "waste." The collection of light and sound emanating from the body suggested non material substances that we continually purge or expel. In conversations with Krzysztof Wodiczko, (see "Conversations with Krzysztof et. All: Ideas/ Questions/Notions to Spur Ideas" on page 293) other notions of flux such as heat and memory and arose. As the spacesuit and space capsule are designed around the body, to accommodate every need of the body, these notions of body flux become crucial to design. Moving from specific to general, one's conception of the body reveals one's notions of truth and reality.

SKIN: MEMBRANE

In many ways, the spacesuit might be seen as a second skin: a skin prosthesis. Exposed to vacuum without protection, the skin is incapable of protecting the body beneath, motivating the need for the spacesuit as a pressure suit. Conceiving of the spacesuit in this way, though, makes many assumptions about skin.

The skin lies closest to the body-surface, controlling the flux between body and other. Although usually conceived of as a barrier, it is a gateway to the body, allowing passage from interior to exterior and exterior to interrior.[3] If skin is seen as protection for the body beneath, it suggests that skin is a wrapping layer, much like clothes (Fig. 2.4). This depiction of the skin separates skin from body, just as the mind/ matter split in western philosophy separates mind from body, or subject from object.

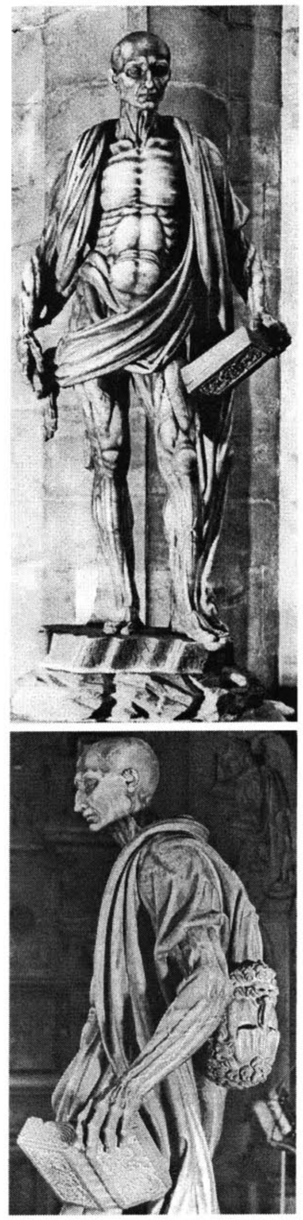


Figure 2.4: The flayed martyr, St. Bartholomew in Il Duomo di Milano.

The depiction of skin as a loose, separate, binding membrane suggests its fabric-like properties. It seems to be draped over our bodies, hanging onto us for its form. There are, how-

3. The Physical nature of the skin / Lancaster, England ; Boston : MTP Press, c1988.

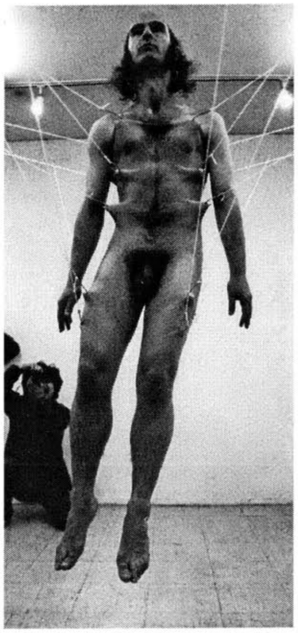


Figure 2.5: Stelarc, Event for Lateral Suspension, Tokyo, March 12, 1978. Photographer - Tony Figallo.

ever, explorations of the skin that suggest the structural nature of this medium.

Considering piercings, it is interesting to note that we consider the *body* to be pierced and not just the skin. In this way we reject the artificial separation between skin and body in favor of a holistic vision of the body. In certain cultural acts, this depiction is strengthened by actually suspending the body from the skin. In this way the skin becomes structure, supporting the body in its fight against gravity (Fig. 2.5). In addition the body is seen as a whole, floating without compressive support. Separations between body and skin dissolve to reveal deeper visions and connections.

Exploring skin in this way clarifies that the spacesuit is not just a protective layer of clothing, but a new organ of the space-body. Just as the earth bound body cannot exist without skin, the space-body cannot exist in alien realms without the spacesuit's protection. This suggests larger definitions of the body which serve to dissolve the object/body dualism westerners are inclined to believe.

BODY: BUBBLE

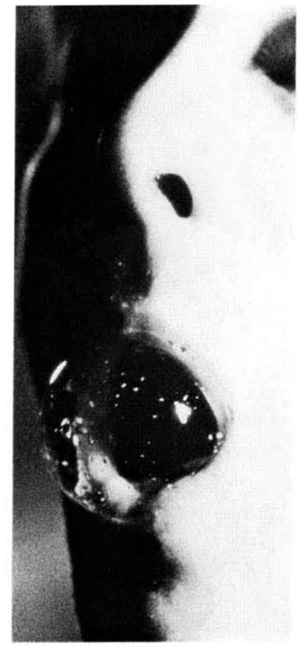


Figure 2.6: Tom Friedman, *Untitled*, 1990 from Thin Skin: The Fickle Nature of Bubbles, Spheres, and Inflatable Structures Independent Curators International, New York.

> Then the Lord God formed man of dust from the ground, and breathed into his nostrils the breath of life; and man became a living being.
>
> \- *The Holy Bible*, Genesis 2: 7

> [The bubble] lends itself to an investigation of the borders and connections, whether physical or emotional, between different entities - what makes something distinct and separate from the thing or situation next to it, what separates outside from inside, where and how exchanges take place, and how such exchanges might create a sense of belonging or of being connected. It helps explore transitions from one physical or emotional state to another, from body to body, and from one discipline to the next.
>
> \- Carin Kuoni, "Thin Skin: The Fickle Nature of Bubbles Spheres, and Inflatable Structures."

In an attempt to understand the body and its needs in the vacuum of space, breath and pressure are central issues of focus. In a literal sense, "the breath of life" is an internal pressure that infuses our body with oxygen. (Fig. 2.6) This breath is poured into our bodies by the weight of the atmosphere around us. We live at the bottom of an ocean of air whose pressure exists around and in us.[d] We live in a state of simultaneous inflation and compression.

d. Atmospheric pressure at sea level is101 kPa (14.7 psi). As oxygen makes up roughly 21% of air, it's partial pressure at sea level is 21kPa (3 psi). Our bodies require roughly 3 psi of oxygen in order to function.

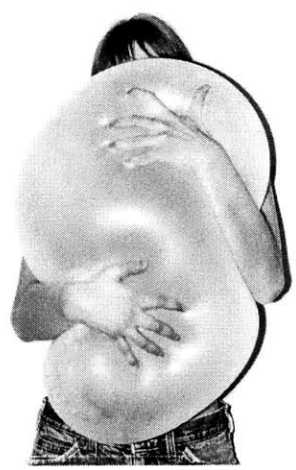


Figure 2.7: Annika von Hausswolff, *Attempting to Deal with Time and Space*, 1997, from *op. cit.*

Ascending through the atmosphere, pressure is relieved until, reaching the vacuum of space, the void surrounds; all pressure/air is removed. Dependent on our own resources for sustenance, we must travel with our own supply of bottled breath if we wish to inhabit the vacuum of space.

As the body is no longer bathed in the breath of life, the traveler must provide a means to control both inflation and compression of the body. If the body is inflated by breath in a vacuum, without an opposing compression, the body wants to swell, like a membrane;[e] if compressed, without inflation, no breath can enter the body. To prevent damage the body must be filled with breath and restrained from swelling; it must be bound.

e. Studies have shown that the body can be exposed to vacuum for periods up to three minutes without side effect. After this point, swelling, blood pooling, and eventual death can occur.

Supplying breath and binding the body are fundamental duties of the spacesuit. A binding membrane is tailored to resist the outward force so that the body-membrane won't over extend. This body restraint pushes back on the inflated body, once again establishing an equilibrium between inflation and compression. The spacesuit, or any pressure suit is thus a bubble filled with the pressure of life: breath, blood, and flesh.[f]

f. Spacesuits typically accomplish this by enclosing the whole body in the pressurized breathing gas. Thus, these gas-filled spacesuits are articulated balloons. An alternative approach to compressing the body is to use elastic materials that mechanically compress the body. This is called Mechanical Counterpressure (MCP).

Figure 2.8: Images of body binding: (from top to bottom) chinese foot binding, corsets, and latex fetish gear.

Considering the pressure forces that allow the body-bubble to exist, the vacuum cuffs presented later in this thesis can be read either as the donning of a vacuum, or the removal of spacesuit earth. In the first reading, the chambers represent alien spaces whose walls hold back the atmosphere. The body outside these spaces exists in the nominal state, while the body inside the vacuum is exposed to unusual conditions that require protection in the form of a spacesuit.

The second reading, however, views the chambers as nominal spaces existing in the same state as most of the universe: in vacuum. As discussed above, the body, inflated with breath, cannot exist in a vacuum without a corresponding compression. Thus, in this reading the spacesuit and earth's atmosphere both provide the same compressing function. In this way an equivalence is drawn between the spacesuit and our surrounding atmosphere leading to a notion of "spacesuit earth."

Just as Buckminster Fuller's notion of "spaceship earth" defines our existence as one shared as travelers on a common vessel, the notion of "spacesuit earth" defines our mutual dependence. Just as the body in the vacuum of space requires the spacesuit for existence, so does the body on Earth require the atmosphere and its protection. If the spacesuit can be seen as a new body organ, the atmosphere, and indeed earth, must be seen as organs of the body. In this way, we all inhabit spacesuit earth, a common, shared organ. All known life is dependent on this organ and is as intimately connected as two inhabitants of the same jacket.

BODY-SURFACE: FLUX

As the body exists at the meeting of internal and external energies, conceptually it describes a surface. As described above, in an attempt to maintain the equilibrium of the body, the spacesuit replicates external forces via a thin membrane. As such, the spacesuit describes a new body surface that strives to mimic the natural, nude surface.

Surfaces describe two dimensional areas,[g] containing length and width, but no depth. They are regions of separation: infinitessimal and yet infinite expanses of distinction. Not existing as material entities, for all material has depth, they exist as abstract realities that cannot be sensed directly.[h]

Our body-surface lies at the separation of self and other. The skin is the material body, air is other; neither contains the body-surface. Its expanse is defined as the intersection, the area of contact between body and environment. It is a constantly flowing surface of contact, a surface of exchange, osmosis, diffusion, flux.

g. Although the surface of a sphere might be said to occupy three dimensions in a global coordinate system, I am interested here in the two dimensions of local coordinate systems: normal and tangent.

h. Pure touch, without sight or consciousness is capable of exploring the expanse of a surface, for touch operates at the surface of exchange. With sight and thought, however, touch perceives multidimensional qualities such as color and volume. Thus, in order to limit exploration to two dimensions, touch must operate as the only faculty of the body.
Pure sight, without thought explores light from surfaces. With thought, however, comes consciousness, turning perceived surfaces into volumes with mass and other dimensions. Both sight and touch are too reliant on the materiality to truly sense a surface for both senses perceive matter whereas the surface exists at the meeting of two different materialities.

Although we are defined in part by the body surface, it is not a barrier of restriction. We always interact with it through our involvement with the physical world, for it is only in relation to an exterior that it exists.[i] As we exert pressure on external entities they push back. The intersection describes a surface of force exchange; a constant pressing of world and body.

i. See "Space Garb/Space Body" on page 101.for a similar discussion of clothing.

As discussed above, space inhabitation requires a restraint membrane: a surface with thickness; a thickness that threatens to isolate the individual from the external world through distance. This exterior membrane must be stiff enough to resist the body's inflation, but it must always retain the capacity for exchange, for flux.[j] This is precisely the power of a mechanical counterpressure (MCP) garment such as that developed for the T^x suit, discussed in Part II. MCP facilitates the creation of a pressure suit that allows the body to be in direct contact with the environment.[k] Thus, in the vacuum of space the explorer can actually touch the void.

j. Current gas-filled suits surround the body with impermeable materials so as to retain the artificial atmosphere. By definition, these materials prohibit flux.

k. See "Mechanical Counterpressure Techniques" on page 131 for a more detailed explanation of this and other MCP capabilities.

Without exposure and flux exploration is impossible. A pressure suit must therefore strive to be a body surface, seeking an area of exposure, not isolation. In the ideal it is transparent, not just to vision, or the other senses, but to the

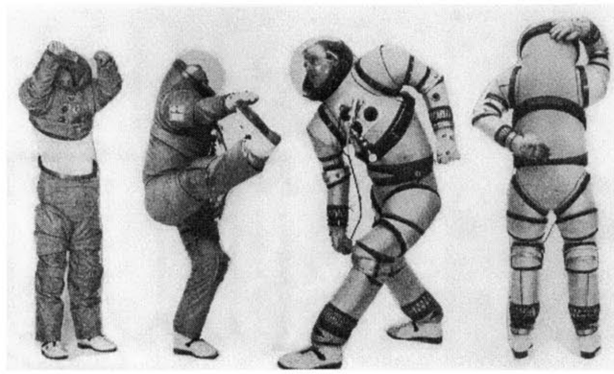


Figure 2.9: Images of spacesuit mobility tests taken from *U.S. Spacegear.*

imagination[1] and all human faculties. It must facilitate exploration of the subconscious[13] as well as cosmos.

13. "I'm reminded of the diving suit in which Salvador Dali delivered a lecture some years ago in London. The workman sent along to supervise the suit asked how deep Dali proposed to descend, and with a flourish the maestro exclaimed: 'To the Unconscious!' to which the workman replied sagely: 'I'm afraid we don't go down that deep.' Five minutes later, sure enough, Dali nearly suffocated inside the helmet.

"It is that *inner* space-suit which is still needed, and it up to science fiction to build it!"

- J.G. Ballard
"Which Way to Inner Space?"

1. The notion of a spacesuit transparent to the imagination was mentioned to me by Joe Davis after hearing 'Space Garb/Space Body' at the 2002 Sky Art Conference in Ikaria, Greece.

The spacesuit embodies our philosophies towards reality and how we are able to interact with it. As it reduces the modes of interaction, it can be seen to represent those modes that are deemed most important, or at very least, most basic. As the spacesuit exists today, the spacesuit reveals a belief in exploration through isolation, much like the stereotypical scientist believes in a pure, objective truth without, and an observer distinct from the observed.

THE SIGNIFICANCE OF MOBILITY

What is the value of mobility and why do spacesuit designers seek greater mobility (see Fig. 2.9)? As motion allows for a larger access to the external world through contact and sensing, its value is that of a manipulator arm whose work volume allows for greater possibility. But mobility is more significant

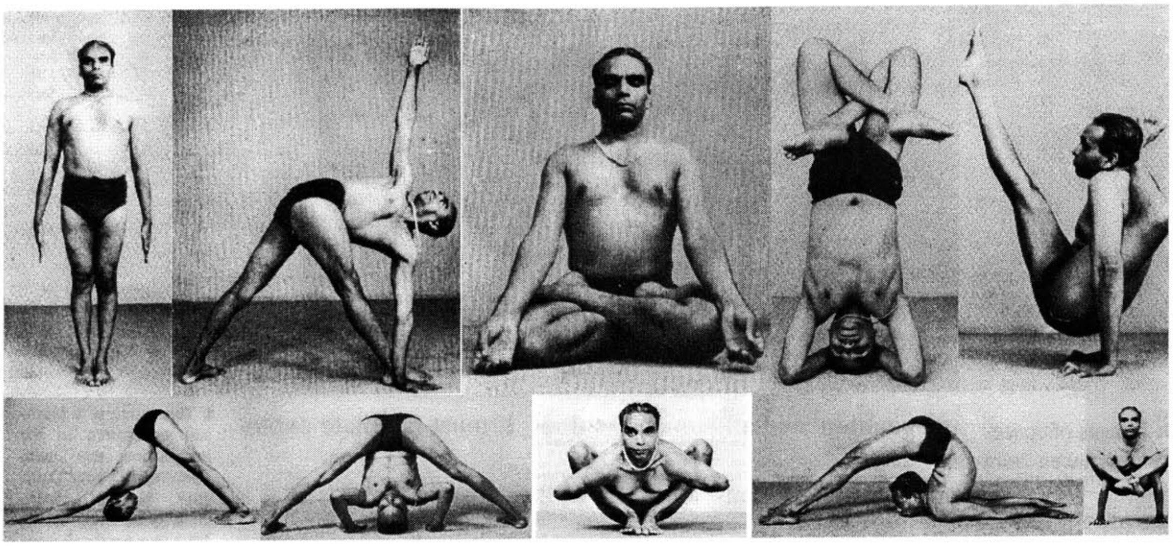


Figure 2.10: Asanas, or postures, from Hatha Yoga. Images taken from *Light on Yoga* by B.K.S. Iyengar

than mere mechanics.

Hatha Yoga demonstrates that the practice of postures introduces us to our own, internal, limitations. In the process, the postures and the mindfulness that they promote, alleviate the limitations imposed by these internal restrictions. The postures are not about performing astounding body tricks, but are used as an exploration of the self including, body, mind, and soul[n] (see Fig. 2.10).

In this context, the mobility of a spacesuit should be more than simply facilitating the manipulators of the astronaut. Even without a task, or external objective, motion/mobility/dexterity is important as it reminds of our own limitations and those that we bring to our vision of reality. Thus, a spacesuit with limited mobility not only compromises spe-

n. Thanks to JC Calhoon and Back Bay Yoga, especially David Vendetti and Cary Perkins, for introducing me to my practice.

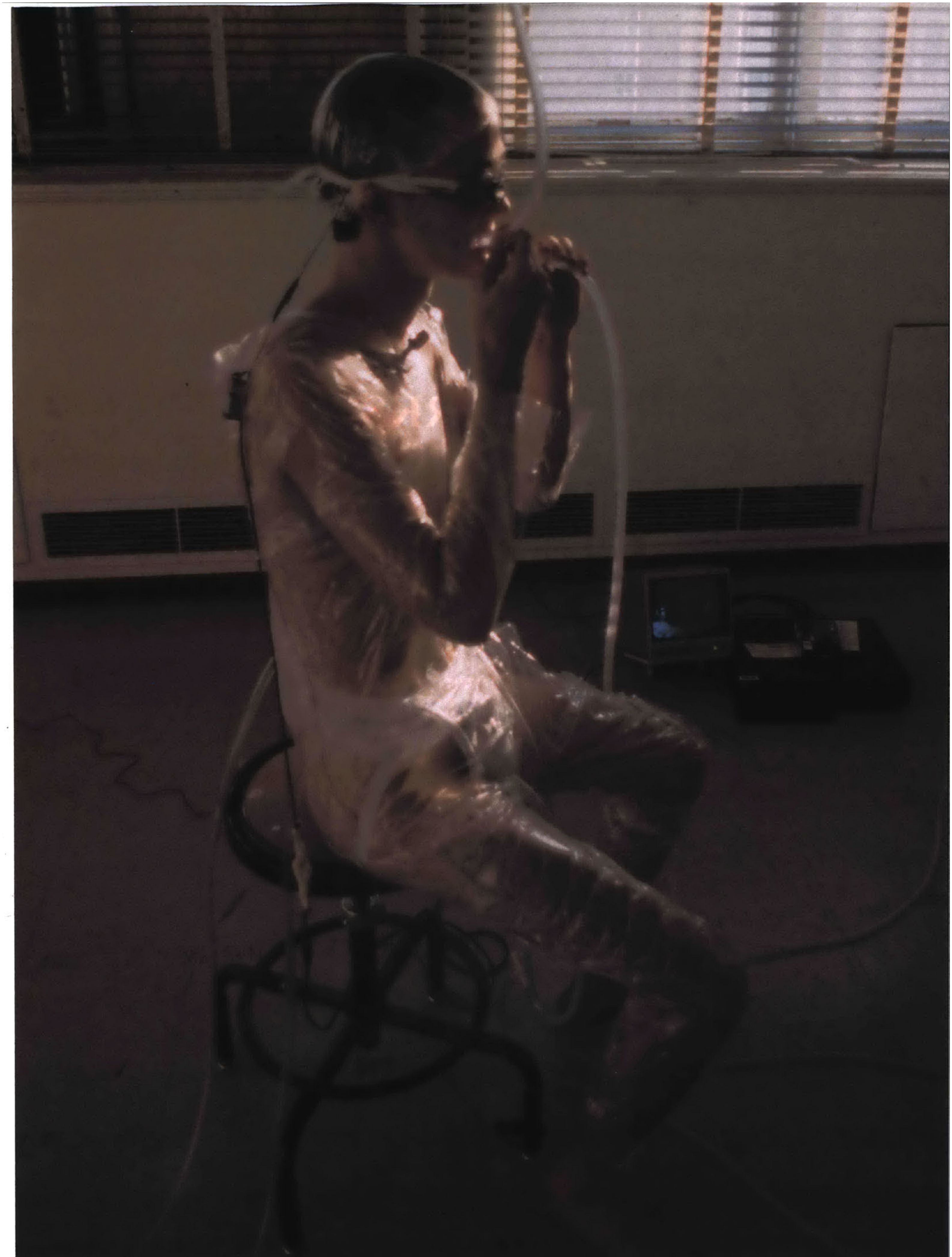
cific goal oriented objectives, but limits exploration in its fullest sense. A person confined by the limited potentials of a spacesuit quickly learns a lot about the spacesuit at its limitations, but is never allowed to realize their full capabilities. This is true in a literal as well as symbolic and spiritual way.

MEANING IN A SPACESUIT

Mediating on the concept of "spacesuit" is a self construction process. As we imagine the protective enclosure we construct it for a specific vision of the human body. This vision represents the definition of our possibilities. By imagining a rigid, exterior boundary we expose our vision of the body as a mechanical object, a marionette, separate and distinct from external reality. Instead, by understanding the nature of the body-surface, we are able to conceive of a flux, a flow that intimately connects us to our environment. In this way we allow ourselves to design for the human as physical, metaphysical, and symbolic. Our visions of a spacesuit expose us to our self image, revealing our beliefs about our larger existence.

WORKS

THE FOLLOWING CHAPTER PRESENTS PROJECTS IN A PORTFOLIO OR CATALOG STYLE. COMPLETED BETWEEN 1996 AND AUGUST, 2003, EACH WORK TIES INTO THE CONCEPT OF "SPACESUIT" IN VARIOUS WAYS SUCH AS EMOTIVE, SYMBOLIC, AND QUANTIFIED. ALTHOUGH MOST PROJECTS TOOK THE FORM OF PHYSICAL ARTIFACTS AND ARE PRESENTED IN A VISUAL WAY, ALSO INCLUDED IN THIS CHAPTER ARE WRITTEN EXPLORATIONS. THE WRITTEN EXPLORATIONS STAND AS DOCUMENTATION OF THE THOUGHTS, FEELINGS, AND BELIEFS HELD AT THE TIME OF THEIR ORIGINAL CREATION.



BODY FLUX

1996
Cambridge, Massachusetts
Body, plastic suit, goggles, bullet camera, tubing,
water, air, breath, sound, video recorder, TV monitor,
tape recorder, hair, nails, urine, faeces.

Exploring the body as a control volume, a volume of flux, *Body Flux* lasted roughly half and hour. All inputs to the body came from the surrounding environment, all outputs were collected. Suspended above the body was a bottle of water from which I could drink. Air, food/water, and sensory stimulus was collected by the body's natural mechanisms. The plastic suit and tubing represented the active collection of outputs such as urine/faeces, fallen hairs, trimmed nails, exhalation, noise, sweat, and reflected light. Sound was captured via tape recorder and contact mic. Reflected light was symbolically captured via a bullet camera mounted in front of the right eye. The feed from the bullet camera was displayed on a monitor and recorded by a video tape deck.

Space Garb/Space Body

Presented at the Sky Art Conference in Ikaria, Greece, October 18, 2002

Hello. I'd like to thank all of you for being here. Since the middle of the summer I've been helping Otto, Elizabeth, and Laura[a] put together this conference and it's very exciting to finally be here in Greece with all of you. It is especially exciting since Otto let me invite those of you that have inspired me with your work. It is wonderful to put a face and personality with the work I know and love.

a. Otto Piene, Elizabeth Goldring, and Laura Knott

As for my background, I am a Masters student at MIT in the Aeronautical/Astronautical Engineering department. I was also at MIT for my undergraduate work studying Aero/Astro as well as minoring in architecture and visual arts. I have always floated between these two realms so you can imagine my excitement when I learned who Otto Piene is and that he resides just a few buildings away from my lab.

Currently I am working in MIT's Man-Vehicle Lab, researching advanced spacesuit design. Because of this, Otto asked me to present on Space Garb today. I hope that my presentation will be informative as well as inspirational or at least thought provoking about the possibilities.

Clothing, it seems, should be defined in relation to the body and the exterior environment, therefore I'll start with a description of these two elements. For the majority of my talk

I will assume that the external environment we are talking about is the vacuum of space as this is where all of our non-terrestrial space experience lies. I say non-terrestrial because our whole lives take place on "spaceship earth" as Buckminster Fuller would say.

Perhaps the best way to approach the subject of body and vacuum is to talk about them in relation to one another. What does the body need, that a vacuum lacks?

The most obvious answer to this question, is that a vacuum lacks an atmosphere, which our body needs for two reasons: breathing and pressure production. We all know the dangers of holding our breath too long, but few of us have had the chance to hold our breath in a vacuum where there is no pressure on the body surface. Let me say that it is not an experiment I suggest even if the opportunity arises. As you can imagine, in this scenario, your body has become the membrane of a balloon, and although you will not explode, as some science fiction suggests, your lungs will be damaged do to over inflation. Without going into further morbid details, please trust me that the best solution is to create even pressure over the entire body surface that is equal to the pressure of the breathing gas. As we sit here, in this room, this is the case. The atmosphere that we breathe is the same atmosphere that surrounds our bodies, and it is pushing, with equal pressure, on our body surface and our lungs. Well, due to the physiology of our lungs, the minimum pressure of oxygen that can sustain life is roughly 3 pounds per square inch (or 21 kPa). I want to briefly mention the ways this body-surface pressure can be produced.

Body-surface pressure can either be produced via an artificial atmosphere or through Mechanical Counterpressure. All spacesuits that have been in orbit have been gas filled balloons. This is the artificial atmosphere scenario, in which the body is immersed in the breathing gas, much like we are now. The other method of pressure production is through tight fitting spandex-like garments. These garments work due to the mechanical tension in the garment, which is in contact with the skin surface. They are known as Mechanical Counterpressure suits and have not been researched extensively. This method of pressure production is the focus of my technical research.

If we assume we have adequate gas to breathe, at the correct pressure, and an equal pressure over the surface of our body we can sustain life in a vacuum for an extended period of time. Other issues must be considered, however, such as asphyxiation. The body must be protected from itself because even though we have supplied the body with air to breath, we must provide a way of removing the carbon dioxide from the breathing. This job is performed by "scrubbers" that usually work via chemical reactions. As we sit in this room, the volume of air is large enough and is mixed with the help of ventilation systems so that scrubbers are unnecessary. On the global scale, however, plant life provides this scrubbing function.

Thermal issues must also be considered as space temperatures range from 149^{o} C in direct sunlight, to -157^{o} C in shadow.

Let me stop here for a moment to reflect. As I stated in the beginning, clothing should be considered in relation to the body and the environment. I hope that I have communicated that in a vacuum, the naked body cannot live long without some form of protective enclosure or envelope. Conceptually, it becomes hard to separate the material body from the surrounding, protective layers, be they gaseous (like an artificial atmosphere), or solid (like the barriers between gas and vacuum). After all, the living body ceases to exist without these layers, so how can we separate them from the body? Is the clothing the most exterior layer, or is it the sum of all layers be they solid, liquid, or gaseous? We could consider every envelope that performs life-sustaining functions to be part of "clothing." OR, in another sense, we should consider the envelopes to be part of the new space-body and only the additions beyond that as clothing, or space jewelry.

No matter how we see these issues, let's consider everything from the rocket, to the spacesuit as clothing, because in the hostile environment of space our organic skin is incapable of protecting our fragile existence. These craft or garments become our protective layers and therefore our space garb.

While we are speaking about the space capsule as clothing, we should talk about the body in relation to the space capsule and the clothing that is used within the capsule. This provides an interesting scenario because the body is within the highly controlled environment of the capsule. Realize that this environment is designed to perfectly accept and protect the human body. The capsule is an artificial womb that is created to protect the body from the vacuum of space as well as such things as microbial infection. Every feature of this environment is designed so that it won't be too hot or too cold, too sharp, too fragile, too disorienting, too dark or too light, too loud or too quiet. In addition, surfaces are designed to be easily cleanable to prevent microbial growth. In this way the capsule even incorporates some features of an immune system. The body and capsule exist in a symbiosis, and so I ask, what function does clothing, in the form of shirts and pants, perform in this environment? As artists, we should ask what function *could* it perform, or what function *should* it perform? I don't have my own answer yet, but I should tell you what the astronauts and cosmonauts wear today when inside the capsule.

Intravehicular Activity (IVA) takes place in a "shirtsleeve environment," meaning that normal clothing can be worn. Typically rugby-type shirts are worn with pants and socks. The pants are striped with Velcro so that pockets can be attached and rearranged at will and so that tools can be kept close at hand. Recently Bennetton designed clothing for the shirtsleeve environment that used anti-microbial fabrics as well as temperature regulating fabrics. For the most part, however, the clothing has maintained a very standard form. Convenient features have been incorporated into the clothing, but the overall design of IVA clothing hasn't strayed far from jumpsuits or shirts and pants.

I don't mean to trivialize the history of space garb, there are certainly interesting garments that have been produced as I'll show you in a moment. I want, though, to suggest the possibilities that have not been explored, possibilities that address cultural as well as human and philosophical issues.

Because my research is on spacesuits, I'd like to take the last few minutes to explore the possibilities here. I have a video of spacesuit test from the Apollo era that I'd like to show and I'll comment as we watch it.

VIDEO (Opposite Page)

As you can see there have been many variations on the theme of spacesuit. Some of these suits became architecture in an obvious way, but I think all suits can be seen as minimal, portable architecture. Archigram would be proud. I'd like to briefly mention two more possibilities.

As one of my mentors and professors, Krzysztof Wodiczko, pointed out to me, although the shape and materiality of spacesuits have varied, the treatment of the head has remained constant, namely, a clear bubble. The technical reasons for this are clear, but perhaps we can go further. A bubble helmet is optically clear, but opaque to the other senses: touch, taste, smell, and hearing. This may not be an issue in the vacuum of space, but if and when we get to Mars, we will be exploring an environment with at atmosphere. All the sudden we can ask, what does it sound like? What does is smell like? What does it taste like? I would like to explore the possibility of a helmet which is transparent to all senses. Indeed, I think the spacesuit should be transparent to all senses.

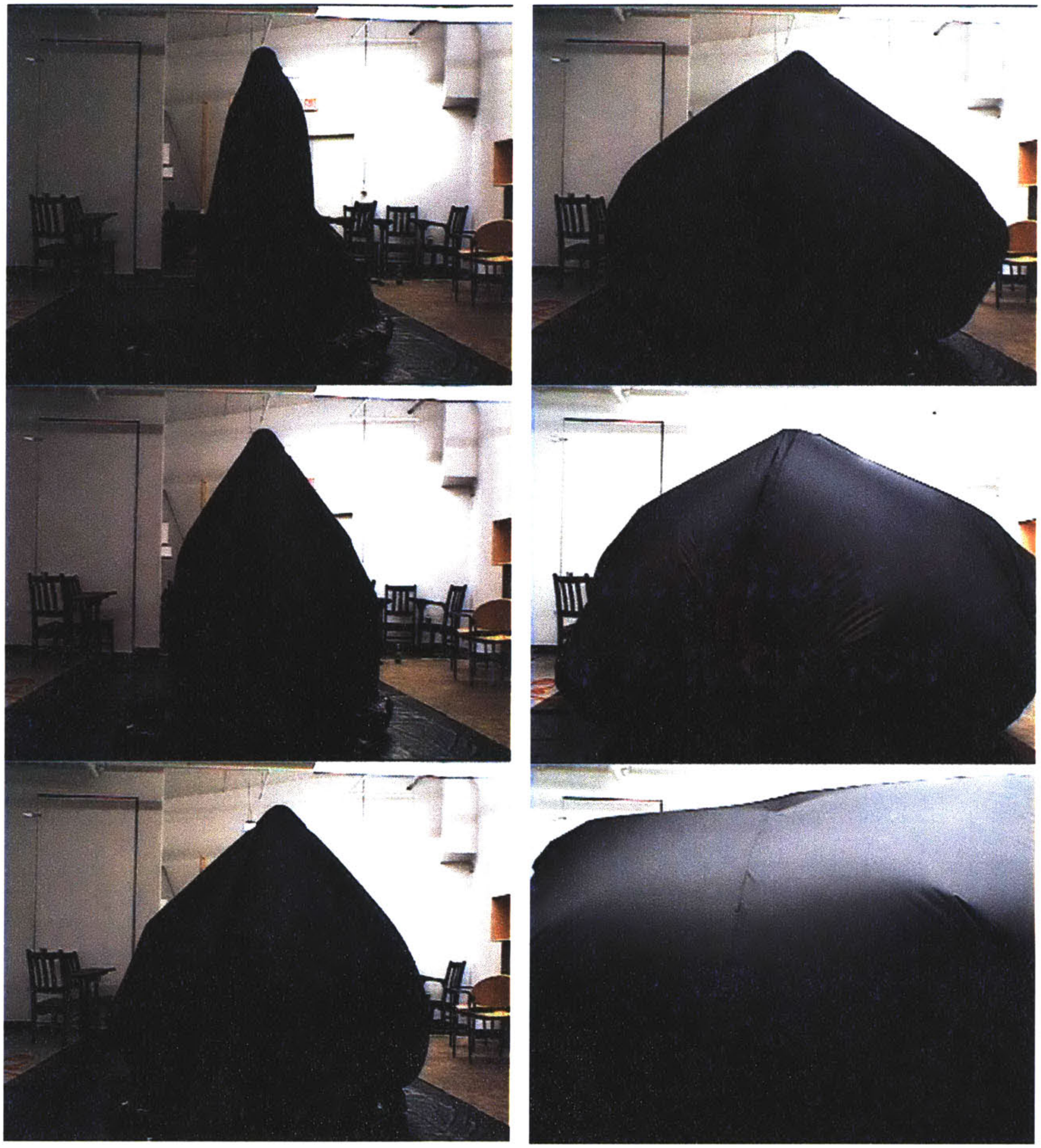
The last possibility is something I feel obligated to bring up especially with Stelarc in the audience and it is that of the cyborg. The term cyborg was coined in 1960 by two research-

ers, Clynes and Kline, as they envisioned space habitation. They argued that we should actively push our evolution to the point where we do not need to carry a fragile bubble of air with us into the vacuum, but are able to survive in these new environments. In fact, I have suggested that the body in space is already cyborgian due to the life support systems that surround it. Now it just becomes a question as to how integrated and attached to our body these systems become.

1. Clynes, Kline, "Cyborgs and Space" in *The Cyborg Handbook*, pp. 29-34, London ; New York : Routledge, 1995.

As a last point I just want to say I have some show and tell items from the current spacesuit and would be happy to get into technical issues of space garb design if anyone is interested.

Thank you



SPACE INFLATION

2002
Isabella Stewart Gardner Museum
Boston, Massachusetts
Body, fabric, plastic, fan, neon light, air.

Inspired in part by John Singer Sargent's *El Jaleo* at the Isabella Stewart Gardner Museum in Boston, *Space Inflation*, explores the body as a presence. The performance displayed the evolution of a single body from a slender, draped silhouette to a volume capable of competing with the surrounding architecture, to a flow of energy from stage to audience, eventually leaving the volume empty and completely flat on stage. At the moment of release, when the filled volume was allowed to collapse, viewers could catch an instantaneous view of the body inside, flooded by a deep red light. This light continued to glow from within the volume as it collapsed and came to lay flat on stage.

BODY-LIGHT-GRAVITY-SPACE

A proposal for transdisciplinary research presented to the Microgravity Interdisciplinary Research (MIR) Initiative, October, 2002.

Throughout human history the order of the visual world has been correlated with the gravitational acceleration experienced at the earth's surface (1 g). This has been true even in micro-gravity endeavors where the visual world has been constructed to give some sense of spatial orientation. We want to explore and reveal the 0 - 2 g bodily experience and its corresponding visual order.

Light reveals space; manipulating light in specific ways can shape space. We wish to employ the *light dance* technique of "sculpting" space through light effects that extend from the body. Joining the sources of illumination with the body allows the light to communicate the subjective bodily experience to the public space.

We want to experiment with *light dance* in the varying gravity of the IL-76 MDK.[a] Specific body-mounted light-instrumentation will extend the movement, posture, and position of the 0 - 2 g body to the boundaries of the cabin, giving architectural expression to the otherwise subjective experience. By translating bodily experience into space-defining light effects, a visual language for the experience of varying gravity will be developed. Once this language is developed it can be used to express the 0 - 2g bodily experience to a 1 g audience.

a. The IL-76 MDK is Russia's plane that flies in parabolic arcs to produce altered gravity environments ranging from micro-gravity (0 g) to twice earth's gravity (2 g).

Gravity/body and architecture/light are cross-cultural in their affect, requiring both artists and scientists to penetrate their significance/meaning. We bring together artistic, scientific and experiential knowledge of body, space, architecture, light, and special orientation. Our intelligences, combined with the MIR program, can bring personal understanding of these issues to the public.

EQUIPMENT/NEEDS:

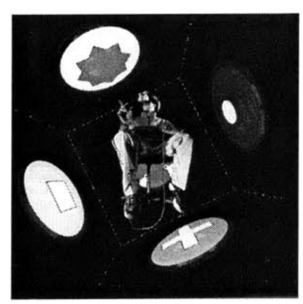
• Battery-powered light instrumentation.

• A section of the cabin made as dark as possible.

• Sound isolation in the form of noise canceling headphones.

• Architectural interventions through the use of draping or other, installed surface treatment. In order for the light to affect the shape of space the interior surfaces must be prepared for light reception (i.e. as dark, visually quiet, uncluttered, and uniform as possible). We plan to physically shape the cabin interior so that it will be as isotropic as possible. This will be done through use of materials such as fabric, rubber, plastic, and/or wood.

BIOGRAPHIES



Berengere Houdou finished her Masters degree in Aeronautics and Astronautics at MIT in 2002. Mixing Engineering and Cognitive Sciences in her MIT research, she studied spatial memory training for astronauts using virtual reality within the Man-Vehicle Lab. She conducted experiments about visual orientation and body perception in microgravity during a CNES parabolic flight campaign in France. She continues to pursue intercultural work and is currently trying to work in Russia.

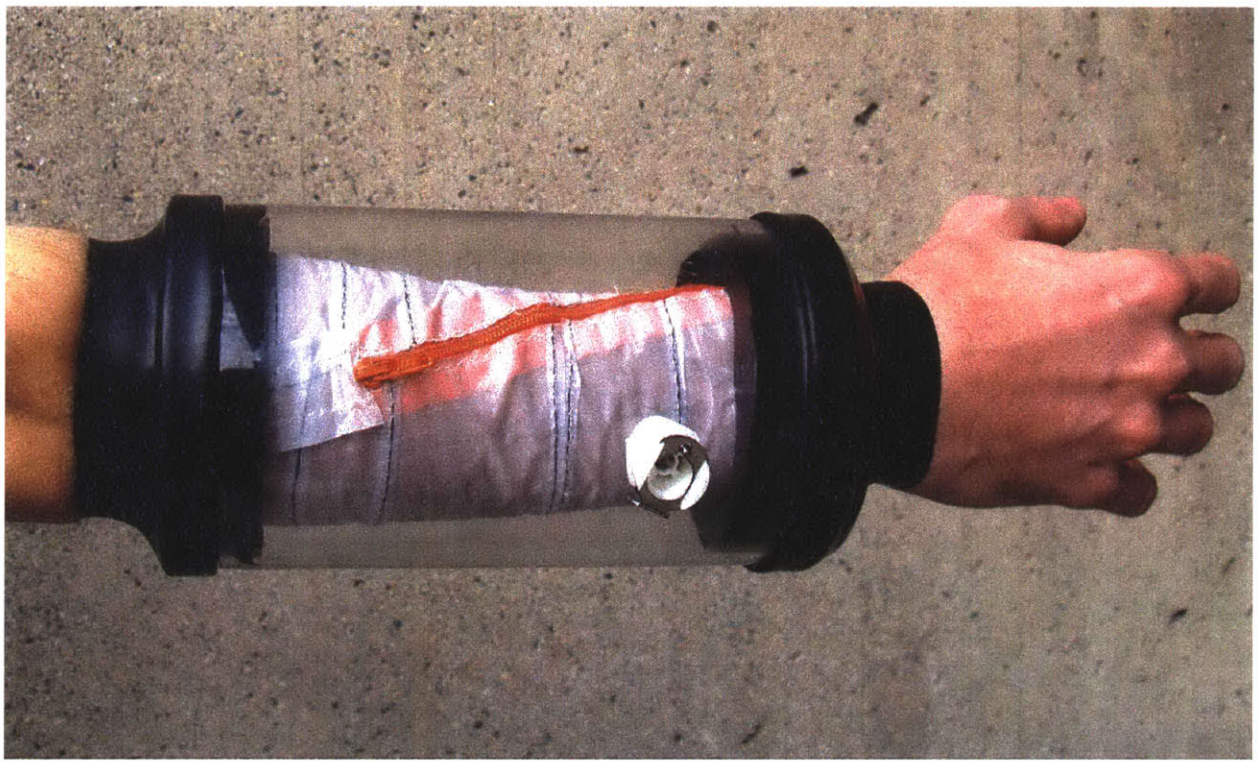
Bradley Pitts is a Masters student in the M.I.T. Department of Aeronautical/Astronautical Engineering researching advanced spacesuit design within M.I.T.'s Man-Vehicle Lab. For him, spacesuit research is an investigation into the body and micro-architectures. He has participated in scientific flights aboard NASA's KC-135 and has worked at NASA's Johnson Space Center in their space architecture division. As a student of Art, Architecture, and Engineering, he aspires to do meaningful work that explores the boarders between these fields.

Noah Riskin studied painting and trained in gymnastics at Ohio State University, 1981-86. In 1985 he shared the N.C.A.A. national gymnastics title on the parallel bars with his identical twin brother, and in 1986 he received his B.F.A. degree. Noah continued his athletic career to become an U.S. Men's National Gymnastics Team member and international champion. In 1993, as a Merit Scholar, he received his M.F.A. from the School of the Art Institute of Chicago. From 1994-97 he was a research affiliate/fellow at the MIT Center for Advanced Visual Studies, and from 1997-2000 he was a faculty member at the California Institute of the Arts.

In addition to coaching the MIT Men's Gymnastics Team, Noah is currently teaching at the Rhode Island School of

Design and working on a book on his experience as an identical twin.

Seth Riskin is known for his Light Dance: silent, space-defining performances of light phenomena articulated through body movement. He also conducts cultural research of light and teaches on the subject. Seth is currently a Research Fellow at the M. I. T. Center for Advanced Visual Studies (C.A.V.S.) and Director of the C.A.V.S. Light Symposium 2003.



VACUUM CUFF

2003
Cambridge, Massachusetts
Munich, Germany
Body, polyester fabric, plastic layflat tubing, zipper, lexan, latex.

Described as "a piece of space wrapped around the arm," *Vacuum Cuff* explores the juxtaposition of alien worlds. Designed as a portable vacuum chamber worn around the forearm, it can be depressurized to vacuum conditions and worn while tending to every day tasks. As it does not need to stay connected to the vacuum pump, it allows space to be worn and exhibited in public. *Vacuum Cuff* can appear next to you on the subway, in line at the grocery store, or at the laundromat, thereby bringing together the otherworldly and mundane.

4 THE T^X SUIT

The explorations presented in Chapter 2, "Meditations on a Spacesuit," on page 53, and Chapter 1, "Works," on page 73, led to a symbolic as well as functional notion of a spacesuit. These notions recontextualize the role of the spacesuit and the meaning of exploration. In the ideal, the spacesuit is transparent to all dimensions of exploration; it is transparent to exploration itself: $[\text{Transparent}]^{\text{Exploration}}$ (T^X).

The T^X suit presented in this chapter and the rest of the thesis is about facilitating exploration in its broadest sense. In order to do this it must facilitate exposure rather than isolation, making both the environment and self part of the terrain for exploration. It must be a gated membrane selectively filtering out harmful elements, but allowing all else to flow through it.

THE HELMET

As discussed in "Space Garb/Space Body" on page 77, the helmet of the spacesuit has stayed relatively constant over the entire history of spacesuit design (see "History of Spacesuits" on page 267). Conceived of as a clear bubble surrounding the head to provide pressure and oxygen, while being transparent to vision, it is a cage for all other senses.

a. I say "official" because we are able to sense our surroundings in far more detail than taste, touch, hearing, smell, and sight allow. We have far greater than 5 senses.

Besides touch, all "official"[a] senses are housed on, and limited to the head: sight, hearing, taste, and smell. Although previous spacesuit helmets have investigated visibility extensively, they have ignored the other senses. The result is that our vision is the only sense chosen to accompany us into the extreme environment of space. A T^X helmet must allow flow between interior and exterior for the other senses as well.

What does space sound like? What does it taste like? What does it smell like? The lack of atmosphere in the vacuum of space seems the ultimate barrier to these senses, but have we ever listened? If so, do we continue to do so? Perhaps there are other things to be heard than pressure waves through fluid. What do the fluctuations of light pressure sound like? Can we hear magnetic fields or radiation of different kinds?

Our explorations of space are not confined to vacuum, though. When humans set foot on the surface of Mars, it will be the first time we have explored an alien atmosphere directly. We should explore that experience with all our capacity. For the first time we can ask in a very literal sense, how does the experience sound, smell, and taste? Although it maybe impossible to step out of the spacecraft for "a breath of fresh air," would it come as a similar release to step out into the Martian wind and hear, smell, and taste the flow around you?

SOUND:

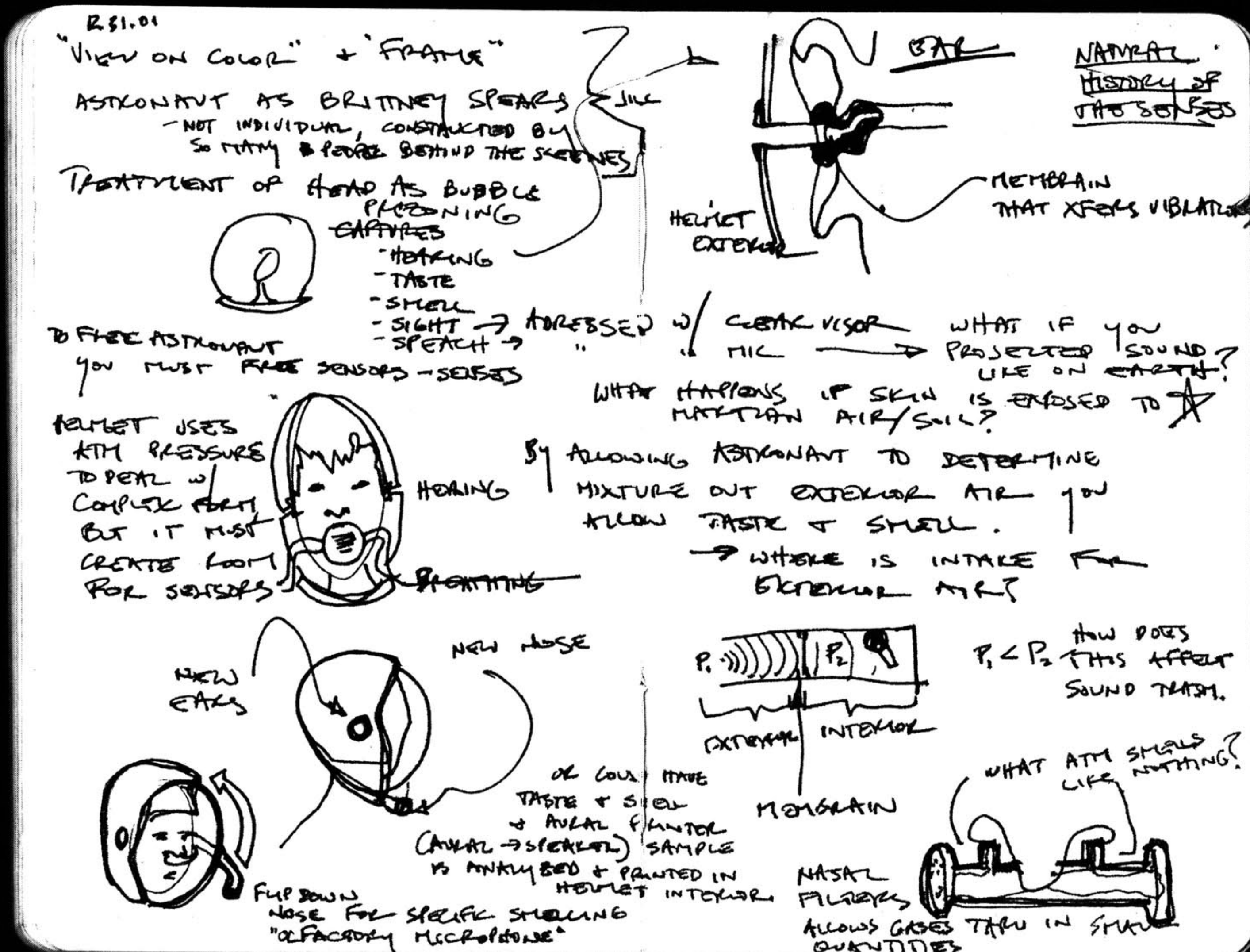
Can you imagine exploring a canyon without ever hearing an echo?[b] Although we assume ourselves to be visually dominant, we are sensitive to so many other stimuli to inform our sense of place, our sense of space.[c] Locations with echoes make this perfectly clear as we suddenly become creatures immersed in sonar. Our sense of sonar must be facilitated in alien realms. This requires a helmet that is transparent to the two-way flow of sound.

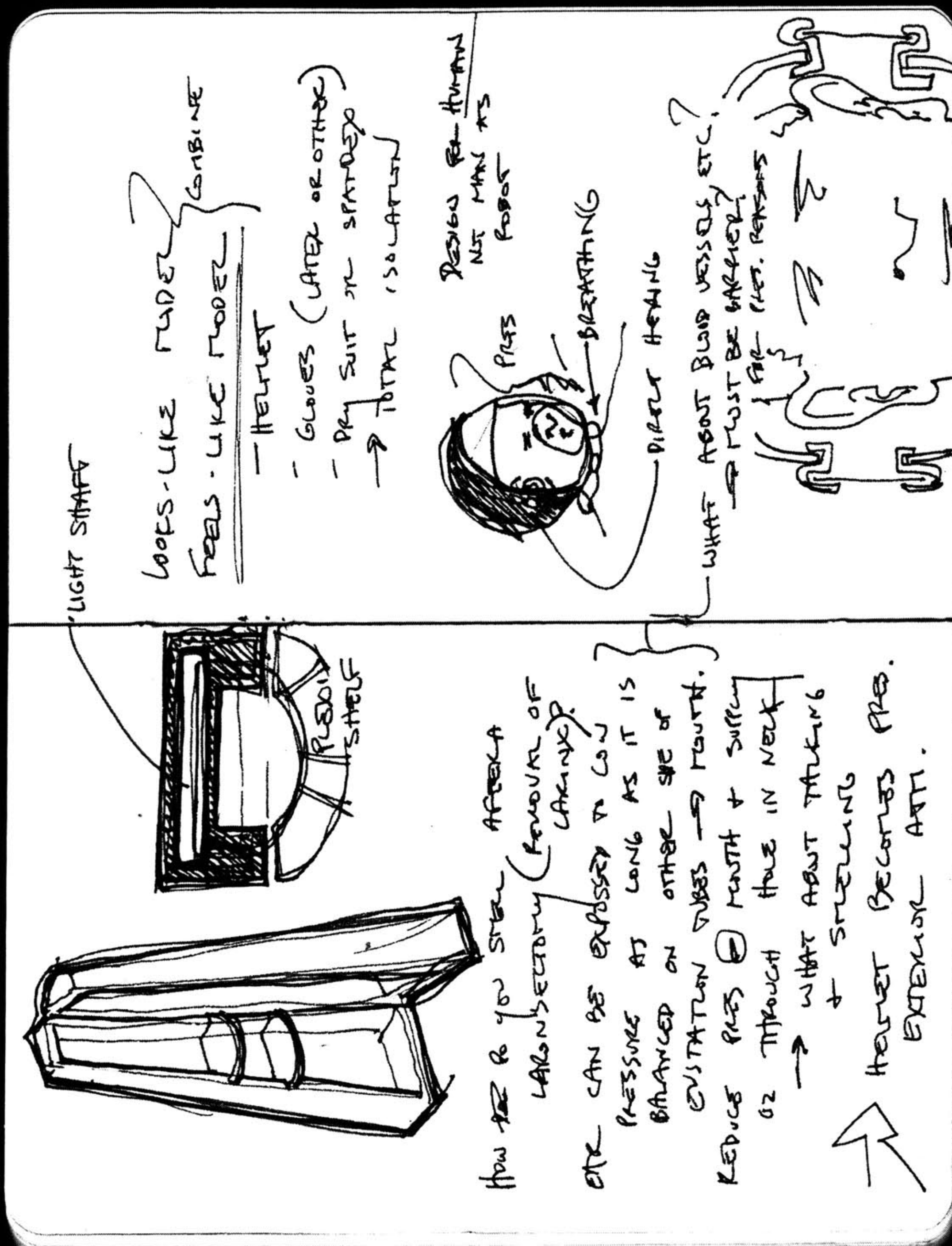
It should be noted that in the current spacesuit there are barriers to the experience of sound beyond the helmet design. Although images of free floating, space walking astronauts seem tranquil and quiet, the pumps of the life support system surround the astronaut in white noise. Although this noise

b. If a stone falls on the surface of Mars and no one hears it, does it make a sound?

c. This was made profoundly apparent to me when I experienced the binaural recordings of Janet Cardiff at PS 1 in New York City. Constructed as a guided tour of the museum, her piece had the ability to transform entire spaces without ever touching their architectural foundations. (see Christov-Bakargiev, Carolyn, Heiss, Alanna, Lowry, Glenn, Brisebois, Marcel, Janet Cardiff: A Survey of Works, with George Bures Miller, P.S.1 Contemporary Arts Center; (January 15, 2002))

Figure 4.1: (Next Spread) The Tx helmet as explored in the author's sketch book. Ideas explored include sound transmission through the helmet from a mechanical and physical perspective. How does frequency and amplitude change as sound moves between regions of high and low pressure? How can the physical vibrations be allowed to pass through the helmet? In addition, some sketches explore the idea of smell transmission. At the bottom left of the image on the right page, a note reads, "Helmet becomes pressurized exterior atmosphere."


2.31.01
"VIEW ON COLOR" + "FRAME"
ASTRONAUT AS BRITNEY SPEARS
- NOT INDIVIDUAL, CONSTRUCTED BY SO MANY PEOPLE BEHIND THE SCENES
TREATMENT OF HEAD AS BUBBLE
IMPRISONING
- HEARING
- TASTE
- SMELL
- SIGHT → ADRESSED W/ CLEAR VISOR
- SPEACH → " MIC
TO FREE ASTRONAUT YOU MUST FREE SENSORS - SENSES
WHAT IF YOU PROJECTED SOUND LIKE ON EARTH?
WHAT HAPPENS IF SKIN IS EXPOSED TO MARTIAN AIR/SOIL?
HELMET USES ATM PRESSURE TO SEAL W/ COMPLEX FORM BUT IT MUST CREATE ROOM FOR SENSORS
HEARING
BY ALLOWING ASTRONAUT TO DETERMINE MIXTURE OUT EXTERIOR AIR YOU ALLOW TASTE + SMELL.
→ WHERE IS INTAKE FOR EXTERIOR AIR?
EAR
NATURAL HISTORY OF THE SENSES
MEMBRAIN THAT XFERS VIBRATION
HELMET EXTERIOR
NEW EARS
NEW NOSE
P1 P2
P1 < P2 HOW DOES THIS AFFECT SOUND TRANSM.
EXTERIOR INTERIOR
MEMBRAIN
OR COULD HAVE TASTE + SMELL + AURAL FILTER (AURAL → SPEAKER) SAMPLE IS ANALYZED + PRINTED IN HELMET INTERIOR.
FLIP DOWN NOSE FOR SPECIFIC SMELLING "OLFACTORY MICROPHONE"
WHAT ATM SMELLS LIKE NOTHING?
NASAL FILTERS
ALLOWS GASES THRU IN SMALL QUANTITIES


LOOKS-LIKE MODEL
FEELS-LIKE MODEL
COMBINE
— HELMET
— GLOVES (LATEX OR OTHER)
— DRY SUIT OR SPANDEX
→ TOTAL ISOLATION
DESIGN FOR HUMAN
NOT MAN AS
ROBOT
PRES
BREATHING
DIRECT HEARING
WHAT ABOUT BLOOD VESSELS, ETC.?
→ MUST BE BARRIER?
FOR PHYS. REASONS
LIGHT SHAFT
SHELF
HOW FAR DO YOU SMELL AFFECTA
LARYNGECTOMY (REMOVAL OF LARYNX)?
EAR CAN BE EXPOSED TO LOW
PRESSURE AS LONG AS IT IS
BALANCED ON OTHER SIDE OF
EUSTATIAN TUBES → MOUTH.
REDUCE PRES @ MOUTH + SUPPLY
O2 THROUGH HOLE IN NECK
→ WHAT ABOUT TALKING
+ SMELLING
HELMET BECOMES PRES.
EXTERIOR ATM.

drifts to the subconscious, it means that astronauts has never experienced the pure silence of the void. A clean pallet must be created before the environment can express itself.[d]

Although speakers and microphones could be used to penetrate the helmet barrier, that approach would have little meaning. There must be a physical flow/transmission of vibrations from exterior to interior as well as interior to exterior. How does the experience of distance change if you need to shout in order to communicate with your companion several yards away? The energy and strain put into the shout is a visceral experience of the dimensionality of the environment. In the Martian atmosphere do you need to shout louder than you do on Earth to cross the same distance?

d. It should also be noted that the white noise in a spacesuit is usually considered a safety feature of sorts. After all, the presence of white noise becomes quite apparent when the white noise stops. The absence of white noise can mean big trouble for the space walking astronaut. It seems to me, however, that other, less disruptive cues could be imagined, such as the slight vibration of the backpack felt on the shoulders or back.

TOUCH:

Although the icon of touch is usually the hand, our entire body surface utilizes this environmental probe. In fact, as areas of the body are covered with more nerve endings and small hairs, they are tuned to different aspects of touch. The surface of the face is powerful site of touch as any kiss, or slight breeze demonstrates. How can the helmet become transparent to touch?

How cold is it in space? Is a warm or cold wind blowing on Mars? Might the temperature of the helmet air be somehow influenced by the temperatures outside?

SMELL AND TASTE:

As an extension of touch, smell and taste require physical contact in order to sense. Once again it would not be enough to incorporate smell and taste "speakers" into the helmet as the "microphones" and analyzers would filter the information before any sense occurred. How can the physical transport of material across the helmet boundary be facilitated?

In environments such as Mars, there are many hazardous substances that are not to be ingested by taste or smell. Are they dangerous at all quantity levels? If so, could the hazardous materials be filtered so that the innocuous remains to be sensed? Perhaps a chamber could be created that samples extremely small samples of the environment and mixes them with the breathing gas. This could be an automatic, continuous function, or could be activated on command.

We should also consider that the location of these senses becomes another design variable. As designing the spacesuit is designing a new body organ, the designer can place senses where ever is thought advantageous. What is the experience of smelling from your toe, or tasting from your hand, or seeing from your knees or back?[e]

e. Sanjit Sethi has done some interesting experiments with these ideas. (See Sethi, Sanjit (Sanjit Singh), *1971- Grey man devices*, MIT Thesis, 2002.)

THE TX GARMENT

As discussed in "Body-Surface: Flux" on page 63 the body surface is a powerful probe of our surroundings. Just as the skin is a membrane organ of selective flux,[1] so must a T^x garment be. It must facilitate nudity and exposure while filtering those elements that are harmful. This should be accomplished by creating a membrane that lies close to the body surface and allows the skin to be exposed as much as possible. In this way, the natural body is allowed to exchange with the environment in a direct and powerful way. As discussed in the next part of this thesis, Part II: Technical Development of the Tx Pressure Garment, it is possible to expose and provide the required restraint to the body if mechanical counterpressure is used.

1. *The Physical nature of the skin*, Lancaster, England ; Boston : MTP Press, c1988.

EXPOSED EXPLORATION:

A T^X garment must allow the explorer to experience the connections between personal and environmental. In this way the entire range of human existence is brought to the exploration process. Instead of probing the exterior and trying to remain apart from it, the interconnections made possible by the T^X garment allow the explorer to play. It is through this play that meaningful explorations and discoveries are made: discoveries of personal and cultural significance.[f.]

f. Just as the scientific paradigm assumes that the scientist can observe without interfering, the current spacesuit assumes that one can explore while maintaining isolation. In this way, these two assumptions further a notion of "objective" reality existing beyond our experience. This notion divides experience into subject and object, mind and matter, creating divisions and isolation instead of involvement and personal understanding.

The garment holds special significance as it literally shapes the reality of the explorer. The garment can either remove or facilitate different ranges of experience. It is not only a channel of flux for sweat and touch, but a channel for mobility, understanding, and interaction. The garment dictates which of our many bodies are brought to the exploration process. These bodies each lead to different forms of discovery.

TX OPERATIONS[g.]

The transparency of the T^X suit should be extended beyond the individual's experience, and into the exploration opperations. We must consider the ways the spacesuit imposes old

g. This section is composed from edited excerpts taken from "Conversations with Krzysztof et. All: Ideas/ Questions/Notions to Spur Ideas" on page 293.

habits on the alien space and how our presence will be experienced after we've left.

TX PROPULSION:

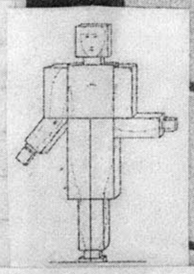
Why should we assume that our method of self-propulsion on earth would be suitable for other gravitational fields? Our bodies have evolved, grown up, and developed within Earth's one-g environment. Everything we know (conscious and subconscious) is related to this magnitude of gravitational acceleration. This is precisely why it is so easy for us to force our methods of movement onto other environments. Not only is it *easy* to force our ways onto alien worlds, but it is *difficult* to imagine alternate modes of self-propulsion. What might these be? What might they look like? On what scale(s) do they operate?

One possibility is to allow the user to go through a conscious adaptation/evolution/development in their new g-field. This would provide the most discovery potential for both the explorer and earth-bound public. It could be accomplished by designing to maintain self-propulsion as we know it in one-g, but would also incorporate features that would allow the individual in the new environment to create an evolved suit that works with the potentials/limitations of this new environment. Thus, the individual arrives much the same as she/he left, but quickly discovers their own strangeness with respect to the alien world. As the strangeness is discovered and explored, the individual is provided the means to learn and create from this strangeness. In the end, the individual has gone through a learning/development process of experimentation much as we do throughout our lives, especially our childhood. The act of creating this new mobility suit would serve as a self realization and documentation process. The astronaut would build and create the new suit as they discovered their environment, and the public, by inspecting the completed suit, would be able to learn about the alien environment in a powerful way.

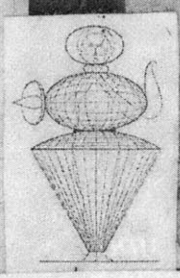
Figure 4.2: (Next Spread) Collages exploring alternate modes of locomotion.


University Florist

The functional laws of the human body in their relationship to space. These laws bring about a typification of the bodily forms: the egg shape of the head, the vase shape of the torso, the club shape of the arms and legs, the ball shape of the joints. Result: *the marionette.*



The laws of the surrounding cubical space. Here the cubical forms are transferred to the human shape: head, torso, arms, legs are transformed into spatial-cubical constructions. Result: *ambulant architecture.*



The laws of motion of the human body in space. Here we have the various aspects of rotation, direction, and intersection of space: the spinning top, snail, spiral, disk. Result: *a technical organism.*

The metaphysical forms of expression symbolizing various members of the human body: the star shape of the spread hand, the ∞ sign of the folded arms, the cross shape of the backbone and shoulders; the double head, multiple limbs, division and suppression of forms. Result: *dematerialization.*

Figure 4.3: Photographic composite of rover tracks looking west on a steep 17-degree grade of Hadley Delta near Spur Crater. Image and text from the book ***FULL MOON*** by Michael Light, copyright 1999/2002.

TX FOOTSTEPS

Out of respect for the unknown, foreign land, there should exist the practice of leaving no trace. The goal should be the displacement of as little alien material as possible. The first step to this goal is a level of respect and consciousness so that pairs of people walk in each other's footsteps and the return journey is made by walking in the footsteps of the out-bound journey. Going beyond this, though, the actual mark must be examined and the mode of propulsion must be designed to the point where contact becomes conscious and directed (see Fig. 4.3).

Figure 4.4: (Opposite Page) A sketch by Krzysztof Wodiczko exploring a lighter than air, leave no trace device.

What if this point of contact is considered a point of opportunity for exchange, a probe rather than a means of static support? The function of this contact would not be to fight gravity, but to engage the surface in a meaningful, conscious way.

TRANSPARENCY

Although the concept of transparency was initially applied to the helmet and the senses of the wearer, it has become a concept of integration and holistic unity. As discussed in Chapter 11, "Humane Factors: a Summary and Expansion," on page 237, these notions are born out of full concept of the human being, their capabilities, and their environment. Thus, the entire endeavor of transparency is led forward by philosophical/spiritual beliefs that connect both the endeavor and its artifacts to our core. With this connection firmly established, technical work can begin. Part II: Technical Development of the Tx Pressure Garment describes the development process for a T^x garment. At each juncture, in the technical development, the original motivations and beliefs were considered before action was taken.

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PART II: TECHNICAL DEVELOPMENT OF THE T^X PRESSURE GARMENT

5 INTRODUCTION TO THE TECHNICAL DEVELOPMENT OF THE T^X PRESSURE SUIT

The modes of inquiry explored in Chapters 1, 2, and 3 have led to a notion of a spacesuit that facilitates exploration in the broadest sense. As our experience of reality is multidimensional, the spacesuit must be transparent to all these dimensions. Do to the very nature of design, it is difficult for design to accomplish unknown goals, therefore, the suit can only be transparent to those dimensions we are actively aware of during the design process. In the ideal, however, the spacesuit is transparent to all dimensions of exploration; it is transparent to exploration itself: $[\text{Transparent}]^{\text{Exploration}}$ (T^x).

INSPIRATIONAL SUITS

The conception/design process for the T^x pressure suit was inspired by at least three suits that came before it. The physical design of the T^x suit as described in Chapter 9, "Construction and Testing" on page 171 is a hybrid of these suits.

As the T^X suit uses mechanical counterpressure as a means to provide body surface pressure, it is highly influenced by Paul Webb's Space Activity Suit (SAS) developed in 1971 (see Fig. 5.1). Described as a "space leotard," the SAS was made of elastic, spandex-like fabric that squeezed the wearer in order to produce adequate body surface pressure (see "Mechanical Counterpressure Techniques" on page 131). As the first mechanical counterpressure prototype spacesuit developed it deserves much credit.

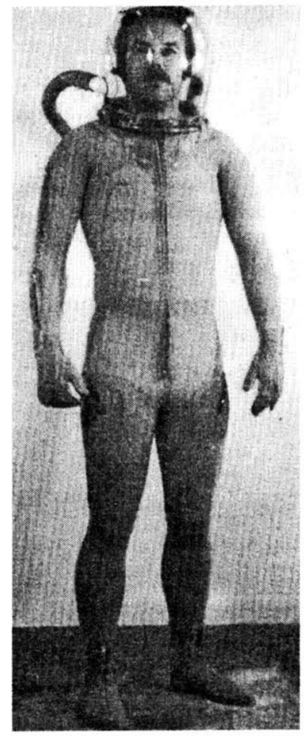


Figure 5.1: Paul Webb's Space Activity Suit, 1971. Annis, J.F., and Webb, P., "Development of a Space Activity Suit," NASA Contractor Report CR-1892, Webb Associates, Yellow Springs, Ohio, 1971

The second suit that pointed towards future directions for the current effort was the Libelle anti-g suit first developed by Prospective Concepts in Glattbrugg, Switzerland.[1] Named after the german word for "dragon fly,"[a] the Libelle is a body tight suit with liquid filled channels running from shoulder height, down the arms and legs (see Fig. 5.2). Because these channels always experience the same hydrostatic pressure gradient that the blood does, they naturally counteract the tendency of high g-loading to pull blood away from the brain. The Libelle can protect its wearer up to 10 g's. Although the Libelle is not a spacesuit, the simplicity of its design and operation made it a clear source of inspiration. The channels

a. The dragon fly is the only creature capable of withstanding 30 g's.

1. http://www.prospective-concepts.ch

described in Chapter 9, "Construction and Testing" on page 171 were inspired by the Libelle.

Figure 5.2: The Libelle anti-g suit, 2003. http://www.autofluglibelle.com/

In the search for an inextensible body restraint facilitating unrestricted mobility, the work of Aurthur S. Iberall was of great importance. His reports and publications described the rational and methods used for his research on the lines of nonextension.[2, 3, 4] These lines run over the surface of the body, mapping the locations on the skin that never stretch during normal body motion (see Fig. 5.3). He used this research to create a restraint for a gas filled suit, whereas, the T^x suit uses these ideas to facilitate mechanical counterpressure for body restraint.

The genealogy of the T^x suit can be seen as taking the concept of mechanical counterpressure from Webb's Space Activity Suit and combining it with the mechanical counterpressure techniques of the Libelle. This hybrid concept then incorporates Iberall's work to attain full mobility. A graphical representation of this genealogy can be seen in Figure 5.4.

Part II: Technical Development of the Tx Pressure Garment describes the quantified, technical development of the T^x concept. It is in this section that engineering methods are

2. Iberall, A.S., "Development of a Full-Pressure Altitude Suit," WADC Technical Report 58-236, ASTIA Document No. AD 303813, Wright Air Development Center, Wright-Patterson AFB, Ohio, June 1958.

3. Iberall, A.S., "The Use of Lines of Nonextension to Improve Mobility in Full-Pressure Suits," AMRL-TR-64-118, Rand Development Corporation report to Behavioral Sciences Laboratory, Wright-Patterson AFB, Ohio, November 1964.

4. Iberall, A.S., "The Experimental Design of a Mobile Pressure Suit," Journal of Basic Engineering, June 1970 pp. 251-264.

used to explore the feasibility of such a concept and to develop initial attempts at a prototype. These prototypes were modeled and then tested to a pressure of 27.6 kPa (4 psi). The results and discussion of these tests can be found in Chapter 9, "Construction and Testing" on page 171.

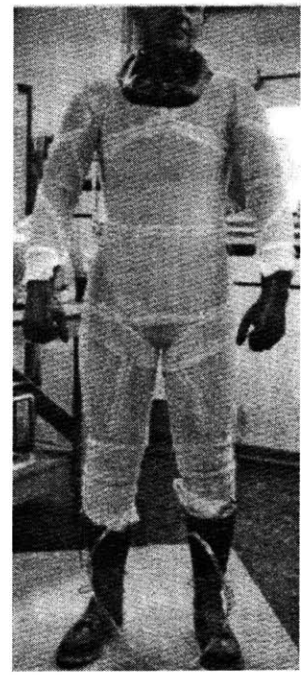
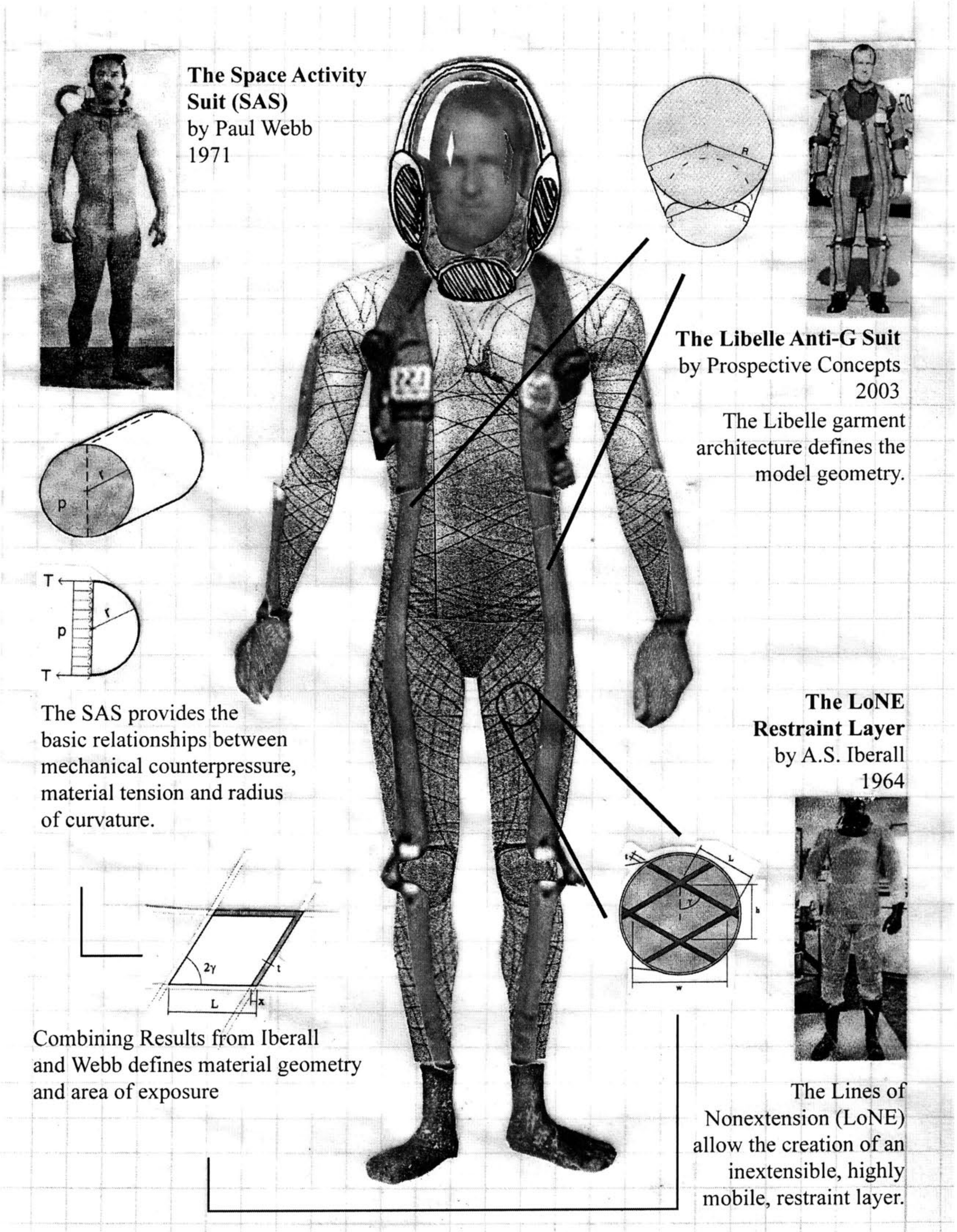


Figure 5.3: The restraint layer of A.S. Iberall's line of nonextension suit. Iberall, A.S., "Development of a Full-Pressure Altitude Suit," WADC Technical Report 58-236, ASTIA Document No. AD 303813, Wright Air Development Center, Wright-Patterson AFB, Ohio, June 1958.

Figure 5.4: (Opposite Page) An illustration of the T^x pressure garment's genealogy and the ways past efforts have been used in order to develop the Tx garment concept.



The Tx garment concept

6 PHYSIOLOGICAL CONSIDERATIONS FOR PRESSURE SUIT DESIGN

The highest level motivation for the spacesuit is that the unprotected human body cannot live long in a vacuum. Although tests have suggested that a human could be exposed to vacuum for roughly three minutes without ill effect,[1] this does not address the need for working and exploring outside the spacecraft environment. Although an operational spacesuit must counteract the numerous dangers posed by the space environment,[a] this thesis focusses on the necessity of pressure production in spacesuits, which play a key role in EVA preparation and spacesuit operability: mobility, imposed joint torques, bulk, and weight. What follows is an introductory description of the physiology underlying pressure suit design.

1. Annis, J.F., and Webb, P., "Development of a Space Activity Suit," NASA Contractor Report CR-1892, Webb Associates, Yellow Springs, Ohio, 1971

a. Dangers include underpressure, suffocation, thermal hazards from the environment and the suit, and radiation hazards.

PULMONARY PHYSIOLOGY

The most obvious difference between a vacuum and the atmosphere we typically inhabit is the defining lack of air. This absence is capable of inducing at least two pathologies: hypoxia and swelling. Although the onset of swelling usually takes up to three minutes, the effects of hypoxia, or lack of oxygen, can onset much more quickly.[b] It is not enough to simply supply oxygen, however.

b. The time of useful consciousness in an oxygen deprived state is roughly fifteen seconds for the average person.

The physiology of the lungs requires that the atmospheric partial pressure of oxygen be greater than or equal to 19.9 kPa (150 mmHg, 2.9 psi) in order for normal oxygen diffusion, or normoxia.[3] Thus, it is not the fraction of oxygen in the atmosphere that matters, but the atmospheric pressure multiplied by the fraction of oxygen per unit volume, known as partial pressure. The current NASA spacesuit encases the wearer in an atmosphere made up entirely of oxygen at 29.6 kPa (222 mmHg, 4.3 psi) in order to achieve the required partial pressure of oxygen.[4] Although this is adequate in terms of assuring normoxia, the physiology of decompression suggests that a higher spacesuit operating pressure would increase the efficiency of extravehicular activity.

3. West, John B. (John Burnard) "Respiratory physiology-- the essentials," Baltimore: Williams & Wilkins, c1995, p.45.

4. Newman, D., Barratt, M. "Life Support and Performance Issues for Extravehicular Activity," volume 2 of Fundamentals of Space Life Sciences, chapter 22, pages 337-364. Krieger Publishing Company, Malabar, Florida, 1997.

Because of the high cabin pressure of human-rated spacecraft,[c] the astronaut preparing for EVA must depressurize in order to reach the spacesuit operating pressure. As any scuba

c. The cabin atmosphere of current, human-rated spacecraft is a nitrogen/oxygen mixture usually kept around normal sea-level conditions: 101.3 kPa (14.7 psi). This is done for various reasons relating to experiment design, operations, hardware design, and thermal control. The concern for experiment design is the reliability of experimental results. The scientific community requires the cabin pressure to be close to sea-level pressure so as to remove pressure as a confounding factor affecting their results. Hardware pressure dependencies include heat rejection issues as well as reliability. Because off-the-shelf electronics are designed to operate in a sea-level atmosphere, it is advantageous to replicate that atmosphere on orbit in order to decrease the need for custom electronics, or specialized certification procedures.

diver knows, this depressurization can cause severe health risks if performed in a hasty manner. During this depressurization process, trace elements of nitrogen in the blood stream can precipitate out of the blood to form bubbles. These bubbles can cause the "bends" and other serious pathophysiologies, such as stroke or embolism, by cutting off circulation. In order to prevent this precipitation from occurring, astronauts must purge nitrogen from their bloodstream before depressurizing. By breathing pure oxygen, nitrogen is exhaled with the normal expiration of carbon dioxide and other gases. Current NASA protocol requires a prebreath time of 105 minutes before every EVA.[5, d]

5. Hoffman, J.A., Personal Communications, 2003.

d. Prebreath time is a function of the pressure differential as well as the exercise protocol.

One solution to the issue of prebreath time is to design spacesuits for operation at a higher pressure. This reduces the pressure difference between cabin and spacesuit and thus reduces the need for an extended prebreath time. As described in "Spacesuit Physics" on page 283, however, there are clear reasons why high pressure suits might limit the effectiveness of EVA. It has been shown that if the change in pressure is less than a factor of two times the higher pressure, no prebreathing is required.[6] Thus, a 55 kPa (414 mmHg, 8

6. Nicogossian, A., Huntoon, C., Pool, S., *Space Physiology and Medicine*, Lea and Febiger, Philadelphia, 1994.

psi) spacesuit would remove the prebreath requirement in a 101.4 kPa (14.7 psi) spacecraft.

CARDIOVASCULAR PHYSIOLOGY

Experience has shown that despite small changes in the cardiovascular system, the heart is quite capable of adapting to weightlessness. Although the hydrostatic gradient of the body becomes negligible, and fluid shifts occur within the body, the heart performs its job beautifully in weightlessness. In fact, the transition back to one gravity is much more difficult for the cardiovascular system to adapt to than is the transition to microgravity.

In the case of spacesuits, the issue is once again a matter of pressure: differential pressure between the inside and outside of the blood vessels. In relation to the respiratory physiology mentioned above, the pressure of the inspired gas, "breathing pressure," and the pressure exerted over the surface area of the body, "body surface pressure," are key areas of concern. Depending on the relationship between these two pressures, cardiovascular function can be normal or dangerously pathological.

In order to understand the issue at hand it is necessary to visualize the circulatory system and, in particular, the part of that system that interfaces with the lungs. Figure 6.1 displays a schematic of this system, with the blood-gas barrier exaggerated for purpose of illustration.

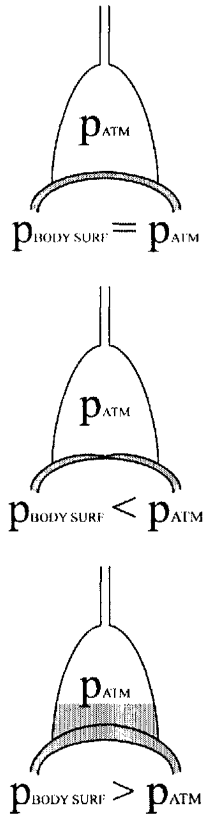
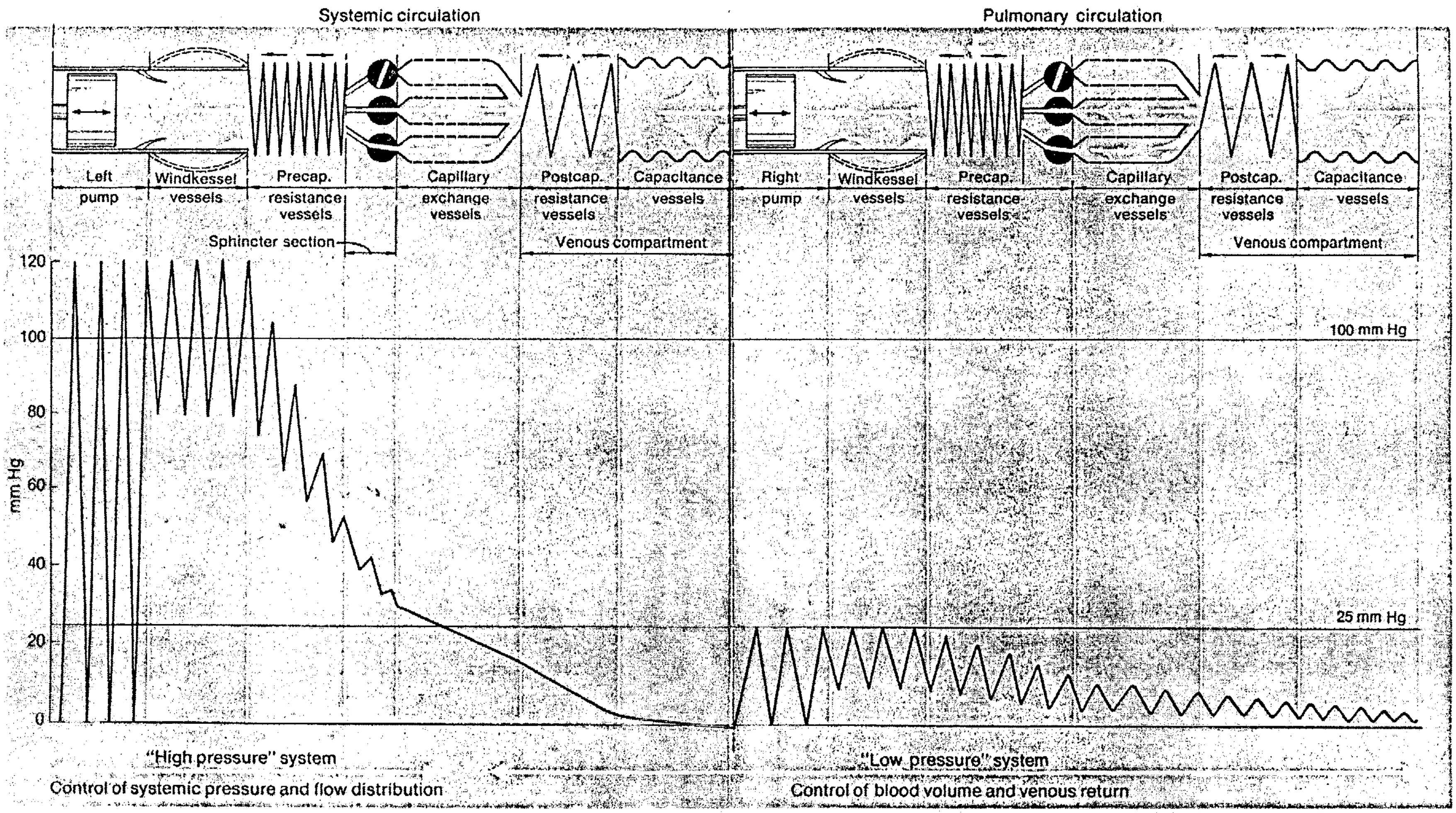


Figure 6.1: Diagrams of the blood-gas barrier in the lungs. If the body surface and lung pressures are not equal, either the circulation can be occluded (middle), or fluid can leak into the lungs (bottom).

Figure 6.2: (Next Page) A graph of blood pressure as a function of location in the circulatory system. Notice how low the blood pressure in the lungs is. Because of this, it can be assumed that the blood pressure at the blood-gas boundary is equal to the body surface pressure.

By examining the blood-gas barrier, it is clear that the relationship between blood pressure and alveolar pressure are crucial in determining the blood flow in the lungs. If alveolar pressure is much greater than blood pressure, the capillaries at the blood-gas barrier will be forced to collapse, thereby, occluding blood flow. If, on the other hand, the blood pressure far exceeds alveolar pressure, fluid will be forced across the barrier resulting in the pooling of fluid in the lungs, known as pulmonary edema. In the first case, oxygenated blood does not circulate due to the occluded capillaries. In the latter case, blood does not become oxygenated due to the pooled fluid at the barrier. In either case oxygen deprivation results.

In order to relate blood pressure to body surface pressure, it is useful to measure the relationship between the two. Figure 6.2 displays a graph of blood pressure as a function of location in the circulatory system. Although absolute blood


Systemic circulation
Pulmonary circulation
Left pump
Windkessel vessels
Precap. resistance vessels
Capillary exchange vessels
Postcap. resistance vessels
Capacitance vessels
Sphincter section
Venous compartment
Right pump
Windkessel vessels
Precap. resistance vessels
Capillary exchange vessels
Postcap. resistance vessels
Capacitance vessels
Venous compartment
120
100
80
60
40
20
0
mm Hg
100 mm Hg
25 mm Hg
"High pressure" system
Control of systemic pressure and flow distribution
"Low pressure" system
Control of blood volume and venous return

pressure is highly dependent on the cycle of the beating heart, it is roughly equal to body surface pressure. Assuming that the capillary pressure at the blood-gas barrier equals the body surface pressure, it is clear that the consequence of a breathing pressure far greater than body surface pressure is occlusion of the capillaries, whereas, the consequence of a breathing pressure far below body surface pressure is fluid leakage into the lungs. Although the pressure extremes are easy to analyze, absolute maximum tolerances between body-surface pressure and breathing pressure are harder to determine. Numerous studies have been performed on positive pressure breathing due to its application in hospitals as well as extreme environments,[7] but little has been done on negative pressure breathing. The safest design approach seems to be to minimize pressure differences between breathing and body surface pressure.

7. Cirovic, S., Walsh, C., Fraser, W., Gulino, A., "The Effect of Posture and Positive Pressure Breathing on the Hemodynamics of the Internal Jugular Vein," Aviation, Space, and Environmental Medicine, Vol. 74, No. 2, February 2003.

In addition to the body surface and breathing pressure relationship, there are local pressure differences that can seriously effect normal physiology. The effects of high local pressure are known to most people from experiences such as limbs "falling asleep," but the effects of low pressure may not be as familiar. The situation is much the same as that explored at the blood-gas barrier, but in the case of local regions of high or low pressure, oxygen deprivation and necrosis occur locally. As with a breathing pressure much greater than blood pressure, an area of high local pressure can result in the occlusion of veins, thereby inhibiting blood flow in the region. As is familiar in the case of a limb falling asleep, this can lead to loss of sensation and discomfort. If the high pressure is maintained for extended periods of time tissue death can result.

In the case of local regions of low pressure, fluid leakage can result much like the case of low breathing pressure. Locally, fluid leaks into the interstitial spaces (edema) and blood pools in the veins as they dilate. Both factors lead to swelling and pose the risk of interrupting normal circulation, leading to effects similar to high pressure regions. In the most severe case, blood pooling can remove enough blood volume from circulation that loss of consciousness results. Once again, although extreme differences in pressure are easy to analyze, absolute pressure tolerances for localized regions are hard to determine. A complicating matter is the fact that these tolerances are clearly dependent on activity level as muscle contractions help mediate these effects in both cases. Once again, the safest design approach seems to be to minimize local pressure differences.

SUMMARY

The physiology discussed above directly relates to spacesuit design requirements. One way of summarizing the role of a spacesuit is to say that it must ensure normal physiology despite the severe change in environment: the vacuum of space. Thus, it is necessary to understand nominal physiology and the factors that affect it.

As discussed above, for proper pulmonary and cardiovascular function, the spacesuit must create a body surface pressure equal to the breathing pressure. In addition, this pressure must be uniform over the entire body. More research needs to be done in order to determine the pressure tolerances around the terms "equal," and "uniform." If breathing pressure and body surface pressure are equalized and applied uniformly, the spacesuit, as a pressure suit, will meet the challenges of sustaining life in the vacuum of space. Because of this, the ultimate goal in the technical development of the Tx pressure suit is to achieve uniform pressure. This goal and it's outcome will be discussed in the following chapters.

7 MECHANICAL COUNTERPRESSURE TECHNIQUES

As discussed earlier, in order to facilitate exploration in the broadest sense, barriers between individual and environment must be reduced to a minimum. This applies to physical barriers, such as those imposed by the spacesuit's materiality, as well as psychological and temporal barriers such as those imposed by the don/doff time of the spacesuit. Only mechanical counterpressure (MCP) provides a way to produce pressure on the body surface while allowing flux between body and environment. Thus, MCP facilitates exchange with the environment: a necessary element of exploration. In addition, the degree of mobility afforded through MCP techniques potentially allows self realization within the alien surroundings, facilitating self awareness, growth, and insight.

Many material justifications for MCP exist as well, such as those suggested by Paul Webb, Mitchell Clapp and others.[1, 2, 3] MCP minimizes weight by removing rigid elements,

1. Annis, J.F., and Webb, P., "Development of a Space Activity Suit," NASA Contractor Report CR-1892, Webb Associates, Yellow Springs, Ohio, 1971

2. Clapp, W., "Design and Testing of an Advanced Spacesuit Glove," Massachusetts Institute of Technology, Cambridge, MA, 1983.

3. Tourbier, D., Knudsen, J., Hargens, A., Tanaka, K., Waldie, J., Webb, P., Jarvis, C. "Physiological Effects of a Mechanical Counter Pressure Glove," Society of Automotive Engineers, 2001-01-2165.

such as bearings, and by greatly simplifying the life support system. Other performance metrics such as flexibility/mobility, don/doff time, system bulk, tactile feedback, and system cost are also improved by pursuing MCP.

MECHANICAL COUNTERPRESSURE FUNDAMENTALS

As Webb and others have demonstrated the fundamental principles behind MCP are those derived from a simple pressurized cylinder. Examining this structural problem, Equation 7.1 shows the relationship between the geometry of the cylinder, with radius r, the internal pressure, p_{gas}, and the resulting tension in the cylinder's wall, T (see Fig. 7.1).

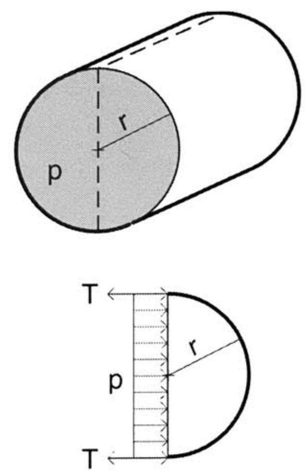


Figure 7.1: Pressure, p, and tension, T, relationships for a pressurized cylinder with radius, r.

$$T = p_{gas} r \quad (7.1)$$

The key to MCP is realizing that it does not matter whether internal pressurization causes wall tension, or whether tension created in the walls produces the internal pressure. MCP works by creating an appropriate level of tension, T, in the garment, thereby, creating pressure at the skin surface equivalent to that derived by the above relationship. Thus, the MCP, p_{MCP}, is shown as:

$$p_{MCP} = \frac{T}{r} \quad (7.2)$$

It should be noted, however, that the radius term mentioned

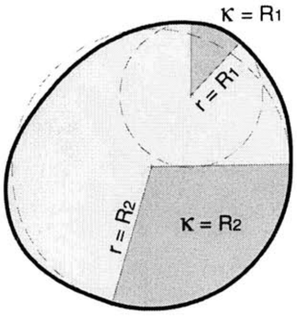


Figure 7.2: An irregular cross section and its local radii of curvature,κ. It is these radii that determine the local mechanical counterpressure production.

above should be interpreted as the local radius of curvature, κ, for rigid, irregular cross sections. Thus, although the tension might be constant around the entire cross section, the pressure production most likely varies with the local radius of curvature (see Fig. 7.2). Substituting κ for r, Equation 7.2 becomes:

$$p_{MCP} = \frac{T}{\kappa} \quad (7.3)$$

In terms of the body, however, the case is not so clear. In most locations, the body cross section is not rigid and therefore is able to deform. In addition, the body lies somewhere between liquid and solid, possibly allowing some pressure to be distributed through the section itself.

BINDING THE BODY

Webb's Space Activity suit was a powerful demonstration of the capabilities and potential hazards of mechanical counterpressure. Although the suit seemed to be a physiological success, the don/doff difficulties imposed severe barriers to exploration and was therefore never accepted by NASA. These troubles came about because the elasticity and tension in the fabric had to be fought against during the donning/doffing process.

In order to store energy, work has to be done. To produce body surface pressure in the SAS, strain energy stored had to be stored in the elastic material, and was experienced as work while donning its six layers. Ironically, the very mechanism by which Webb created MCP was the biggest source of Space Activity Suit's problems.

The MCP strategy explored in this thesis is to design in such a way that the donning/doffing and pressure production do not compete, thereby decoupling this issue. Donning/doffing should be as easy as putting on clothes and pressure production should occur only after the donning process is complete.

A quickly donned/doffed MCP garment is possible in at least two ways: shrinking the garment around the wearer or "enlarging" the body. Shrinking the garment would allow a loose garment to be donned and then constricted around the body to the point where adequate surface pressure is produced. "Enlarging" the body is exactly the opposite: the garment remains static while the interior swells to meet it. In this theory, the garment goes on skin-tight, but no tighter. Tension in the garment is created by pressurized channels which fill the small gap between garment and wearer.

SHRINKABLE MCP

Creating the ability for the suit to shrink around the wearer was investigated during a NIAC Phase I study.[4] The mechanical counterpressure aspect of this endeavor focussed on the use of active materials to assist in the donning/doffing of a mechanical counterpressure suit. In many ways, this research was predicted by Webb in his discussions on future research. In his final report, he suggested that advanced closure mechanisms might be designed to facilitate the donning of the SAS. In deed, from this perspective, the SAS can be seen as a "distributed," "shrinkable" MCP garment, as defined below.

While exploring design strategies for shrinkable MCP, two branches emerged. Initially advanced materials were envisioned to be distributed throughout the suit, making every square centimeter of the suit an active component. Upon further investigation, however, it seemed that a more efficient use of the technologies could be achieved by using advanced technologies locally. Thus, each technology was used in a highly defined region for maximum benefit. By acting in a localized manner, these technologies were able to produce distributed effects. A representative concept illustration can be seen in Figure 7.3.

4. Pitts, B., Brensinger, C., Saleh, J., Carr, C., Schmidt, P., Newman, D., "Astronaut Bio-Suit for Exploration Class Missions," NIAC Phase I Final Report, Cambridge, Massachusetts Institute of Technology, 2001

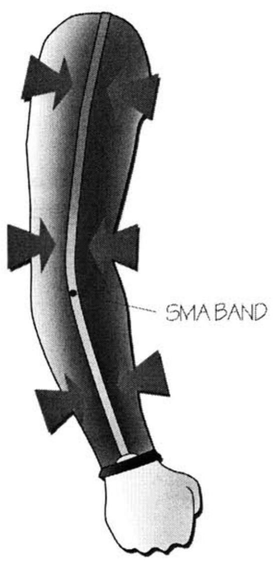


Figure 7.3: A concept for incorporating Shape Memory Alloys (SMAs) into an MCP suit. Illustration by Cam Brensinger from the NIAC Phase I Report.

ENLARGING THE BODY

In order to create MCP against the skin, the garment must somehow reach the necessary tension once donned. This is experienced as the garment becoming tighter. Shrinking the garment, as described above, assumes that the cross sectional area enclosed by the garment remains constant. If this assumption is removed, however, it becomes possible to envision a garment that goes on skin tight, becoming tighter as the body "enlarges" to the point that adequate tension is produced. In operation this is accomplished by inserting inflatable channels between the garment and wearer. As the channels inflate, they produce tension in the garment that is equally spread around the body's cross section (see Fig. 7.4).

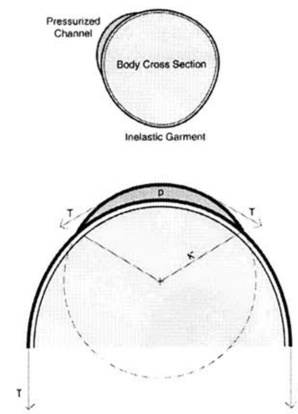


Figure 7.4: An illustration of an MCP garment that uses the "enlarging" body concept.

OPERATIONAL COMPARISONS

In addition to the poetic justifications for the current garment design discussed in the main body of this thesis (see "Meditations on a Spacesuit" on page 53, and "The Tx Suit" on page 93), more typical motivations exist: motivations that are more in line with standard aerospace engineering thought processes.

CURRENT AND PAST DESIGN STRATEGIES

In order to synthesize past and current research it is useful to abstract each endeavor into a series of design decisions. Looking at these efforts in this way allows investigation of the advantages and disadvantages of each choice made during the design process. In this way the repercussions of these choices can be made explicit, facilitating concept generation.

In deciding what suit designs to include in the comparison, certain choices were obvious while others required more imagination. Specific features of specific suits were not as relevant as a comparison of high-level design strategies. For example, there was no distinction made between the current NASA Extravehicular Mobility Unit and the Russian Orlan Spacesuit, as both are contemporary gas filled suits. In addition, certain design strategies were speculated on without having reference to realized designs. This was the case, for example, with the strategy of a liquid-filled spacesuit. Although no such suit exists to my knowledge, the conceptual possibility certainly does and can be explored as such.

Long underwear was considered because it provides an example of a well designed garment that meets many of the usability requirements of advanced spacesuit concepts:

Table 4.1: An analysis of spacesuit design strategies

	Design Choice	Property	Advantage	Disadvantage
Long Underwear			Ignorable Inexpensive Comfortable Light weight Packs small Washable Repairable	
	Material		Responds appropriately without monitoring or control Designed as part of a layered system of clothes.	
	Form		Available in standard sizes.	
Mechanical Counterpressure (MCP)			No loss of oxygen with tear Minimal profile Minimal life support system Improved mobility Improved energy cost Light weight	
	Passive, Elastic MCP (Webb)		No control issues (Simplicity of design)	Cannot change to accommodate changes in body. Don/doff difficulty Creates imbalance between breathing and surface pressure until helmet is donned and pressurized Custom tailoring required
	Active/Actuated MCP		Provides capability of changing the suit locally, real-time.	Requires local monitoring and control Increased power requirement
G-Suits	Minimal pressurized volume		Minimizes torque required to bend joints. Low bulk Less chance of leakage	
	Liquid filled (Libelle)		Works instantly due to basic laws of physics.	
Current Space Suits			Track record Various sizes without custom tailoring	Bulky Pressurization fluid is required for breathing Don/doff difficulty Limited mobility/dexterity Heavy Requires a thermal control system (LCVG)
	Fluid filled suit		Uniform pressure Fluid fills the shape of its container (no need to think about body contours) Pressurization occurs at the same rate on all parts of the body.	Requires fluid barrier Need to consider constant volume design Possibility of leak
	Gas	Compressibility	Provides design flexibility by lessening the isovolumetric requirements	Adds design complexity by coupling temperature, pressure, and volume
		Density	Gravitational gradient does not significantly effect pressure	
		Viscosity		Creates pressure losses if gas flows
		Other	Gas barrier does not have to be a vapor barrier	
	Liquid	Incompressibility	No thermodynamic relationships	Liquid tight barrier restricts the local breathe-ability Inforces isovolumetric requirement.
		Density		Gravitational gradient effects pressure
		Viscosity		Creates pressure losses if liquid flows
		Other	Possible radiation protection	Fluid barrier must also be a vapor barrier.

simplicity of design/operation, comfort, minimal weight, and stowage volume. The results of the comparison can be seen in Table **4.1**.

SELECTED IDEA/CONCEPT

While Table 4.1 displays some trade-offs and implications of various design strategies, it also formulates future (ideal?) spacesuit concepts. By extracting the list of advantages from each strategy and compiling them, the conceptual and physical requirements, or guiding principles, of an advanced spacesuit emerge, crystallizing the vision of a hybrid, MCP-micro-volume spacesuit that is the focus of this thesis. The current concept focuses on leveraging off the benefits of both fluid-filled spacesuits and MCP concepts.

The best design and development strategy is to "decouple and conquer," meaning that requirements and their implications, where possible, should be decoupled through the use of design. For example, as stated in Table 4.1, one clear asset of long underwear is that it is designed to solve only one problem: thermal regulation. By focusing on this issue alone and not worrying about abrasion resistance, wind permeability, etc. the designers have decoupled issues that might have complicated their design. In a similar way, the development process of this thesis focuses on pressure production at the body surface, leaving radiation, thermal, and abrasion resistance issues, among others, to other garments, which can be layered into a full spacesuit system. Once solutions are found to decouple design issues it becomes possible for the designer to recouple whatever features they desire. In the following chapters some initial experiments with the T^X garment are laid out.

8 Body Restraint

As discussed in the previous chapter, mechanical counter-pressure (MCP) enables many transparent qualities in spacesuit design. Having identified this mode of pressure production and various ways of achieving it, this chapter discusses modeling efforts that facilitate insight into the dynamics of a specific MCP concept.

In any state of force equilibrium it is impossible to identify what is applying a force and what is being forced. When pushing against a wall it cannot be said what is doing the "pushing" as without the wall the body would merely continue its natural movement, and without the body the wall would stand unaffected. Thus, pushing is mutual. So it is with the body and a spacesuit.

As discussed earlier in this thesis, past attempts to achieve MCP spacesuits focussed on squeezing the body. From this perspective the body is treated as static, requiring an applied force in order to maintain health. The shrinkable MCP strategy discussed in "Binding the Body" on page 133 operates from this perspective; as the garment moves closer to the body it starts to squeeze as if the body were a static form.

Alternatively, the spacesuit can be seen as restraint, resisting the body's natural bulging do to the inflation of breath (see "Body: Bubble" on page 60). Imagine the body cast solidly in a block of concrete, with the head exposed. Cover the head with a bubble helmet, supply oxygen and you will have succeeded in protecting the body from vacuum. In this scenario the concrete does not shrink so as to squeeze the body, but instead resists any outward bulging of the body. All pressure is supplied from within the body, via the pressurized helmet and lungs.

Although the concrete spacesuit maintains life, it is clearly ineffective on other levels. The question becomes one of reducing the thickness of the inextensible restraint to the point where motion becomes possible. Although a skin tight, inextensible garment might appear the solution, it does not address the issue of joint mobility where skin and suit clearly need to stretch.[a]

a. Additionally, an inextensible, skin-tight garment does not address the realities of material properties. Even the stiffest materials display slight elastic properties. Thus, there must be some mechanism to pre-stress the garment material. As described below, this is accomplished in this thesis via pressurized channels. Active materials or other mechanisms would also be possible solutions.

DEFINING THE BODY SURFACE

In order to create a pressure restraint membrane for the body, it is necessary to understand the body surface. Without destroying it, or misperseiving it, we must grasp the body surface and mimic it. As this surface is constantly shifting, warping, and distorting, it is necessary to first understand which moment of body surface is of interest.

The ascension beyond the atmosphere is usually a slipping out of weight, into weightlessness. As the body has no weight, neither does skin or inflated flesh and blood. In microgravity, the body surface changes as fluid is redistributed much like a drop of water progressing from the moment of stretched attachment to the moment of spherical free-fall. Thus, like all surfaces, the body surface is described by the interaction between body and environment: it is multidimensional. Fixing and defining it removes the dimension of time, thereby destroying the surface's very definition.[b]

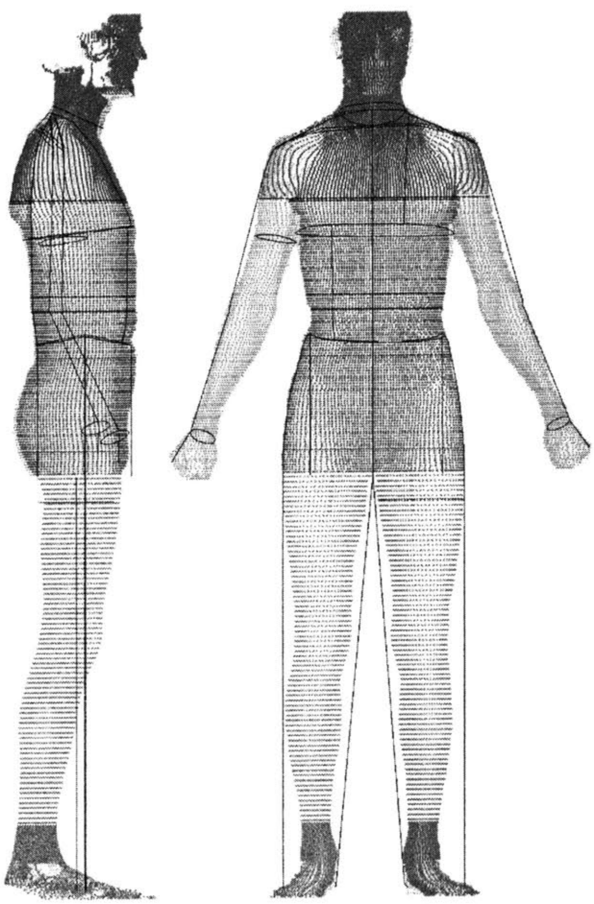
b. In order to mimic the body surface in all its dimensions we must resist interacting with it. As Heisenburg's Uncertainty Principle dictates, it is impossible to observe without distorting the reality of observation. The surface of the body exists in a state of probability.

As mentioned in "Body-Surface: Flux" on page 63, sight provides one opportunity to sense without disturbing the body surface. Technologies that allow for the capture of reflected light, such as laser scanning, provide one opportunity for body surface definition. It is not enough, however, to

Measurements

Chest1 = 36.18
NewOverarm = 44.57
Stomach1 = 31.33
PantWaist = 29.79
CoatWaist = 30.44
AcrossBack = 13.95
ShoulderHeightLeft = 60.17
ShoulderHeightRight = 59.87
ShoulderSlopeLeft = 2.28
ShoulderSlopeRight = 2.60
Biceps = 11.15
InclineDistance = 7.83
InclineHoriz = 3.39
InclineVert = 7.00
NeckHeightBack = 62.43
ScanBackNeckLength = 7.86
ScanSideNecktoBust = 9.86
ScanBustHeight = 53.38
ShoulderToShoulder = 17.32
Seat = 36.88
ScanCoatSleeveLeft = 31.22
ScanCoatSleeveRight = 31.42
Scancollar = 15.20
ScanShirtSleeveLeft = 35.44
ScanShirtSleeveRight = 35.48
ScanNecktoWaist = 18.65
ScanLeftWrist = 6.64
ScanRightWrist = 7.06
ScanWaistHeightFront = 44.00
ScanWaistHeightBack = 44.08
ScanWaistHeightLeft = 44.67
ScanWaistHeightRight = 44.83
scanSeatFront = 18.27
ScanSeatBack = 18.61
ScanAbdomen = 31.71
ScanThigh = 19.89
scanOutseamLeft = 43.91
ScanOutseamRight = 44.12
ScanInseamLeft = 32.88
ScanInseamRight = 32.82
scanRiseLeft = 11.22
ScanRiseRight = 11.42
ScanVRiseBack = 10.39
ScanVRiseFront = 10.31
ScanVRiseLeft = 10.98
ScanVRiseRight = 11.14
ScanBusttoWaist = 9.34

Brooks Brothers
digital_tailoring



3rd Floor
346 Madison Ave
New York City
New York 10017
Tel: (212) 885-6814

Measurements

capture the reflected light onto the flat, two dimensional surface of film. The light must be captured in three dimensions in order to truly produce a body surface snapshot, as seen in Figure 8.1.

To be clear, the snapshot is not the surface, it is the surface with time removed. In this way the static, scanned surface is a barrier to all time dependencies. Constructing a body membrane as a static surface imprisons the body in that surface. The body, becomes an object, no longer capable of exploring and interacting with external reality. Although not necessarily isolated by the thickness of the membrane, the body is isolated without motion: without time.

The surface must be dynamically explored in order to facilitate the creation of a transparent membrane. As the pressure suit is a type of skin prosthesis, it must mesh with the body and follow its dynamics.

Figure 8.1: (Opposite Page) A full body scan of the author obtained in 2002 at Brooks Brothers in New York City. The scanner operates with white light and the entire scanning process takes roughly twelve seconds. Body dimensions are automatically pulled from the scan via computer algorithms. The scans are used to create affordable, custom tailored garments.

LINES OF NONEXTENSION

To understand the dynamic body surface we must visually observe identified positions as they shift with time. A mapping capable of capturing the inherent dynamics of the body surface is required. As developed by Iberall, the mapping of the body's Lines of Nonextention (LONE) facilitate the mapping of the multidimensional body surface.[1, b] Topical marks, in the form of circles, are drawn on the body surface and their dynamics are observed as the body moves. As ink cannot support tension or compression, it does not impede the body's natural motion, allowing for minimal distortion of the reality being observed.

b. For a more technical discussion of the lines of nonextension and their justification, see "Spacesuit Physics" on page 283

1. Iberall, A.S., "The Use of Lines of Nonextension to Improve Mobility in Full-Pressure Suits," AMRL-TR-64-118, Rand Development Corporation report to Behavioral Sciences Laboratory, Wright-Patterson AFB, Ohio, November 1964.

The lines can best be understood by describing the process used to reveal them. If a circle is drawn on the skin and the body is allowed to move freely, the circle will distort as the skin stretches. Observing these distortions, it becomes clear that, in general, the circles deform to become ellipses, typically with a minor axis smaller than the original circle diameter. This being the case, the original circle can be inscribed on top of ellipse and will, in general, intersect the ellipse at four points. Connecting these four points to make an "x," it is clear that the lines of the "x" never change length as the circle distorts to become an ellipse: they describe the circle diameter both before and after distortion. In the process of distortion they have merely rotated about their intersection as if they were pinned (see Fig. 8.2).

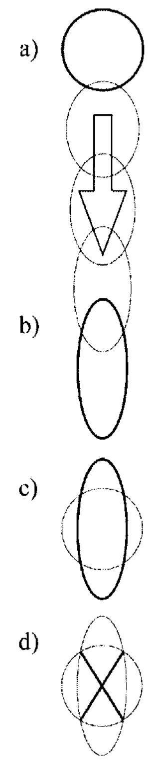


Figure 8.2: The derivation of the Lines of Nonextension. A circle, a), is drawn on the skin. As the body moves, the circle becomes and ellipse, b). If the original circle is superimposed on the ellipse as in c), the two meet at four points. Connecting these points as in d) reveals the lines of nonextension. Although the circle has deformed with body motion, the lines have not changed length, they have merely rotated about their intersection.

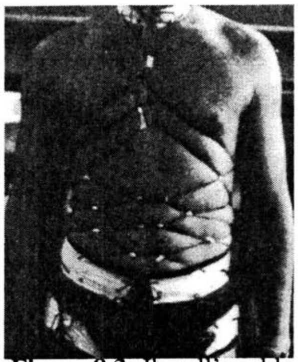


Figure 8.3: Iberall's cable garments used to verify the lines of nonextension.

By carrying out this process over the entire surface of the body, Iberall mapped the local lines of nonextension. In order to map the lines as they continually flow over the body surface, he then constructed mesh garments using thin cables (see Fig. 8.3). These cables ran over the body in such a way as to follow the local lines of nonextension. Once created, subjects wore these garments and tested their mobility in order to verify that no range was lost. In this way Iberall managed to map the lines over most of the body surface(see Fig. 8.4).

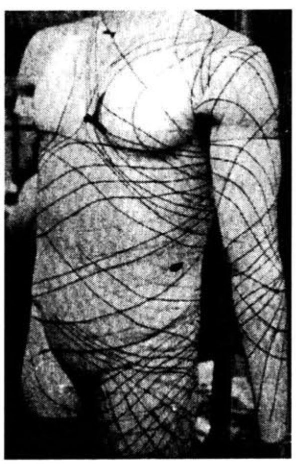


Figure 8.4: Iberall's mannequin displaying the lines of nonextension.

Using these lines as a template, an inextensible mesh garment can be created that allows full mobility and is capable of restraining the bodies internal inflation. It is important to note that there are a few regions that have no lines of nonextension, such as the knee cap and elbow. In these areas it seems that elastic or active materials are the only option. Clapp was correct in noting that if elastic materials are used, it would be highly advantageous to use materials with a flat region in their stress-strain curve.[2., c] This would facilitate even tension, and therefore MCP, over the entire range of motion.

2. Clapp, W., "Design and Testing of an Advanced Spacesuit Glove," Massachusetts Institute of Technology, Cambridge, MA, 1983.

c. A flat region describes an operation zone within which the material stress, or tension, is constant for a range of strains.

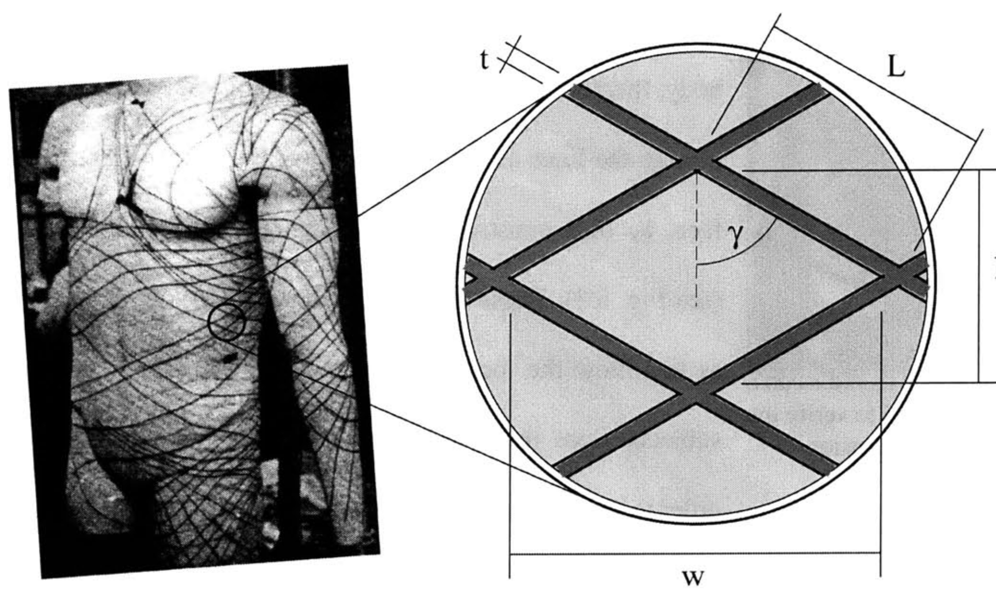


Figure 8.5: Geometric parameter definition of a line of nonextension mesh. L and t represent the mesh length and strand thickness respectively, while h and w represent the diamond height and width, respectively. The distortion ratio is defined as h/w while the mesh ratio is defined as L/t.

Iberall's suit had to combine the nonextension layer with other layers to prevent the limbs from lengthening due to internal pressurization. In his report he states, however, that the lines of nonextension would act much like a finger trap if placed directly on the skin. In this scenario the friction between the garment and skin would keep the garment in a stable location. This is how a line of nonextension garment is envisioned for the T^X pressure suit.

LONE MATERIAL DEFINITION

In order to create a mesh garment from the lines of nonextension, the required mesh density and material properties must be determined. Although the process described above describes the way the lines are revealed, it does not inform

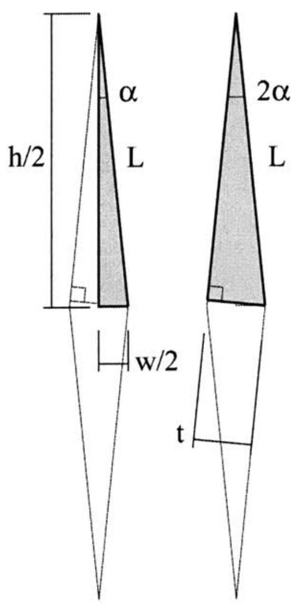


Figure 8.6: Geometric relations used to determine the relationship between the distortion ratio, h/w, and the mesh ratio, L/t.

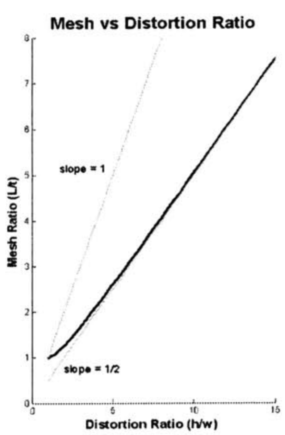


Figure 8.7: The Relationship between the mesh and distortion ratio. Lines of slope one and one half are presented for reference. Contrary to Iberall's report, the mesh ratio is equal to half the distortion ratio.

the designer as to how dense the lines must be: how big each diamond can be. This definition is determined by geometric and physiological considerations as described below.

During normal body motion, the ratio of diamond height to width, h/w, the distortion ratio, is no greater than 10:1 (see Fig. 8.5). As shown below, it is this ratio that sets the allowable ratio of diamond strand length to strand thickness: the mesh density ratio.

Consider Figure 8.6 displaying a typical, fully distorted diamond with width, w, height, h, strand length, L, and strand thickness, t. Examining the geometry, it becomes clear that:

$$\alpha = \operatorname{atan}\left(\frac{w}{h}\right)$$

$$t \le L\sin(2\alpha)$$ [d]

Rearranging and substituting these equations yield:

$$\frac{L}{t} \ge \frac{1}{\sin\left(2\operatorname{atan}\left(\frac{w}{h}\right)\right)} \qquad (4.1)$$

Figure 8.7 displays a graph of the mesh ratio as a function of the distortion ratio. Inspecting this graph reveals that for diamond distortion ratios, h/t, of 6 or greater,

$$\frac{L}{t} \ge \frac{1}{2} \cdot \frac{h}{w} \qquad (4.2)$$

Thus, contrary to Iberall's report,[e] the mesh ratio, L/t, must

d. The inequality exists because a smaller strand thickness, t, will allow a greater distortion ratio, thus meeting our requirement for the LONE distortion ratio.

e. In his 1958 report, Iberall stated that

L/t = h/w

but did not include his derivation. Iberall's result is obtained if the dimension, t above, is made 2t. Although it is easy to make this mistake, the correct dimension is t due to the fact if the diamond represented in Fig.ure 8.6 is stretched to its maximum ratio, only a thickness of t remains. All of this assumes perfectly pinned joints.

be greater than or equal to *half* the maximum ratio of diamond distortion, h/w. According to Iberall's investigations, this ratio is 10:1, setting the requirement that the strand thickness must be five times smaller than the diamond length.

$$t = \frac{1}{5} \cdot L$$

In order to fully characterize the mesh material, we must determine values for L and t. To do this we can utilize numbers supplied by Webb:[f] the maximum area of skin that can be exposed to vacuum is 1 mm^2. Thus, in order to assure this is achieved for all diamond distortions,

f. There has been much research on the mechanical properties of skin since Webb's reports. Webb's numbers are used here due to the fact that they have been tested in a spacesuit application and therefore seem most reliable.

$$L \leq \sqrt{1^2} = 1.0mm$$

This also sets the strand thickness to be,

$$t \leq \frac{L}{5} \leq 0.2mm$$

Currently it is unclear whether this thickness is large enough to meet physiological requirements on spacesuit performance using currently available materials. The model must be adapted to take into account non-isotropic materials before this can be determined.

FACILITATING FLUX

The human skin has many characteristics of an ideal pressure suit, such as "a high tensile strength, almost no gas permeability, and very good water retention characteristics."[7] In addition the skin allows unrestricted mobility while protecting us from vacuum conditions for up to three minutes.[8] Beyond that time period, the skin requires a body surface pressure equal to that of the breathing gas to maintain normal functionality. (See "Pulmonary Physiology" on page 121) Given the performance characteristics of our biologically grown skin, it seems reasonable to envision a second skin, or prosthetic skin, capable of augmenting our biological skin to the point where it can withstand the absence of a pressurized environment indefinitely.[i]

In order to protect the body from the vacuum of space while maximizing the flux between explorer and explored, regions of the body surface must be exposed to the environment. As reported by Webb, this is possible through mechanical counterpressure. MCP allows the simultaneous realization of protection and exposure through the use of a porous material, covering the body in a fine grid-like array. Potentially this could leave the majority of the body surface exposed. In this way, MCP creates the absence of a spacesuit more than a material spacesuit.

7. Clapp, W., "Design and Testing of an Advanced Spacesuit Glove," Massachusetts Institute of Technology, Cambridge, MA, 1983.

8. Webb, P. and Annis, J.F. "Principle of the Space Activity Suit," NASA CR-973. National Aeronautics & Space Administration, Washington, D.C., 1967.

i. For a discussion of the skin see "Skin: Membrane" on page 58.

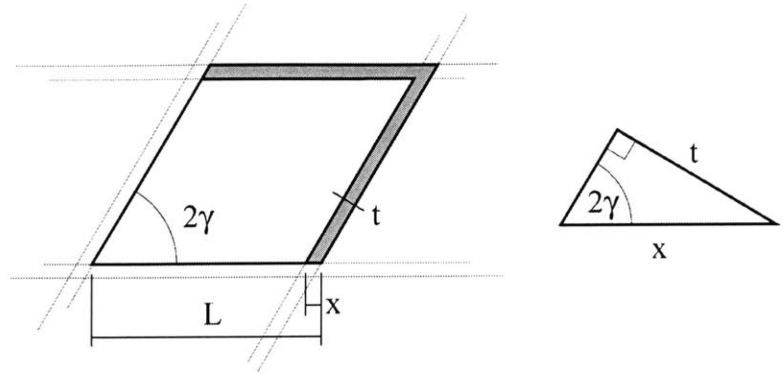


Figure 8.8: Geometric relations of fabric mesh used to calculate exposed area, where L is the diamond length, and t is the strand thickness.

The 45% Spacesuit:

In order to explore exactly how much surface area could be exposed via the T^x suit, anthropometric data, geometric relations, and reported numbers were used. As described in "Lines of Nonextension" on page 145, the lines of nonextension facilitate unrestricted mobility while providing a garment map for an inextensible restrain layer. During normal body motion, Iberall reported that the ratio of diamond height to width, the distortion ratio, was no greater than 10:1. As shown on page 149, a distortion ratio of 10:1 sets the mesh ratio, m = L/t, to 5:1. It is this ratio that determines the percentage of exposed body surface area.

Consider the Figure 8.8. The total area of each unit diamond is:

$$A_{Total} = L^2 \sin 2\gamma \tag{9.1}$$

The area exposed between the strands of the diamond is:

$$A_{Exposed} = (L-x)^2 \sin 2\gamma \tag{9.2}$$

Where x is,

$$x = \frac{t}{\sin 2\gamma} \tag{9.3}$$

Substituting the mesh ratio, m = L/t, into the above equation and solving for the ratio of exposed to total area yields:

$$x = \frac{L}{m \sin 2\gamma}$$

$$(L-x) = \frac{mL\sin 2\gamma - L}{m \sin 2\gamma}$$

$$\frac{A_{Exposed}}{A_{Total}} = \frac{\left(\frac{mL\sin 2\gamma - L}{m\sin 2\gamma}\right)^2}{L^2} = \left(\frac{m\sin 2\gamma - 1}{m \sin 2\gamma}\right)^2 \tag{9.4}$$

Thus, the exposure ratio is only a function of γ and m, the mesh ratio. Iberall states the maximum diamond ratio to be,

$$d = h/w = 10$$

which, as shown on page 149, translates into

$$m = L/t = 5$$

He also states that, on average, the lines of nonextension are aligned 25 degrees off of vertical. Substituting these values for m and γ, we find that a material based on the lines of non extension exposes 55% of the surface area. Another way to think of this result is to say that the area density of the garment material is only 0.45.

Ideally this would mean that the spacesuit would expose 55% of the body surface to the environment,[j] but realistically, items such as a bubble helmet and chest bladder[k] (see Fig. 8.9) would cover additional surface area. To account for these factors, anthropometric data was used to approximate the percentage of total body area taken up by the head and chest (see Chapter Appendix H:, "Exposed Surface Area of the Tx Suit," on page 333,). Once these areas are accounted for, the percentage of body area exposed drops to 44.5%. Additionally, in the proposed concept, pressurized channels cover the body. Assuming these channels are 10.3 cm (4 inches) wide and run the length of the limbs, the figure drops to 33%. If gas pressurized boots are used and the area covered by the fluid filled channels are accounted for, this figure drops further to 29%.One way to increase the exposed surface area would be to increase the mesh ratio, m. As discussed below, L is set by physiological considerations, but the strand thickness, t, is not. Thus, if the strand material is strong enough, the strand thickness can be reduced, thereby increasing m and the percentage of exposed area (see Fig. 8.10).

Figure 8.9: The chest bladder used for Webb's Space Activity Suit.

j. Some would be concerned about exposing too much area. Of course there are hazards that need to be considered when exposing an astronaut to her/his environment. If however you consider the line of non-extension suit as one layer of the T^x suit, it is clear that other, protective layers can be added if necessary. There exists many technologies to protect people from hazardous substances. In addition, through the concept of flux and exposure, the T^x suit can be considered a wearable filter. Technologies such as electrospinlacing are able to produce filters capable of creating selective exposure.

k. A chest bladder is an inflated volume connected to the helmet that covers the chest area. This volume allows the chest to expand with respiration. Without this bladder the chest must fight against the tension in the mechanical counterpressure restraint. To read more about the requirement for such a bladder see Annis, J.F., and Webb, P., "Development of a Space Activity Suit," NASA Contractor Report CR-1892, Webb Associates, Yellow Springs, Ohio, 1971

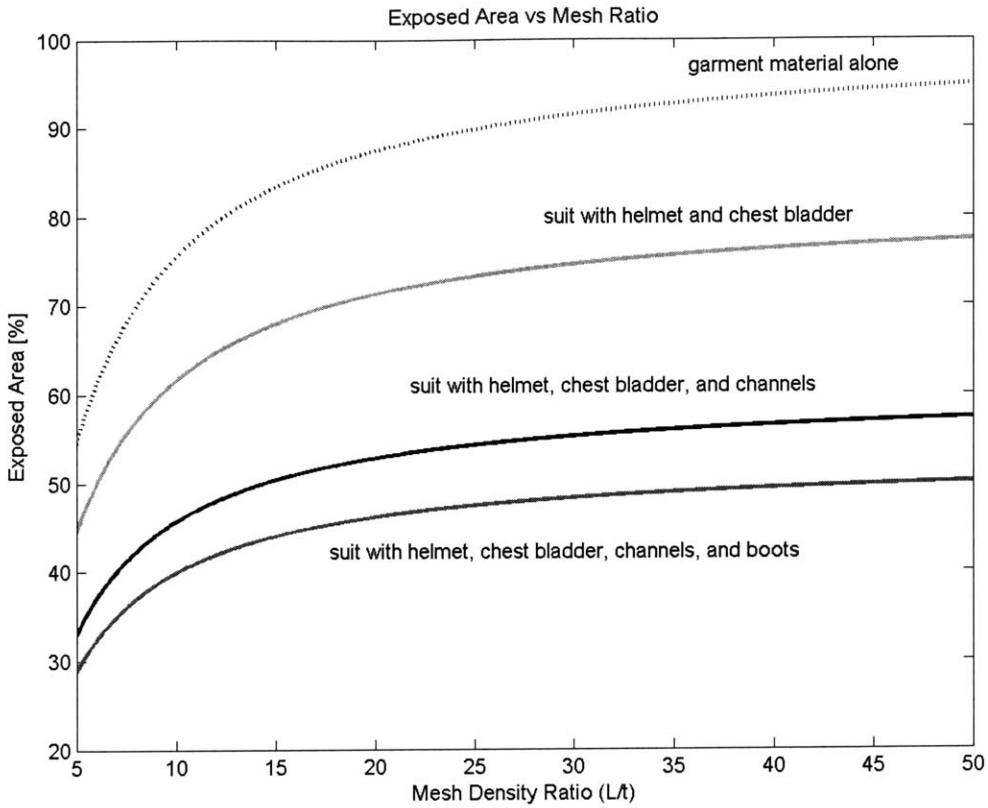


Figure 8.10: Graphs of exposed area as a function of the mesh density ratio, L/t. The top line represents the exposed area of the mesh restraint material. The other lines consider a full suit with components such as a bubble helmet, chest bladder, and boots.

OPERATIONAL ADVANTAGES OF BODY FLUX

Natural body cooling is one example of the flux enabled by MCP.[1] Just as we are accustomed to here on earth, in mechanical counterpressure suits sweating is allowed to cool the body by evaporating to the environment. "Without the need for a convective gas cooling system or liquid cooling garment, the life support system becomes essentially a tank of oxygen with pressure regulators. In addition to being less

1. In gas pressurized suits, the materials must be impermeable to air in order to maintain the pressure required. This causes thermal issues due to the fact that our normal mode of thermal control, evaporation of sweat, cannot be implemented. This motivated the need for thermal garments such as the Liquid Cooling and Ventilation Garment (LCVG) which complicates the life support system.

bulky and heavy, [MCP suits] would be much less costly to produce than current garments."[13]

13. Annis, J.F., and Webb, P., "Development of a Space Activity Suit," NASA Contractor Report CR-1892, Webb Associates, Yellow Springs, Ohio, 1971

Safety is also improved via flux and MCP suit design. Especially on planetary surfaces where explorers will be exposed to highly abrasive environments and activities, tears become an issue of increasing concern. In a gas pressurized suit, a small tear not only means the possibility of loosing pressure but also oxygen. In an MCP suit a small hole would leave the wearer unharmed. There would be no loss of breathable oxygen, and the skin would not suffer any damage. Should the hole be larger than 1.0 mm^2, the wearer would still have plenty of time to return to a pressurized environment due to the fact that the effects of the reduced pressure would be highly localized.

MODELING THE GARMENT ARCHITECTURE

In order to characterize the required material properties for the T^x spacesuit, a mathematical model of the garment's physical dynamics was created. The goal of this effort was to determine the modulus and thickness of material required to evenly distribute the channel pressure around the cross section without excessive bulging, as determined by physiological requirements.

In order to simplify the model, the body was assumed to be made of rigid, cylindrical elements. Although this is clearly far from reality, this assumption was made to over, rather than under, estimate the required material properties. It was thought that in order to meet the required performance metrics on a ridged cylinder material requirements would be more stringent than on the body. If true, this would guarantee success on the body. Additionally, the garment material was assumed to be an isotropic, elastic film even though fabrics display large degrees of anisotropy and hysteresis.[14]

14. Schmidt, P., "An Investigation of Space Suit Mobility with Applications to EVA Operations," Doctoral Thesis, Massachusetts Institute of Technology, Cambridge, MA, 2001.

The ratio between the channel pressure and the induced mechanical counterpressure can never be identical on the surface of a ridged cylinder. This gave rise to a "pressure distribution efficiency" term that is the ratio of these two pressures. Physiology determines the maximum allowable pressure differences on the body surface (see "Cardiovascular Physiology" on page 124) and therefore sets a lower limit on pressure distribution efficiency. This, in turn, sets an upper limit on bulging, which can be defined as the change in garment diameter with pressurization.

As discussed in Chapter 7, "Mechanical Counterpressure Techniques," on page 131,, the basic garment architecture can be reduced to that in Figure 8.11. Notice that as the fabric wraps from cross section to channel, it describes the tangent between the two cross sections. In the case of a rigid, circular cross section, this means that a gap is formed, creating a region of zero pressure production. The effect of this gap on test results and physiology are discussed in Chapter 9, "Construction and Testing," on page 171, and Chapter 6, "Physiological Considerations for Pressure Suit Design," on page 121, respectively.

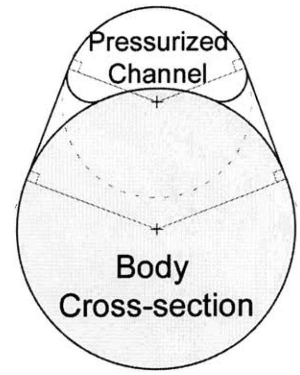


Figure 8.11: The generalized hybrid-MCP garment architecture.

To understand the dynamics of the architecture more clearly, it is useful to picture how the garment architecture reacts to increasing channel pressure. Figure 8.12 displays how the response is dependent on both pressure and channel width, w.

Although the derivation is not discussed here, it was assumed that the exterior surface of the bulging channel always forms a circular cross section. This geometry describes the maximum volume to surface area ratio and therefore the minimum energy state.

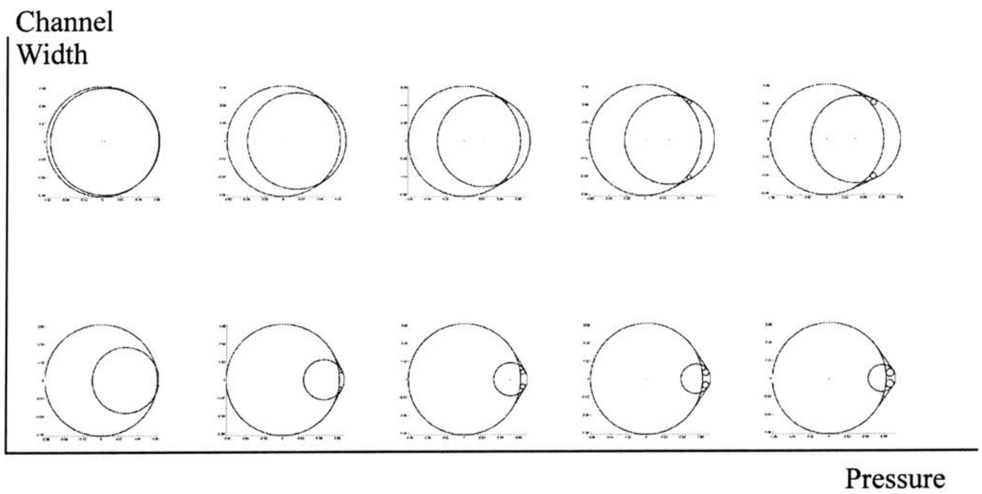


Figure 8.12: A qualitative graph displaying the garment's response to increasing channel pressure, p, as a function of initial channel width, w. As pressure

In general, the known quantities are the radius of the cross section, R, the garment's modulus, E_g, the channel's modulus, E_c, the thickness of the garment material, t_g, the thickness of the channel material, t_c, and the channel pressure, p. Other parameters, such as the radius of the channel under pressurization, r, must be determined through the general theory of elasticity. As this architecture describes an indeterminate structure, equilibrium, compatibility, and constitutive relations must be invoked in order to solve for the garment's deformation under pressure. Figure 8.14 displays a detail of the deformed state and the geometrical representation used to develop the mathematical model.

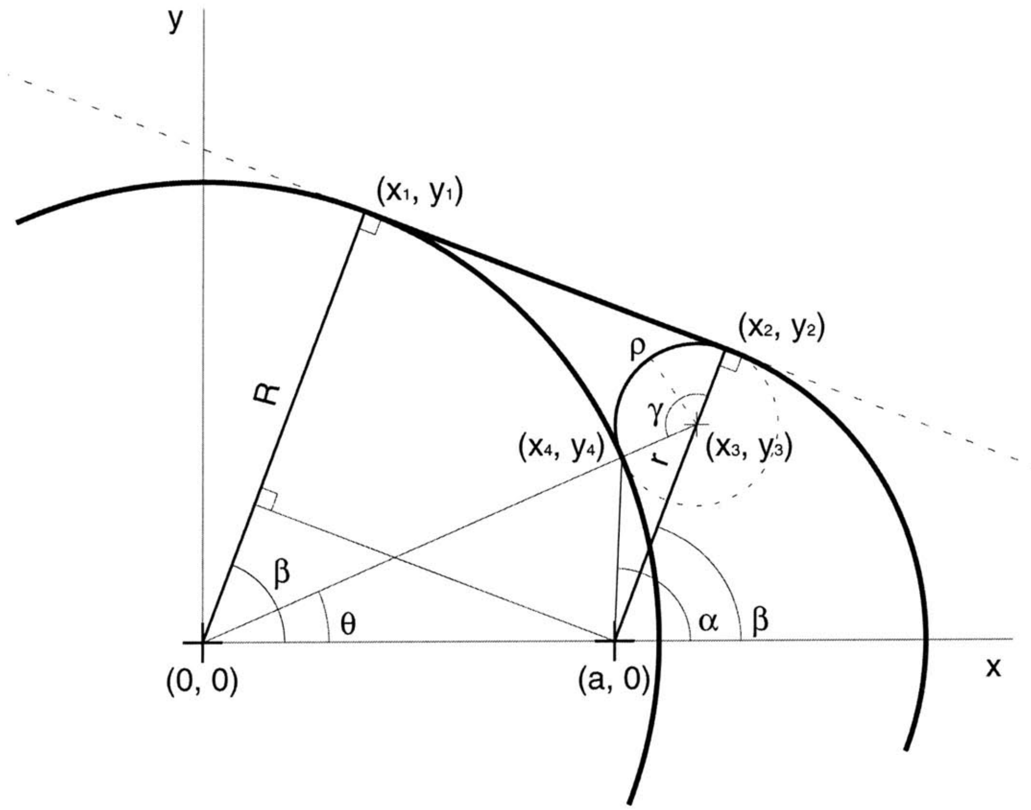
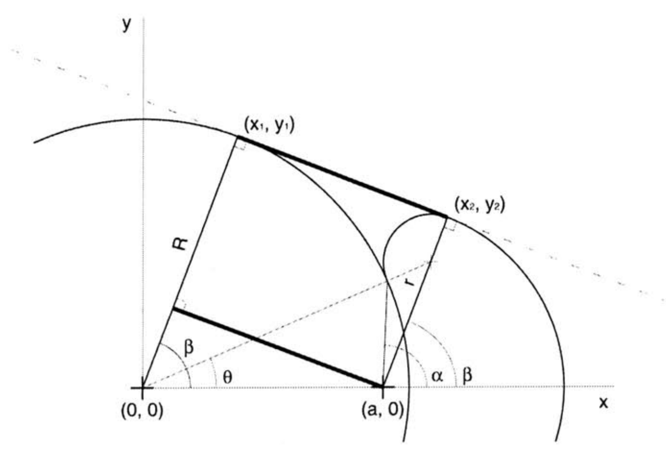


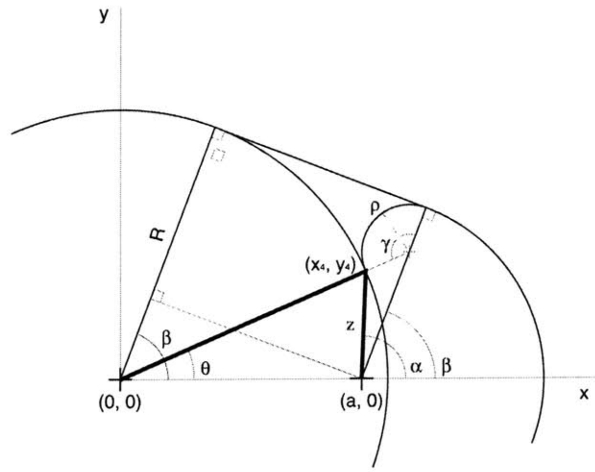
Figure 8.14: Geometric relations used to derive the Hybrid-MCP model. The three cross-sectional radii are R, r, and ρ, representing the body cross-section, the channel's constrained radius of curvature and the channel's free radius of curvature, respectively. The circles R and r are separated by a distance, a.

The relations needed to solve the indeterminate system are found by analyzing the geometry of the system. Constructing the line through point (a, 0) that runs parallel to the common tangent, it is clear that:



$$\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} = a\sin\beta \tag{14.1}$$

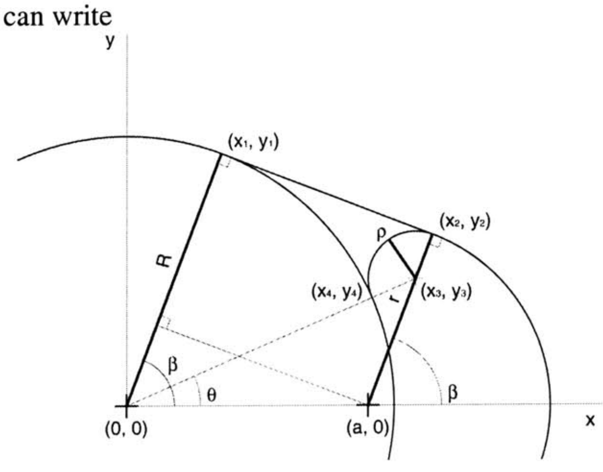
Considering the triangle formed by the center of each circle and the point where the channel and cylinder intersect, we can write:



$$R\sin\theta = (r - \rho)\sin\beta - \rho\sin\theta \tag{14.2}$$

$$a = R\cos\theta - (r - \rho)\cos\beta - \rho\cos\theta \tag{14.3}$$

Evaluating ρ and the (x, y) locations of the important points, we can write



$$\rho = \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2} = \sqrt{(x_4 - x_3)^2 + (y_4 - y_3)^2} \tag{14.4}$$

$$x_1 = R\cos\beta \tag{14.5}$$

$$y_1 = R\sin\beta \tag{14.6}$$

$$x_2 = r\cos\beta + a \tag{14.7}$$

$$y_2 = r\sin\beta \tag{14.8}$$

$$x_3 = (r-\rho)\cos\beta + a \tag{14.9}$$

$$y_3 = (r-\rho)\sin\beta \tag{14.10}$$

$$x_4 = R\cos\theta \tag{14.11}$$

$$y_4 = R\sin\theta \tag{14.12}$$

After simplifying and substituting these equations into 14.1, 14.3, and 14.4 we see:

$$a\sin\beta = \sqrt{[(r-R)\cos\beta + a]^2 + [(r-R)\sin\beta]^2} \tag{14.13}$$

$$\rho^2 = [R\cos\theta - (r-\rho)\cos\beta - a]^2 + [R\sin\theta - (r-\rho)\sin\beta]^2 \tag{14.14}$$

By inspecting the geometry of the pressurized channel we can realize that the channel width, w, equals:

$$w = R\theta + \rho\gamma + r\beta \tag{14.15}$$

Where γ equals:

$$\gamma = \theta + \pi - \beta \tag{14.16}$$

Yielding:

$$w = R\theta + \rho(\theta + \pi - \beta) + r\beta \tag{14.17}$$

The final equation comes from the stress strain relations. As shown in "Mechanical Counterpressure Fundamentals" on page 132,

$$T = pr = \sigma t$$

where T = the tension in the material, p = the pressure in the channel, σ = the stress in the material, and t = the thickness of the material. Combining this with Linear Elastic Theory we obtain an equation for the strain, ε.

$$\varepsilon = \frac{pr}{tE}$$

The final perimeter length of the stretched garment, L_f, can be written as

$$L_f = 2R(\pi - \beta) + 2r\beta + 2a\sin\beta$$

Noting that the initial perimeter of the garment, L_i, is just the perimeter length of the cross section and invoking the definition of strain we obtain the final equation.

$$\varepsilon = \frac{L_f - L_i}{L_i}$$

$$\frac{pr}{t_g E_g} = \frac{(r - R)\beta + a\sin\beta}{\pi R} \tag{14.18}$$

Similarly for the channel materials, where w_i equals the initial channel width,

$$\frac{p\rho}{t_c E_c} = \frac{w - w_i}{w_i} \tag{14.19}$$

Because the channel material is unsupported only around the ρ radius, this is the determining factor for the tension in the above equation.

At this point there are seven independent equations and seven unknowns. Table 8.1, below, lists the known and unknown parameters as well as the seven independent equations.

Table 8.1: Garment modeling parameters and equations.

Known Parameters	Unknown Parameters	Independent Equations
R (cross section radius of curvature)	r	$R\sin\theta = r\sin\beta - \rho\sin\beta - \rho\sin\theta$
E_g (garment modulus)	a	$a\sin\beta = \sqrt{[(r-R)\cos\beta + a]^2 + [(r-R)\sin\beta]^2}$
t_g (garment thickness)	ρ	$a = R\cos\theta - [(R\cos\theta - a)^2 + (R\sin\theta)^2]\cos\alpha$
E_c (channel modulus)	β	$\rho^2 = [R\cos\theta - (r-\rho)\cos\beta - a]^2 + [R\sin\theta - (r-\rho)\sin\beta]^2$
t_c (channel thickness)	θ	$w = R\theta + \rho(\theta + \pi - \beta) + r\beta$
w_i (initial channel width)	α	$\frac{pr}{t_g E_g} = \frac{(r-R)\beta + a\sin\beta}{\pi R}$
p (channel pressure)	w	$\frac{p\rho}{t_c E_c} = \frac{w - w_i}{w_i}$

In addition to the parameters listed above, the pressure distribution efficiency, η, can be derived as follows. As discussed in the beginning of this section, this term describes the ratio of MCP to channel pressure. Thus it can be written as:

$$\eta = \frac{T/R}{p}$$

Where T = the tension in the garment material, and p = the channel pressure. This can be reduced by noticing that T is dependent on p and r.

$$T = pr$$

$$\eta = \frac{(pr)/R}{p} = \frac{r}{R} \qquad (14.20)$$

As can be seen from this equation and generalized garment architecture, this term also relates to the amount of bulging that occurs due to pressurization. If bulging is reduced, r approaches R, and η tends towards unity. This means that the pressure is more even around the entire cross section, improving circulation as described in "Cardiovascular Physiology" on page 124.

In order to solve these equations MATLAB was used. The basic code can be found in Appendix Appendix I:: "MATLAB Codes" on page 335, but the model visualizations are presented below.

MODEL VISUALIZATION

In order to get a sense of the garment design space, three parameters were of particular interest: the pressure distribution efficiency, η, as a function of the material stiffness, Et, and the fraction of the cross section covered by the channel, $w_i/(2\pi R)$. Figure 8.15 displays the three-dimensional graph

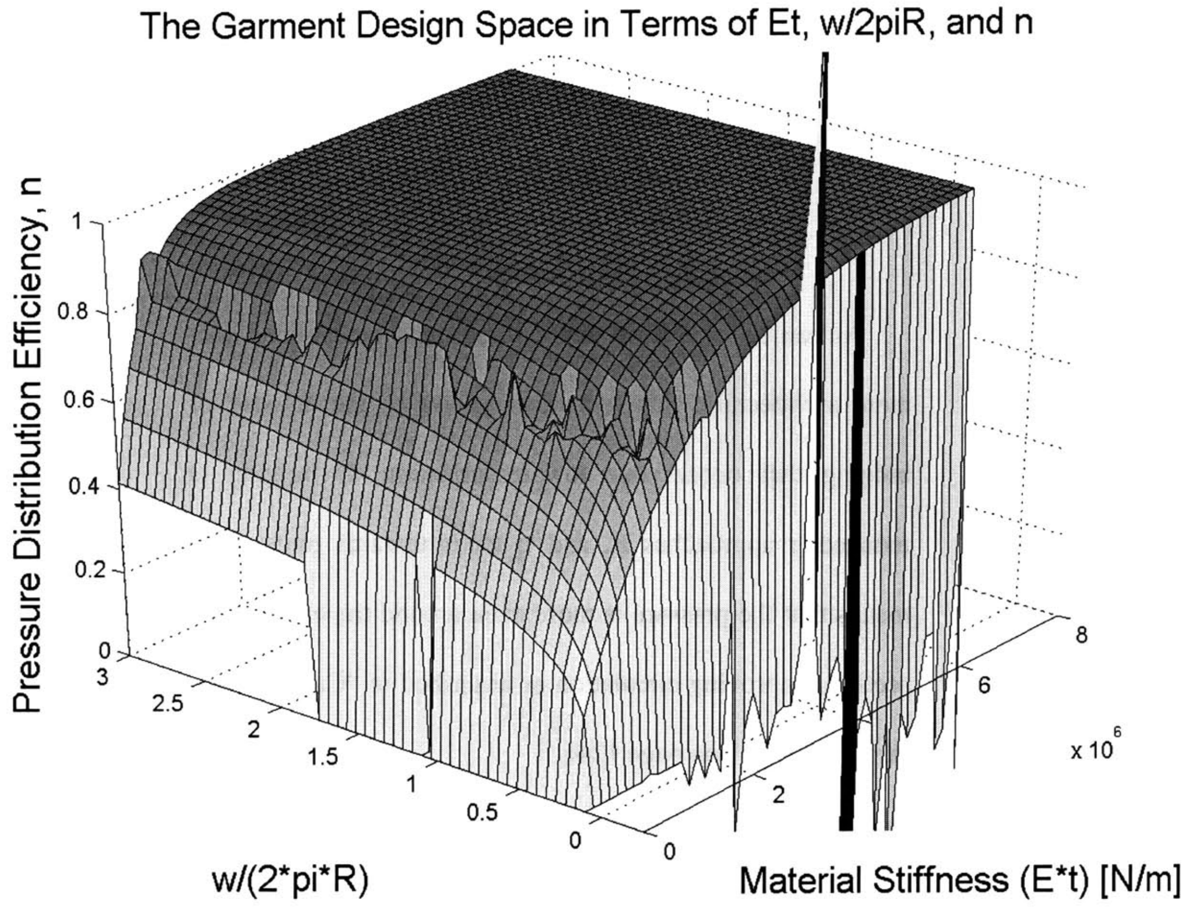


Figure 8.15: The pressure garment design space for the Tx suit. As would be expected, the efficiency increases with material stiffness and channel coverage, $w_i/(2\pi R)$. The surface is generated for R = 6.19 cm.

of these parameters. As would be expected, the efficiency increases with material stiffness and channel coverage.

The discontinuities in the three dimensional graph, occur at a constant value for the efficiency and are as of yet unexplained. Due to the accuracy of the model in its predictions of a teflon garment's performance, it is felt that these discontinuities arise due to the MATLAB solving scheme rather than modeling errors. This must be investigated further.

The surface presented in Figure 8.15 displays asymptotic behavior near an efficiency of one. Considering the geometry it is clear that the efficiency around a rigid cylinder can never exceed one as long as the channel width perimeter, 2w, is less than the cylinder's circumference. In order for the efficiency to be greater than one, the radius of curvature of the channel, r, would have to be greater than the cylinder radius, R. Another way of saying this is to say that the channel would have to be "flatter" than the cylinder. This can only happen if the channel's perimeter is greater than or equal to the cylinder's circumference.

The above modeling only applies for isotropic, homogeneous materials. Using a mesh patterned off the lines of non-extention changes the material properties and therefore the model. Altering the model for anisotropic materials on a non-uniform, non-rigid cross-section has been left for future research.

DESIGN AND PLACEMENT OF CHANNELS

Although placing channels on a rigid cylinder is an easy task, care should be taken when deciding the channel placement on the body. The variables that determine proper channel placement include the cross section geometry, the location of bones or other rigidizing elements, and joint dynamics. Proper channel placement ensures even pressure distribution around the body, through all motion.

As discussed in "Modeling the Garment Architecture" on page 156, in the case of a rigid circular cross section, the pressure distribution efficiency will never exceed unity. This is not the case for irregular cross sections. If, for instance, the channel covers a region with a very high radius of curvature compared to other locations around the section, the minor radius, r, might be larger than the local radius of curvature, κ. this would tend to create a pressure distribution efficiency greater than one (see Fig.. 8.16).

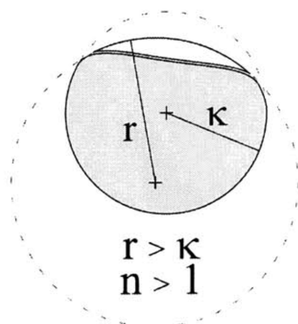


Figure 8.16: An illustration of how the pressure distribution efficiency can be greater than one for an irregular cross section.

Although this might pose a danger of reduced circulation, in certain areas, such as the joint, this might be an advantage to be capitalized on. As discussed in "Bending Pressurized Cylinders" on page 290, a lower pressure in a pressurized cylinder lowers the torque required to bend it. Thus, if channels could be placed such that the efficiency is always greater than one, a lower channel operating pressure could be tolerated, thereby reducing the imposed joint torques.

Both garment design and anatomy determine channel placement and design. The effects of anatomy and channel placement on the resultant mechanical counterpressure is discussed more in Chapter 9, "Construction and Testing," on page 171,.

SUMMARY

The models developed in this chapter characterize the design space for a MCP garment that utilizes inextensible materials and pressurized channels. Key parameters include the radius of the cross section, the width of the channel and the material properties of the garment material. As will be discussed in Chapter 9, "Construction and Testing," on page 171, the model was successfully validated by testing a Teflon garment on a PVC pipe. In addition body test were performed to test the models capability of predicting MCP on the human form.

9 CONSTRUCTION AND TESTING

Although the modeling effort described in Chapter 7, "Body Restraint" on page 141, elucidated subtleties of the Tx garment's physical dynamics, it was necessary to physically construct and test prototypes in order to get a full understanding of the concept and how it might work operationally. The model idealized the human body and garment by assuming rigid, cylindrical, body elements surrounded by a uniform, elastic restraint material. This facilitated the development of relationships between channel pressure and mechanical counterpressure. Also, the model provided insight into how sensitive these relationships are to the material properties of the garment and channel width.

This chapter describes the process of designing, constructing, and testing the performance of T^X prototypes for both cylindrical elements and a human test subject. Although tailoring garments for a ridged cylinder proved relatively easy, the challenges of creating an inextensible, skin-tight, garment for the body quickly became apparent.

Past MCP efforts including Webb's and Clapp's used elastic materials that squeezed the body. Since these garments would conform themselves to the body once donned, they could be constructed as tubes of varying circumference. The experience of trying to create an inextensible garment, however, was more similar to creating an exoskeleton than a leotard.

As a first step toward a full MCP suit, the human leg was the first site of interest. This region provides several types of learning opportunities. First there are the non-joint sections of this region, which provide both regular sections, like the thigh, which are almost circular, and irregular sections, such as the lower leg, with the sharp curves of the shin. Second, this area contains a simple one-degree of freedom joint that imposes challenges of its own, such as the concavities that develop upon flexing of the local muscles. In addition, there are sizing challenges due to the narrow regions, such as the ankle, that lie beyond wider regions, such as the heel, during the donning process. At the time of this writing, only a garment for the lower leg has been designed, built, and tested.

At the heart of the challenge, as with any garment design, was the patterning of two-dimensional fabric pieces to create a three-dimensional form. Creating the pattern for a comfortable, well designed garment is itself a challenge; creating a pattern for the complex forms of the body was an experimental process.

FORM CAPTURING AND FLAT PATTERNING

Two techniques, draping or patterning, are usually used to determine a garment's construction. Draping describes the process of hanging fabric off a mannequin and pinning it to create the form as desired, much like sculpting with fabric. Patterning, on the other hand, describes the process of drawing a series of two-dimensional shapes that, when joined at their seams, form the three-dimensional form of the garment. Both techniques were used to create the hybrid-MCP garments discussed in this thesis.

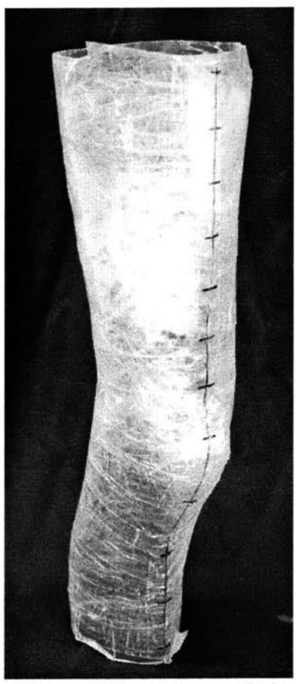


Figure 9.1: A form of the thigh, knee, and upper calf created from packing tape wrapped around the subject. The black markings highlight the seam where the form was cut and act as keys for realigning the seam.

In order to accurately capture the body form, regions of the body were covered with stocking material and then taped to "rigidize" the fabric form (see Fig. 9.1). Clear packing tape was applied in strips, making sure that the application process did not distort the form. In this way a clear, thin shell was created around the body. This shell could then be cut down a seam and removed easily due to the stocking barrier between adhesive and skin. Once removed, the shell could be re-joined to form the original body form. These shell forms could then be used to determine the pattern necessary to reproduce them from two-dimensional fabric pieces.

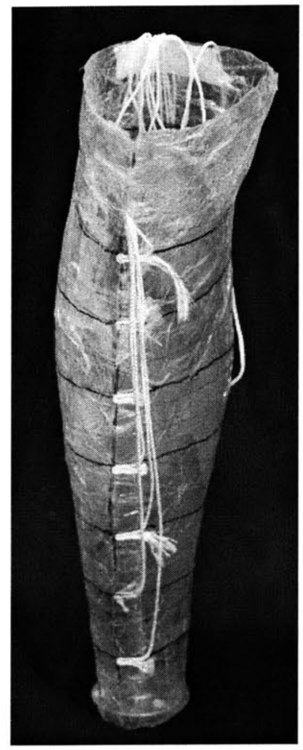


Figure 9.2: A form of the right lower leg created by wrapping packing tape around the subject. The black lines running circumferentially indicate lines of minimum circumference and were created by wrapping the white strings around the section.

In order to translate the form into two-dimensional pieces, the form was inspected for regions of high curvature, or other rapid changes in the axial direction. High curvature was of interests as it is these areas that are hardest to construct via two dimensional, inextensible fabric pieces. The axial direction was of interest as it was decided before-hand that the garment would be constructed via circumferential strips. This was thought to be beneficial in terms of garment loading where the material, rather than the seams, would take the stress.

Once these points of rapid change were identified, lines of minimum circumference were constructed through them. It was thought that using lines of minimum circumference would further reduce stress across the seams. These lines then described the strips of fabric that needed to be joined in order to create the body form (see Fig. 9.2).

Figure 9.3: (Next Page, Top) The sail-cloth garment made from eight strips of material. The pattern pieces for this garment were generated using the tape form in Figure 9.2. After construction, the garment had to be tailored to fit the lower leg snugly. See Appendix Appendix E: for the pattern pieces used to construct the sail cloth garment.

The transcription process from form to fabric was itself an involved task requiring tracing paper in order to copy the

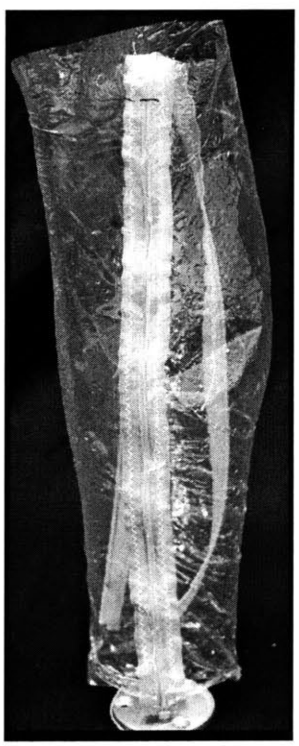


Figure 9.4: Image of the clear shrink wrap garment with zipper attached.

shape of the strips. Of course, the process required several iterations as the chances of error were great. In the end, however, a body conforming garment was produced out of a lightweight, polyester sail cloth donated by Doyle Sailmakers[a] (see Fig. 9.3).

a. Thanks to Dr. Robbie Doyle and Kristen Heissenbuttel, Doyle Sails, Marblehead, MA.

In addition to the involved process described above, three other techniques were investigated, all using shrink-wrap materials. In the first case, tubing was shrunk around the limb to create the garment in one easy step. Care had to be taken to minimize the risk of burning, but the garment created was skin tight and maintained its form well. The tubing was cut off and a zipper was attached so that it could be donned/

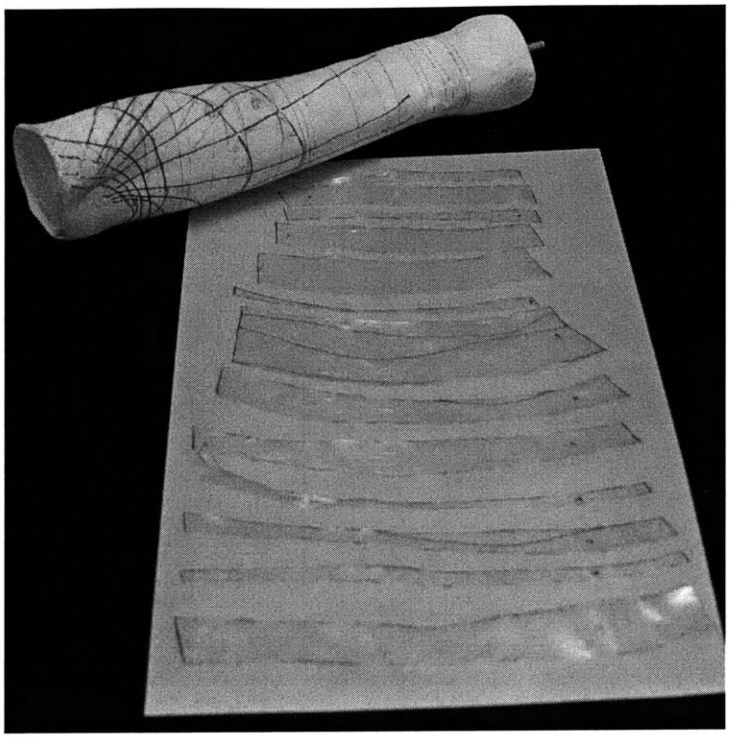


Figure 9.5: (Left) A plaster cast of the a forearm with pattern pieces for forearm garment. Lines of minimum circumference were first drawn on the cast. The cast was then shrink wrapped with plastic and the lines of minimum circumference were traced onto to the plastic. The plastic was then cut along the lines of minimum circumference to produce the pattern pieces seen in the photo. These were traced and documented for future use.

doffed easily (see Fig. 9.4). Films inherently tend to rip. Thus, at the seams between zipper and film, the garment tended to tear. This could be fixed in the future, however, by using non-stitch connections, or a non-film material such as shrink-wrappable polyester cloth.

The second use of shrink-wrap tubing was to quickly create a different version of the tape form described above. Here the limb was shrink-wrapped, and then the lines of minimum circumference were drawn directly on the shrink-wrap. Once the shrink wrap was removed from the body, the film itself could be cut along the lines of minimum circumference in

Figure 9.6: An image of the draped shrink polyester before heating. A single piece of fabric was pinned as tightly as possible to the form before shrinking.

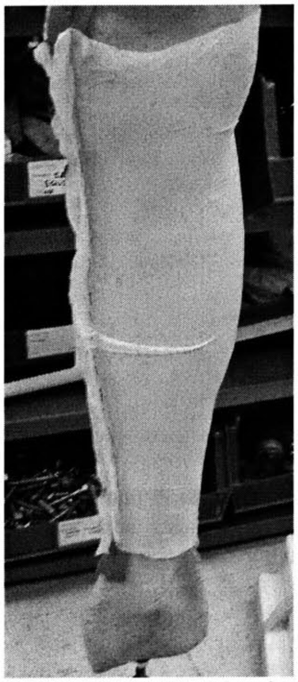


Figure 9.7: The shrink polyester garment after heating and attachment of a zipper. A total of four seams were required: one on each side of the zipper, and two located half way up the lower leg running horizontally. An example of each can be seen in the above photo.

order to create the pattern pieces (see Fig. 9.5). These pieces could then be traced or scanned to capture the pattern.

The third shrink-wrap technology investigated was that of shrink-wrap polyester fabric. This canvas-like material is woven from heat-shrinkable polyester fibers. Typically used in aircraft construction, we obtained samples from Geodesic Airolite Boats.[1, b] This material was draped and pinned around the 3D printed leg (see Fig. 9.6) and then shrunk to a skin tight fit. After it had been formed using a heat-gun, the material was then sewn and a zipper was added (see Fig. 9.7). This process reduced the labor and time required to construct a fitted lower leg garment by at least a factor of four; the inextensible, sail-cloth garment mentioned above required 16 sewn seams whereas the heat-shrink polyester required only 4.

Late in the development of these garments, we were able to 3D print a scan of the author's leg. Scans were obtained from the Natick Soldier Center and printed on a ZCorp 3D printer (see Fig. 9.8). The print provided and accurate leg mannequin that facilitated draping and tailoring. Although the taped forms described above also provided this capability, the taping process inherently added thickness to the form,

b. Thanks to Seth Riskin and Donna Marcantonio.

1. http://www.geodesicairolite-boats.com/

thereby disrupting the tailoring process. The 3D print, on the other hand, was highly accurate, durable, and easy to work with. It was the 3D printed form that was used for shrink-wrap experiments as temperatures during the shrink fabric heating process were uncomfortably high.

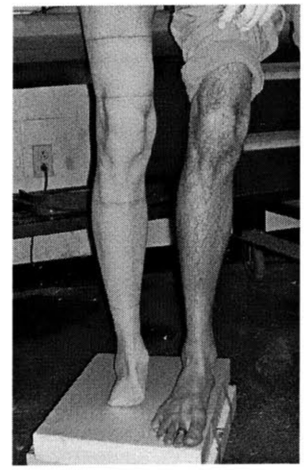


Figure 9.8: A photo of the 3D printed leg next to the author's.

Although both the sail cloth and polyester shrink wrap garments were tested by a subject in a vacuum chamber, only the sail cloth garment is presented in this thesis. Future work will analyze the shrink garment and compare the performance against the sail cloth garment.

EXPERIMENTS/TESTS

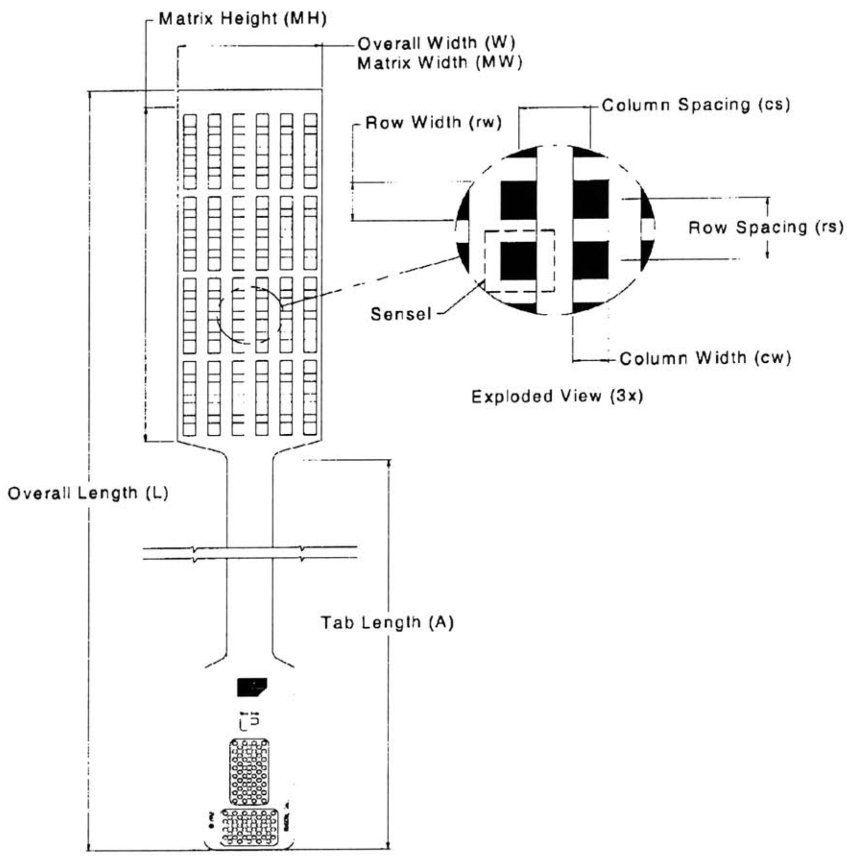
In order to test the predictive capabilities of the model described in "Modeling the Garment Architecture" on page 156, garments were constructed and tests were run on a PVC pipe section, R = 6 cm. As the PVC pipe is a rigid cylinder, it satisfied the assumptions of the model. In order to reduce the friction between garment and pipe, the pipe was wrapped by a thin Teflon film.

Figure 9.9: (Next Page) A diagram of the Tekscan 9801 pressure sensor. This sensor was used for both PVC cylinder measurements and body measurements. As discussed later in this chapter, the sensor was altered for body measurements by cutting the sensor between the columns. In addition, the air pockets in each sensel had to be punctured so that the sensor could perform properly within the vacuum chamber.

TEST SET-UP

A variety of garments were tested on the PVC pipe in order to quantify their various levels of performance. For the

MAP AND SENSOR MODEL NUMBER: 9801
SENSOR NAME: TRIMPAD



Sensor 9800 Shown

Type	General Dimensions			Sensing Region Dimensions								Summary	
	Overall Length *L*	Overall Width *W*	Tab Length *A*	Matrix Width *MW*	Matrix Height *MH*	Columns *CW*	Columns *CS*	Columns *Qty.*	Rows *RW*	Rows *RS*	Rows *Qty.*	No. of Sensels	Sensel Density
US	(in)	(in)	(in)	(in)	(in)	(in)	(in)		(in)	(in)			(sensel per sq-in)
9800	24.5	3	15.5	3	8	0.25	0.5	6	0.31	0.5	16	96	4.0
Metric	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)		(mm)	(mm)			(sensel per sq-cm)
9800	622	76	394	76	203	6.35	12.7	6	7.87	12.7	16	96	0.62

Application Examples: Handgrips, clothing fit, diaper and pressure garments.

Special Feature: Can be slit into six independent strips of 16 sensing cells each.

most part, garment and channel materials were chosen based on their availability. The channel material was off the shelf, 2 mil polyethylene lay-flat tubing (E = 20,000 psi), typically used to wrap such things as posters. Bike inner-tube nozzles were attached to the polyethylene using spray adhesive (see Fig. 9.10). Although the adhesive did not work well under tension, the garment architecture assured that this joint would always be under compression. Garment materials included Teflon, Polyester sail cloth, Polyester shrink-wrap fabric, and a durable Polyester mesh.

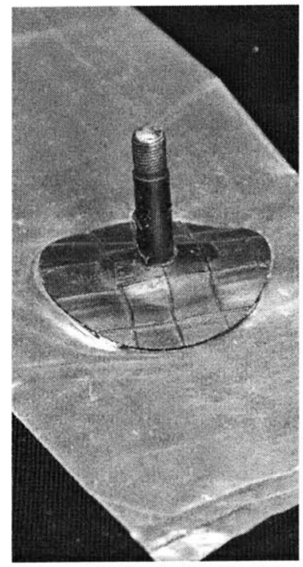


Figure 9.10: A detail of the polyethylene channel and the attached bike inner tube nozzle.

Mechanical counterpressure measurements were taken using a Tekscan 9801 sensor (see Fig. 9.9). Initially the pressure sensor was positioned beneath the channel so that a uniform pressure could be applied for equilibration and calibration. This was done before each test. Once calibrated, the sensor was moved to various regions of the pipe circumference so that mechanical counterpressure measurements could be taken.

To satisfy the assumption of a uniform, isotropic, elastic film, Teflon film was used. The Teflon was wrapped around the cylinder, polyethylene channel, and pressure sensor and then glued to itself with rubber cement. In this way a tube of

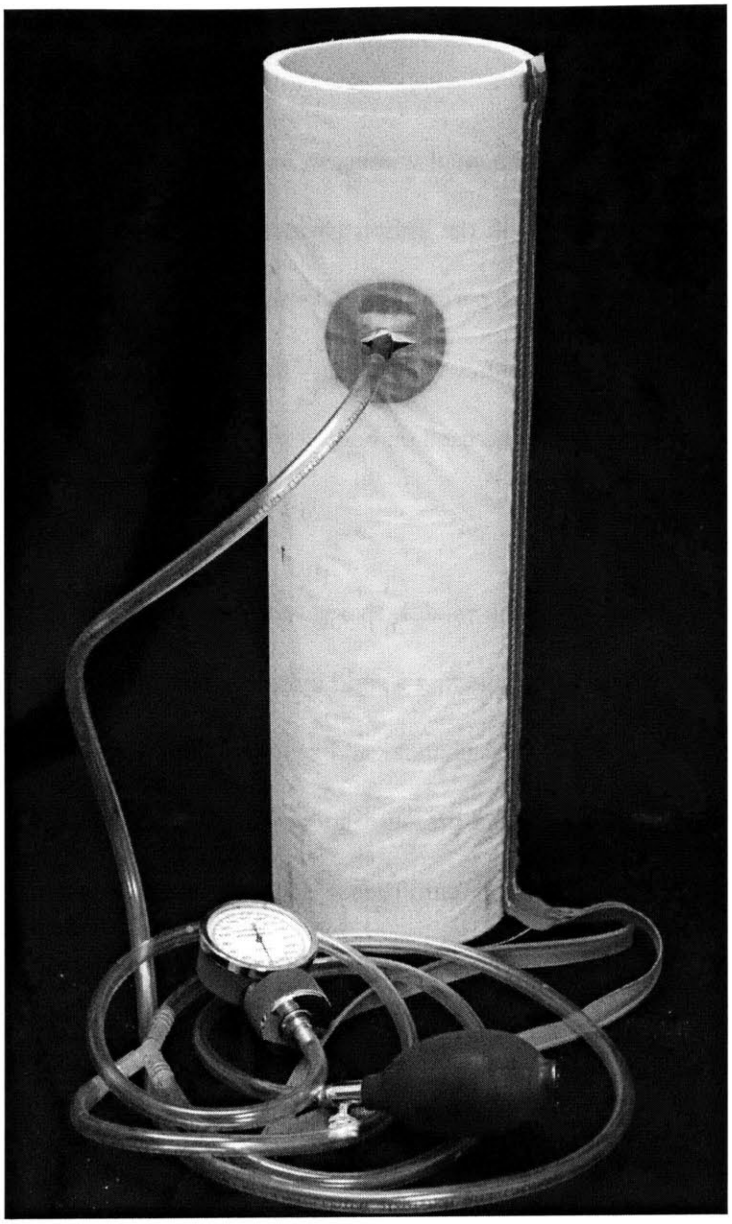


Figure 9.11: The PVC cylinder test set-up with the pressure gauge and hand pump attached. In this photo, the sail cloth garment surrounds the pipe and is secured with a red zipper.

Teflon surrounded the entire PVC .section, with a channel between the Teflon garment and the pipe. This channel could then be inflated via a standard blood pressure cuff hand pump, and the channel pressure could be read from a gauge (see Fig. 9.11).

Two different channel widths, $w_i = 2.5$ cm and $w_i = 10.3$ cm, were tested with the Teflon garment in order to test the way width affected performance. With the other garments, only the larger channel width ($w_i = 10.3$ cm) was tested as this was the one to be used on body tests.

RESULTS

According to the model, two results should be immediately apparent when testing a rigid cylinder. First, there is the gap between inflated channel and cylinder which results in the absence of applied pressure. In general, the pressure distribution around the circumference of the cylinder should be constant and equal to the channel pressure underneath the inflated channel, and constant everywhere else where the garment material is in contact with the cylinder's surface. This was tested with the following results.

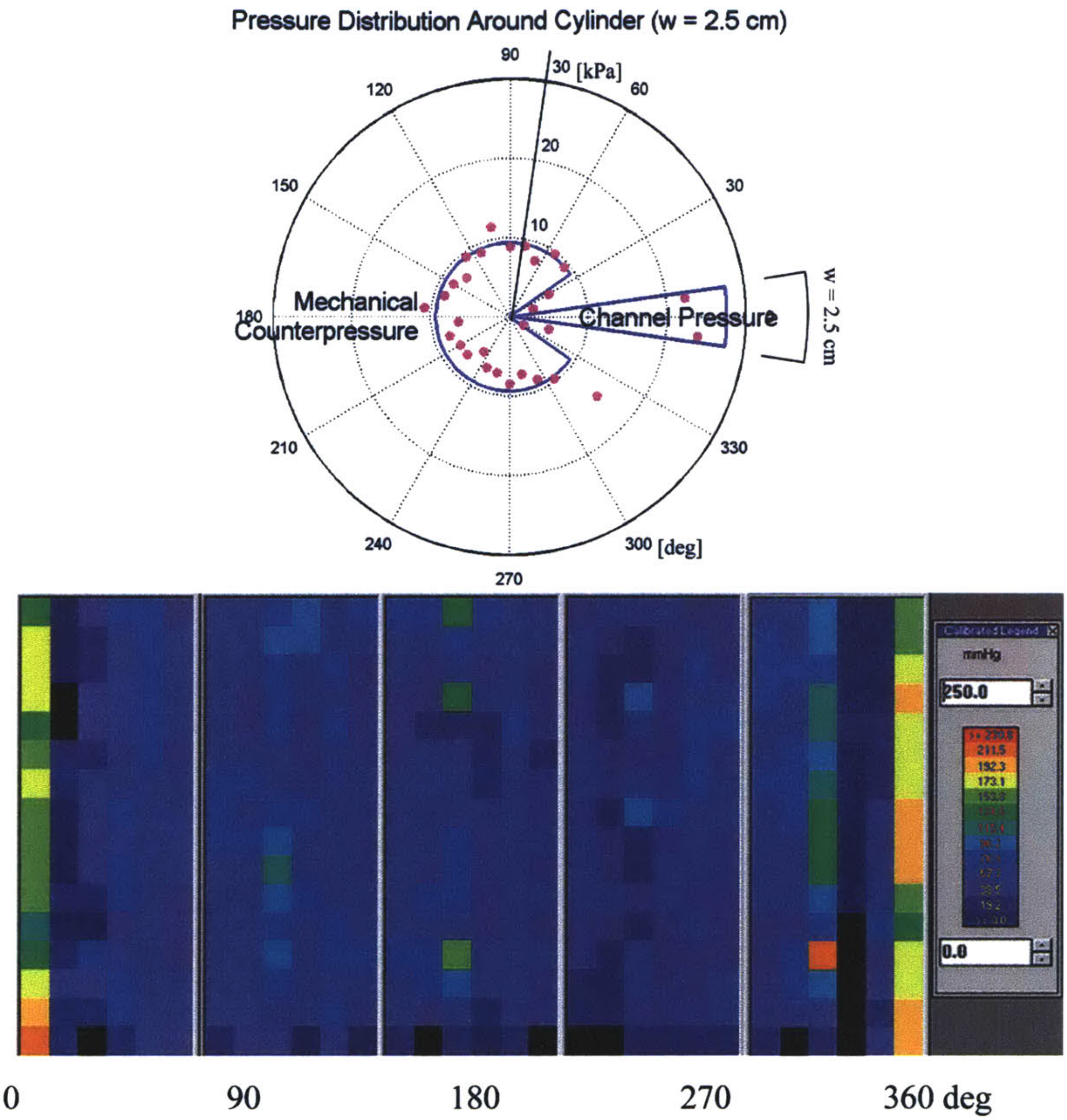
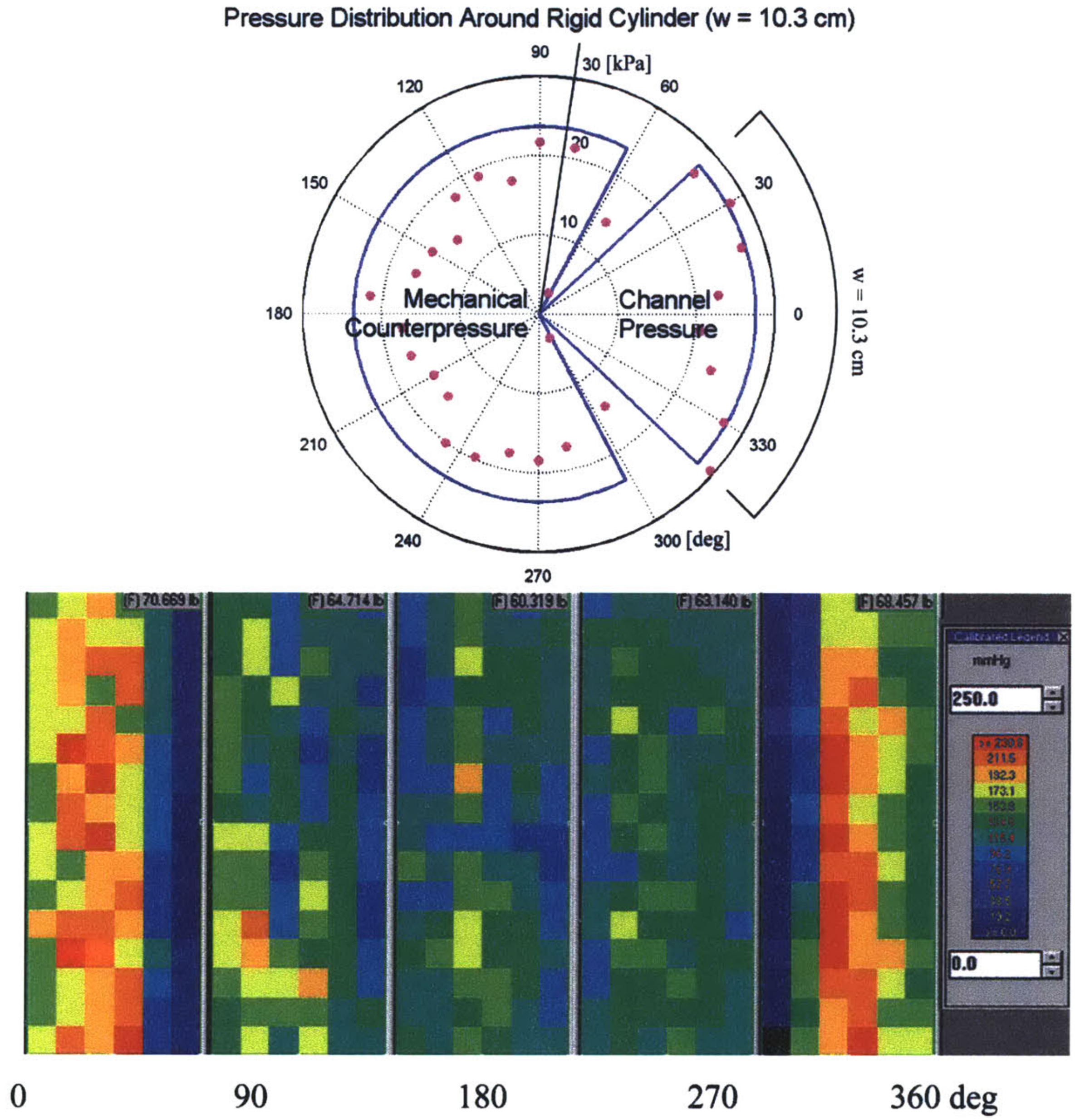


Figure 9.12: Models and data representing the pressure distribution around a rigid cylinder for a channel width of 2.5 cm. Below the polar plot is a Tekscan sensor output displaying the pressure around the cylinder's surface area.

Figure 9.12 and 9.13 display the predicted pressure distribution around the cylinder for both channel widths, $w_i = 10.3$ cm and $w_i = 2.5$ cm. Superimposed on top of each of these graphs is data from physical tests. These data points represent



the average pressure of each individual column of the sensor. The color coded sensor outputs can also be seen in Figure 9.12. As can be seen from these results, the model adequately

Figure 9.13: Models and data representing the pressure distribution around a rigid cylinder for a channel width of 10.3 cm. Below the polar plot is a Tekscan sensor output displaying the pressure around the cylinder's surface area.

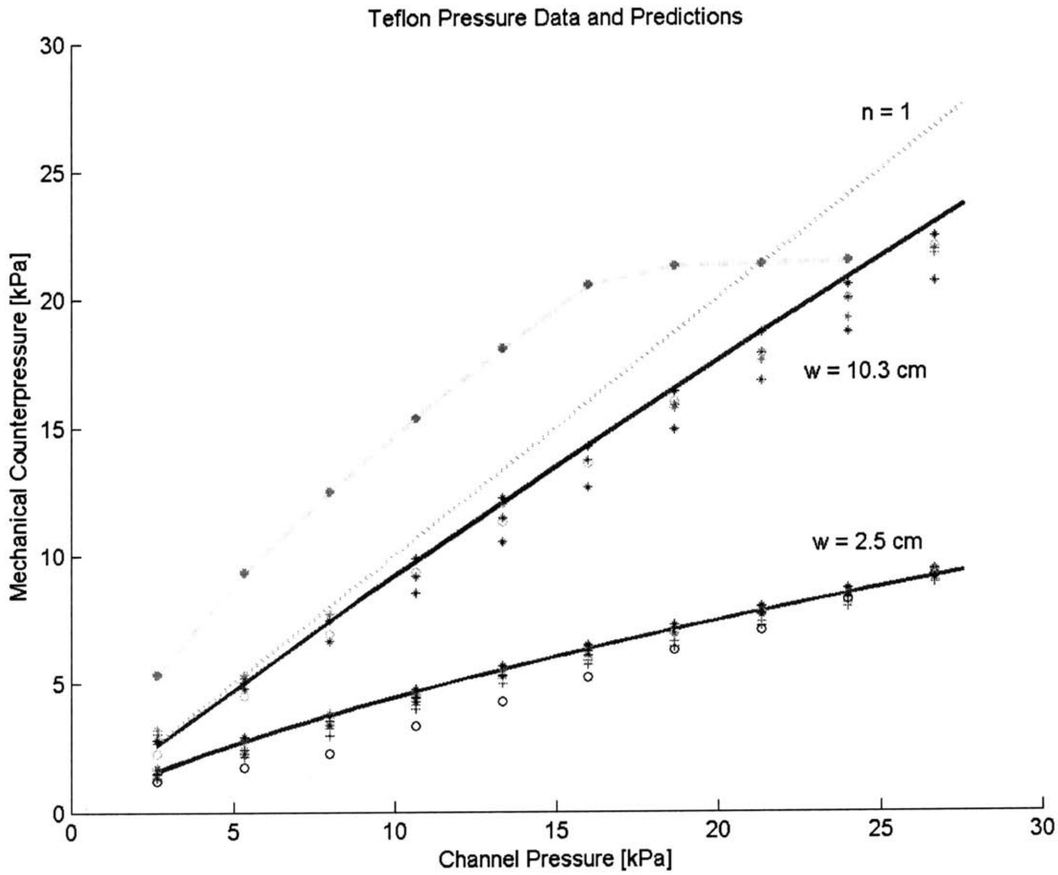


Figure 9.14: Predictions and data for a Teflon garment around a rigid cylinder. Two channel widths are presented (w = 2.5 cm and w = 10.3). Red lines represent modeled predictions; symbols locate data points; the yellow line plots data results for decreasing channel pressure. Decreasing pressure was not modeled.

predicts the regions of even pressure distribution as well as the gaps that form on either side of the channel.

In order to validate the model's predictions of MCP as a function of channel pressure, a series of tests were performed on Teflon garments surrounding the PVC cylinder. Figure 9.14 displays the results from these tests. The solid lines correspond to the models prediction of MCP as a function of the channel pressure, with initial channel widths of 10.3 and 2.5

cm for the upper and lower lines respectively. The data is coded by shape and color such that the "+"s correspond to the first day of tests and the "*"s correspond to the second. Four trials were run each day. The colors of the symbols (red, magenta, green, blue) represent the trial number (1, 2, 3, 4) for each day, respectively. The cyan, dotted line has a slope of one and is presented in order to give an idea of the channel distribution efficiency, n. As discussed in "Modeling the Garment Architecture" on page 156, the efficiency for a rigid cylinder should never be greater than one.

The yellow, dotted line in Figure 9.14 connects data points during channel deflation. The deflation process was not modeled. This interesting result is most likely due to sticktion between the garment and cylinder as evidenced by the flat, horizontal line on the graph at the beginning of the deflation process.

The polyester sail cloth, obtained from Doyle Sails, was the only fabric that was provided with material properties. Because of this, it was the only fabric modeled with any degree of certainty. A simple, tubular sail cloth garment with one zippered seam was constructed for the PVC pipe and tested in similar ways mentioned above. The major difference

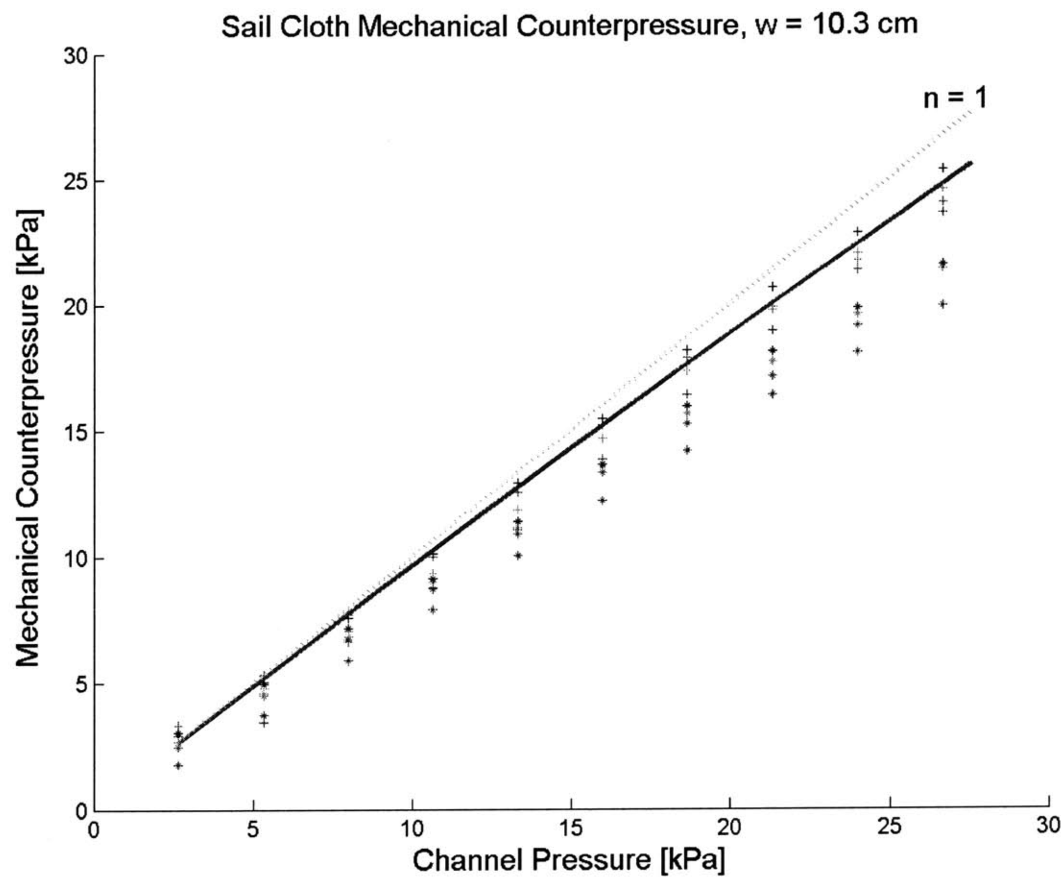


Figure 9.15: Predictions and data for the sail cloth garment performance around the PVC cylinder.

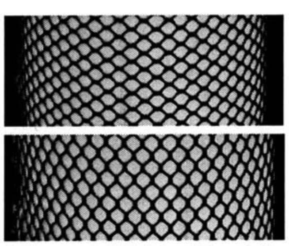


Figure 9.16: Details of the two mesh orientations: "horizontal" (top), and "vertical" (bottom). Measuring from horizontal, the strand angles were 36.9 and 56.3 degrees, respectively.

was that only the larger channel width, the one that would be used on the body, tests, was tested. Figure 9.15 displays the predictions of the sail cloth garment performance, with data superimposed.

The shrink-polyester fabric and two mesh garments were tested in the same way as the sail cloth. Although it would have been possible to tailor the shrink poly without heat, this garment was heat shrunk around the cylinder so as to capture any material property distortions the shrinking process may have induced. The mesh garments were made from the same

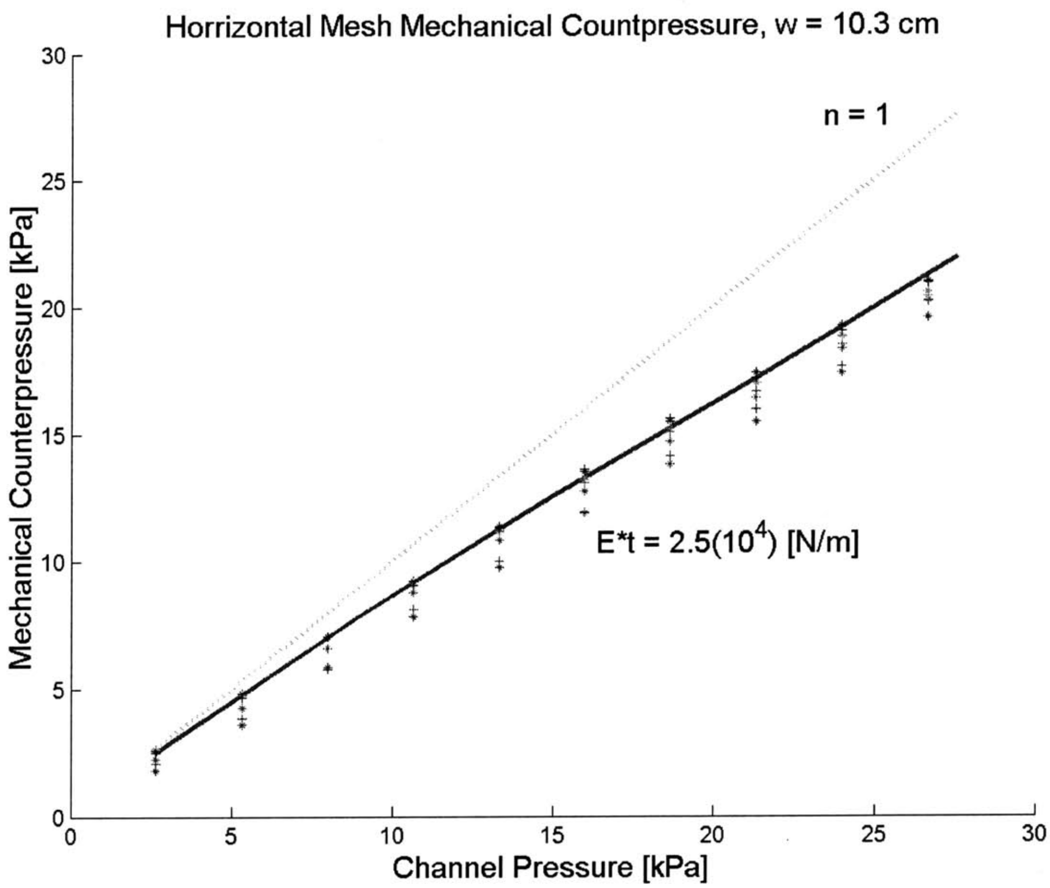


Figure 9.17: Mechanical counterpressure data for the horrizontal mesh garment around the PVC pipe. As the modulus of the material was not know before the tests, the red, solid line represents the model's predictions after a modulus had been guessed.

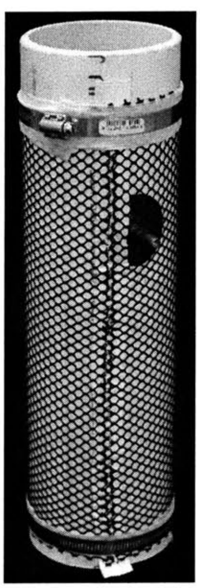


Figure 9.18: The mesh test set-up with pipe clamps.

mesh material, but were tailored such that the mesh was aligned differently for each garment (see Fig. 9.16). This allowed the data to capture the effects of the strand angle, γ. In order to prevent the mesh from sliding axially along the cylinder, pipe clamps and rubber strips were used (see Fig. 9.18).This set up assured that the stretch of the mesh was due mostly to strand strain instead of diamond distortion

As stated above, the properties of these materials were not known beforehand. Because of this, no predictive model could be used. After the data was obtained, however, modulus

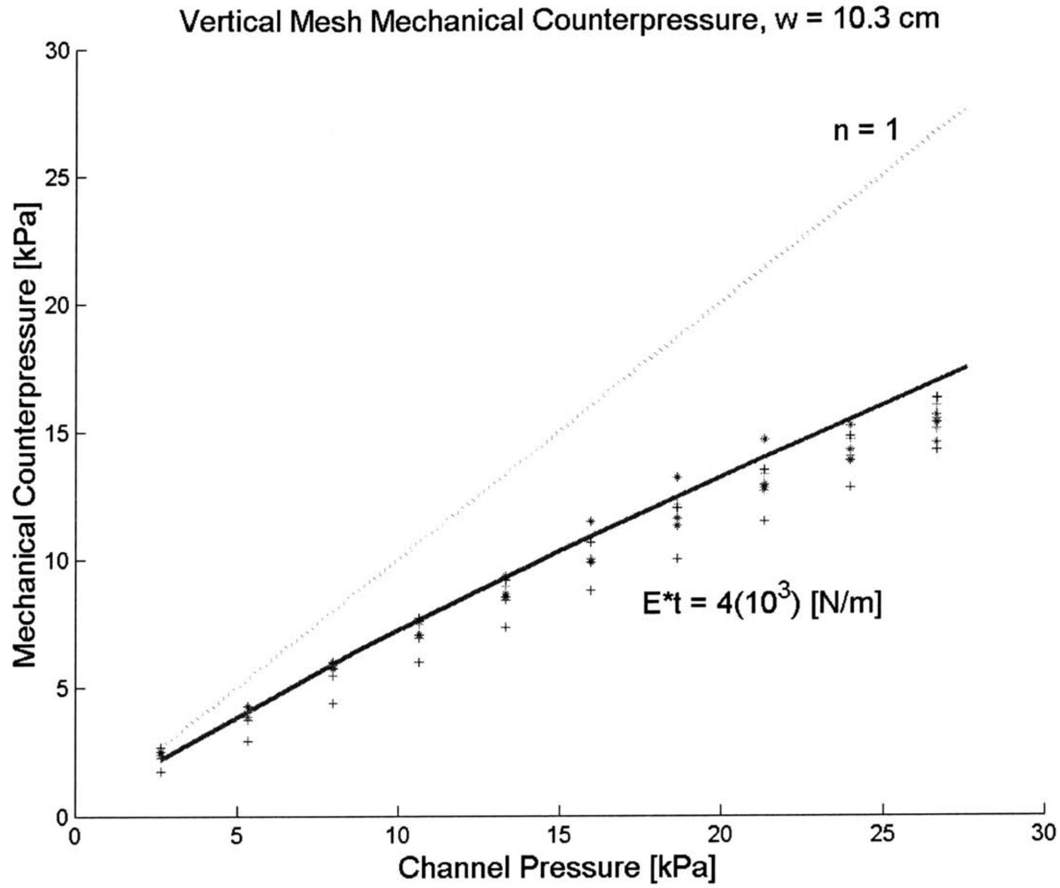


Figure 9.19: Mechanical counterpressure data for the vertical mesh garment around the PVC pipe. As the modulus of the material was not know before the tests, the red, solid line represents the model's predictions after a modulus had been guessed.

could be estimated by altering the coded value until a reasonable data match was achieved. Thus, the solid lines in Figures 9.17, 9.19, and 9.20 represent fitted curves, used to determine the modulus of these materials. The assumed modulus is pre-

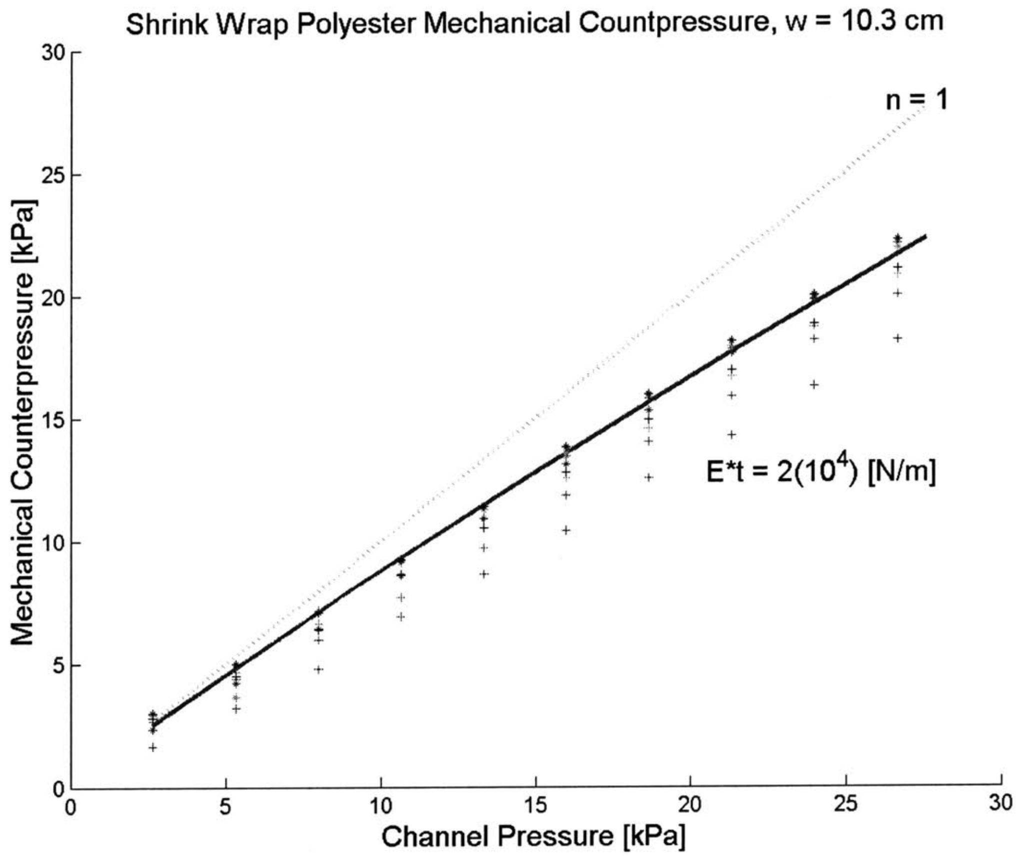


Figure 9.20: Mechanical counterpressure data for the shrinkable polyester fabric garment. Once again, the red line represents the models predictions given a reasonable guess for the modulus.

sented next to the data and model. The results are summarized in Table 9.1.

Table 9.1: Material properties determined through MCP test on a PVC cylinder.

Material	Stiffness [N/m]
Sail Cloth	$1.75(10^5)$
Horizontal Mesh	$2.5(10^4)$
Vertical Mesh	$4(10^3)$
Shrink Poly	$2(10^4)$

TEST ON THE HUMAN BODY

Although the model was easily capable of predicting the mechanical counterpressure produced by a uniform film surrounding a rigid, circular cross section, the true utility of the model is in predicting the performance of the architecture on the human body. To this end garments were constructed to fit the lower leg using the techniques mentioned in "Form Capturing and Flat Patterning" on page 173. As discussed at the beginning of this chapter, this region of the human body poses many of the challenges presented by the true human form.

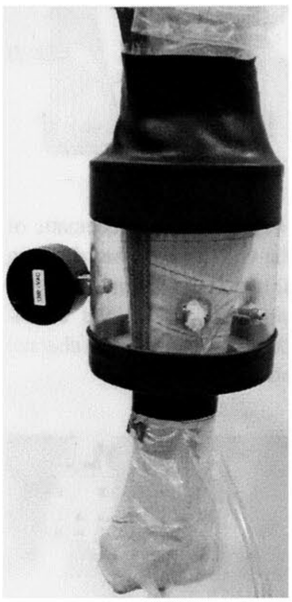


Figure 9.21: The lower leg vacuum chamber on the 3D printed leg. The chamber was made of 1/8 in thick polycarbonate and was sealed against the body with latex gaskets from kayaking dry-suits. The white, sail-cloth garment surrounded the lower leg and pressure channel and was donned with a zipper (red). On the right side of the chamber is an air port to allow atmospheric pressure to fill the pressure channel in the suit. This connected to the channel via a quick release pressure connection (center, white). The back of the pressure gauge can be seen on the left. For more information on the vacuum chamber see Appendix Appendix D:.

HUMAN TEST SET-UP

Initially, tests were made in normal atmospheric conditions, with an inflated channel. Not surprisingly it was quickly discovered that the garments in this configuration, acted much like a blood pressure cuff, cutting off circulation to the foot. Additionally, as a blood pressure cuff squeezes the wearer, it reduces the amount of fluid in the cross section, thereby turning a gel-like cross section into a more rigid form. It was thought that this tourniquet effect altered the body cross-sectional properties enough to significantly effect mechanical counterpressure results.

In order to avoid the tourniquet effect, a localized vacuum chamber was made so that instead of increasing the channel pressure, as described above, the pressure surrounding the body and garment could be reduced (see Fig. 9.21). With the channel pressure exposed to atmosphere, the chamber's pressure could be reduced to the desired differential pressure. In this way, if the garment worked properly, the entire body surface, both inside the chamber and out, would be kept at the same pressure (see Fig. 9.22).

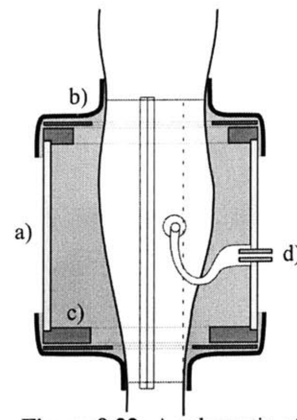


Figure 9.22: A schematic of the vacuum chamber showing a) the lexan cylinder, b) the latex gaskets, c) the aluminum caps, and d) the channel pressurization port.

Once again, Tekscan 9801 sensors were used in order to measure the mechanical counterpressure between garment and body. In order to facilitate their conformance to the 3D curves of the body, the sensors were altered by cutting them into strips, while care was taken not to affect the individual sensing units, known as sensels. As Tekscan sensors have sealed air compartments, these had to be punctured to allow the sensor to register the mechanical pressure (see Fig. 9.23).

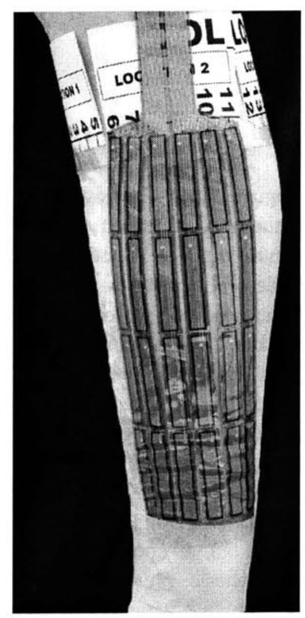


Figure 9.23: A photo of the sensor on the left lower leg (location two) of the 3D print. The sensor has been cut between columns so that the sensor can accept the 3D curves of the body. In addition the air pockets needed to be punctured in order to let the sensor work in vacuum

Unless specifically stated otherwise, all the body data is presented in mmHg.

RESULTS/DISCUSSION

In order to determine the variability of pressure measurements, tests were conducted over three days. On each day four repetitions were run so that a total of twelve measurements were collected for each point on the surface of the lower leg. The sensor was positioned in four different locations so as to observe the entire surface of the body under the garment. As the sensors were made up of a sixteen by six sensing array, this process captured 4,608 measurements.

It should be noted that the garment and vacuum chamber remained in place between repetitions within each location. Between locations, however, the garment and chamber had to be removed so that the sensor could be repositioned. This repositioning could have introduced variability in the test set up. It is recommended that future tests use a multiple sensor system so that the entire surface can be measured at once, under exactly the same conditions. To make sure the measurements for each repetition were independent, the chamber was repressurized and then depressurized between repetitions.

In discussing the data, the locations around the circumference of the lower leg are numbered 1-4 such that:

1 = Shin (Front Left)

2 = Left Calf

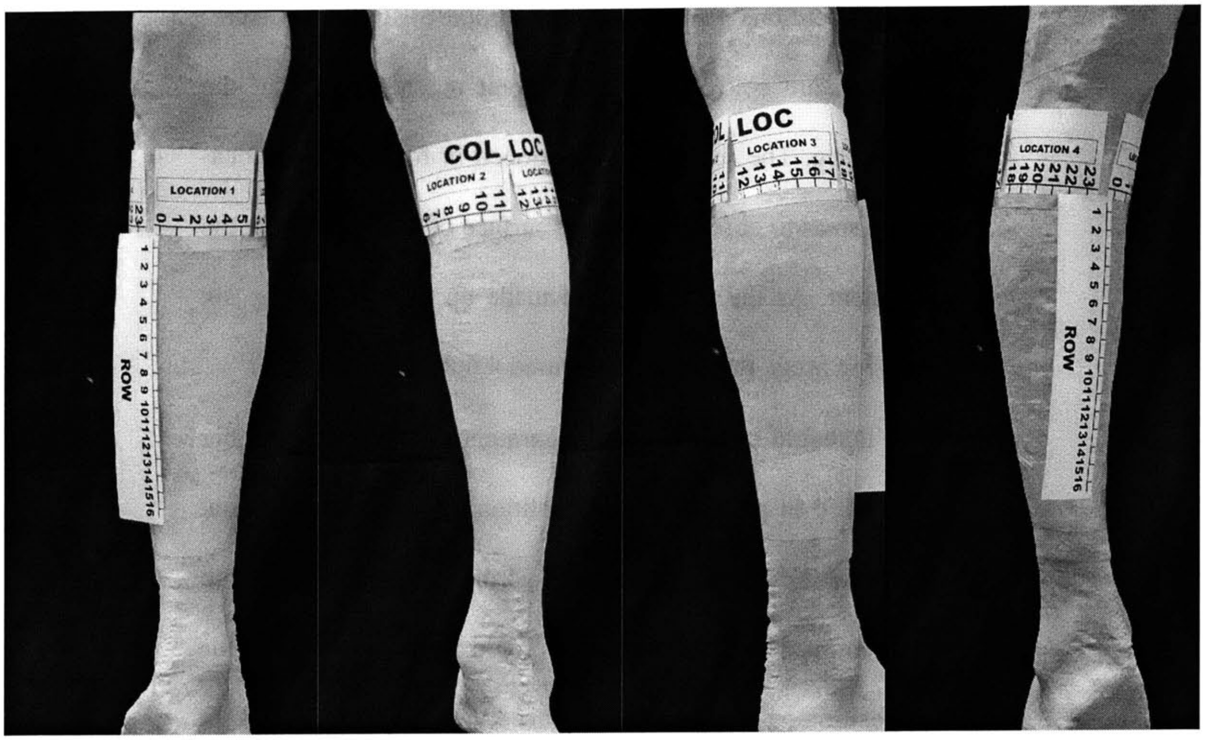


Figure 9.24: Photos displaying the sensor locations, one through four, the column-locations, zero through twenty three, and the rows, one through sixteen. The combination of the row number and the column-location number uniquely determine the location of each sensing element.

3 = Right Calf

4 = Front Right

As all tests were conducted on the right lower leg, this numbering of locations follows the circumference of the lower leg in a counterclockwise manner (from the subject's perspective) starting and ending with the leading edge of the shin bone (the tibia).

In addition to this nomenclature, the rows of the sensing array were numbered one through sixteen such that row one was closer to the knee; row sixteen lay closer to the ankle. In

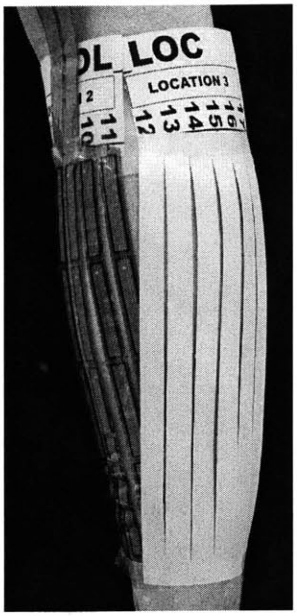


Figure 9.25: A photo of how the sensor locations overlap near the ankle. The green sensor is in location two, while the white paper is cut and positioned like a sensor in location three. Notice how they overlap towards the ankle.

this way, individual rows describe a constant altitude above the ankle (see Fig. 9.24).

In parts of the analysis, the columns and locations were combined such that a new variable, column-location, was created. The column location, col_loc, locates each sensing column, consecutively, around the circumference of the lower leg. Whereas the row number describes the vertical height (decreasingly), the column location describes the longitude around the lower leg. Thus, column locations zero through five made up location one; column locations six through eleven made up location 2; etc. (see Fig. 9.24). As the sensor was rectangular and the lower leg is roughly conical, however, column locations overlapped near the ankle (see Fig. 9.25).

In order to present the data in a clear and informative manner, several graphical representations are presented. Three-dimensional bar graphs allow comparison between locations, days, or other parameters. These graphs are easiest to use when looking for local maxima, seen as ridges. Two dimensional bar graphs with error bars are sometimes presented along side the 3D bar graphs. These allow for a more detailed, quantified perspective.

In addition, 2D mosaics were created so that they could be applied directly to the 3D printed form. In these plots, the third dimension of the graph is represented by a color range from blue to red, where blue is a low value. This method of visualization allows direct comparison between data and anatomy and was found to facilitate the most insight. This method of analysis is presented through photographs of the graphical models. This method of visualization allows relative comparison between sensing elements and the anatomy as well as identification of local minima, seen as dark stripes in the mosaic. For a quantified presentation, the two and three dimensional bar graphs should be referenced.

Model Predictions for the Body:

As stated above, initially, the goal of the body test were to compare actual performance to that predicted by the model of a rigid cylinder surrounded by an isotropic fabric. Although this comparison was performed and is presented in Figure 9.26, it was clear that the variability in measurements and the measurements themselves had to be understood before clarifying modeling work could be undertaken. Thus, the goal of the effort was revised. The new goal was to under-

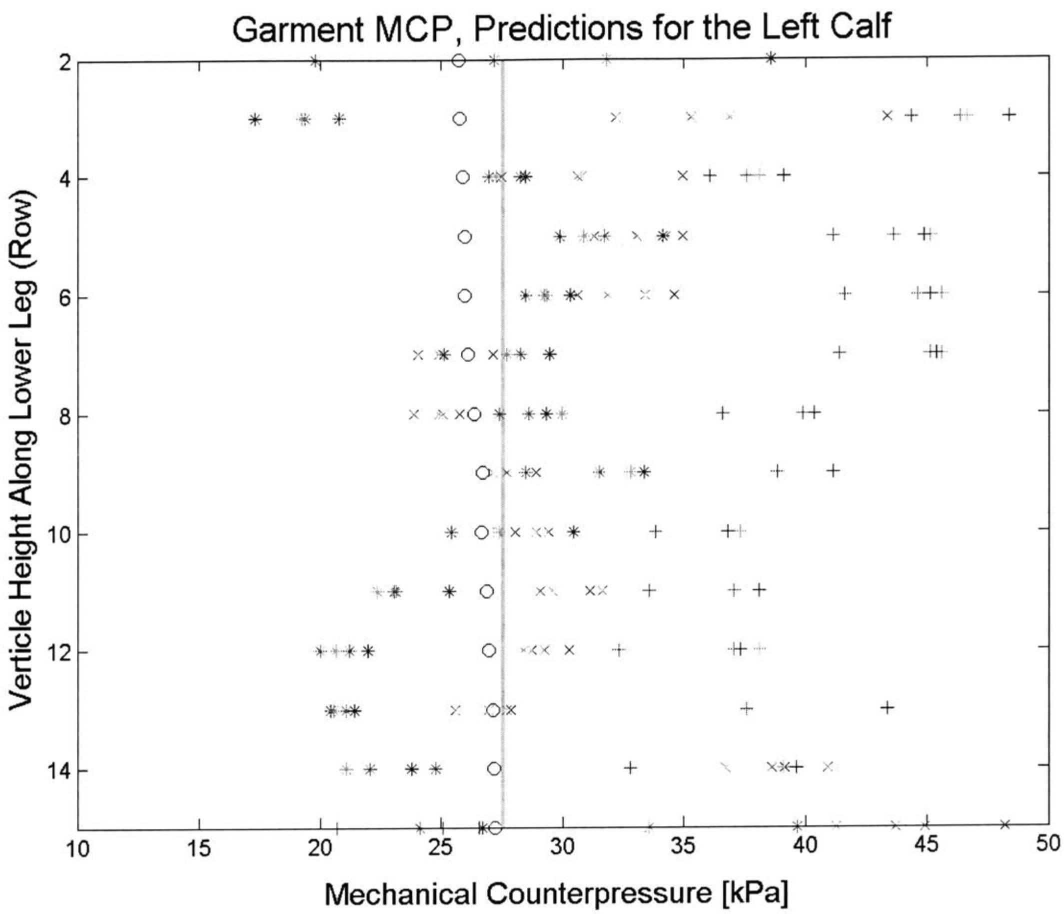


Figure 9.26: The model's predictions of mechanical counterpressure at different points along the axis of the lower leg with data superimposed. The circles represent the model's predictions; the solid cyan line represents the channel pressure; data points for different trials are represented by symbols. Graphs like these displayed the large degree of variability in the data and focussed the analysis on understanding the data rather than trying to update the model to accurately predict the garment's performance on the human body.

stand the pressure measurements. Future work should attempt to revise the model so that it reflects the body data.

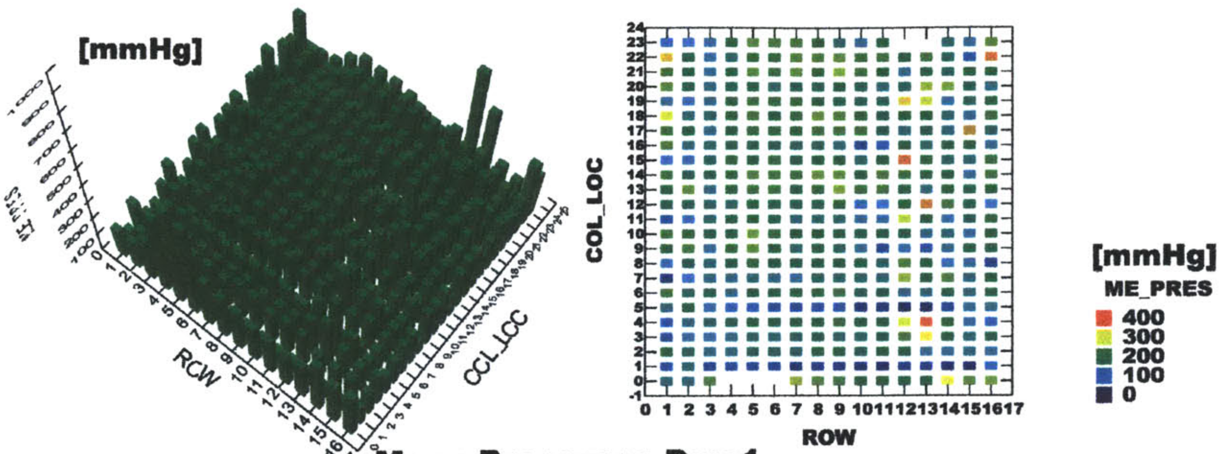
Mean Pressures on the Lower Leg Surface:

Figure 9.27 displays mean pressure measurements over the surface of the lower leg for each day, by averaging over repetitions. More detailed plots for each can be seen in Figures Appendix "Additional Body Data Plots" on page 319. Of interest are the “hot” and “cold” pressure spots. Hot spots are located near the top and bottom of the lower leg as well as on the shin. The peculiar results from rows 1-3 and 13-16 are assumed to be an artifact of the vacuum chamber boundary condition and are therefore ignored for most of the analysis.

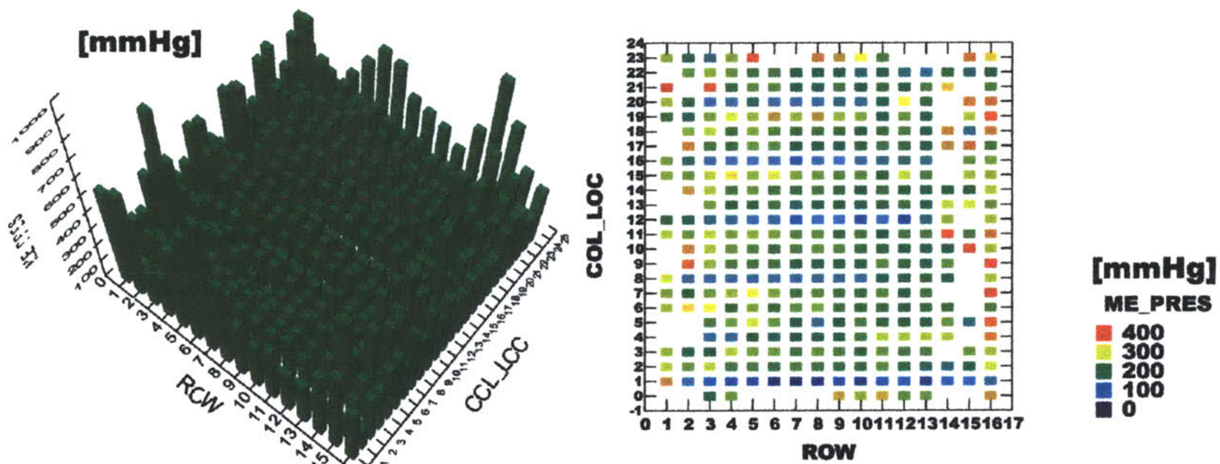
Certain commonalities appear upon inspecting the mean pressure distributions for each day. As mentioned above, the highest values occur near the edges of the plot and are explained by either the effect of the vacuum chamber or the presence of the low radius, rigid tibia. In addition, although the values of the measurements differs between day, the interior of the plots is relatively even for a given day, as can be seen in the 2D mosaics.

For each day there is also a common pattern of low pressure bands occurring roughly every two inches around the circumference of the lower leg. This can be seen most clearly in the 2D mosaic for day 3 where stripes occur at column-locations 1, 4, 8, 12, 16, and 20 (see Fig. 9.28). These bands are of particular interest as the column-locations in which they occur are not related modulo six. This suggests that the stripes are not artifacts of the sensors, which have six col-

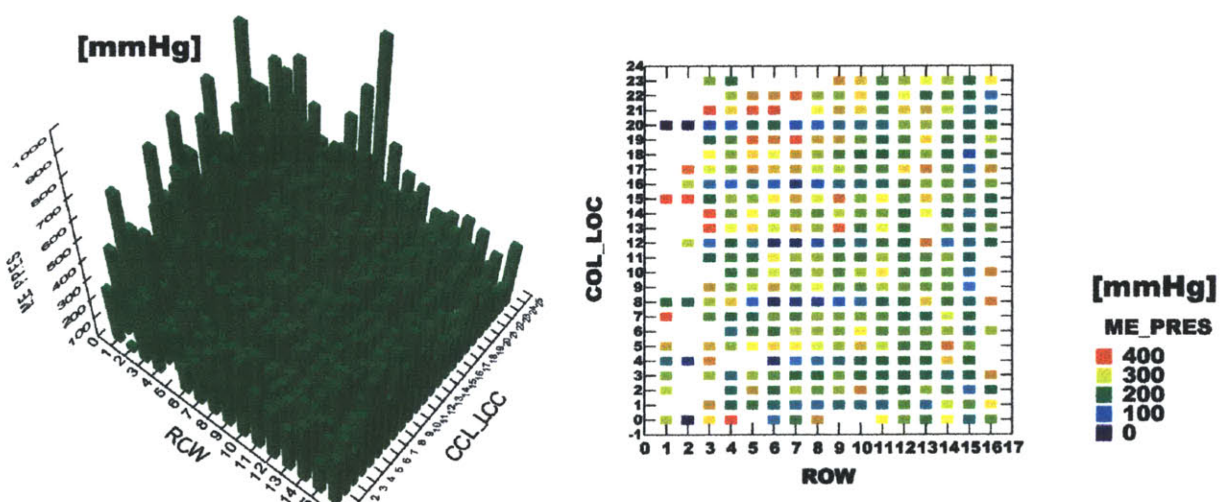
Figure 9.27: (Opposite Page) Mean pressures for each day. Each plot displays the mechanical counterpressure data from the lower leg taken on a specific day. This data is averaged over repetition so that only one value for each row, column-location is given. 3D graphs presented to the left display large mean values occurring round the perimeter. Each day shows high mean values for column-locations 0 and 23, which are both located on the leading edge of the shin. In addition, low values can be seen running in strips along column locations, 1, 5, 8, 9, 12, 16, and 20. Points within the interior of the figures display relatively even pressures.



Mean Pressures Day 1



Mean Pressures Day 2



Mean Pressures Day 3

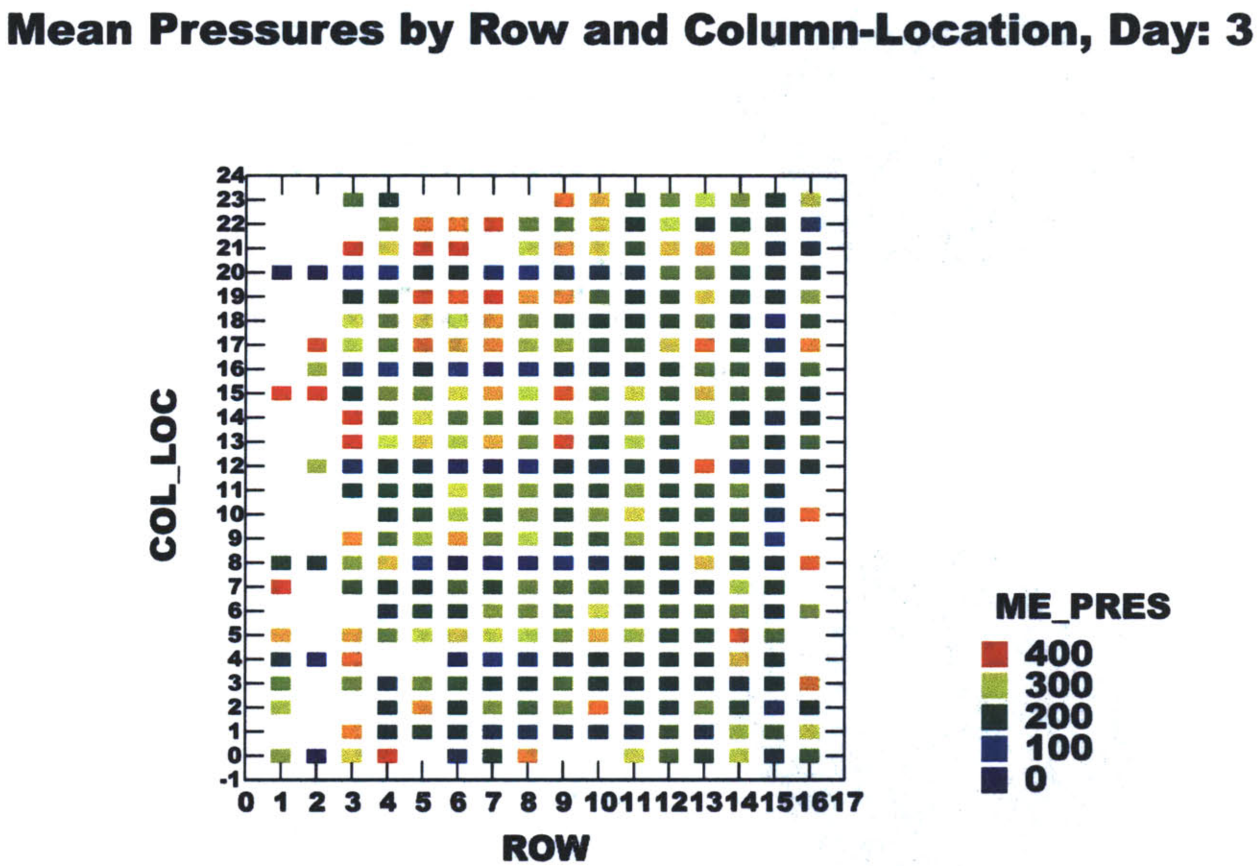


Figure 9.28: The mean pressures for day three. Notice the stripes of low values located at column locations 1, 4, 8, 12, 16, and 20. Seeing as these numbers are not modulo six, it suggests that these low values are due to anatomical features or garment features, or both.

umns, but of the body and/or garment. In order to investigate this issue in more detail, the mean pressure for day three was applied to the 3D printed leg. As each day exhibited these low, striated pressure regions, the mean for day three was thought acceptable for investigating this phenomenon (see Fig. 9.29).

It is unclear why these bands of low pressure occur where they do. It could be argued that at these locations on the circumference of the lower leg the cross section has a high

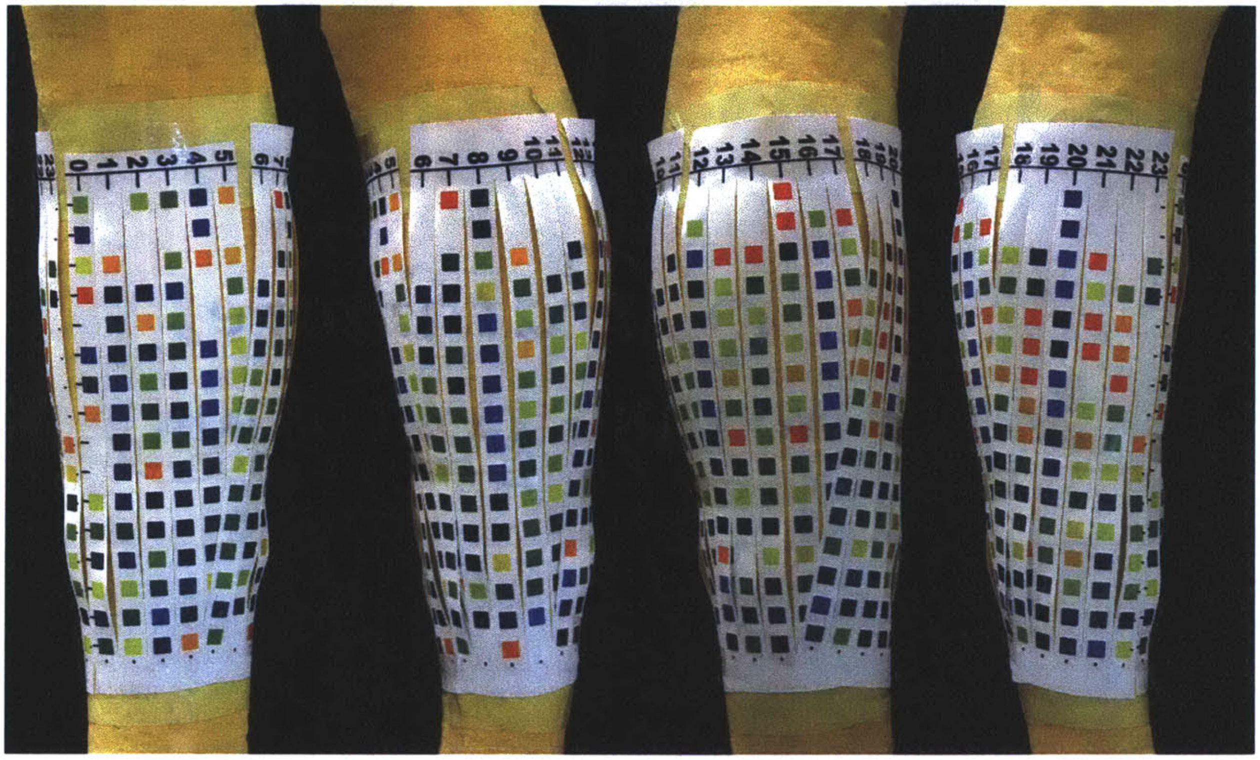


Figure 9.29: Images of the day 3 mosaic applied to the 3D print so as to highlight the relationship between mechanical counterpressure and anatomy. Stripes of low pressure can be seen in column locations 1, 4, 8, 12, 16, and 20.

radius of curvature and therefore displays low pressure, but it would be surprising if this explained the highly localized phenomena. In addition, locations 4, 8, and 12 fall in the most muscular parts of the lower leg which would tend to evenly distribute the pressure. This is because muscle is compliant when relaxed and can deform to a minimum energy state: even pressure. In order extract better insight from the data, the average across all days and repetitions was applied to the 3D form (see Fig. 9.30).

The first observation to be made is that the leading edge of the shin displays the largest average pressures. This could

Figure 9.30: Photos of the average pressure data applied to the 3D print. Each point represents the data averaged across repetitions and days.

be due to the low radius of curvature and the rigidity of the region. In addition, this is where the zipper ran, which might have created high point loads between the zipper and tibia. In the future, the zipper should be placed directly over the channel so that this issue disappears completely.

The effect of the chamber on pressure measurements seems to be most profound on the upper calf. This fit with the experience of wearing the chamber as some pinching was experienced in this area. As the cross sectional area of the lower leg is greater towards the knee than the ankle, the chamber had the tendency to suck its way up the leg. This might have been the source of the pinching. In the future, vacuum chambers like this should be designed with a stirrup to prevent chamber migration.

The lower calf seems to have lower pressure than the upper calf. Perhaps this is due to the rigidity differences between fleshy upper-calf and boney/tenuous lower-calf. In addition, the cross section of the lower calf is almost semicircular. In this region, the channel bulges to the point of completing the circle, thereby facilitating even pressure distribution.

Another observation to be made about the average pressure data is that the lowest pressures seem to be directly under the channel. This leads to two questions: why is the pressure under the channel so low? and, why is the pressure elsewhere higher? To answer the first question it is important to note that during the tests, the tube connecting the channel with the atmosphere was often found kinked. Although this was specifically watched for, it is possible that the kinked tube prohibited the channel from fully equilibrating with atmospheric pressure.

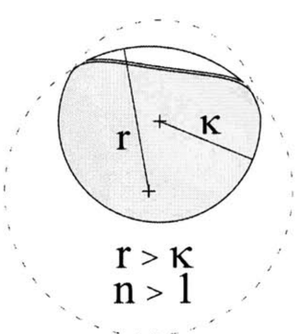


Figure 9.31: A diagram of how the pressure distribution efficiency, n, can be greater than one for an irregular cross section.

Figure 9.31 explains the higher pressures around other locations of the lower leg. In this diagram, the channel spans a flat region of the section, much like the shin. If the garment is highly inextensible, the radius of curvature of the channel, r, will be higher than the curvature of the section, κ, leading to a pressure distribution efficiency greater than one.

The channel was intentionally placed in a flat region of the cross section (large radius of curvature) so that it could round the cross section, facilitating even pressure distribution around the channel. It was thought that if the channel were located elsewhere, the shin region would experience low pressure due to its high radius of curvature and rigidity. Due to the body geometry and the low strain material, the channel radius of curvature, r, might have been held high enough to surpass the other radii of curvature around the section, thus causing the pressure distribution efficiency, $n = r/\kappa$, to be greater than one. By definition, this would result in a higher mechanical counterpressure than the channel pressure.

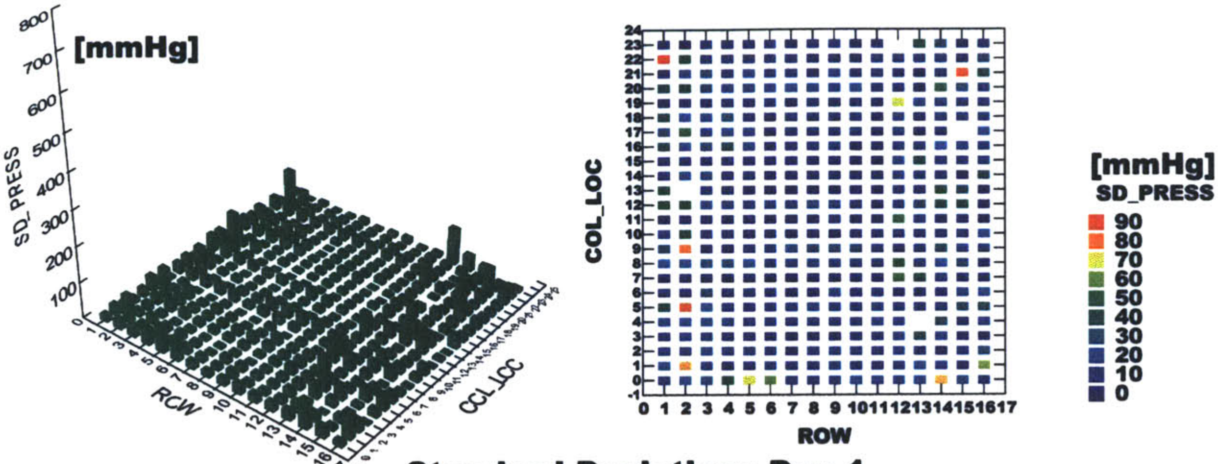
In the future, it might be advantageous to design the garment so that the channel is allowed to bulge to the point where the cross section becomes more circular. This might help with pressure distribution, but also suggests another opportunity: the channel pressure can be lower than the required body surface pressure. If this is the case, joint torques can be minimized both by channel placement and by lowering the channel pressure while maintaining body surface pressure.

Standard Deviation of Pressure Measurements:

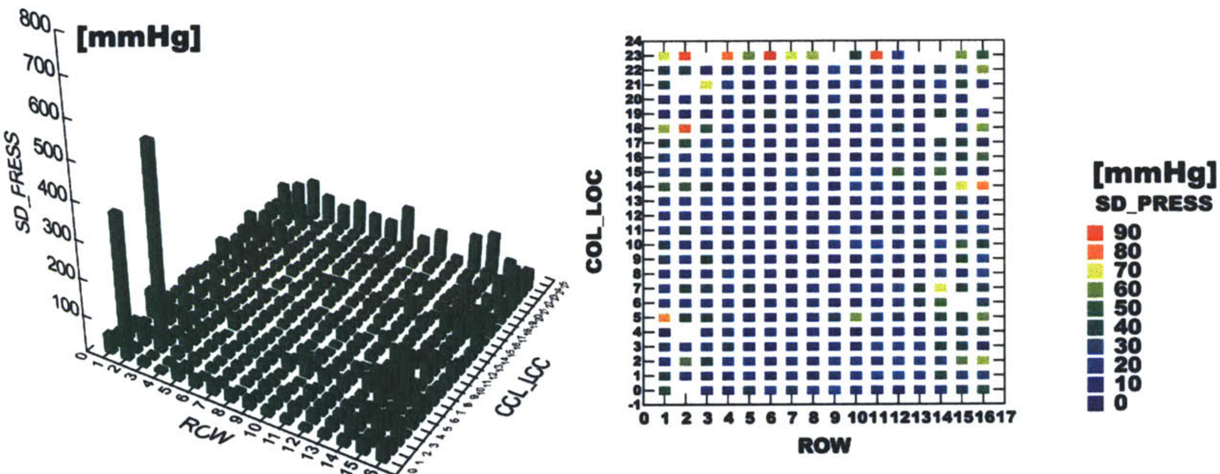
In order to get a sense of the variability associated with each sensing element, the standard deviation of each element was plotted. Measurements from each repetition on a given day were compared. The result can be seen in Figure 9.32. These plots are able to locate garment/body areas of interest, as locations with high standard deviations are more sensitive to differences between repetitions. Once again, more detail for specific days can be seen in Appendix "Additional Body Data Plots" on page 319.

Figure 9.32: (Next Page) The standard deviation of pressure measurements for a given day. 3D plots, to the left, are helpful for identifying local maxima, seen as ridges. 2D plots, presented to the right, are helpful for identifying local minima, seen as strips of blue. Notice that high ridges occur roughly where the low mean values occurred: column-locations 4, 5, 8, 9, 12, 16, and 20.

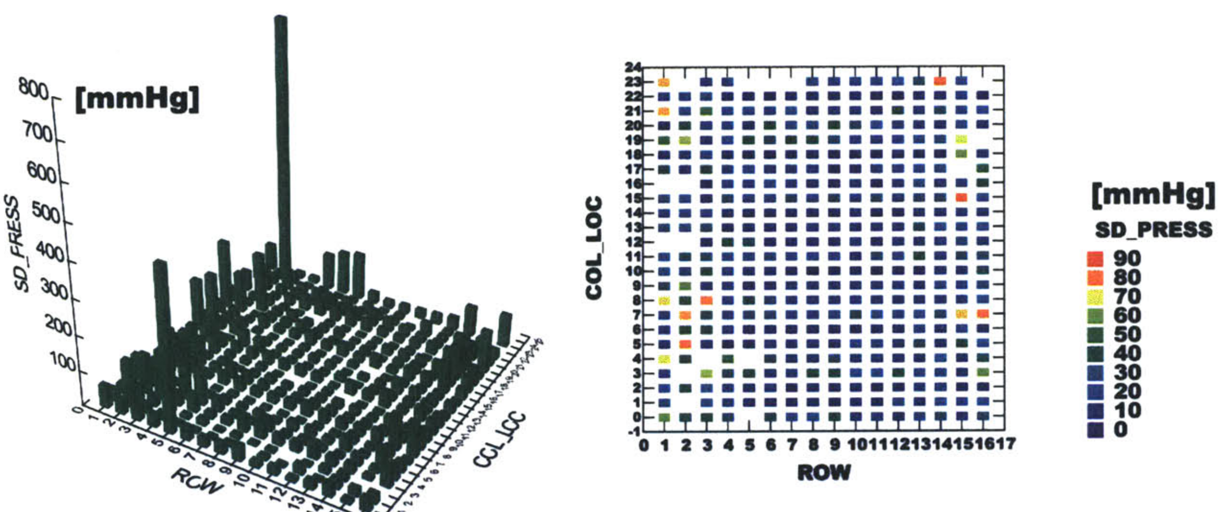
Several commonalities between days appear in these plots. Again, local maxima or minima and can been seen as ridges in the 3D plots, or dark stripes in the mosaics and fall roughly every four columns, suggesting garment/body sources of interest. As with the stripes in the mean data, as of yet the sources of these stripes is unclear.



Standard Deviations Day 1



Standard Deviations Day 2



Standard Deviations Day 3

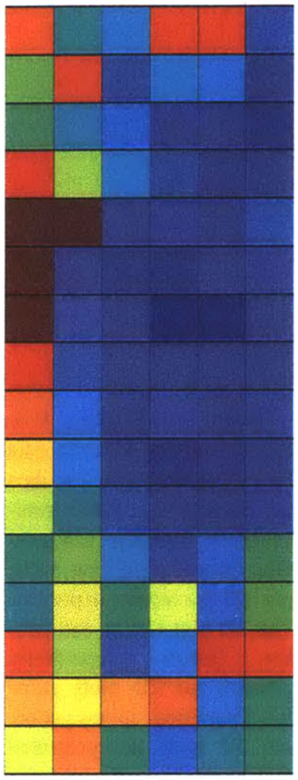


Figure 9.33: An image of the average pressure distribution over the shin for all days. When analyzing the row data, care was taken so as not to include dissimilar measurements. Thus, for the shin, the hot spots seen in the first column were not included.

Pressures as a Function of Altitude and Circumference:

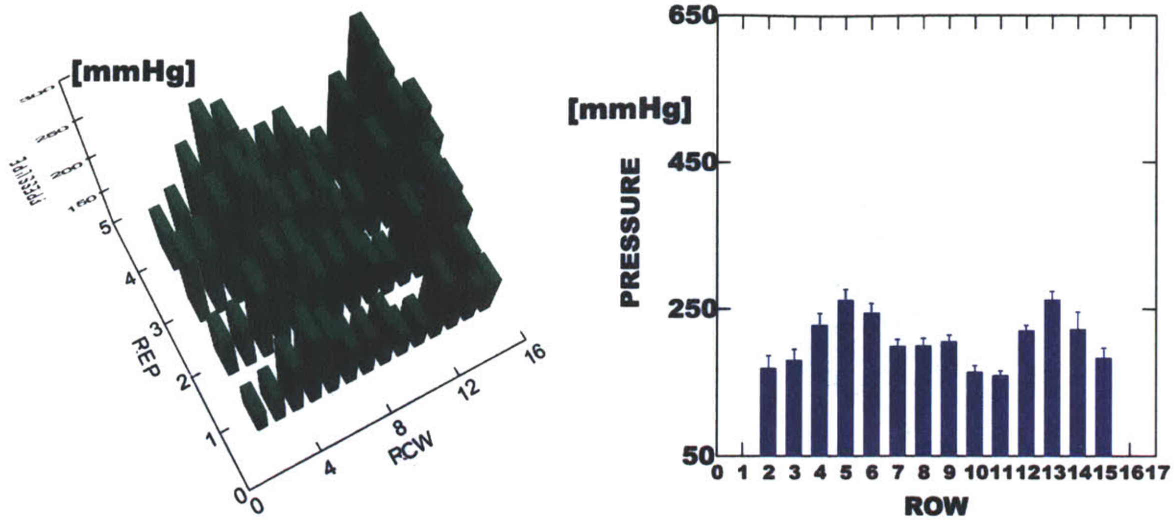
Beyond looking at the data element by element, elements at the same vertical height (altitude) were averaged over each location in order to get an estimate for the local pressure at each altitude and circumferential location. In the process of averaging across the columns, care was taken not to average over dissimilar measurements. For example, location one, the shin, typically displayed high pressures near the leading edge of the tibia, whereas low pressures occurred away from the shin (see Fig. 9.33). In cases such as this, the measurements were averaged over similar columns such that the high pressures of the shin were not included in location one. As the objective of this analysis was to determine the pressure at each location as a function of row/altitude, averaging over similar columns was acceptable. Graphs of this altitude-circumference data are presented below.

Altitude Pressure Analysis by Day:

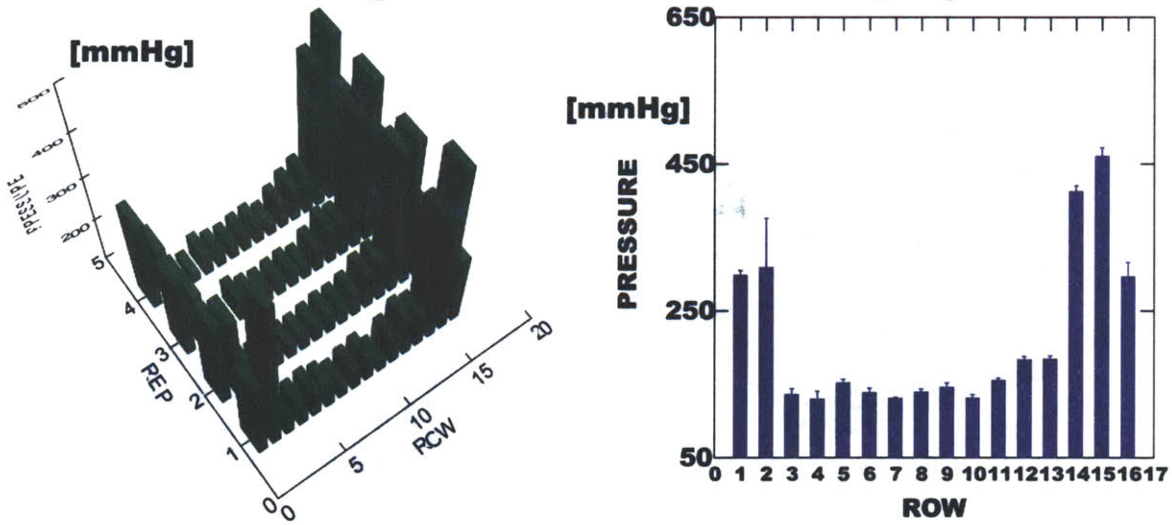
Because the chamber and garment had to be removed each time the sensor was moved between locations, it is hard to compare location to location or day to day. Removing the chamber and garment introduces variability in channel placement, garment position, as well as chamber dynamics (such as the behavior of the tube connecting the channel to atmospheric pressure). All of these variables were monitored, but could have affected results. The following plots display comparable measurements to show how the mechanical counterpressure varied given a constant garment, channel, and chamber set-up. As can be seen by inspecting each combination of day and location, the shape of the pressure contour is very constant between reps. In addition, if the 2D plots are inspected, it can be seen that the error bars are small, revealing that the measured pressure between repetitions is also consistent (see Fig. 9.34).

Figure 9.34: (Next Few Pages) Average pressure data for each sensor row. The data has been averaged over similar columns within each location, resulting in one value per row per repetition per day. The 3D plot allows comparison across repetitions, whereas the 2D plots allow for quantified investigation. All 2D plots are presented with standard error bars.

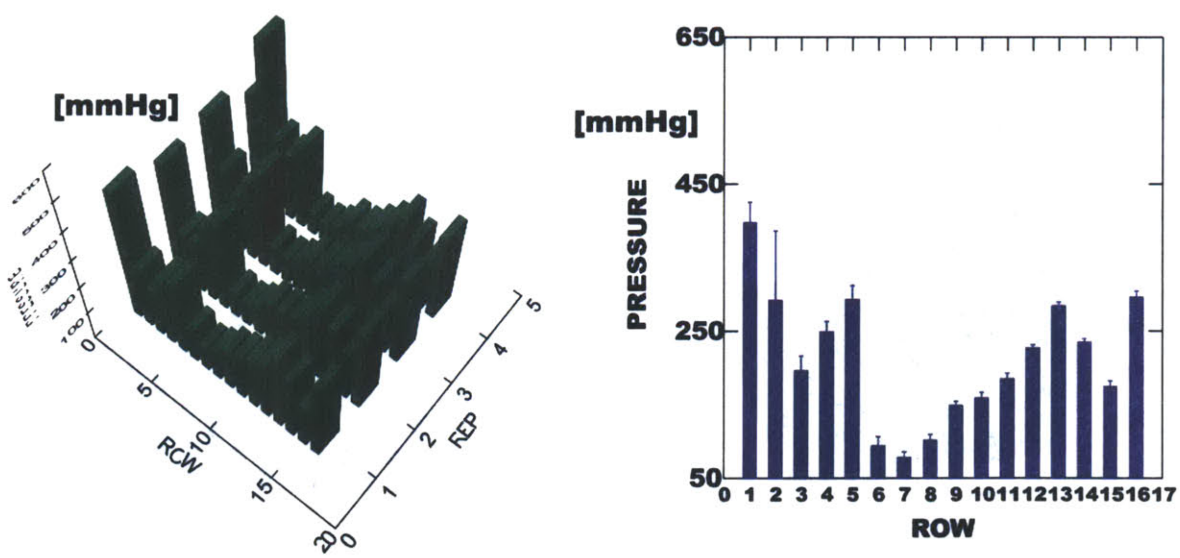
Each 3D graph suggests an increasing trend with day which is significant under the robust, nonparametric Page test ($p < 0.00005$). This analysis was performed by averaging over repetitions within a day, and columns within a location. Rows one and two, and thirteen through sixteen were ignored due to the chamber's effect on these pressure measurements. This left 40 measures (4 locations by 10 rows) for each day. The Page Test tested the upward trend of those 40 averages over locale and repetitions, treated as independent, over 3 days.



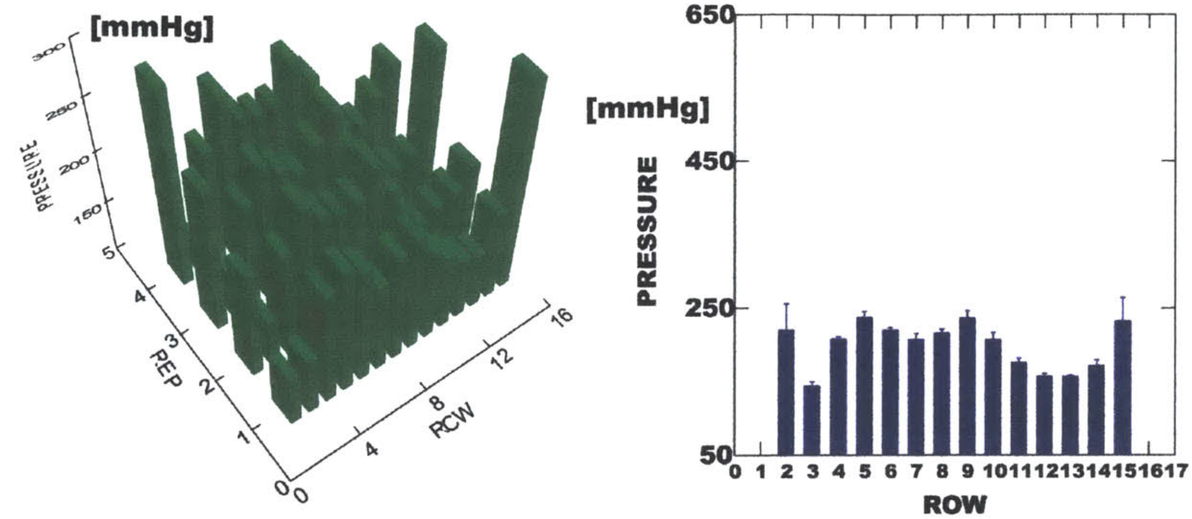
Average Row Pressures Location 1, Day 1



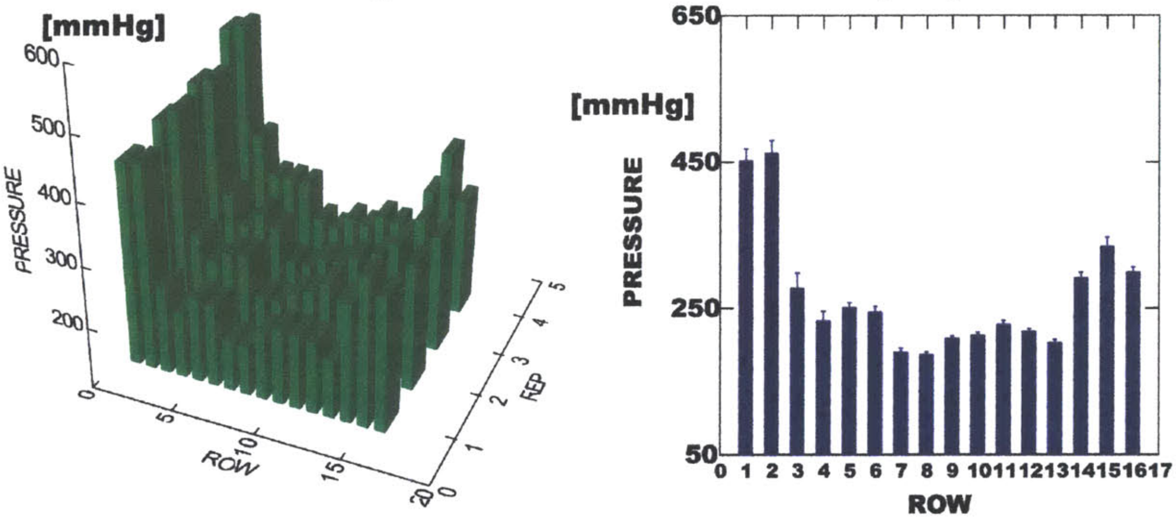
Average Row Pressures Location 1, Day 2



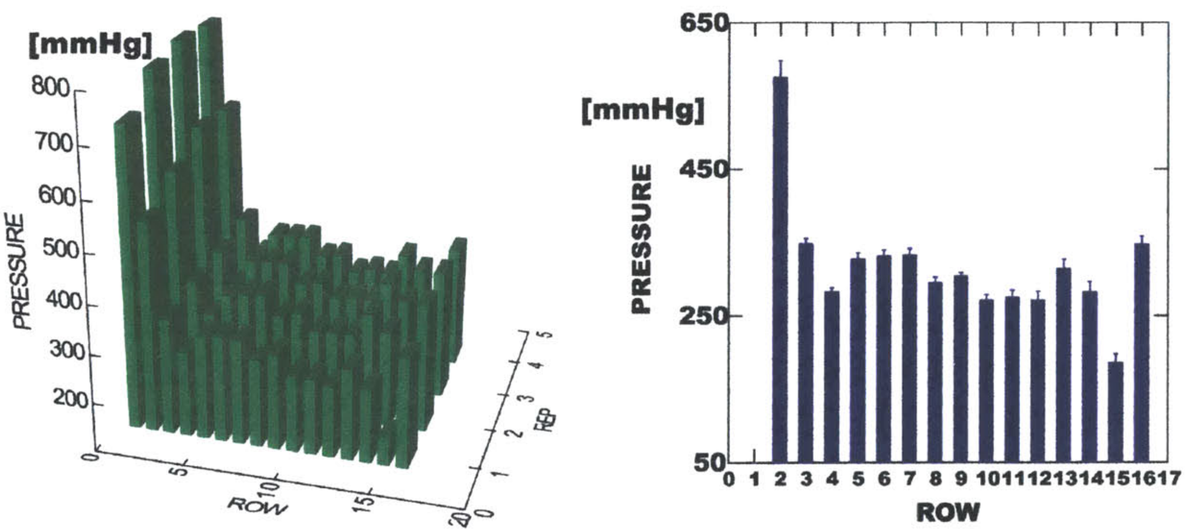
Average Row Pressures Location 1, Day 3



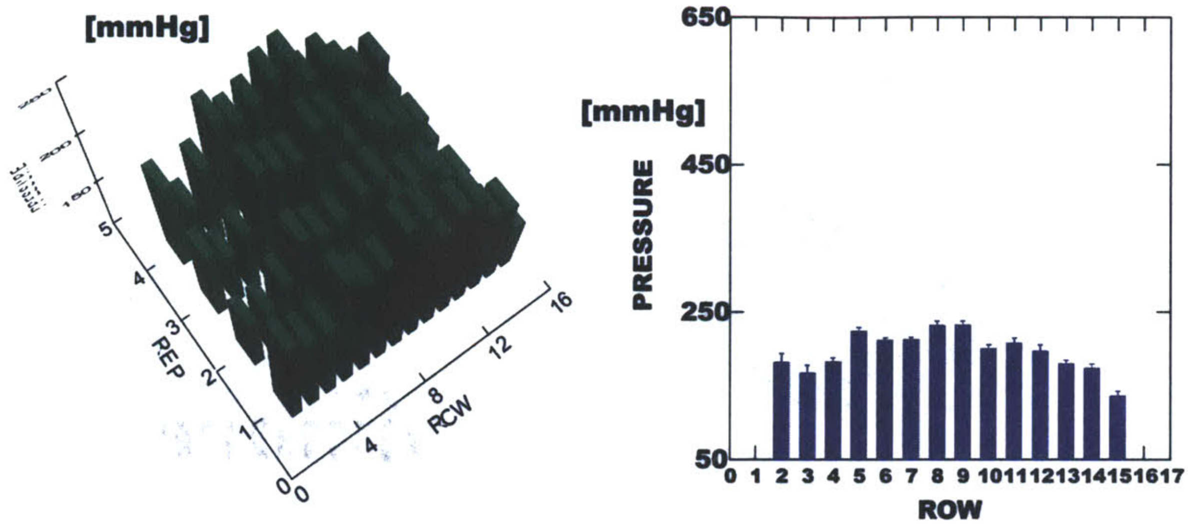
Average Row Pressures Location 2, Day 1



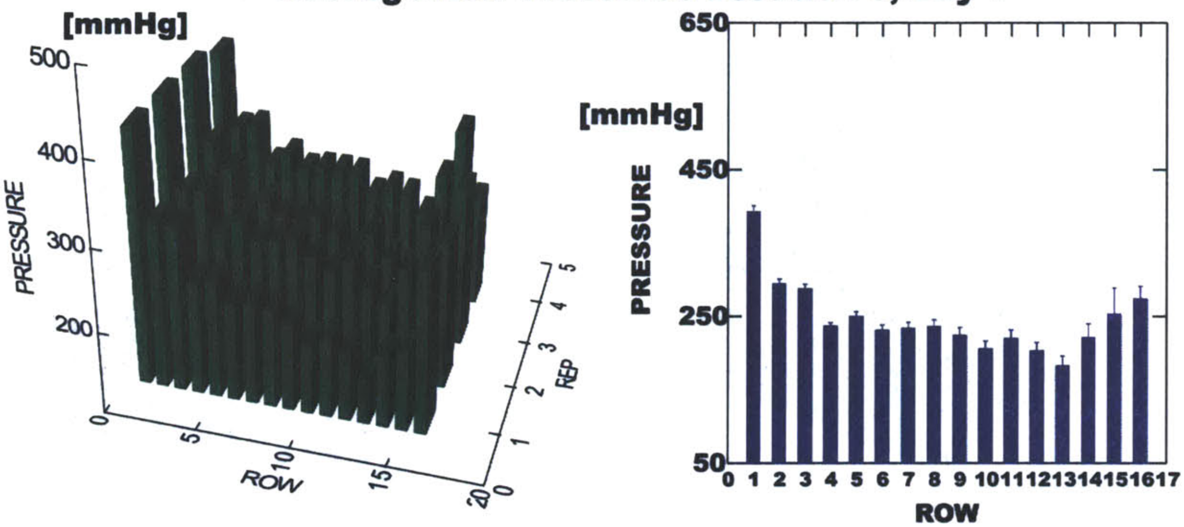
Average Row Pressures Location 2, Day 2



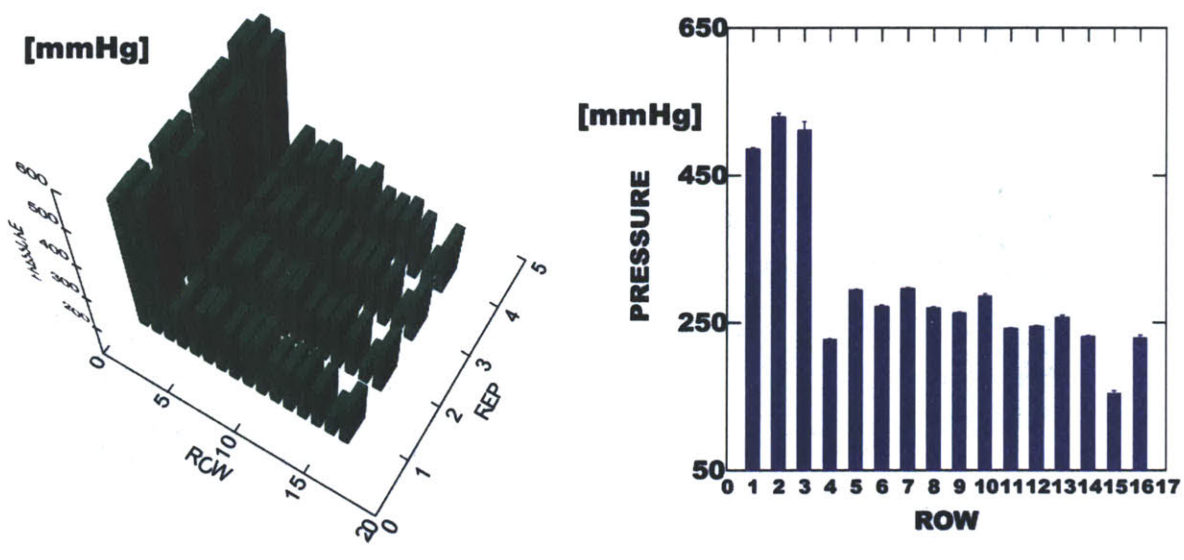
Average Row Pressures Location 2, Day 3



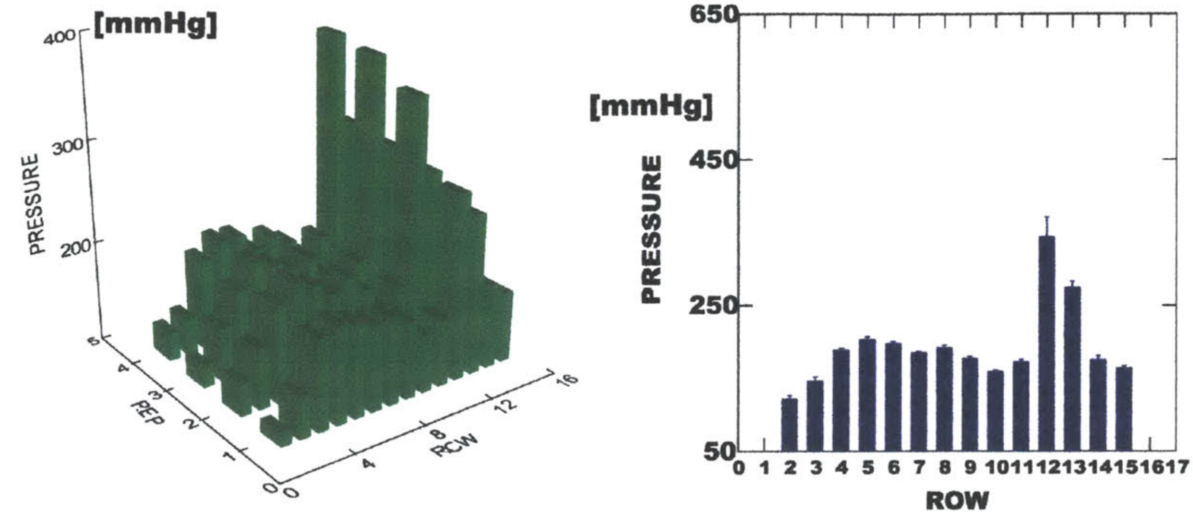
Average Row Pressures Location 3, Day 1



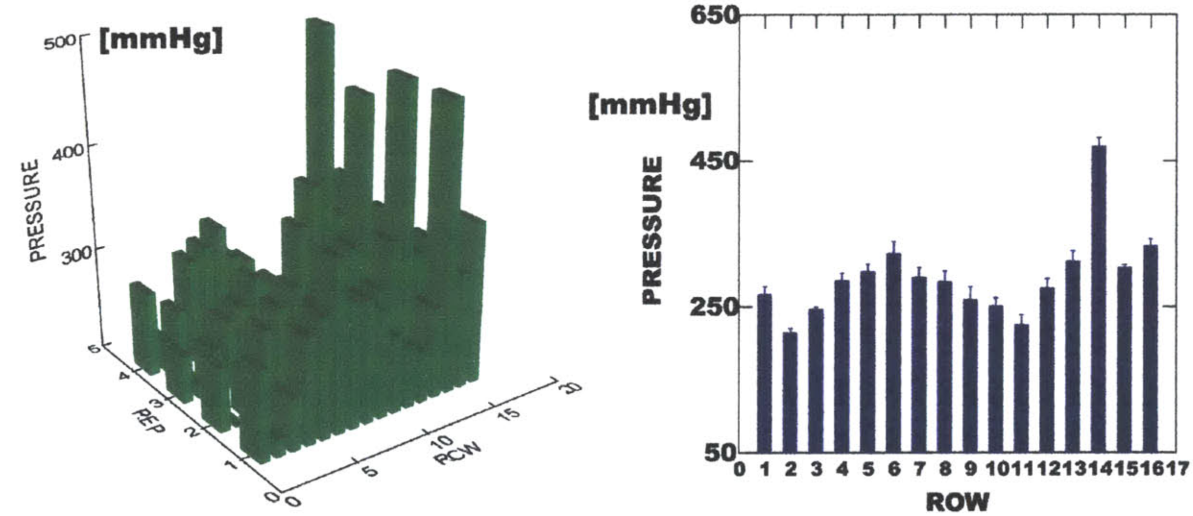
Average Row Pressures Location 3, Day 2



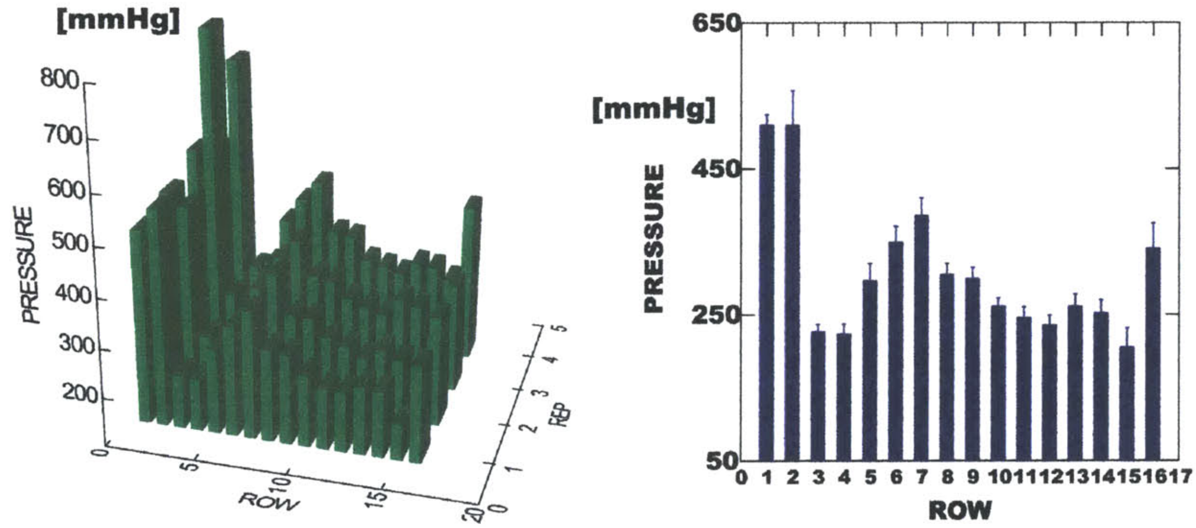
Average Row Pressures Location 3, Day 3



Average Row Pressures Location 4, Day 1



Average Row Pressures Location 4, Day 2



Average Row Pressures Location 4, Day 3

Assuming this is due to the changes in the garment it would suggest that the garment is getting stiffer (E*t is increasing) and therefore straining less. This could be the case, for example, if the garment was undergoing plastic deformation. Alternatively the body could be growing so that the garment was less loose. This is doubtful. A more reasonable explanation would implicate sensor drift.

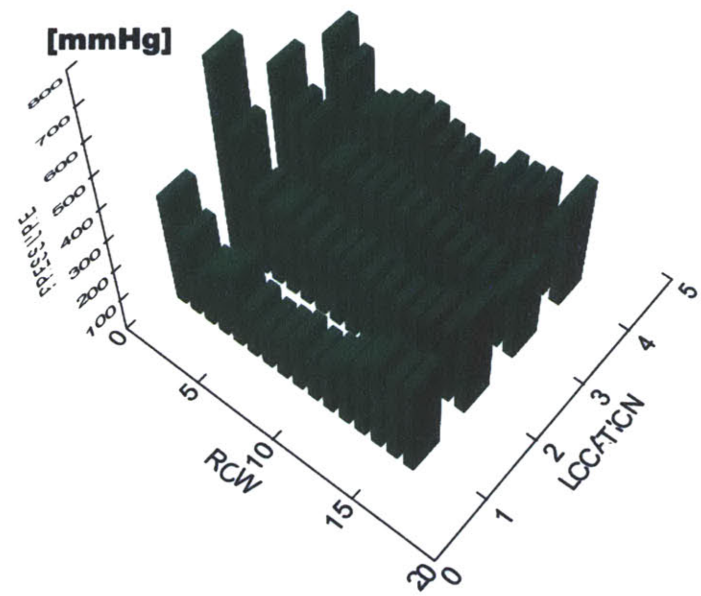
Average Pressures:

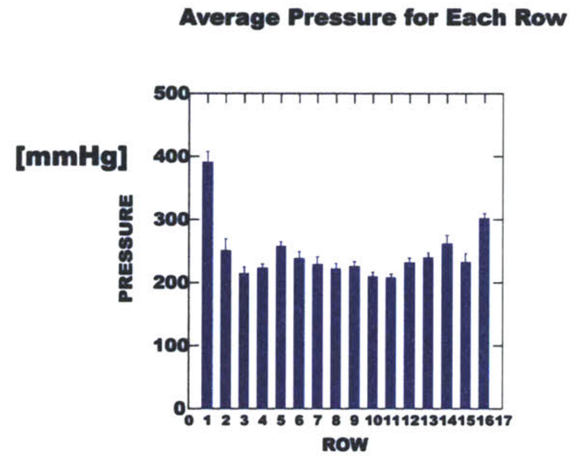
In order to summarize the data in a condensed manner, the altitude data for each day were averaged and accumulated. This resulted in both three and two dimensional graphs depicting the mechanical counterpressure for each row at each location. These plots describe the most global level of analysis and suggest the way the pressure varies around the circumference of the body at different lower leg altitudes (see Fig. 9.34).

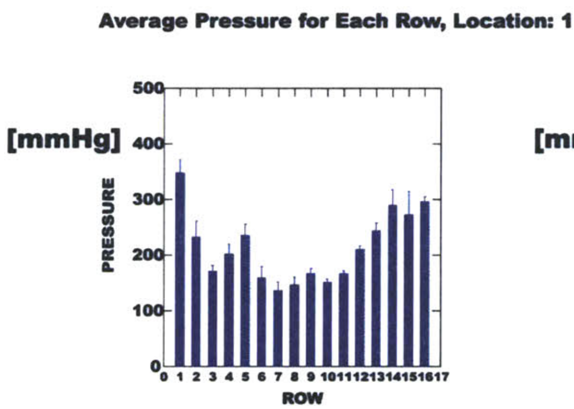
Figure 9.35: (Next Page) Average pressure data for each sensor row for a given location. The top right graph displays row data averaged over location. Notice how close to the channel pressure (207 mmHg) the mechanical counterpressure falls at this level of abstraction.

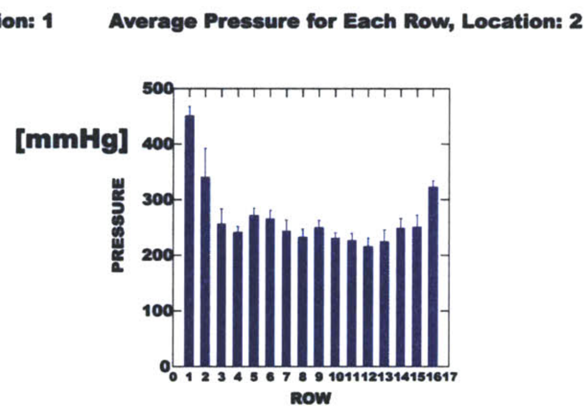
The 2D graph in the upper right corner of Figure 9.35 displays data that is averaged over repetition, day, and cicumfrential location. Although this might represent averages of dissimilar measurements, it is interesting to see that, on average, the pressure of every altitude lies very close to the chan-

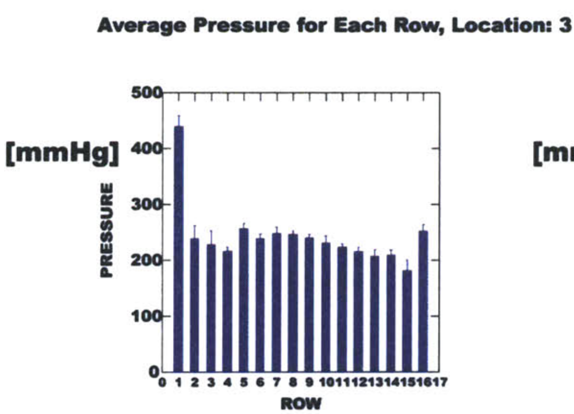
Average Pressure for Each Row by Location

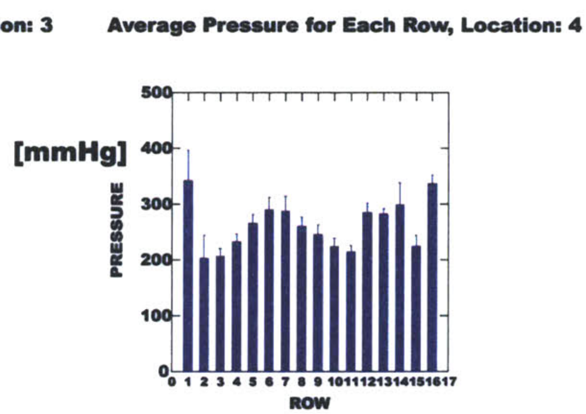












nel pressure (207 mmHg). There seem to be two local maxima, one at row 5 and one at row 14.

This figure seems very promising, demonstrating that there are no major issues with the garment design. It is possible, however, that it is a result of energy conservation rather than successful garment design. As the control volume of the chamber only contains so much energy, one would expect that on average, the energy would be evenly distributed. Future analysis should look into this issue and determine if averaging over so many measurements masks important features, leaving only general physical principles such as total energy conservation.

In location four, there is a hump in rows 4-11 which occurs at the same altitude as the flattest section of the shin. This flat region might cause a large radius of curvature in the channel, leading to high tension, as discussed above. If the radius of curvature in location 4 is lower than the channel radius of curvature, a higher mechanical counterpressure will result. This hump could also be due to the final column of the sensor lying between the zipper and shin. The zipper has a low contact area which could create a large point load, registering on the sensor as a high pressure.

Even at this level of abstraction, it is unclear why the pressure in location 1 is so low. These sensors are directly under the channel and therefore should read atmospheric pressure (207 mmHg). There were some issues with kinking in the hose connecting the channel with the atmosphere. This might lower the channel pressure, although this was always checked and corrected before taking readings.

Another source of sensor error and drift might be due to temperature. Although the sensors were equilibrated and calibrated before tests each day, the sensor was calibrated on the PVC pipe discussed above. This provided evenly distributed pressure, but was at room, rather than body temperature. Perhaps, as the sensors warmed near the skin, they lost accuracy. In the future, the sensors should be equilibrated and calibrated at body surface temperatures.

In the 2D average plot for all days, there is a slight hump in rows 5-8. This occurs in a region where the circumference of the leg changes rapidly due to the contour of the lower leg. This could make the garment slightly looser, but a loose garment should result in lower, not higher, mechanical counterpressure.[2] These humps remain unexplained.

2. This is because a loose garment would allow the channel to bulge more, lowering its radius of curvature, thereby lowering the garment tension and mechanical counterpressure.

CONCLUSIONS/DISCUSSION

In the end, the modeling and prototype work proved successful. The dynamics of the garment around a cylinder were well understood and could be modeled to a high degree of accuracy. Tests on the body did not conform to the model, but provided great insight into future challenges. The mechanical counterpressure was successfully measured and analyzed to show that there were no major design flaws. Instead the data suggested a promising direction for future research. This is discussed in the next section, "Areas for Future Research."

In future work, much attention should be given to reduce the variability of the test set-up between runs. It is still unclear where the sources of variability are entering into the data and it is only once this is controlled that a fuller understanding of the garment dynamics can occur.

10 AREAS FOR FUTURE RESEARCH

In the course of developing the T^X pressure suit, models were created to characterize the design space of the. These models included dynamic structural analysis as well as tools for material property definition. Beyond the pressure producing capabilities of the garment, issues such as flux were considered which allow direct exposure to the explored environment. Depending on the exact configuration of the suit, it was shown that the T^X suit is capable of exposing up to 55% of the body surface area to the environment.

This process has also highlighted several promising research areas that deserve attention. These areas range from issues of analysis and physiology, to design and testing, to construction and production. Many of these topics will be explored in the near future under a NASA Institute for Advanced Concepts Phase II Study starting at MIT in September, 2003.

SPACESUIT THERMODYNAMICS

The broadest understanding of spacesuit dynamics stems from energy considerations, or thermodynamics. Although many researchers have investigated the thermodynamics of gas-filled suits, work should be done to determine the energy required to operate an "ideal" mechanical counterpressure spacesuit. It is clear that if the spacesuit's pressurized volume changes, it will require work. This is true whether the pressurized volume is filled with gas or the pressurized body. Thus, it would be advantageous to determine if the body remains isovolumetric throughout its range of motion.

Although this would be easy enough to determine given a large, contained volume of water with a subject inside, the test set up would be time consuming. The container must be carefully constructed to avoid all leaks so that the motions of the fully immersed subject would translate directly into displaced volume changes. These volume changes could be measured by monitoring the water level. It would be interesting to see how the results change based on whether the subjects held their breath after an inhale or exhale.

Work done while straining the suit material is also of interest for MCP suits. It would be advantageous to know whether or not the total body surface area changes during motion for this would determine one component of the work required to operate such a suit. This test would be harder to perform, but might be accomplished with laser scanning technology. Snap shots of different postures could be analyzed. It is important to note that the surface area and body volume results are independent even if the body is assumed incompressible.

In addition, the subtleties of bending work could be further developed. Iberall's work analysis stated that the material should be designed in the membrane rather than plate region. This was concluded after stating that bending work is inversely proportional to material thickness. These statements seem to contradict as a membrane has minimal thickness, which according to Iberall's analysis, would maximize the bending work. A concrete spacesuit would minimize work do to the fact that it is immobile. Because work equals force times distance, the immobile concrete suit would require no work, in the simple analysis. Clearly this makes no operational sense and therefore needs to analyzed more carefully. Analysis needs to be done to determine relationships between bending work and material properties with the addition constraint of maximizing mobility.

PHYSIOLOGY

Several interesting physiological unknowns presented themselves as well. In order to fully understand the limits of skin exposure, more research is needed. As the strength of the skin varies with body location, it might be possible, for example, to expose more skin on the palms and pads of the hand than the back of the hand. This would allow for greater tactile feedback as well as increased dexterity.

Other physiological tolerances could be refined as well. In regards to a pressure suit, pressure tolerances are required. Currently, mechanical counterpressure suits must be thoroughly tested with blood flow meters and thermometers to determine proper physiology. If extensive pressure tolerance studies could be conducted, these would take some of the guess work out of mechanical counterpressure design.

Although it doesn't seem to be discussed in the literature, mechanical counterpressure could also adversely affect joint dynamics by reshaping the body. For example, the tendon connecting the hamstring to the lower leg creates a powerful torque by stretching away from the femur during flexion. If a mechanical counterpressure suit were to restrict this stretching, the moment arm and therefore the force capability of the joint would be compromised. Analysis should be done to determine bio-mechanical tolerances such as these.

On the positive side, however, research has shown that compressing muscles such as the thigh will increase their efficiency. This effect is leveraged in many athletic arenas such as cycling, running, and now swimming. Mechanical counterpressure could leverage off these results to enhance the capabilities of astronauts. This is to say nothing of active performance augmentation through actuators embedded in the suit itself.

MODELING

For design purposes, it would be helpful to alter the presented model so that it can take into account the unique properties of the body cross section such as it's ability to distort. Clearly these properties depend both body location as well as the location on the cross section. For example the calf is very compliant when relaxed, but the shin is extremely rigid. Fluctuations in time are also important such as those between a relaxed and flexed muscle. Initially, the 3D printed leg could be used to test how sensitive the data is to an accurate rigid form as opposed to the compliant human form. The results from such a test could greatly inform future directions for the modeling endeavor.

Beyond the unique properties of the body, the properties of a mesh material must be considered if a line of nonextension garment is to be used. The model presented in this thesis assumes isotropic materials. This needs to be updated if more detailed design is going to take place with the lines of nonextension.

DESIGN AND TESTING

The pressure suit prototypes produced in this thesis greatly expanded the understanding of the T^x concept. In order to meet stringent physiological requirements, however, more research needs to be done to determine channel design as well as garment sizing and material properties. Beyond non-joint regions, joint regions need to be designed for and tested as well. Although this is a challenging task, it is possible that through collaborations with experienced teams such as the Libelle design team, these issues could be quickly resolved.

The joint regions deserve special attention as the channel placement and garment design are particularly sensitive there. Due to the fact that there are no lines of nonextension on the knee-cap and elbow, it seems that elastic materials must be used. This once again raises the issues of don/doff difficulty encountered by Webb. This critical design area requires much focused research.

In addition, channel placement in these areas must be designed to minimize bending torque. This torque will be determined by the channel's change in volume throughout the range in motion. Inspecting the lines of nonextension it seems that certain lines tend to twist more than bend as the knee bends. This opens up hopeful opportunities for low joint-torque design. Although it is difficult to design and isovolumetric bending joint, it is relatively easy to design an isovolumetric torsion joint. Thus, by running channels along the lines of nonextension, it should be possible to greatly minimize joint-torques. Of course, this does not address the work required to stretch the elastic patches over the outside of the joint. This work could be minimized if active materials were used.

Mechanical counterpressure joint design also presents the challenges of concavities. These could be taken up by bladders, but once again, volume change is an issue. Perhaps these and other pressurized volumes, such as the channels, could be actively controlled by a piston in the life support backpack. If the channels and bladders are filled with an incompressible liquid, the piston need only control for constant pressure/force. Controlling a gas volume would be a more difficult task. Alternatively, clever design of additional reservoirs around the suit could automatically compensate for increased or decreased volume based on their restraint material and tailoring.

Although donning and doffing can be easily accomplished with zippers and accurate tailoring, on-orbit or during mission resizing is a concern. Fluid shifts, muscular deconditioning, and natural body changes all affect body shape and therefore require accommodating design features. Although the prototypes presented in this thesis do not contain these features, lacings, or other sizing mechanisms could be added. The Libelle faces this same challenge and addresses it, in part, through lacings that allow the garment to be tuned locally.[3]

3. Stumpen, Peter. Personal Communications, 2003.

Before more throughout analysis and testing can take place, the test set-up must be revised so that it is more reliable and consistent. Although the foot was not a focus of this thesis, it would make sense to create a gas-filled sock so that instead of creating a vacuum chamber that is penetrated by the limb, the limb can be surrounded by the chamber, much like a glove box. This would reduce the variability that comes about due to the leaking of the latex gaskets. This would also prevent the chamber from riding up the subject's leg as it did in the tests for this thesis. If the vacuum chamber used in this thesis is to be used in the future, it should be outfitted with a stirrup-like mechanism to prevent chamber migration.

CONSTRUCTION AND PRODUCTION

Before the Tx suit can become fully operational, a line of nonextension mapping tool needs to be developed. The most applicable technologies seem to be laser scanning and advanced motion tracking systems. If the surface of the skin could be analyzed during its motion, a flow field could be constructed and analyzed in order to reveal the lines of non-extension. This work could be realized by such systems as those presented in P. Vescovo's paper, "Optical analysis of displacement and strain fields on human skin."[1]

Creating a line of nonextension garment is also a time consuming process that could be stream-lined. Several computer technologies suggest their applicability to this endeavor. First, much like the current Phase VI EMU glove, CAD/CAM packages could be used to pattern and cut garment sections.[2] If the lines of nonextension were stored digitally along with a full body scan, mesh pattern pieces could be generated automatically and sent to assembly. The laser scanning and tailoring process is already used for such systems as the Libelle anti-g suit.[3]

Non-woven possibilities also exist for creating a line of nonextension garment. Technologies such as electrospining hold great promise in this area. Although controlled deposition of fibers is still an area of ongoing research in the field, electrospining holds the potential to generate a one piece line of nonextension garment out of extremely strong fibers such as kevlar or carbon nanotubes. This would allow the creation of an extremely thin garment with a large degree of exposure.

CONCLUSION

The T^x suit holds much promise for the future of space explo-

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3. Stumpen, Peter. Personal Communications, 2003.

ration. Through clever design strategies and increased understanding of physiology, the concept promises the capability of a minimum joint torque spacesuit as well as dramatically altering the space exploration paradigm. The ultimate goal of the suit would be to facilitate free exploration. To meet this challenge, a technical roadmap will be developed as part of the upcoming NIAC Phase II study. In addition cultural investigations will continue to take place in order to reveal, highlight, and expand the cultural potential of space exploration.

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PART III: HUMANE PERFORMANCE IN EXTREME ENVIRONMENTS

11 HUMANE FACTORS: A SUMMARY AND EXPANSION

> "Before the question of **What can we do?** one has to ask **How must we think?**"
>
> - Joseph Beuys
> "Apeal for the Alternative"

> "only new ideas can lead to the achievement of a new reality."
>
> - Joseph Beuys
> "We are the Revolution"

The T^X suit explored and presented in this thesis is a work of body design and/or facilitation. As discussed throughout, the process of designing a spacesuit is intimately connected with thoughts, feelings, and beliefs about self and purpose. As the spacesuit is a wrapping between explorer and explored, it has the ability to facilitate or censor capabilities of the body. The spacesuit designer must have a strong vision of what body(ies) should be brought to the endeavor of exploration.

In the conception of the T^X suit, various aspects of the body were considered and investigated. Works such as Oskar Shlemmer's study of stage costume suggested the many possible depictions/roles of the body and how they might be leveraged in the design of a garment. His work also made it clear that one aspect of the body can be highlighted while suppressing another. An organic, human balance must be reached in order to foster exploration in all its forms.

When considering the body, non-material, non-quantified elements were also considered. Although our science is profoundly useful in discovering and explaining cause and effect relationships, it is limited in that it typically censors all else.[1, 2] Eastern depictions of the body were used as inspiration to consider the role of the body above and beyond it's material existence. In addition, aspects such as mobility were reconsidered and given importance above and beyond the "practical utility" of object manipulation.

1. "today's concept of science has an extremely partial significance, and is certainly not anything that extends to all of man's problems, because it is based prevalently upon the laws of matter. And what refers to matter cannot – necessarily – refer to life."
-Joseph Beuy
'We are the Revolution's

2. "Science, in modifying environmental conditions, sets itself up as a revolutionary factor. Yet, effectively speaking, is this a question of freedom in the full sense of the word? Scientific freedom has its limit in the inexorable demands of logical thought."
-Joseph Beuys
'We are the Revolution'

These conceptual investigations displayed the spacesuit as a metaphysical object with the ability to free or confine the wearer. Because of the power of such a garment, preconceptions and assumptions must be made apparent so that the wearer is not subjected to the designers tyranny. Much like Lebbeus Wood's "an-architecture,"[3] the Tx suit strives to be transparent and non-dictatorial, allowing the individual limitless, personal freedom in the extreme environment.

3. Woods, Lebbeus. *Anarchitecture : architecture is a political act* London : Academy Editions ; New York St. Martin's Press, c1992.

Pursuing these ideas further required quantified, technical analysis as well as a continued concern for belief and human experience usually found in spiritual practices or the arts. In many ways, the technical aspects of this work can be seen as a feasibility study or initial investigations into the realities of creating such a garment. Central to these investigations were topics such as human physiology, physics, and engineering. These fields provide immense capabilities for understanding and shaping the material world. Endeavors such as this one we be nearly impossible without them. Although concepts, beliefs, and assumptions are of central importance, achieving a physical object that can be experienced and explored is the ultimate goal. Only in this way do the philosophies manifest themselves in such a way that they can truly interact with others and have a life of their own.

There is clearly much work that needs to be done in order to reach the goal of a fully operational T^X garment let alone complete spacesuit. In order to reach this goal, however, engineering principles will not be enough. This endeavor must be pursued with constant connection to the original inspirations and beliefs from which it was born. It must consider the human in ways not typically considered in engineering or science. Although disciplines like human factors engineering will clearly hold a pivotal role, a broader vision must be explored: humane factors engineering.

Humane[4] factors would consider all avenues of thought and experience. It would be a playful endeavor and as such would allow those involved, both creators/designers and users, to be truly free and genuine humans. As a playful endeavor, the concept of humane factors is also highly artistic. [5]

4. Main Entry: hu·mane
Pronunciation: hyü-'mAn, yü-
Function: adjective
Etymology: Middle English humain
Date: circa 1500
1 : marked by compassion, sympathy, or consideration for humans or animals
2 : **characterized by or tending to broad humanistic culture** : HUMANISTIC <humane studies>
-Merriam-Webster Online
http://www.m-w.com
(Emphasis added)

5. "I should like to quote Schiller once again: 'Only the man who plays, free from the restraints of logic, sensitive only to the fascination of the beautiful and aesthetics, only the man who determines his own fate is a free man.' ... He considered that man was a man only in play, and that only in play is he free, And, as such, a real man! "Therefore art, understood in the sense of play: this is the most radical expression of human freedom."
-Joseph Beuys
"We are the Revolution"

ART

> "art is not an aesthetic operation regarding the skin but, instead, it concerns the interior, the inner nature of things."
> -Achille Bonito Oliva

There are so many notions of the word "art"[6, 7, 8] that I would like to communicate the notion that drives me forward. Especially in the technical world, "art" usually conjures visions of painting, sculpture, photography, and other "fine arts." Also associated with this word are terms like aesthetics and beauty. Although clearly these are all elements of the term "art," I am much more interested in the mode of understanding which lies beyond and behind these manifestations. Just as it would be wrong to consider the discipline of engineering to be

6. For me it's that feeling or that sense that can't be quantified, that can't be contained, that can't necessarily be named.
- Ann Hamilton

7. You don't say what it is. You say, "What is it?" ... Then we can go home and think about it."
- Robert Wilson

8. Meaningless work is potentially the most abstract, concrete, individual, foolish, indeterminate, varied, important, art-action-experience one can undertake today. ... Meaningless work can contain all of the best qualities of old art forms such as painting, writing, etc. It can make you feel and think about yourself, the outside world, morality, reality, unconsciousness, nature, history, time, philosophy, nothing at all, politics, etc. without the limitations of old art forms.
- Walter De Maria

bridges and aqueducts, it is wrong to consider art to be limited to specific media.[9]

Many accuse art of lacking definition. Many view Artists as hitch-hikers on the highway of progress. Indeed, many are jealous of the limitless potential of artistic activity and therefore grow to represent both the practitioners and their artifacts. This lack of formal limitations, however, is the ultimate justification for, and definition of, art.

Just as other paradigms shape us and focus our perception on identified goals, art focuses us on exploring all aspects of our human existence without limitation. Scientific discourse considers the mechanical, material, and energy aspects of our existence, but we all know from experience that there is more. That "more" is culture.[10] The "culture of science," or any other field, describes the human activities and interaction that take place within that field. Thus, the *culture* of science is precisely the *humanity* of science. It is exactly this humanity which is at the heart of art; it is exactly this humanity which is at the center of humane factors.

Some would argue that science and engineering take culture and humanity into account through such disciplines as Human Factors Engineering. A look at the history, utility, and

9. "when I speak about art, I can only say that there are two kinds of art: the traditional art, which is unable to bring up art at all, or to change anything in society or in the ability and the joy for life; and then, there is another kind of art, which is related to everybody's needs and the problems existing in society. This kind of art has to be worked out at the beginning; it has to start from the molding power of the thought as a sculptural means. If this sculptural agent is not active in the beginning, it will never lead to result in any physical form; or the physical form will only be pollution for the world and will only enrich the whole rubbish of production we already have."

-Joseph Beuys
Energy Plan for the Western Man

10. Main Entry: 1cul·ture
Pronunciation: 'k&l-ch&r
Function: noun
Etymology: Middle English, from Middle French, from Latin cultura, from cultus, past participle
Date: 15th century
2 : the act of developing the intellectual and moral faculties especially by education
4 b : acquaintance with and taste in fine arts, humanities, and broad aspects of science as distinguished from vocational and technical skills
5 a : **the integrated pattern of human knowledge, belief, and behavior that depends upon man's capacity for learning and transmitting knowledge to succeeding generations** b : **the customary beliefs, social forms, and material traits of a racial, religious, or social group** c : the set of shared attitudes, values, goals, and practices that characterizes a company or corporation

- Merriam-Webster Online
http://www.m-w.com
(emphasis added)

paradigms of this field, however, shows that within this discipline humans are abstracted, via quantification and equations, into cogs in a machine.[11] As applied science is concerned with creating machines, it is only within this context that humans are considered. As an alternative, I propose a new notion, closer to humanity: human*e* factors. Although humane factors is capable of considering such mechanical concerns as ergonomics, it also reaches beyond to philosophy and intuition. It is capable of doing this because it does not rely on quantification or an objective reality. Instead it is a branch of artistic inquiry, free from these limitations or any others except those that are self imposed.[12]

11. Mindell, David A. Between human and machine: feedback, control, and computing before cybernetics, Baltimore : Johns Hopkins University Press, 2002.

12. "We must come to realize the extent to which we are controlled and governed not by things themselves, but rather by our ideas about things, by our visions, and by our images of things."
- Lucrezia De Domizio Durini
The felt hat: Joseph Beuys, a life told

In that art considers the whole of a human's capabilities, it represents a paradigm of freedom: freedom from the constraints of thought defined by other paradigms.[13, 14] In this depiction, art represents creativity no matter where it is manifest. As creativity is something that springs from free will, it is above and beyond the mechanics of life and survival. Thus, as Scott McCloud noted, art is "any human activity which doesn't grow out of either of our species' two basic instincts: survival and reproduction."[a]

13. "a radical model of freedom, art"
-Joseph Beuys

14. "Man is only truly alive when he realizes he is a creative, artistic being."
-Joseph Beuys
Energy Plan for the Western Man

a. As noted above, many feel uncomfortable with this concept of art due to its "lack of definition." It should be noted, however, that it only lacks definition as a paradigm, thus, societal, political, or cultural limitations are frequently placed on it, for right or wrong. Although, by this definition, anything *can* be art, not everything is, and all that is art is not necessarily good, or good art.

Due to the history of engineering, science, and technology, the statement, "engineers are human" seems to suggest extreme limitations. Typically if things go wrong engineers talk about "human error" and make statements such as, "we are only human." Why "only?" The situation has gotten such that the word "only" can be removed and the statement still belittles the human state. If not human, what? Machine? Matter? Certainly not animal for that seems like an "even lesser" position. The only other option seems to be some version of a spiritual, omnipotent being, but how can science and technology suggest that possibility when it is clearly not a scientific entity? The situation needs to be rectified so that we can celebrate life and the true spiritual, philosophical and analytic capabilities of humanity. We must come to realize that we *are* omnipotent in that we are made up of the universe, and the Universe is omnipotent in all senses. As one of the conscious appendages of the Universe we demonstrate the consciousness of the Universe. In all ways, we make up (at least a fraction of) the consciousness of God/Universe/Cosmos.

12 SPACE CRAFT

Space Craft: ('spAs "kraft); *n.; Date: 2003;* 1) the crafting of space; 2) the craft of working with, manipulating, expressing, and experiencing space; 3) articulated space.

Bearing similarity to "spacecraft," the notion of "space" referred to by "space craft" is larger than the vacuum that exists beyond the earth's atmosphere. Space exists in all dimensions, physical and non physical: psychological as well as measured space.[a] Although it need not contain any matter, it is a profound medium of expression. It is the primary medium, existing before any thought or consciousness interrupts.

As space exists in all realms, so should Space Craft. Length and time can be measured, but they represent a highly refined, limited notion of space. In order to fully grasp the space of reality, we must explore it on personal, emotional, intuitive, and spiritual levels as well. It is this space explora-

a. Contemporary Physics considers n-dimensional space. Last I checked, Superstring Theory contained 16 dimensions. Although I used to consider these dimensions to literally be measurable lenghts mutually perpendicular to the length, width, and depth of 3D, perhaps these other dimensions are other aspects of experience such as emotion, belief, consciousness, and intuition. Considered in this way it is easier to conceive of a multi-dimensional universe. In fact this conclusion seems obvious; clearly our experiences of reality are multidimensional. I never *could* picture hypercubes in four or more dimensions!

tion that contains the utmost possibility for expanding our intelligences and informing culture.

THE CASE FOR SPACE EXPLORATION

The argument that Space exploration is validated by technology spin-offs is misleading. Any goal pursued intently will produce "spin-offs." Yes, the goal of space exploration (manned and unmanned) has brought about technologies that were unavailable before, but that is what any pursuit is about: the ability to think/create/do in ways that were never before possible. The directed, goal-oriented, abilities of any pursuit can be abstracted into larger, less directed abilities which can be applied to any intent, thus producing spin-offs.

I would like to suggest that you can never find the motivation for space exploration in a logical way. Space endeavors are not about the highly mechanistic gears of logic and reason, although much logic and reason is used in order to carry them out. Space endeavors are about the opposite, the elements that make us human, above and beyond the molecular billiards that science has made us into. They are truly an act of humane factors engineering.

SPACE MAKE-UP

In the 1980's and '90's, women astronauts had the option to carry with them a space make-up kit. The kit contained all that was necessary to transform a disheveled astronaut into a well kept Houstonian. Rationalized as a required amenity for video conferences and public appearances, kits like this flew on many missions. Initially horrified to discover its existence, I grew to admire it for its humor and tenderness amidst the stoic technopoly of aerospace engineering. It stands as a key-hole through which art has already entered the weightless realm.

When viewing space exploration as an extreme expedition much like the attempts to get to the North or South Pole, the kit is shocking. Weight and space are so precious in space that frivolous items like these are rarely allowed. After-all there are certain amenities one must due without when inhabiting extreme conditions. Thoughts like these frame the make-up kit as frivolous, irrational, and ridiculous.

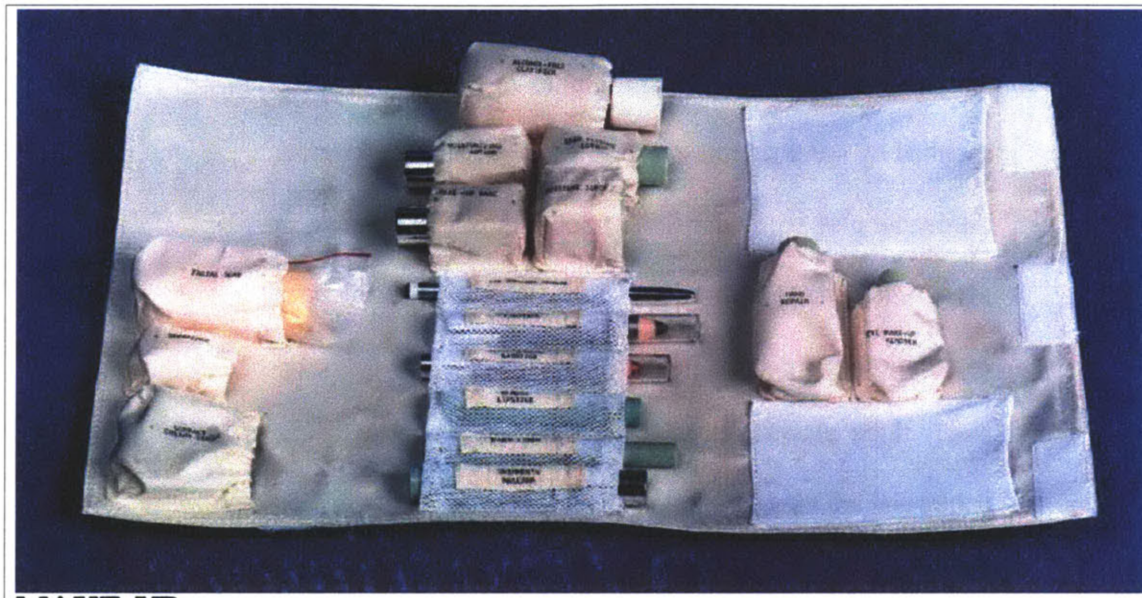
With time the idea grew on me as I saw it in a new light. It was not a frivolous invader into the pristine, rational realm of rocket science, it embodied one reason why we were there. Space exploration is the ultimate exercise of self definition through choice. Just as the spacesuit asks what body we want to bring, space exploration asks what we are willing to work towards. Our answers reflect our definitions of ourselves and our beliefs on a societal and world scale.

Figure 12.1: (Opposite Page) NASA Space Make-Up Kit. All photos and information courtesy of NASA.

When traveling in a vacuum there is little opportunity to pull resources from the environment and thus one must seriously consider what can and should be brought along. Items of sustenance and survival are the first considered: air, water, and food. Systems designed to mesh with natural body functions are designed and built so that hardware and body can exist in symbiotic relationships. As the body becomes mechanized through its dependence on the hardware, the machine becomes humanized.

The biggest question, though, is why are we there? Is our goal to simply sustain life in space, encapsulated and isolated from the extreme environment? Is survival the ultimate goal, or is there more? There are rationalized, quantified, benefits of science and technology development,[b] but there is more: life. Whether conscious or not, it is impossible to send a human without sending humanity as evidenced by the space make-up kit.

b. All of these investigations focus on matter, as opposed to life. Even biology experiments focus on the mechanics that make life possible, but are unable to truly investigate the experience of living, or what it *means* to live.



MAKE-UP

Part No.	**528-20357**	**-1**	**Clinique Creamy Blush**
		-2	**Clinique Blush Compact Assy**
	528-20728	**-21**	**Clinique Skin Texture Lotion**
	528-43067	**-1**	**Clinique Mild Facial Soap**
		-2	**Clinique Hand Repair**
		-3	**Clinique Touch Liner**
		-6	**Clinique Lipgloss**
		-7	**Clinique Eye Shadow (Violet)**
		-8	**Clinique Eye Shadow (Quartz)**
		-9	**Clinique Swimmer's Mascara**
		-10	**Clinique Eye Shading Pencil**
		-11	**Clinique Eye Pencil Sharpener**
		-12	**Clinique Moisturizing Lotion**
		-13	**Clinique Make-Up Base**
		-14	**Clinique Stay True Makeup Base**
		-16	**Clinique Plum Brandy Lipgloss**
		-17	**Clinique Mascara, Swimmer's (BLK)**
		-18	**Clinique Eye Shading Pencil (BLK)**
	528-20728	**-22**	**Clinique Skin Texture Lotion**
	528-43025	**-1**	**Skin Emollient, Aloe Vera Gel**

Description:

- Crew preference makeup items

Weight: Varies
Volume: Varies
Type: Consumable
Restraint: Stowed when not in use
Stowage: Standard Stowage Trays

Development Lineage:
Modified Off-the-Shelf products
Vendor: See Above

Contact: Anna Burt

Many space activities highlight the humanity of the astronauts, but there are few manifestations of humanity that are supplied by space administrations. In moments of relaxation, astronauts play with their food, tumble in weightlessness, or even swing dance. All of these activities involve an open exploration of weightlessness capable only in play. Unfortunately these playful activities are rarely celebrated with the public and are viewed as cute side notes to the otherwise serious mission goals, rather than being relished for what they are: humanity, culture, art.

The space make-up kit represents an administration acknowledged humanity in space. As such it steps beyond human factors into humane factors. It is an art kit supplied for the sole purpose of human expression. It does not suggest a goal or objective, but merely exists as a opportunity for expression. Unlike most of the activities that astronauts perform, using the space make-up kit is not programed by a sequence of operations or tasks. It exists as an opportunity for pure human creativity: the ultimate potential of human existence.

c. For purely human explorations of flight, see the work of Panamarenko.

All space hardware contains human aspects, and rightly so.[c]

Looking at the Saturn V rocket that took us to the Moon, it is incredible, in fact ridiculous, to realize that despite its tremendous size and complexity, it is only the upper-most cone of the stack that contains the inspiration and quest: human passengers (see Fig. 12.2).

All the technology of transportation and life support in space exploration is truly secondary to the ultimate mission goals; they exist as facilitators. The only fascination behind these objects is their capability to transport humans into a new realm. There is immense human ingenuity behind these devices, but their purpose is to allow humans, humanity intact, to explore, to *play*, in a new environment so that they can return to their own with new eyes. The history of technology development behind each screw and connection is a fascinating story of challenges encountered and surpassed, but we must not let it distract us from the ultimate goal: cultural knowledge development.

Figure 12.2: (Next Page) The first test flight of the Apollo Saturn V Moon rocket. At liftoff the 111-meter (363-foot) vehicle weighed 2,821,356 kilograms (6,220,025 pounds), with the first-stage engines producing 3,401,943 kilograms (7,500,000 pounds) of thrust and burning 13,608 kilograms (15 tons) of fuel per second. Color transparency taken by the Intermediate Ground Optical Recording Camera (IGOR) shortly after liftoff. Apollo 4 (unmanned), November 9, 1967. Image and text from the book ***FULL MOON*** by Michael Light, copyright 1999/2002.

The universe, matter, energy, and all things unknown, exist with or without our discovery of them. They go on functioning and changing as their interactions dictate. Our interest in deriving theories from our observations is not for the universe's benefit, but for ours. Our machines are not important

because they add new capability to the universe. Through their creation they demonstrate that the universe, by definition, already held this capability. They are important because of the ways they interact with humans, with humanity, with culture. As creators of capabilities via technology, engineers must actively engage this cultural dimension of their work. As a society we must not become blinded by our intense quest for "objectifiable" physical truth. We must realize that this truth is centered on matter and energy, without life. Our sciences are extremely well equipped for these dead substances, but are not capable of dealing with life in its full glory.[1] *Life* is the underlying goal we all seek.

HUMAN EXPLORATION OF SPACE

As former astronaut Dr. Jeff Hoffman has stated, exploration is "everything that expands the realm of human experience and of human consciousness."[2] Exploration is about expanding our awareness of existence on all its levels. Thus, explorations can focus on those things that are exterior or interior to our own consciousness. As many yogis, meditators, or philosophers attest, there is plenty to explore internally without ever leaving the confines of a room. Indeed, as the body is the

1. "If [materialism, the concept of science] is considered from an historical point of view, and one asks oneself on the basis of what method this concept of science - or why it has cropped up today - really acts, then a need emerges to hearken back to the entire history of philosophy. ... The ancient mythological nexus talked about life more than anything else, whereas the whole of [Plato's analytical] speculative line concentrates on death: that is, on matter. Matter is not at all suited to the depiction or representation of life. It consists of metrically measurable values, values that can be placed on scales, values whose length can be measured – all actions that can be performed on dead matter. These fail in man because man is not a dead but a living being. On the other hand, however, it becomes clear that it is necessary to face death, that one must pass through the phase of death. With a view to future development, as well, through thought, it is first necessary to know death. In the first phase death has to be experienced in order to be able later to think exactly, abstractly, in terms of natural science. I believe that this is the methodology within philosophy: they are all reductive procedures, methods of reduction. The concept can be formulated in a different way: by saying that it has been proved (or else it will be very clearly seen in the future) that the first phase of the development of human consciousness – that is, of the process of liberation – must necessarily pass through death."
- Joseph Beuys, 'Conversation between Joseph Beuys and Achille Bonito Oliva, 1972' *A Felt Hat: Joseph Beuys, A Life Told.*

2. Annual Massachusetts Space Grant Consortium lecture, May 1st, 2002.

primary sensor or receiver,[3] even physical explorations requiring travel and distance are simply new conditions in which to explore inwardly. By paying attention to the internal reactions to the external stimuli we come to know both universe and self.

3. Recent advances in medical and communications technology have expanded our body's capability to function as a permeable sensor, transcending many limitations of its physical shell. As we move through these new environments, we are therefore in continuous osmotic exchange with them ...

- Carin Kouni

Scientific and artistic explorations are similar in that they both explore and probe the nature of reality. Physical explorations such as those to the moon or on the far corners of the earth usually involve experiments of some kind. These experiments probe the alien reality, bringing a new internal understanding to the human explorer. These measurements become a language through which a new reality can be communicated to a larger audience, once again altering the internal aspects of the receivers.

Whereas scientific explorations focus on measurements and the search for objective reality in order to seek internal understanding, art focusses on the individual and their personal means of coming to terms with the explored. Although certain measurements might be taken to facilitate the process, measurements are not the goal. Instead, a personal, intimate, understanding is sought through any means necessary. This understanding is then communicated to a larger public through actions that strive for personal communication, not necessarily "accurate" documentation. In this way scientific and artistic explorations both strive for internal understanding, but differ in their focus and means of communication.[4]

4. In our attempts to decipher the world's mysteries, we rely on art as well as science to gain an understanding of the structures inside and outside our bodies, to break through the current boundaries of knowledge, and to reveal new ways of seeing.
- Barbara Clausen

The question and answer session of any public lecture given by astronauts usually begins by a small hand being called upon. The young individual, routed on by a parent or two, timidly asks, "What's it like in space?"[5] Although there is plenty of literature to be read on the environment of space including temperatures, light conditions, pressures, etc., it is clear that none of these quantifications could ever answer the question. What the public seeks is a human experience that they can slip into, so that they too can experience the wonders of alien realities.

5. When people find out that I am an astronaut the first question they ask me is, "What's it like in space?" This is a simple question, but think about it for a moment. It is a very human question that we would never think of asking a machine, even though automated space probes do a superb job of measuring temperatures, pressures, and many other aspects of their surroundings. But this is not what people are asking. They want to know, "What is it like to be in space?"
- Jeff Hoffman, Massachusetts Space Grant Lecture, May 1, 2001

Connecting into a larger human culture is the ultimate responsibility, the entire purpose, of any exploratory mission. Currently the primary culture that the space programs connect into is the scientific community. It is *their* experiments and data that are transported back and forth between orbit and the labs on the ground. *They* are the ones privy to the information and its interpretation. *They* are the ones intensely interested in the results. As Jeff so clearly noted, this is not the primary interest of the world community.

Space exploration must focus more attention to connecting with human culture on the broadest scale.[6] The current situation seeks measurements, leaving human experience as a residual effect.[7] Although humans cannot travel without bringing their humanity, this should not be seen as a mere added benefit, for this is of primary interest to humanity. Although technically trained astronauts do an inspiring job of relating their human experiences, this is clearly not what they've dedicated their lives too. The paradigm of science and technology is not one of human expression, but one of measurement, quantification, and "objectivity." In many ways, the quest of these fields is to remove humanity from the discussion. In order to truly explore the human experience of space we must allow and encourage astronauts to explore the full extent of their humanity while in orbit. We must, therefore, look to those that have dedicated their lives to human expression and culture: artists.[h]

Books on famous explorations, or photography from distant lands illustrate the effect on culture that artistic explorers have had. Typically, though, this recognition is limited to

6. An important part of the tradition of exploration is to report on your travels and your discoveries, to share your experiences with other people, and ideally to make the new territory you explore part of general human culture and human consciousness.
- Jeff Hoffman, *op. cit.*

7. I need to make a disclaimer and remind you that NASA does not send me or my colleagues into space so that we can see beautiful views or experience the physical bliss of weightlessness. ... We were sent there to do important work.
- Jeff Hoffman, *op. cit.*

h. This is not to say that artists should necessarily be the sole explorers of space, but they should certainly be a fundamental part.

artistic documentation of otherwise scientific explorations.[9] Although artistic documentation is a further exploration of the environment, for the most part, it takes place after the fact and is therefore only accessible to the consciousness left over after the scientific work is done. It is clear that artistic exploration within the alien environment would explore vast experiences inaccessible by scientific methods, and, perhaps, it is artists that are best able to communicate subjective human experience.

As to the age old question of robots and humans, this notion of artistic exploration makes certain choices clear. The point is that humans are the only means to achieve a personal understanding of an alien environment. Although many argue the benefits of human exploration by talking about human physical capabilities, this justification misses the point.[11, 12, 13, 14, j] Humans are not simply manipulators capable of extreme dexterity, nor are they merely advanced computers capable of amazing feats of real-time flexibility.[16] They are *human*, a distinction that brings spiritual and emotional capabilities such as empathy and identification.

As Oskar Schlemmer stated, "A further emblem of our time is *mechanization*, the inexorable process which now lays

9. I hope that at least one of [the human explorers of Mars] turns out to be another Jack London, who will be able to give the rest of us who will never go there a sense of what Mars is really like, not just data, not just the views, but a sense of what it is like to be on Mars.

- Jeff Hoffman, *op. cit.*

11. The overwhelming majority of scientific and utilitarian achievements in space have come from unmanned, automated and commandable spacecraft...

The burden of experience is that, apart from serving the spirit of adventure, there is little reason for sending people into space.

- Van Allen

12. One of the foremost uses for human resources in space is to provide technical support... The alternative of providing failure-proof instruments capable of long term, complex, remote operations in space is simply not practical within the limits of engineering practice and cost, as we know them today.

- Banks and Black

13. The International Space Station is not a platform for cutting-edge science. Unmanned probes can explore Mars and other planets more cheaply and effectively than manned missions can. And a moon colony is not in our destiny.

- Fancis Slakey

14. Human capability is required to install and maintain complex scientific instruments and to conduct field exploration. These tasks take advantage of human flexibility, experience and judgement. They demand skills that are unlikely to be automated within the foreseeable future. A program of purely robotic exploration is inadequate in addressing the important scientific issues...

- Paul D. Spudis

15. Anything you can identify to do in space you can do more efficiently, more effectively and more safely with machines. ... when you put humans on a spacecraft, you limit its capabilities to do exploration and research because the primary function of the space craft then becomes getting humans back alive, not conducting the mission.

- Alex Roland from ABCnews.com

16. There is another area where human presence has an advantage that transcends just the ability to manipulate objects physically. ... In unplanned time-critical situations, humans are far more efficient and flexible than even our best robots.

- Jeff Hoffman, *op. cit.*

j. Typically the debate is one centered on money and risk. There is no question that human missions cost far more than robotic missions and are inherently more risky due to the lives on board. From here the debate usually turns to scientific gain and the other rewards capable from each type of mission. Because robots have the upper hand in terms of money and risk, the pro-human side typically tries to make the argument that humans can accomplish more than robots due to their flexibility, dexterity, and thought process. In a debate centered around quantified utility, the pro-human side of the debate quickly becomes, "humans are the best robots."

Unfortunately, the statement, "humans are the best robots," when combined with positivism, the culture of technology, and the search for objectivity, quickly becomes, "robots are the best humans."

The horror around such a debate is the devaluation of human existence. Space exploration can be seen as an exercise in determining the relative value of things when faced with extreme isolation. If our argument for human presence is that they are the best mechanical devices around, we are not placing humanity on our "top ten list" of most valued traits. What does this say about our self-image?

claim to every sphere of life and art. Everything which can be mechanized *is* mechanized. The result: our recognition of that which can *not* be mechnanized."[17] Thus, the rationale for humans in space is not their physical dimensions or capabilities, but their humanity, their culture, their spirit. Humans and machines are apples and oranges. To compare them as equals is to be blind to life.

17. Gropius, Walter, and Wensinger, Arthur S. *The Theater of the Bauhaus*, John Hopkins University Press, Maryland 1961

This realization also adds insight into the fervor of the human-robot space debate. The paradigm of science and technology is one of quantification and utility, but this is not the way most people live their lives, nor are these things dearest to them. As Jeff noted, "In general, decisions about using humans or automated systems in most endeavors are made on the basis of utility and economics," but clearly this misses the essence of life. The either-or debate over humans and robots in space does not merely resemble the religious, it *is* religious:[18] it is about the individual's construction of reality. No matter what equations or quantifications can be produced, they will always miss the point. There are those who believe that their reality is constructed solely of quantifiable parameters, and there are those who focus on the non-quantifiable. In many ways, space is the arena where these issues are played

18. The question of humans and robots in space has assumed the nature almost of a religious conflict.
- Jeff Hoffman, Massachusetts Space Grant Lecture, May 1, 2001

out in a profound way. In our core we dream and long for space, we always have. The means of exploring this dream embodies our cultural definition of reality itself.[19]

19. an understanding of technical devices has somehow merged with the most intimate levels of self-understanding.
- Langdon Winner
The Whale and the Reactor

In the early Soviet space program, piloted vehicles were first designed as autonomous spacecraft and only later retro-fitted for cosmonauts. As historian Slava Gerovitch pointed out, "Soviet spacecraft designers clearly assigned the manual control system a secondary role, and they probably did not seriously believe that it would ever be used." In fact, Gerovitch goes so far as to say, "Soviet cosmonauts were asked not to interfere with the automatics."[20]

20. Since all the control functions on board were already automated, the only role assigned to cosmonauts was to monitor onboard equipment and to back up the automatic systems of orientation and retrofire in case of emergency.
- Slava Gerovitch

From an American perspective where astronauts fought hard to maintain their pilot status while inside spacecraft, the Russian philosophies seem almost stereotypically Soviet in their apparent stoicism. As history showed, however, the Soviet attitude proved Schlemmer correct.

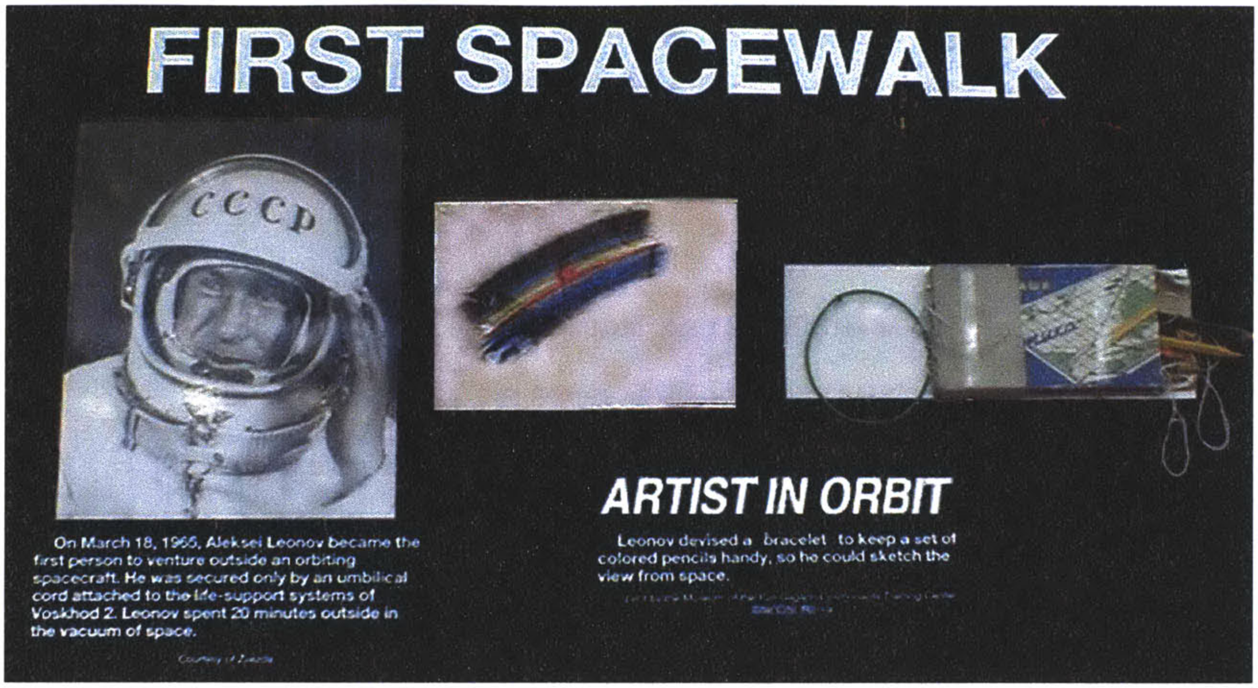


Figure 12.3: Aleksei Leonvov and his sketch kit taken to orbit for a truly human expression of the extreme environment. Photo of the display at the Smithsonian Air and Space Museum in Washington, DC.

On Aleksei Leonov's first flight he carried with him an invention that no machine would have or could have: a colored pencil bracelet, and a sketch pad. With these tools he sketched the horizon of the earth as seen from space, a true human manifestation of space exploration.

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APPENDIXES

APPENDIX A: HISTORY OF SPACESUITS

Spacesuits developed from pressure suits, used in diverse applications from high altitude aircraft, high performance aircraft, and vacuum tube experiments. Much of this researched focussed on "partial pressure suits" which applied pressure to defined regions of the body, leaving other areas exposed to environmental conditions. G-suits, used to maintain consciousness during high performance maneuvers in aircraft, still use the partial pressure technique, but most low pressure environments require "full pressure suits" if exposure is to be maintained for extended periods.

The terms "partial" and "full" pressure should not be confused with the level of pressurization the suit produces. A partial pressure suit might provide one atmosphere of pressure or more. Similarly a full pressure suit, like the current Space Shuttle and International Space Station (ISS) spacesuits, might provide only a fraction of an atmosphere of pressure. "Full" and "partial" only refer to the area of coverage or protection.

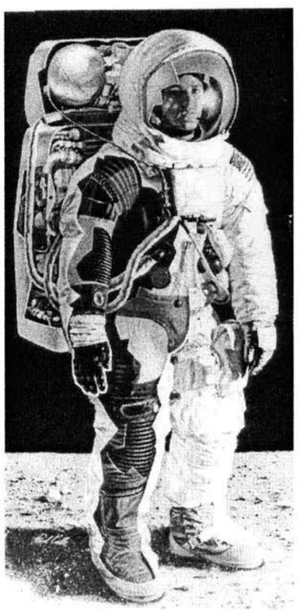
GAS-FILLED SPACESUITS

MERCURY AND GEMINI 1961 - 66

By the time the Mercury program started, the U.S. Air Force had extensive experience in designing full pressure suits to protect their high altitude pilots from cabin depressurization. Mercury spacesuits could be updated versions of these full pressure suits because there was to be no extravehicular activity during the Mercury missions. The spacesuits, therefore, were needed only in case of an emergency. As with earlier full pressure suits, the Mercury suits severely limited astronaut mobility when pressurized.

Gemini spacesuits had more demanding requirements due the longer duration missions and the scheduled space walks. Again, these suits were worn throughout the flights as a back up to the cabin pressurization, which increased the need for unrestricted mobility. The Gemini suits evolved over the course of the program to handle increasing demands, but common features included an entirely soft construction (excluding the helmet and its connections) and joint design based on mesh restraint layers that allowed mobility while minimizing ballooning. In addition, both Mercury and Gemini spacesuits relied on the spacecraft's life support system and therefore required umbilicals even during extravehicular activity.

APOLLO AND SKYLAB 1968 - 75



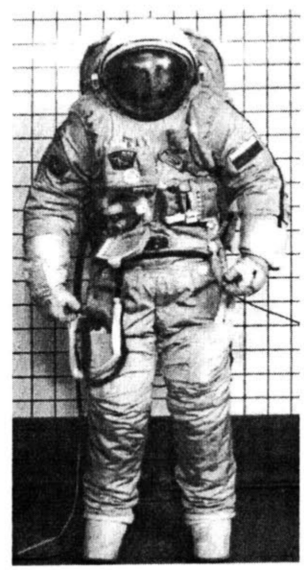
Apollo missions were the first to impose the requirement of a self contained life support system due to the increased range of activities. Also, because of the partial gravity work to be done, much attention was given to reducing the metabolic cost of operating the space suit. Novel joint designs, such as convolutes, increased mobility. Many other modifications were made to spacesuit systems such as the life support system, helmet, thermal and micrometeoroid protection layer, and spacesuit interfaces. Skylab suits were altered Apollo suits and were donned much like all previous suits: with zippers.

SHUTTLE AND INTERNATIONAL SPACE STATION 1981-PRESENT

Major requirements on the Extravehicular Mobility Unit (EMU) included the ability to be reserviced between mis-

sions, fitted for a large range of body sizes, and to allow unrestricted mobility. These goals were pursued through a modular construction and constant volume, low torque joints. The EMU is donned much like a pullover jacket and pants with a rigid bearing connection between the two elements. Rotational mobility is facilitated by air-tight bearings.

The Extravehicular Mobility Unit (EMU) has been incrementally improved over the history of the Shuttle program with significant improvement made for ISS compatibility. Most of these changes have been focussed on decreasing the required frequency of ground reservicing due to the fact that the EMU has to be reserviced on-orbit. In addition, significant work has been done to reduce joint torques and increase system safety.



ORLAN 1969 -PRESENT

The Russian EVA hardware has undergone a similar evolution as mission requirements have changed. The Orlan is the current family of suits and are very similar to the EMU in terms of functionality. Key differences include sizing, life support placement, and the don/doffing procedure. The Orlan suit is "one size fits all." Sizing adjustments are made by shortening/lengthening limb segments via axial restraint chords. Because of this, suit mobility is dependent on the wearers size, with maximum mobility available to the larger cosmonauts. This sizing system also limits the population size accommodated by the Orlan suit.

A major difference in design philosophy is apparent by looking at the placement of the Orlan's life support system. In the EMU, the LSS is placed outside the pressurized environment of the spacesuit and is therefore exposed to vacuum. Russian engineers made the opposite decision when designing the Orlan suit. The Orlan's LSS is within the pressurized environment which complicates safety issues associated with fire, but reduces structural and thermal loads on system components.

Donning and doffing the Orlan suit is significantly different due to its rear hatch entry. The suit's life support "backpack" functions as a hatch door. When donning, the LSS swings out, exposing the hatch, allowing the cosmonaut to enter the suit, unaided, through back of the suit. Because of this configuration the suit always maintains its integrity, limiting the number of pieces to be assembled during the donning process.

Despite these differences, the Orlan Spacesuit is subject to the same dynamic models as the EMU in terms of mobility and joint torques. Added complications arise to do the sizing issue mentioned above, but the principle challenges associated with constant volume joint design remain.

MECHANICAL COUNTERPRESSURE THROUGH THE AGES

THE SPACE ACTIVITY SUIT, 1971[1, 2, 3]

In 1971, the originators of the MCP concept, James F. Annis and Paul Webb, published a report of their Mechanical Counter Pressure (MCP) suit known as the "Space Activity Suit" (SAS). They were able to develop a prototype suit made up of six layers of elastic material that created the mechanical pressure against the wearers skin. Accompanied by a full bubble helmet, "The ultimate goal of the SAS [was] to improve the range of activity and decrease the energy cost of work associated with wearing conventional gas filled pressure suits."

Webb stated the motivations for a MCP suit, which still apply today and into the future. Besides the improved energy cost, a MCP suit "should be safer and more reliable than full

1. Annis, J.F., and Webb, P., "Development of a Space Activity Suit," NASA Contractor Report CR-1892, Webb Associates, Yellow Springs, Ohio, 1971
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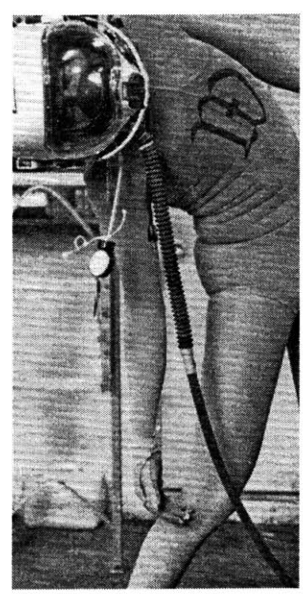


pressure suits since suit rupture would not mean loss of life supporting gas pressure." If designed properly, a small tear in a MCP suit would only expose a local body region to reduced pressures. This exposure would cause the wearer discomfort, and possibly pain, but would allow them to return to safety without major injury.

In addition to safety concerns, Webb also notes that the life support system of a MCP suit could be greatly simplified due to the fact that the body can enable "physiologically controlled cooling" by means of sweating. This assumes that the suit is porous (as was Webb's), allowing sweat to evaporate through the second skin. The Space Activity Suit directly exposed areas of skin no larger than 0.5 mm^2 to vacuum (5 mmHg, 0.1 psia, 0.7 kPa) without problems. There were no signs of excessive fluid loss, or freezing of the skin. This also demonstrated that, at such a scale, the skin with-stood the tensile loads.

Without the need for thermal control, the life support system would become a tank of oxygen with pressure regulators and a carbon dioxide scrubber. A MCP suit might also be an order of magnitude less expensive because it could be less bulky and lighter than current garments thus taking up less pay-load resources.

Space Activity Suit Limitations

Though strongly articulating the benefits of a MCP approach, Webb was also able to demonstrate the major challenges of such a system. Through a series of demonstration tests, the SAS was effective to breathing pressures of 24 kPa (170 mmHg, 3.3 psi) within the laboratory environment (101 kPa, 14.7 psi, 1 atm). Major issues encountered included don/doff time and swelling/edema in parts of the body. Webb specifically notes that "the most difficult areas to pressurize occur where the limbs join the torso." In order to prevent blood pooling, the pressure across these regions needed to remain smooth. Despite the physiological problems encountered, Webb's research suggested that, "energy cost of activity, and mobility and dexterity of subjects is the SAS, were found to be superior to those in comparable tests on subjects in [gas pressurized suits]." They also suggested that every problem encountered was primarily mechanical in nature, and could be solved by the development of new materials and tailoring techniques.

Simplifying the donning process was also specifically noted as a critical area for future research. Webb's troubles in this area came about because the elasticity and tension in the fabric had to be fought against during the donning/doffing process. Ironically, the very mechanism by which they created MCP was the biggest source of their problems. They suggested that future research might look into advanced closure mechanisms like those mentioned below in the Bio-Suit Phase I Report, which incorporate active materials.

THE SKINSUIT GLOVE, 1983[4]

4. Clapp, W., "Design and Testing of an Advanced Spacesuit Glove," Massachusetts Institute of Technology, Cambridge, MA, 1983.

In 1983, W. Mitchell Clapp published an article on his development of a MCP glove that he called the "Skinsuit Glove." His motivations were similar to Webb's, but he focused on the glove as an area where more mobility/dexterity and tactile feedback was required to enhance space operations. After developing a prototype, he tested the glove against a bear hand, and an Apollo A7L-B glove (a pressurized glove) in the areas of mobility/dexterity, strength/fatigue, aeromedical effects, and tactile feedback.

Clapp claimed that "the skinsuit glove showed a sizable mobility and dexterity advantage over the A7L-B glove.

There was also less strength degradation with fatigue. Tactile feedback was considerably higher in the skinsuit glove as well." Although subjects were only subjected to thirty minutes of partial vacuum exposure (23 kPa, 3.5 psi, 176 mmHg), Clapp stated that "only a minor swelling of the hand occurred." He noted that "small amounts of edema fluid, accompanied by a slight swelling, were... observed, mainly in the palm, but also in the wrist and web of the thumb." Although he was probably correct in stating that these effects, after thirty minutes of exposure, did not pose a risk, it seems reasonable to assume that after an eight hour EVA these problems might have grown in complexity and severity.

Clapp concluded that his glove achieved improved mobility, tactile feedback, and fatigue characteristics over the A7L-B glove. The mobility and tactile feedback results were explained by the use of stretchy, lightweight material. While addressing the aeromedical issues, Clapp notes that the palm of the hand swelled "only a very small amount." He suggested that this swelling was due to the concavity of the region and "could probably be prevented by inserting a small foam pad between the glove and the palm where the fabric gaps across."

After developing the Skinsuit Glove, it was suggested that future research focus on the effects of enhanced tactile feedback on learning and on comparing the MCP glove to the (then new) EMU glove design. He hypothesized that due to the increased tactile feedback, the Skinsuit Glove would be able to reduce the time needed to learn EVA tasks. Seeing as the EMU glove design focussed on improved glove mobility, he suggested comparing the effectiveness of both designs against each other.

Skin Suit Glove Limitations

As noted above, the Skin Suit Glove did not adequately address the issues of body concavities or equal pressure distribution. In addition, the work does not mention don/doff ease, leading to the conclusion that this was not a area of focus.

University of Maryland Space Systems Lab Hybrid-Elastic Glove[5]

5. Korona, Frank Adam, "Development and Testing of a Hybrid Elastic Glove," Masters Thesis, University of Maryland, 2002.

Although not technically a mechanical counterpressure glove, the Space Systems Lab has developed a glove that leverages off mechanical counterpressure technology. The glove is much like a conventional gas pressurized glove, but uses an elastic restraint. This reduces joint torques on the knuckles and other areas of the hand as well as allowing greater tactile feedback.

HONEYWELL'S MECHANICAL COUNTERPRESSURE GLOVE, 2001

Honeywell International is currently in the process of designing a MCP glove to be compatible with the current, gas-filled spacesuit. From the limited published material available, it seems the design approach has been to use MCP in conjunction with gas pressure. This is accomplished by underpressurizing the suit gloves and using MCP to compensate for the reduced pressure. In this arrangement, the required body surface pressure is met through the summation of gas and MCP pressure forces. Due to the lower gas pressure in the gloves, the work against pressure forces is reduced, See "Thermodynamics" on page 283. At this time this is all that is publicly known about Honeywell's proprietary efforts.

THE BIO-SUIT CONCEPT, NIAC PHASE I REPORT, 2001[6]

6. Pitts, B., Brensinger, C., Saleh, J., Carr, C., Schmidt, P., Newman, D., "Astronaut Bio-Suit for Exploration Class Missions," NIAC Phase I Final Report, Cambridge, Massachusetts Institute of Technology, 2001

The MCP and thermal concepts illustrated in the report "Astronaut Bio-Suit for Exploration Class Missions: NIAC Phase I Report, 2001," represent a glimpse of future possibilities. The Bio-Suit design group felt that the technologies investigated have the possibility of revolutionizing the way extraterrestrial terrain is explored by allowing the explorer a true sense of freedom. This freedom is realized from the moment of donning and throughout the EVA by facilitating actions that were previously thought impossible in these extreme environments.

Design concepts were conceived to allow the explorer the same ease of donning as is experienced with clothes. Conceptually this was achieved by creating a suit that would shrink around the wearer once it was donned. In each concept, the wearer could slip into the MCP garment as if it were a pair of long underwear. Once the wearer was ready, the suit would slowly shrink to the point where adequate MCP was achieved. The "pressurized" suit would minimally restrict movement if at all. Designs such as the Electric Alloy Remote Zipper Suit (EARZS) allowed tweaking of the suit tension at local points on the body. These concepts would allow the wearer to "resize" their suit real-time, thus facilitating maximum comfort. In addition, these concepts accommodated changes of the body during the mission due to things such as muscle atrophy, weight gain, or spinal elongation.

Bio-Suit Study Limitations

Due to the long term projections of the Bio-Suit Phase I report, and the rapid advancement of material technologies, the Phase I work did not include numerical analysis of the concepts envisioned. This phase of the effort was approached as a concept development exercise that would serve to free thoughts from the constraints of tradition and currently actualized systems. Because of this, strategies to provide the required skin pressure were investigated without modeling and analysis, which was to take place in the future in the form of this thesis and a follow up NIAC Phase II study. The Phase I study encompassed many meetings with developers of the technologies mentioned which allowed the group to get a sense of the state of the relative arts and their applicability to the needs of the Bio-Suit system. These meetings determined whether or not such technologies could truly advance the capabilities of space suits, or whether they would complicate issues. This feedback permitted revised design concepts and pursuit of solutions to these high level issues.

This effort was also limited by its focus on space suit pressure issues. In environments such as Mars or the Moon, radiation, temperature control, maintenance/repair, and other life support features will clearly be a major concern. As these issues are already being investigated by other researchers, it was decided that the Bio-Suit project would focus on revolutionary pressure and mobility issues. As shown by previous research, the limited mobility of current suits originate from pressure issues, thus in order to facilitate the type of activities required on future exploration class missions this area must be greatly advanced or else be a limiting factor for exploration possibilities.

APPENDIX B: SPACESUIT PHYSICS

THERMODYNAMICS

1. Iberall, A.S., "The Experimental Design of a Mobile Pressure Suit," Journal of Basic Engineering, June 1970 pp. 251-264.

As explained by Iberall,[1] spacesuit mobility is governed by energy relations, or thermodynamics. In order to deform, or bend, a spacesuit, work must be put into the spacesuit system. The origins of this required work is twofold, that done against pressure forces, and that done in bending the suit material.

$$\Delta W = \Delta W_p + \Delta W_e \quad (1.1)$$

where ΔW is the work required to deform the spacesuit, ΔW_p is the work against pressure forces and ΔW_e is the work against the suit material. In order to maximize the mobility of a spacesuit while minimizing imposed joint torques, designers strive to minimize ΔW by minimizing its components, ΔW_p and ΔW_e.

Work against pressure forces, ΔW_p, can be related to spacesuit design parameters through simple work relations. In general, the change in work equals a force times the change in distance

$$\Delta W = F \bullet ds : \quad (1.2)$$

In the case of pressure forces,

$$\Delta W_P = \int_{v_1}^{v_2} p dv \qquad (1.3)$$

where p is the pressure difference between the inside of the suit and the exterior environment, and v is the volume of the suit. In spacesuits, the pressure is maintained at a constant level, p_S. This expression then becomes,

$$\Delta W_P = p_S \int_{v_1}^{v_2} dv \qquad (1.4)$$

In order to minimize this term, designers can alter two variables, p_s and dv. Mathematical analysis suggests that both terms should be made to equal zero so that the ΔW_p term will vanish, but clearly if $p_s = 0$, the suit is operationally useless as a life support device. As described in "Pulmonary Physiology" on page 121, p_s has a lower bound. This leaves suit designers with the challenge of creating an isovolumetric suit. Much of spacesuit history has been dedicated to this quest.

To better understand the design variables that effect the change in volume of spacesuits it is possible to write,

$$dv = SdA \qquad (1.5)$$

where S = the separation between the suit and wearer's body, and dA = the change in area of the suit material. Given this perspective, an isovolumetric suit can be achieved by minimizing S (dA has a lower bound prescribed by the change in surface area of the body). This explains one rational for exploring mechanical counterpressure spacesuits, as they reduce S, and therefore dv, to zero.

The other component of work against a spacesuit, ΔW_e, can itself be split into two components: work against the spacesuit's bending stiffness, ΔW_b, and work done while stretching, or straining, the spacesuit materials, ΔW_s:

$$\Delta W_e = \Delta W_b + \Delta W_s \tag{1.6}$$

Once again, in order to maximize the mobility of a spacesuit the terms on the right hand side should be minimized.

From Simple Beam Theory, it is possible to relate ΔW_b to material properties.

$$\Delta W_b \propto \frac{1}{EI} \propto \frac{1}{Et^2} \tag{1.7}$$

where E = the Young's Modulus of the material, I = the second moment of area, and t = the thickness of the material. These relations show that it is possible to minimize the work done in bending by maximizing the modulus or the thickness of the material, however this would lead to a useless spacesuit.

Maximizing E or t reduced the bending work do to the fact that it drives the deflection to zero. As work is force times distance, no work is done if a very large force is applied, but no deflection occurs. Thus, in order to analyze this aspect of spacesuit thermodynamics it is necessary to try to solve a dually constrained problem: minimize bending work while maximizing mobility. As stated in "Areas for Future Research" on page 219, this would be a useful analysis for future work.

By analyzing the work against stretching the spacesuit materials, $\Delta W_{S,}$ the primary trade-off for spacesuit design becomes evident. Stretch work is proportional to the strain energy.

$$\Delta E = \frac{1}{2}\sigma\varepsilon \qquad (1.8)$$

where ΔE = strain energy pre unit volume, σ = stress, and ε = strain.

Relating stress to strain using Young's modulus, E

$$\sigma = E\varepsilon \qquad (1.9)$$

it is possible to write Equation 1.8 in terms of strain and stress.

$$\Delta E = \frac{1}{2}\frac{\sigma}{\varepsilon}\varepsilon^2 = \frac{1}{2}E\varepsilon^2 \qquad (1.10)$$

$$\Delta E = \frac{1}{2}\sigma^2\frac{\varepsilon}{\sigma} = \frac{1}{2}\frac{\sigma^2}{E} \tag{1.11}$$

When bending an elbow to a prescribed angle, the strain of the spacesuit is prescribed due to the geometry of the body. In this case, Equation 1.10 dictates that the energy required to stretch the spacesuit materials is proportional to E. This fact would lead designers to minimize the material's modulus.

When considering pressure forces, however, the stress in the spacesuit material is prescribed due to the hoop and longitudinal stresses. This is the case which Equation 1.11 describes, leading designers to maximize the modulus of the spacesuit materials. Clearly Equations 1.10 and 1.11 drive design choices in opposing directions. Figure XX is presented in order to summarize the thermodynamic analysis of spacesuit mobility.

As Iberall states, "The horns of the dilemma can be separated if it is realized that strain and deflection are only associated in a homogeneous isotropic material." Thus, designers must look to inhomogeneous materials or structures for a solution.

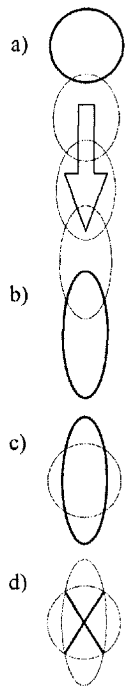
As is discussed in the next section, 'Modulus Considerations', Iberall developed an ingenious way to structure an inhomogeneous material by observing the skin of the body.

MODULUS CONSIDERATIONS

As discussed at the end of "Thermodynamics" on page 283, spacesuit design requires materials that exhibit inhomogeneous properties. This inhomogenaity can be due to the material itself, or the way it is tailored for the spacesuit. As an example of how material can be tailored to increase its inhomogenaity, the current EMU uses pleats in the knees, elbows, and gloves that run parallel to the axis of rotation (Fig.). In this way, the material properties in the hoop direction remain unchanged, but the modulus along the long axis of the limbs is reduced to near zero.

A detail of the current EMU's restraint layer around the knee joint.

As part of Iberall's work on full pressure suits, he developed an alternative method of producing material, or structural, inhomogenaities. These inhomogenaities vary continuously over the body as opposed to the pleat method which is discretized around areas of interest. Considering the skin to be a thin shell, Iberall drew circles on subjects' bodies as they stood in a neutral body posture. Asking the subjects to stretch and flex their body to maximize the deformation of the circles on the skin, he noted that, in general, the circles distorted to become ellipses, and, in general, if the original



The transformation of a circle as the shell deforms: a) initial circle, undeformed, b) the deformed circle, now an ellipse, after deformation, c) the ellipse with the original circle superimposed displaying four points of intersection.

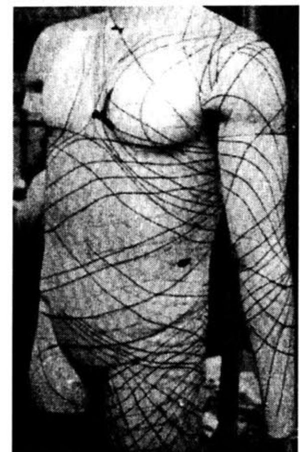
circle was superimposed on the distorted, elliptical figure, the two intersected in four locations (see).

Connecting the four points of intersection to form an "x," it is clear that although the lines of this "x" have rotated about their intersection, they have not changed length as the circle deformed. Thus, a material with infinite modulus can be placed along these lines without interfering with the deformation of the circle. Assuming the intersection at the center of the "x" is a perfect pin-joint, there will be no resistance to deformation.

In order to reveal the body's full compliment of "lines of nonextension," Iberall drew circles over the entire body surface of his subjects. The result was a body map of how the skin stretches due to body motion. (Fig.) Checking his results, he used inextensible fibers to create a mesh-like material whose strands ran parallel to the lines of nonextension. (Fig.) According to the development rational, this inextensible mesh suit should have allowed complete mobility, as he claims it did.

In order to create a full garment from off-the-shelf materials, he used available mesh material and patterned it in a way that closely approximated the lines of nonextension. This garment also allowed complete mobility.

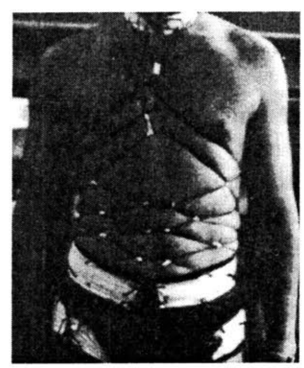
Thus, Iberall's mapping of the lines of nonextension reveal the way an inextensible, homogeneous fiber can be woven to form an inhomogeneous structure capable of reconciling the competing requirements on Young's Modulus presented at the end of "Thermodynamics" on page 283.



The lines of nonextension mapped over the entire body and transcribed to a mannequin.

BENDING PRESSURIZED CYLINDERS

As described in many previous documents, work is required to bend pressurized cylinders due to a change in volume. Although one might guess this is due to an increasing pressure as the volume gets smaller, this is only one component of the work. A pressurized cylinder controlled so that pressure is held constant will still require work in order to bend it. This can be understood by considering a piston.



An inextensible material laid parallel to the lines of nonextension in order to validate full mobility while constrained by the lines on nonextension.

As force is equal to force times distance and pressure is a force over an area, it takes work to move a piston, even if the pressure is maintained constant. The pressure forces are distributed over the area of the piston creating a force that must be opposed when moving the piston through a distance. This is the origin of the work. Similarly, although it might help slightly, regulating the pressure of a cylinder under bending moments will not reduce the work to zero. The work is a function of (pressure) x (area) x (distance) = (pressure) x (change in volume) = (force) x (distance). As can be seen here, in order to minimize the work required to bend a pressurized cylinder, either the pressure of the cylinder or the change in volume can be reduced. Much of spacesuit design history has been filled by the quest for an isovolumetric soft joint.

In this thesis, the strategy has been to minimize the change in volume by reducing the radius of the cylinder. In addition, as discussed in "Design and Placement of Channels" on page 167, the channels can be placed along lines that bend minimally throughout a range of motion. Given the results discussed in "The shrink-polyester fabric and two mesh garments were tested in the same way as the sail cloth. Although it would have been possible to tailor the shrink poly without heat, this garment was heat shrunk around the cylinder so as to capture any material property distortions the shrinking process may have induced. The mesh garments were made from the same mesh material, but were tailored such that the mesh was aligned differently for each garment (see Fig. 9.16). This allowed the data to capture the effects of the strand angle, g. In order to prevent the mesh from sliding axially along the cylinder, pipe clamps and rubber strips were used (see Fig. 9.18).This set up assured that the stretch of the mesh was due mostly to strand strain instead of diamond distortion" on page 188, it seems that the current garment architecture is capable of producing higher mechanical counterpressure than the channel pressure. This would suggest that the channel pressure could be reduced. Thus, the concept discussed in this thesis would provide a way to minimize the change in volume as well as the pressure, thereby minimizing the required joint torque.

APPENDIX C: CONVERSATIONS WITH KRZYSZTOF ET. ALL: IDEAS/ QUESTIONS/NOTIONS TO SPUR IDEAS

The following writing is made up of notes taken while engaged in an independent study with Professor of Visual Arts, Krzysztof Wodiczko, during the spring semester of 2002. Our independent study was centered around explorations of space or other strange realms. Initially these notes were generated solely by our weekly discussions, but soon came to document discussions and ideas encountered elsewhere as well. In preperation for this thesis, the notes have been edited and condensed. They can be read as journal entries, essays, or simply streams of consciousness.

QUESTIONS:

• How can you enter space (planetary or other) with respect? Humility? Open to newness and unknown rather than arrogantly, as if you already know what is there?

• How does the traveler view the exploration experience and how can this be used to influence the action taken before arrival, during arrival, and once landed? How does the psychology and culture of the traveler affect the entire design process (objectives, hardware, etc.)?

• Due to culture, how does the traveler view him/herself? What are his/her motivations? What do they search for?

• Once the traveler has grown to know the strange land, the traveler returns to see his/her home as alien. How can you prolong this distance so that additional knowledge and experience is gained from this phase of exploration?

• Can art produce knowledge?

• Can science produce art?

• What is the difference between experiment and artistic act?

> Jeremijenko suggests that it is a matter of the local community. They are one and the same except an experiment is performed by a scientist and an artistic act is produced by an artist.

• What are the different rolls/responsibilities of the scientist and artist?

> Natalie Jeremijenko suggests that it is a matter of accountability. The artist is ultimately accountable to the public, she suggests, whereas the scientist is only accountable to his/her peers.
>
> Is this really true? Certainly "good science" is determined by a community of scientists that judge other scientific endeavors. I may produce work that I believe to be science, but unless my methods and reasoning are sound (as determined by the community of scientists) it will not be considered science. Does this matter? Does the public's view matter? Whether or not there is a group within the public (laymen) that view my work as science, my science will still not be incorporated by other scientists and therefore will not receive respect in the public sphere?
>
> Looking at the art world, if I produce something which I consider art, does it matter what other people think? This same question could be asked within the scientific realm except that science is bent on furthering knowledge and culminating in an under-

standing of the universe. Therefore, in order to leave the realm of personal belief and enter into "science" it must be incorporated.

Returning to my artistic act, though, will it be art if the art community does not accept it? As a personal, human act, yes, it will be art and therefore art is only accountable to individuals. But, in a broader view there is still the issue of experts within the art field that have the ability or power to determine what is art and what isn't.

Is this true? Do they decide what is art, or do they decide what is "good" art.? Similarly does a scientific community decide what is science, or what is "good" science? Science, like art, is a noun and therefore should carry no qualitative assessment.

Science is defined by process/method where as art is defined by motivation? Art-motivation in the sense that art is a form of communication or expression. Therefore, the curator of the MOMA can walk down the street and see "bad" art and still accept it as art whereas the editor of a science journal will read a submission and dismiss it as "unscientific" if it doesn't meet certain criteria. So can you have bad science?

Maybe bad science is defined as useless science. Useless in the sense that it cannot contribute to the whole or it does not lend itself to application or further discovery. It goes nowhere and its implications are specific instead of general. Is this what art does?

Is art and experiment that reveals specific and isolated, rather than general truths? Art is a comment whereas science is an explanation? This might fit with a notion hinted at by Jeremijenko about the fact that science is rarely questioned by the public whereas art is. Explanations appear firm and static, especially when backed by a whole community, whereas comments are inherently questionable and individual. Even when a comment is supported by a community it can still be questioned by any individual who isn't knowledgeable in that field.

• What happens if science becomes art? Or what happens if science becomes recognized as art?

• Does a designer engage in design if they are already supplied with all the boundaries? (site, program, cost, etc.) Is true design designing need or acknowledging need at the start of design?

• True design must start with an evaluation of the current situation and the need as well as the question(s), e.i., "what will happen if I DON'T/do do this?"

• Is the role of the astronaut a prosthesis for ground based scientists, or an individual endowed with certain resources and opportunities?

• What are some differences between science and art? Science is accountable to its profession whereas art is accountable to the public? Science = knowledge and is therefore accepted whereas art = thoughts and is therefore questioned?

THOUGHTS:

• Space dress (as oposed to suits)

• Designing a *need* to go to space

• Agonistic exploration crew

• Not space exploration with humans, but HUMAN exploration through space (or exploring human interactions/culture/etc. through the medium of space)

• We must design meaning into exploration (and artifacts in general).

• Affective vs. effective technology.

• Working with space you can, 1) make something that allows us to view our world as alien so that we can truly see our conditions/environment/surroundings; 2) design a need to go to space so that we can truly gain from that environment; or 3) integrate both.

• An exploration suit (spacesuit) should not protect and isolate the traveler, it should *expose* the traveler to the experience of the strange land. Why go if you are going to remain unchanged?

• The worst thing about humans is that they can adjust.

• Art is between fact and fiction.

• No such thing as progress in art, but science is centered on this notion.

• There has always been a debate as to whether or not humans should be in space. From a cost perspective, robotic missions are cheaper, but people argue whether or not a robot can accomplish as much as a human. By debating in this way, the human becomes viewed as the ultimate robot, and no longer retains his/her humanity. Humans are the ultimate robot, but they are more. We must start using their true humanity as this it the reason to send humans (and it doesn't cost any more once they are up there).

• Human Factors Engineering has nothing to do with humans. A human is not made up of their dimensions, their physiology, and there (in)abilities. Being human means more, and none of us would accept these quantifications as a representation of who we are. To truly address HUMAN factors, we must enter the realm of art.

• One can design the need to go to space and design for space with this need in mind, and/or one can bring the experience down to the earth and design for the earth as if it were alien. Similarly, we can design interventions for the current space program or we can project and conceptualize about the designs for the space program as we think it could be.

> One way to explore both might be to create a "looks-like" and "feels-like" model suit/capsule/etc., thereby exploring the experience of inhabiting such a design and the performative aspect of using such designs. How does the design alter the way you experience your surroundings and what benefits/drawbacks are created through this alteration?

• Exploring an alien world with an atmosphere opens the possibility of senses other than touch and sight. We can ask, "What does this place sound like? What does this place taste like? What does this place smell like?" Because all of these sense organs are located on the head, these questions require an investigation into different head treatments (other than the bubble helmet). Can the helmet be altered, or should a new form of head protection be envisioned? The bubble helmet also captures the individual's speech. This is addressed via a microphone system, but what would happen if the speech were actually projected out into the space of exploration? In a place like Mars, with its canyons, this might allow for the experience of echoes, etc.

• Space exploration as performance/theater. (See <u>The Theater of the Bauhaus)</u>

• The astronaut as Brittany Spears: not an independent individual, but constructed by many people behind the scenes.

• Astronaut shield

• Objective: facilitate risk taking for the astronaut

• Exploration as map making. How do you map? What do you map? Etc.

• List of inputs and outputs of the astronaut/capsule/womb. **IN**: Food, Sound, Smell, Touch, Sight, Feelings, Experience, Power, Solar rays, Fuel, Radio signals, Etc. **OUT**: Noises, Smells, Visual communications, Memories, Emotions, Desires, Wastes (skin, urine, feces, hair, breath, etc.), Heat, Exhaust, Radio signals, Etc.

• Space virtuosity

• Astronauts drunk off oxygen

• Space as a podium/stage

• A machine can be designed to fit the human, but the human can also be adapted to fit the machine through training and/or biological/genetic manipulation. Once this door is opened, human factors engineering can no longer take the human as a given, static component of the design. When projecting into the future, we must realize the humans of the future will not be what humans are now. How can design account for this and grow from it?

• Space kiss (in vacuum)

• Space sex (in vacuum, or in capsule)

• The Art of Exploration

• Binaural recording (i.e. Janet Cardiff). The Sounds of Space/Vacuum. Space Walk. Etc.

• Symbiotic relationships are designed between the astronaut and the capsule. We can no longer view the astronaut and the capsule as separate. As the human is mechanized, the capsule is humanized.

• *Arts*tronaut

• Artistic Engineer

• Poetic Engineer

• Aerospace endeavors highlight/represent the strongest values of our society. What are we willing to pay for? What are we willing to work towards? These questions should be answered on multiple scales from individual to international. Currently the answers to these questions seem to be science and engineering. Everything must be rationalized through return value. (usually quantified return value). Because, in many ways, space activities do not directly relate to life on earth, space activities can be construed as frivolous or unnecessary. The choice of what we do with this realm is therefore telling of who we are and who we aspire to be. Defining and highlighting societal/cultural values is the true power of space travel and exploration.

02.12.02 SPACE EXPLORATION AS SPORT

It seems ridiculous to assume that our method of self-propulsion on earth would be suitable for other gravitational fields. Our bodies have evolved, grown up, and developed within Earth's one-g environment. Everything we know (conscious and subconscious) is related to this magnitude of gravitational acceleration. This is precisely why it is so easy for us to force our methods of movement onto other environments. Not only is it *easy* to force our ways onto alien worlds, but it is *difficult* to imagine alternate modes of self-propulsion. What might these be? What might they look like? On what scale(s) do they operate?

Although we do not have enough experience/opportunity to have fully developed alternate strategies for reduced- or micro-gravity-self-propulsion, we do have experience with unusual environments, which might provide insight.

Marine life is foreign enough from our daily experience that it can provide inspiration and insight into what alternate propulsion mechanisms might look/function like. (Consider a crab [REF] or other bottom feeder moving on the ocean floor. The buoyancy of the water facilitates the thin, pointed legs, which also impose a minimal impact on the environment as is discussed in "LNT Exploration.") As outsiders to this watery realm, we have rarely tried to extend our current modes of propulsion to this alien environment. Our posture shifts from vertical to horizontal, we use prosthetics, such as flipers, which prevent walking, but promote fluid propulsion, and we begin to use our other appendages to assist us in our propulsive attempts. This level of alteration occurs even before the depth of the water is above our noses.

Consider, for example, a lifeguard running into the sea. She does not attempt to run into the water until she cannot stand any longer and then start to swim. Instead, she runs to the point where she cannot lift her feet out of the water any longer. Perhaps even sooner than this she performs a transitory act, converting her body from a land-propulsion device into a marine-propulsive device (a dive).

A further level of adaptation/alteration occurs when we venture beneath the surface of the water. This might come in the form of oxygen tanks, but can go much further, into the realm of encapsulating the individual and providing her/him with anatomical impossibilities such as propellers and digital technologies. Although a submarine is not usually considered a "suit," it must be considered as such in order to realize new possibilities.

Just as the driver of a car becomes one with her/his mechanized body prosthetic, so must the operator of a submarine. The act of operating a car has become such a natural, integrated, part of our reality, that we are able to control our new bodies with precision. In many cases we don't need to use mirrors or other devices to know the distance between our mechanized self and external objects. We also must acknowledge the fact that our motions within the car have no association with the movements they produce except through convention. The car/submarine is a propulsive suit that converts our internal movements into external movements. The spacesuit might also be thought of as such a suit. [image of "tin can spacesuit"]

Perhaps the notion of "suit" in these instances is obscured by the many individuals that can inhabit these devices. Perhaps it is the detachment from biological, one-g movement that limits the ability to view these devices as suits. Neither of these deviations from other suit forms should concern us. Instead these differences should lead us to new possibilities/ realizations. For example, what ways could a vehicle transform the physical act of walking taking place within it, into an efficient movement, taking place on the exterior?

The notion of efficiency is important in order to get us back to the original point/goal of space exploration as a sport. One way of exploring a new surrounding is to try to remain the same and take notice of all the differences that make themselves apparent. The current push of spacesuit design towards higher mobility and minimized bulk resides within this approach. In this approach you do not truly explore the differences of the environment while designing. Instead the differences are discovered in the moment of use by the difficulties and feelings of strangeness/alienation that occur. This philosophy can lead to the notion of exploration as a sport.

When sport-climbing a mountain, or swimming a race, the human is clearly not trying to achieve optimum performance (depending on how you define it). We have technologies that have been developed to facilitate the activities. Helicopters can get us to the top of a mountain more quickly than climbing and motorboats can travel distances on water more quickly than swimming. This being the case, however, neither sport climbing nor swimming will ever cease to be a human activity. This is because these activities are not about speed or linear goals as much as they seem to be. They are about challenge, human challenge. Is this what space exploration is/should be/can be? Are we trying to "do these things, not because they are easy, but because they're hard," or are we trying to do hard things in the easiest way? The answer to this question significantly impacts the design of a spacesuit.

One possibility that generates knowledge throughout the journey, and also contains the potential to address the developmental issues addressed at the beginning of this discussion, is to allow the user to go through conscious adaptation/evolution/development in their new g-field. This would provide the most discovery potential for all parties and could be accomplished by designing to maintain self-propulsion as we know it in one-g. In addition, though, one could design capabilities that would allow the individual in the new environment to create an evolved suit that works with the potentials/limitations of this new environment. Thus, the individual arrives much the same as she/he left, but quickly discovers their own strangeness with respect to the alien world. As the strangeness is discovered and explored, the individual is provided the means to learn and create from this strangeness. In the end, the individual has gone through a learning/development process of experimentation much as we do throughout our lives, especially our childhood. The act of creating this new mobility suit will both serve as a realization and documentation process.

a. Excerpt taken from a 03.04.01 entry.

The Hybrid.[a] The hybrid is not traditional. It holds no past in terms of technique or respect. The hybrid is not "proper." The hybrid does not belong to any family and will not find fellow hybrids on the river. But the hybrid is evolved. The hybrid looks at the challenge as one of integration: integration into the environment and its true demands. The hybrid looks at the problem and asks, "How can I most efficiently maneuver in this new environment?" "How can I achieve ultimate freedom in this environment so I can do anything at will?" These questions stand in sharp contrast to those asked by the typical sport crafts: "While in this craft, what is the technique that will allow me to get where I want to go?" "Given that I am constant, how can I change my motions to facilitate my desires?"

This is the key. The traditional sports view the body/craft as an immutable fact. They are not concerned with evolving to the point where motion and desires become effortless. This is exactly why they are sport: they are concerned with maintaining challenge while striving for the "best" result. The hybrid approach, on the other hand, is not concerned with tradition or past notions. Instead it is interested in moving forward and evolving every element to the point where ultimate efficiency is achieved.

It is wrong to think that the hybrid removes the learning curve, just as it is wrong to think that by maintaining the body's "natural" features and functions you will minimize the amount of required learning. The hybrid could be just as, if not more, difficult to master than using the natural body in the strange environment. In both cases there are newnesses that must be explored and assimilated. The new environment is the only constant, everything that is brought to this environment is open to change and adaptation.

When designing a spacesuit, it is assumed that the learning time to accomplish tasks will be minimized by facilitating the explorer's use of her/his body in a manner closest to their use of it on earth. How can this be the case? The body in a new environment is strange. It is the total body-environment system that matters. By designing a fully evolved suit that is capable of moving with great efficiency this learning time will not be minimized either. The fact is that a new mode of movement is necessary in each case and will take time to learn.

The argument could be made that it is harder to learn how to use your own body in a new way than it is to learn the use of an external tool. Is the tool just a form that suggests functional reexamination of the body? The preconceptions of the body and its functions cannot be placed on this external object. The object demands that you mold yourself to it. That is its function: a mold. To use it you must reshape your form and functions in order to mesh with it. Without it you must be self sufficient in learning to critically reexamine the functions of your "natural" body.

02.12.02 LEAVE NO TRACE (LNT) EXPLORATION

A footprint on the Moon lasts for millenia. Without wind, erosion, or other geological forces to disturb the regolith, marks on the surface survive until meteorite impacts remake the appearance. Given that the marks made by human presence were made on the near face of the Moon, these marks will last longer than they might have in other locations on the lunar surface.[b] How should we design given the permanence of these "superficial" marks?

b. The earth acts as a shield for the near side of the moon, making it harder for objects to hit the near face.

Despite the fact that there is no known life on the Moon, the marks that we left (not to mention the trash and hardware) represent an audacious and arrogant sensibility that can fill one with disgust. Perhaps one footprint or other specifically considered, conscious, and placed mark would not create such unrest, but the sheer carelessness with which these marks were made and left behind calls into question the philosophy of the act. Ethical considerations such as "respect for the unknown" must be called into consideration.

During the conception and design phase of planetary missions, these repercussions must be considered. How can you design to enter these alien unknowns with respect and humility? We must recognize our strangeness and therefore our status as temporary guest. We are not in the process of conquering. (Or are we?) We are not in the process of "tagging" or "marking our territory." (Or are we?) Our actions must be considered and designed so that these destructive interpretations are not possible.

Currently, in the outdoor sports, there is a practice referred to as "Leave No Trace." LNT is a philosophy that promotes taking care of the environment and leaving an area as you found it so that others may enjoy it as you have. The added care and effort required for these practices are easily justified within the context of our home planet. Here we have other forms of life to respect as well as our own (current and future) happiness and well being to consider. It is clear that the choices we make on our planet will effect and affect us and our future generations. The rational cannot be so clearly defined for alien worlds.

Many would question the importance of LNT philosophies on other worlds, looking at the technical difficulties as well as the fact that there is no life there. But reason cannot fully capture the justifications for ethics. A certain level of poetic thought needs to be considered. The poetry of the act is the whole impetus for space exploration to begin with. (To enter into a "scientific/rational" justification for LNT on alien worlds, we could think of a crime scene and the level of care that is taken in that context. There, the focus is on preserving information. Care is taken so that every detail is maintained as it was so that information can be gathered from these clues. Is this enough?)

To achieve the goal of leaving no trace, there are two strategies that can be adopted. First you can try to never make a mark. This simplifies matters greatly and allows marks to be consciously made when desired. Technically, it is hard to imagine how we could achieve this, though. We should consider what level of mark making is acceptable. Are we only concerned with marks in the soil, or are marks left in the atmosphere, etc., a concern too? Are we concerned with imperceptible marks?

Another strategy is to cover any marks that are made. This brings up the questions of how accurate the replacement has to be. Are we interested in putting each grain back where it came from or are we simply interested in the sum visual impact? Are we interested in preserving every surface feature or do we just want to make the surface *appear* untouched?

Within all these considerations we must consider the experience of another. Part of the disgust that comes from the carelessness displayed by the Apollo missions comes from the thought of another revisiting those sites. What is the impression that this visitor is left with upon entering these used spaces. Do they appear used and discarded? Used without waste? Scavenged? Used at all?

How can our actions design these impressions? Clearly there are better ways to leave a trace of these acts of exploration that talk more about our capacities and less about our narcissism and arrogance.

03.20.02

In order to bridge the concept of "Leave no Trace Exploration" and "Evolved Self-Propulsion" we can consider the point of contact between the individual and the environment. What if this point of contact is considered a point of opportunity for exchange. A probe, not a means of static support. The function of this contact is not to fight gravity, but to engage the surface in a meaningful, conscious way.

By doing this you decouple "anti-gravity" work and point of contact. One question that then arises is, how do you counteract gravity? In environments with atmospheres the possibility of lighter-than-air vehicles (LTAV) exists, but these require tremendous size and offer a challenge in windy conditions. An atmosphere also allows for aerodynamic forces such as those produced by helicopter blades. In a low density environment these too would have to be extremely large and they also pose the challenge of creating aerodynamic forces capable of disturbing the ground plane, such as wind.

Another strategy might be to increase the time between moments of contact with the ground. In this time, care could be taken as to where the next contact should be made. Partial gravity environments naturally suggest this option without the need for physical modification. Perhaps this delay could be furthered by creating a device that magnifies the "bounce" of each step, such as a pogo stick. In addition, the fall back to the surface could be delayed through the use of drag enhancing devices such as a parachute. This parachute could be designed so that on the way up it provides minimal drag, but on the way down it opens to increase drag.

More would be needed, however to allow the individual to guide the placement of their next point of contact. Otherwise, this placement would be do to ballistic motion instead of conscious placement. To achieve this, some mode of "airborne" propulsion is needed such as a propeller, jet, or rocket.

In addition, these modes could be combined so that a small balloon furthers the experienced partial gravity.

In terms of leaving no trace, the most rational motive is to disturb as little as possible. The goal should not just be the superficial impression of a pristine environment, but instead the displacement of as little alien material as possible. The first step to this goal is a level of respect and consciousness so that pairs of people walk in each other's footsteps and the return journey is made by walking in the footsteps made on the way to the destination. going beyond this, though, the actual mark must be examined and the mode of propulsion must be designed to the point where contact becomes conscious and directed.

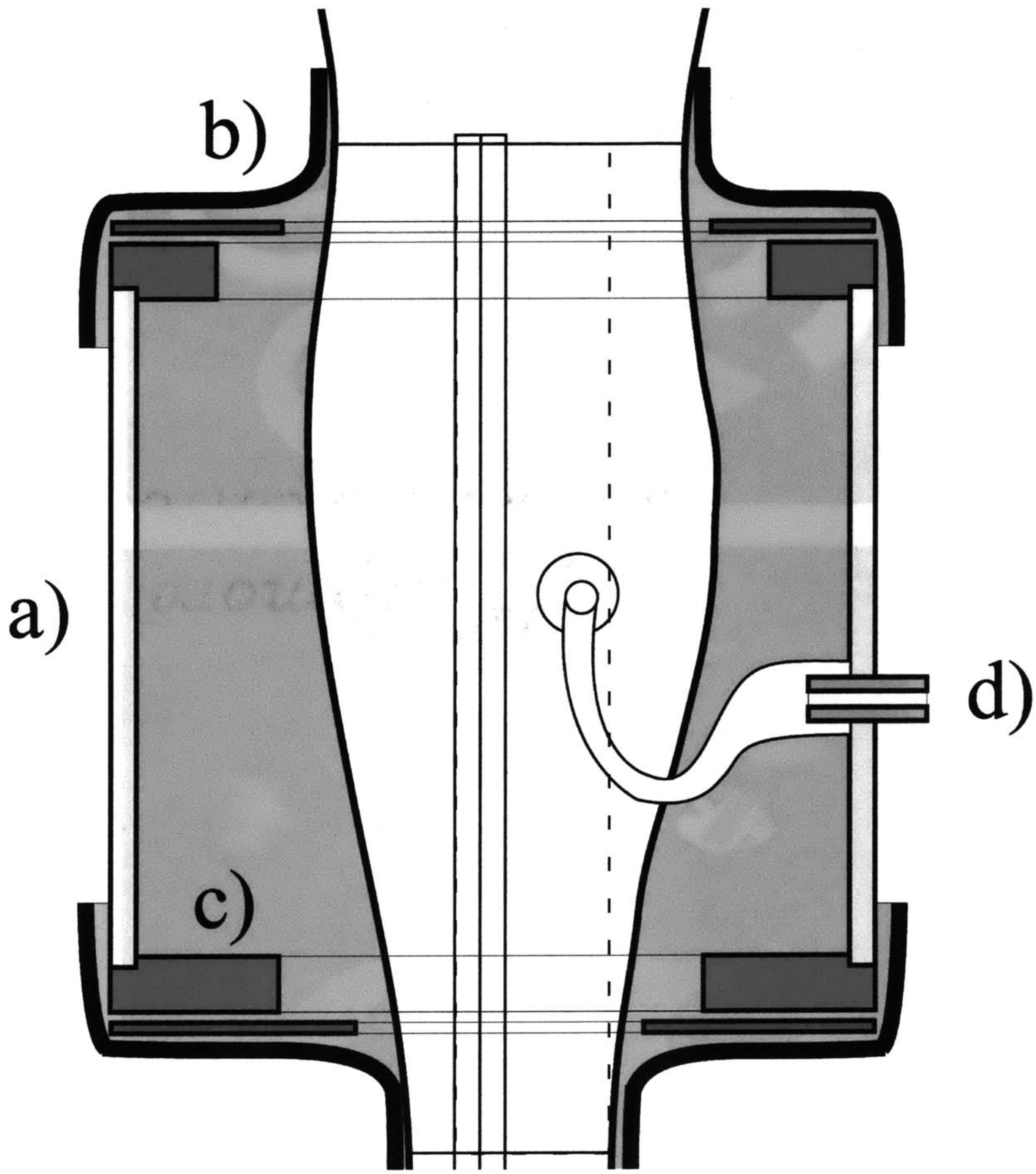
04.24.02

> Locomotion, movement through the environment, is the behavior that most dictates the morphology and physiology of animals. Evolutionary pressures for efficient, rapid, adjustable, or just plain reliable movement often push the envelope of organism design.
>
> – Dickinson et. al, "How Animals Move: An Integrative View"

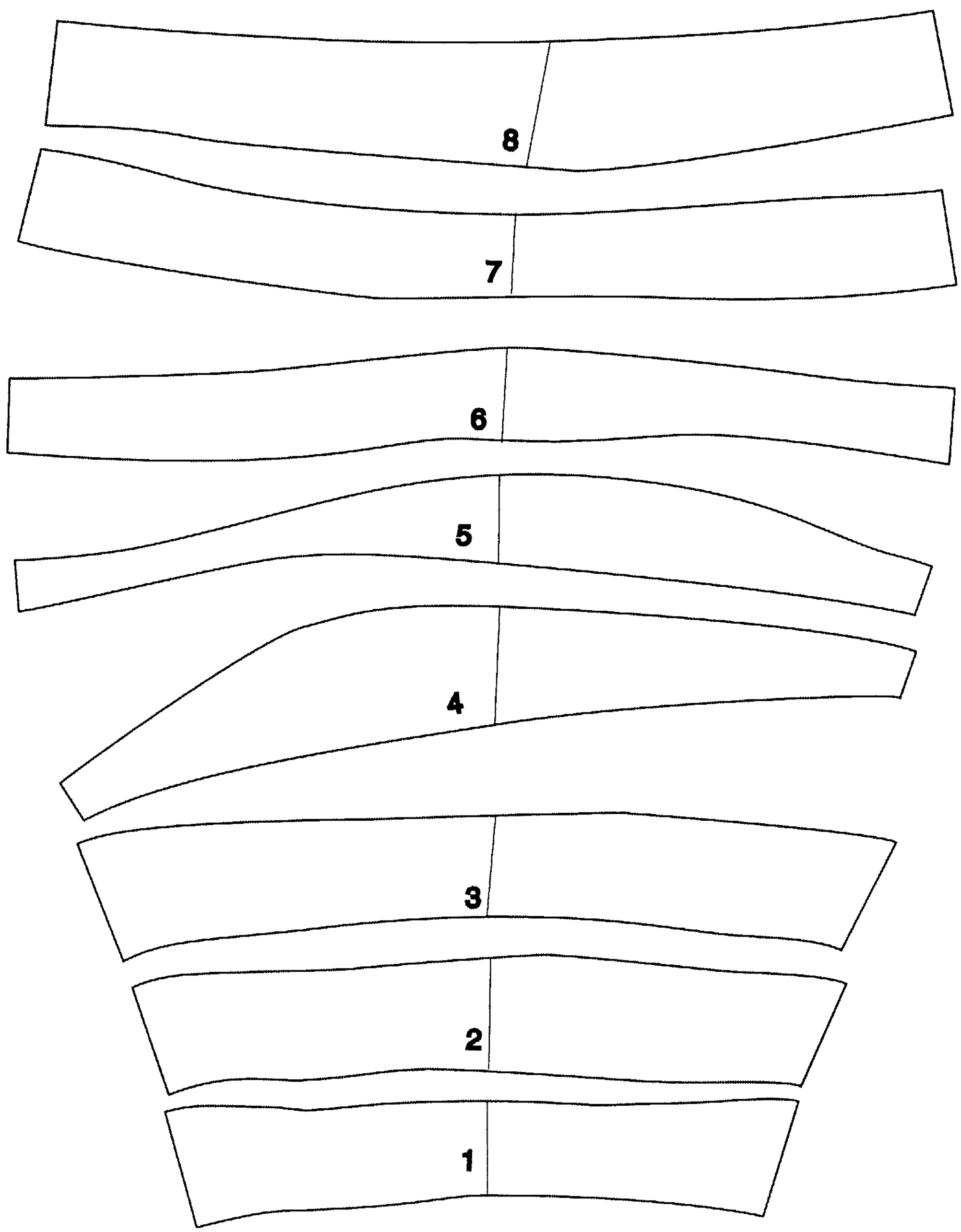
In order to move through terrain in a delicate, respectful manner, one must minimize their impact on the terrain while at the same time maximize their ability to perceive and learn from that terrain. In order to achieve this it becomes useful to minimize your weight so that your only connection with the terrain is through the act of probing or investigating. No longer do extremities become support structures, but instead take an active, inquisitive role as gatherers, feelers, sensors, or delicate propellers.

> Although treadmills, running tracks, flumes, and wind tunnels have been important tools for studying animal locomotion, knowledge of how animals move in the real world and interact physically with their natural environments is also critical to understanding locomotory performance.
>
> – Dickinson et. al, "How Animals Move: An Integrative View"

APPENDIX D: DETAILS OF THE CALF VACUUM CHAMBER

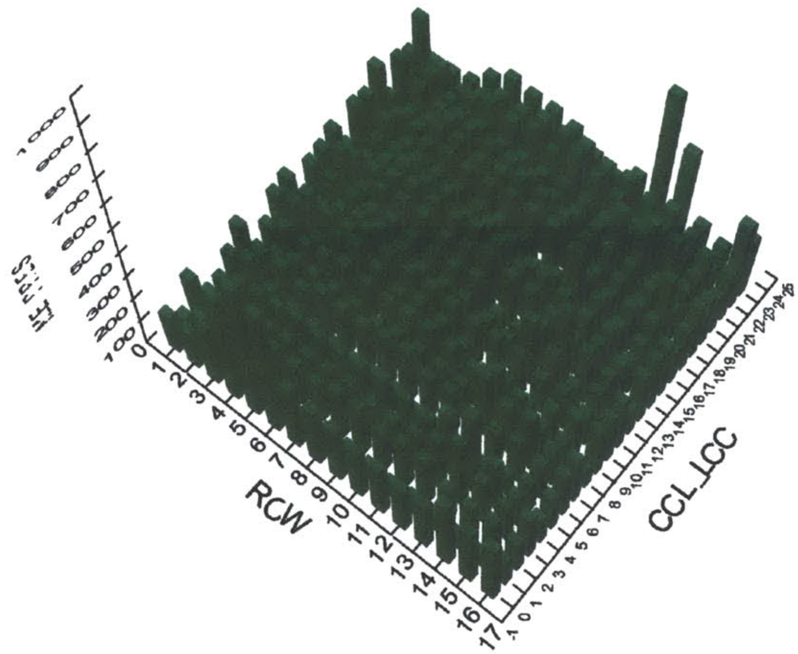


APPENDIX E: CALF PATTERN AT 3/8 SCALE

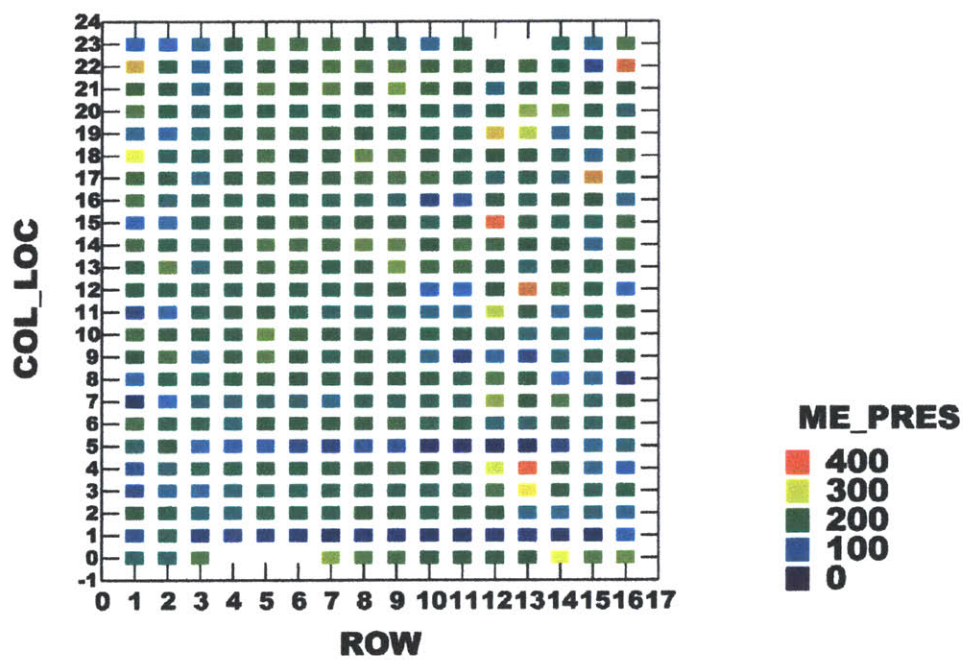


APPENDIX F: ADDITIONAL BODY DATA PLOTS

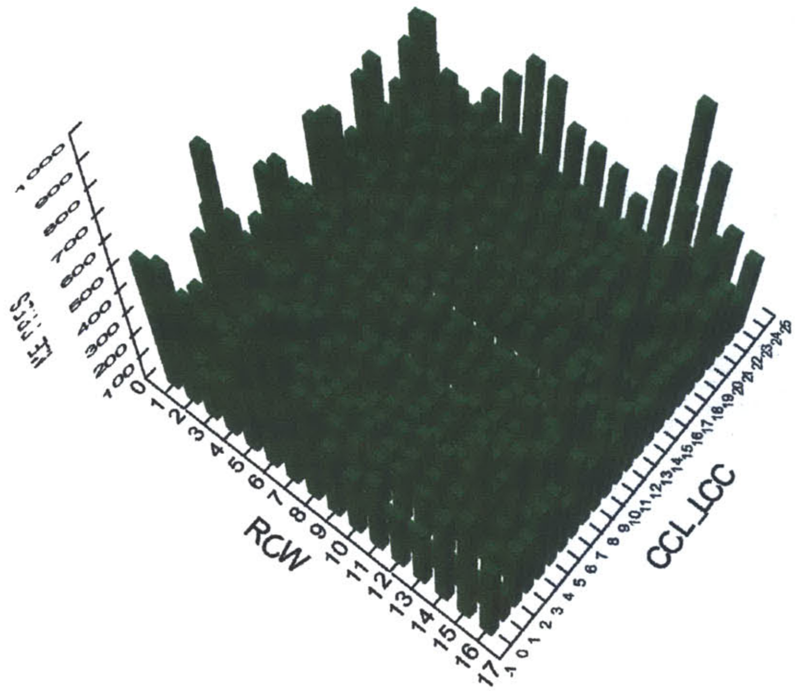
Mean Pressures by Row and Column-Location, Day: 1



Mean Pressures by Row and Column-Location, Day: 1



Mean Pressures by Row and Column-Location, Day: 2



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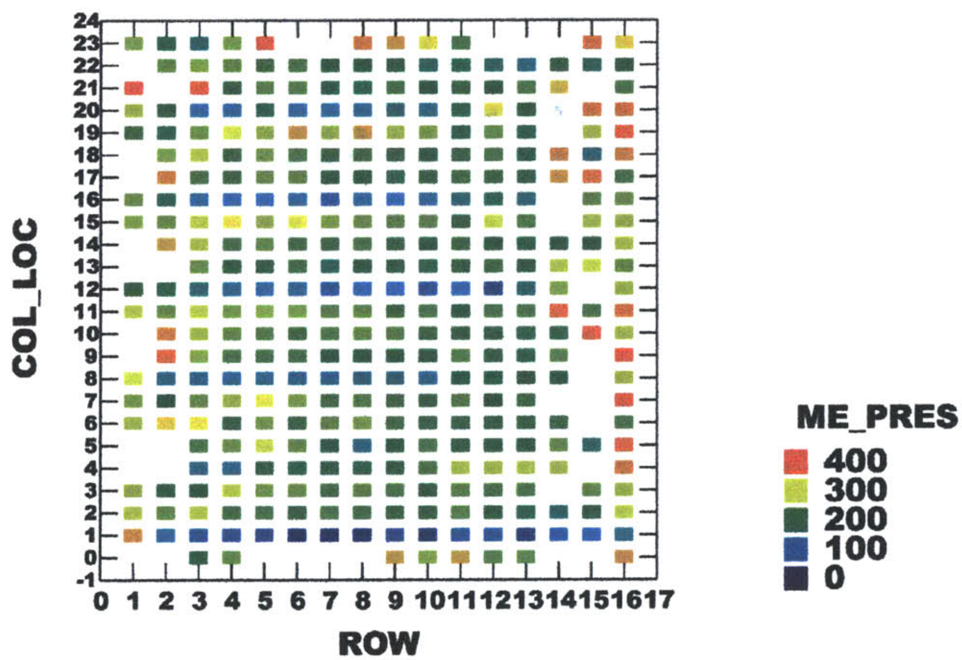
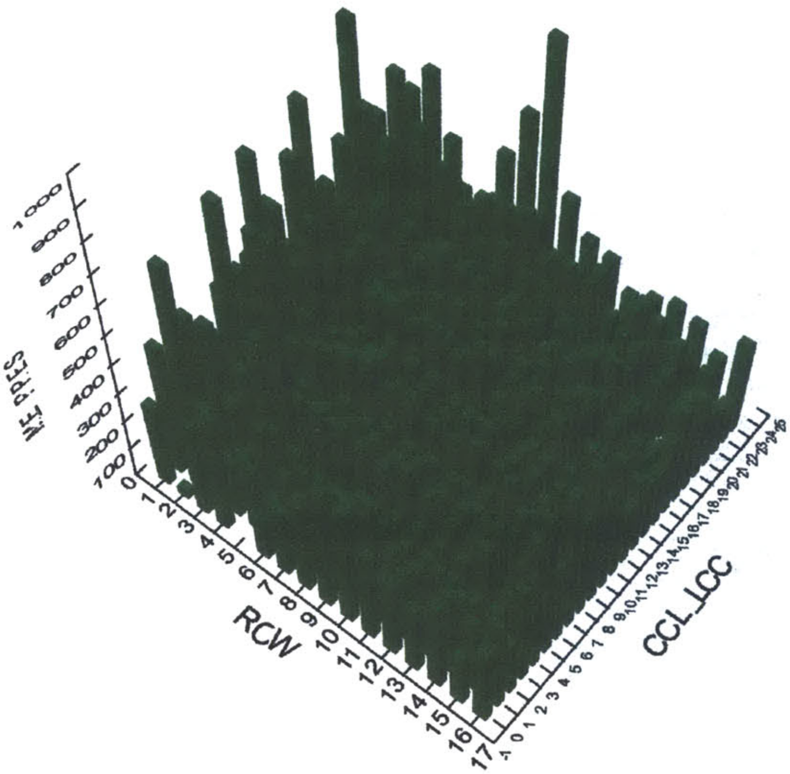
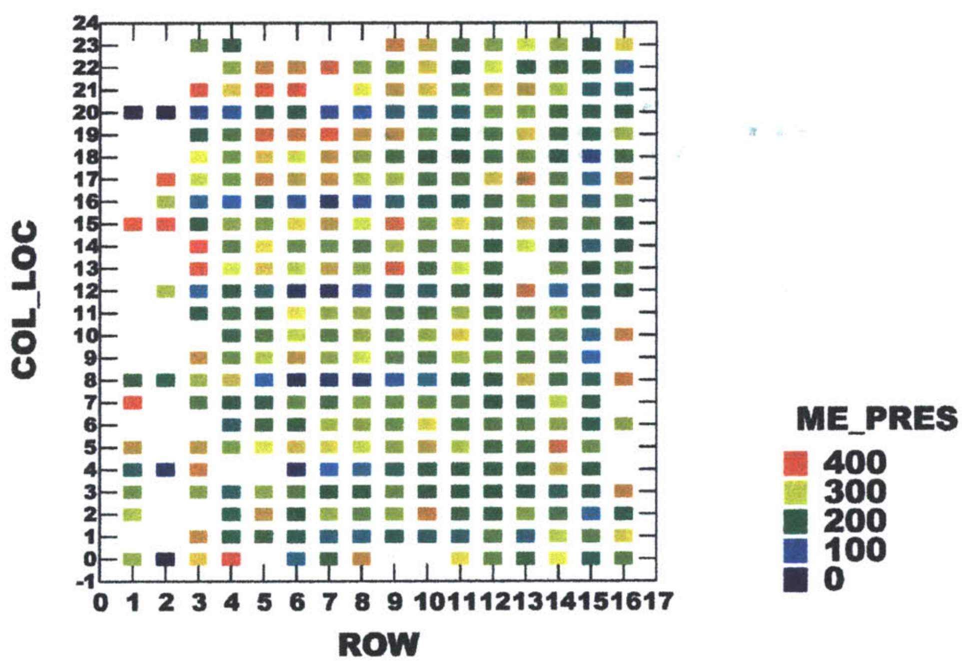


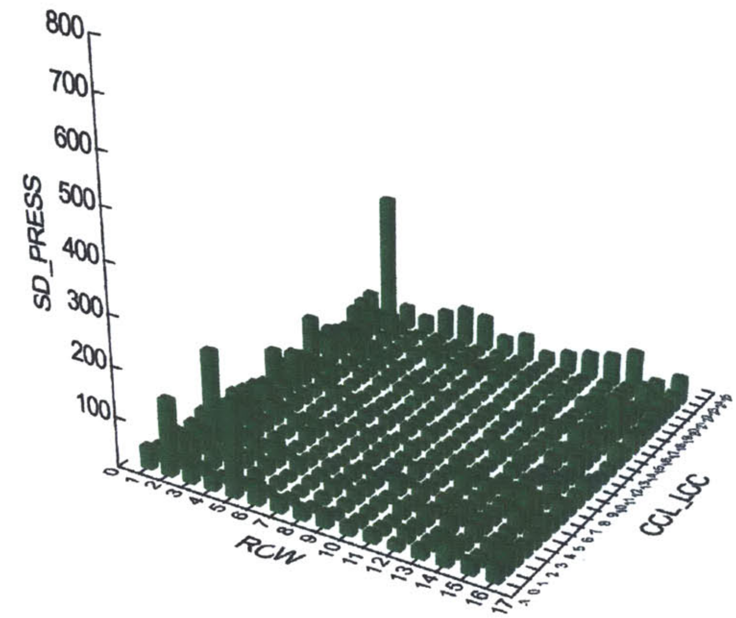
Mean Pressures by Row and Column-Location, Day: 3



Mean Pressures by Row and Column-Location, Day: 3



Standard Deviation of Pressures by Row and Column-Location



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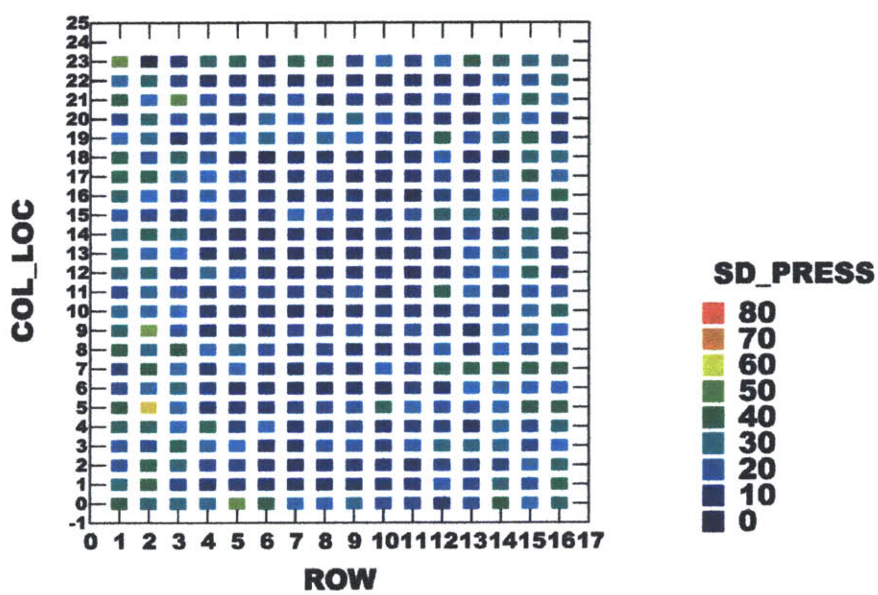

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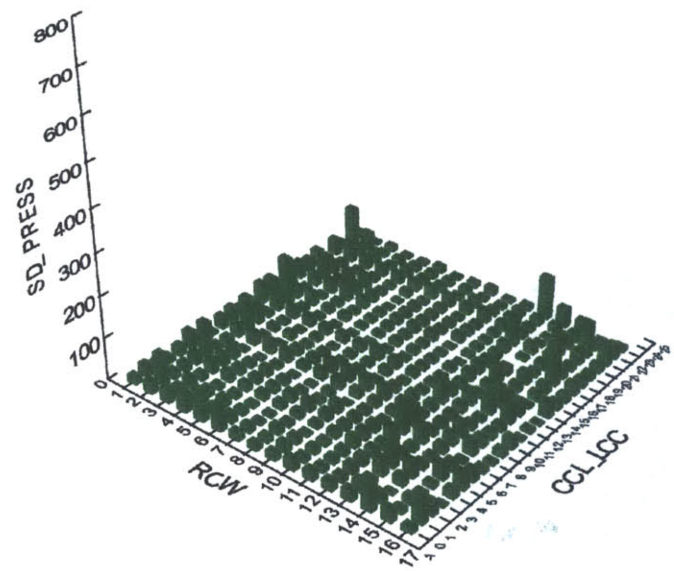

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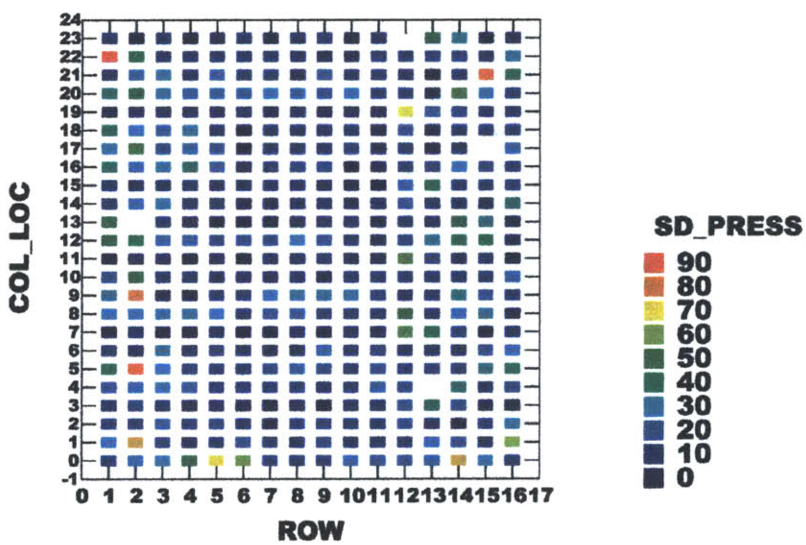

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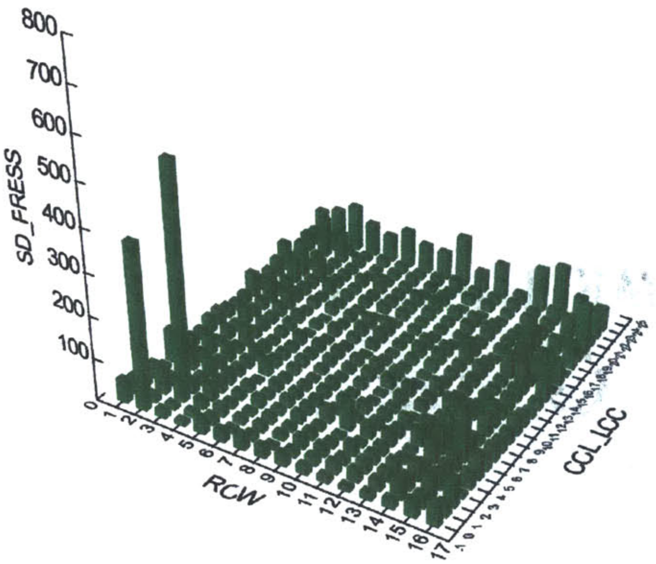

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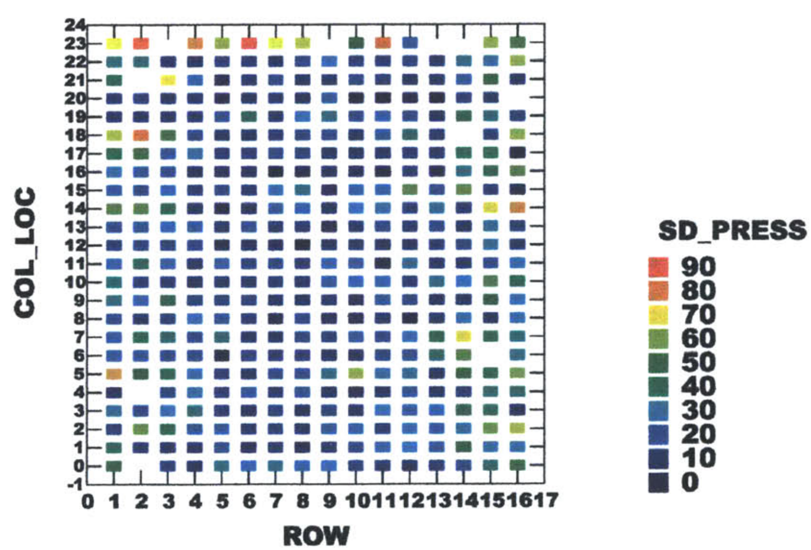
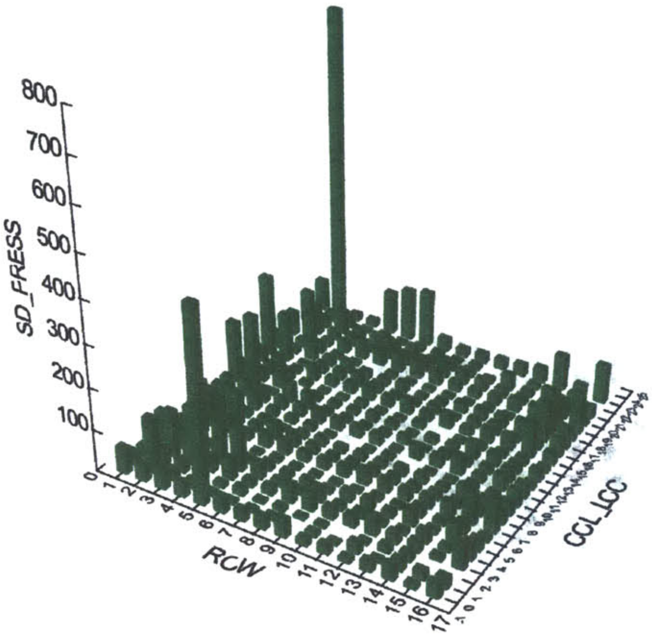
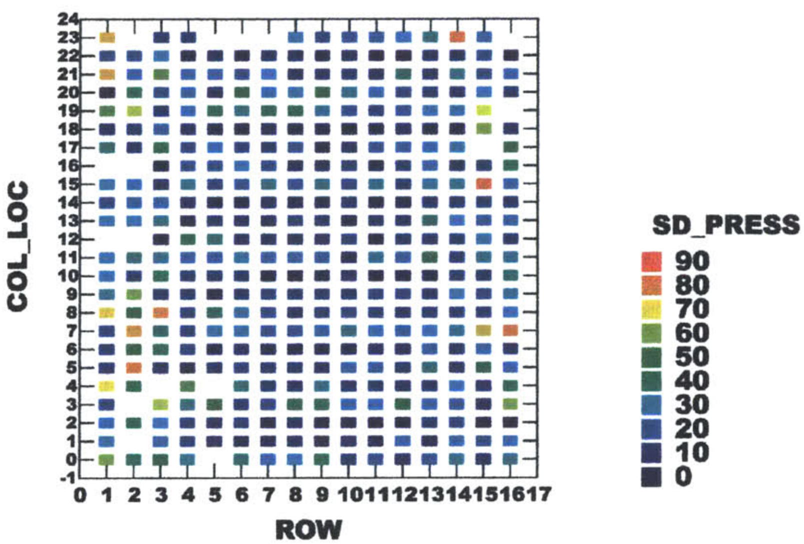


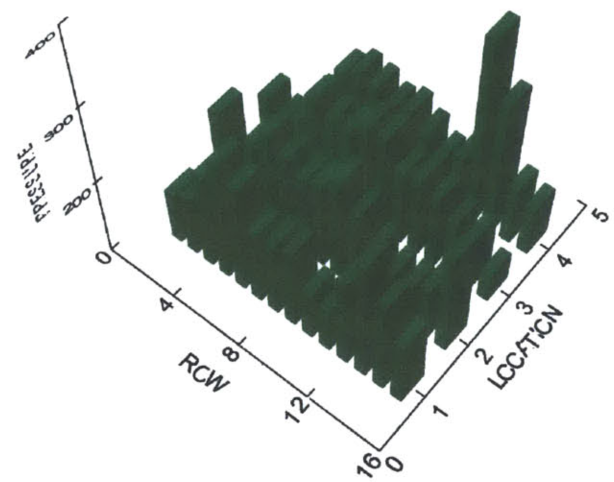
Standard Deviation of Pressures by Row and Column-Location, Day: 3



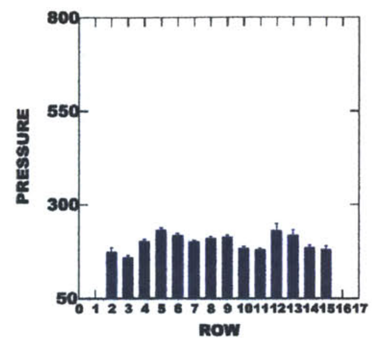
Standard Deviation of Pressures by Row and Column-Location, Day: 3



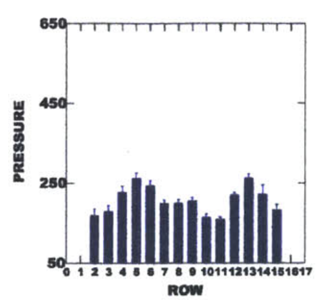
Pressure Measurements by Row and Location, Day: 1



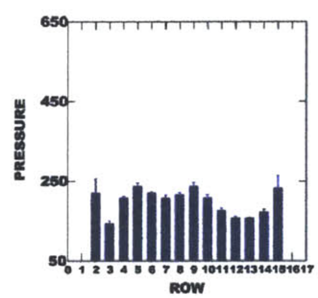
Average Pressure Measurements, Day: 1



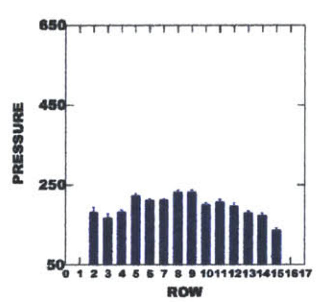
Average Pressure for Each Row, Location: 1, Day: 1



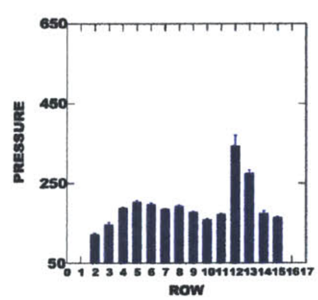
Average Pressure for Each Row, Location: 2, Day: 1



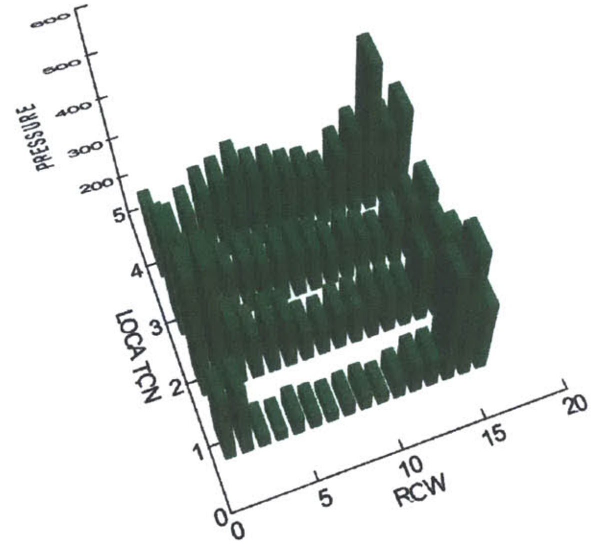
Average Pressure for Each Row, Location: 3, Day: 1

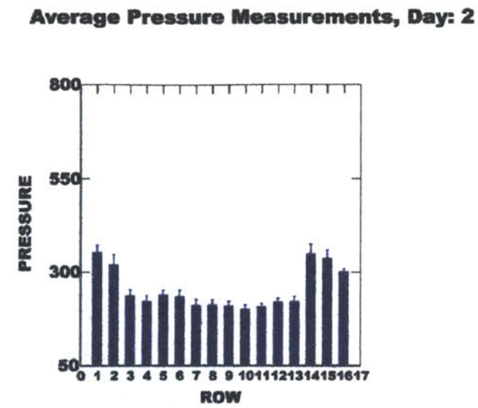


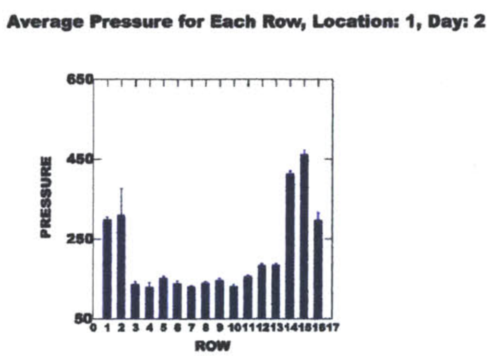
Average Pressure for Each Row, Location: 4, Day: 1

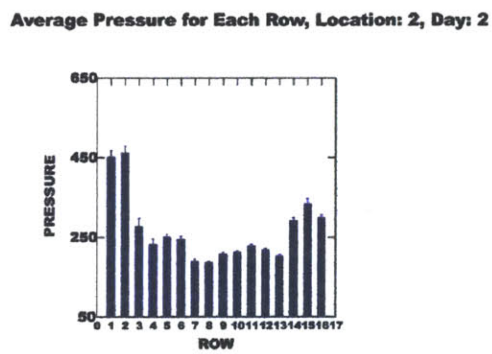


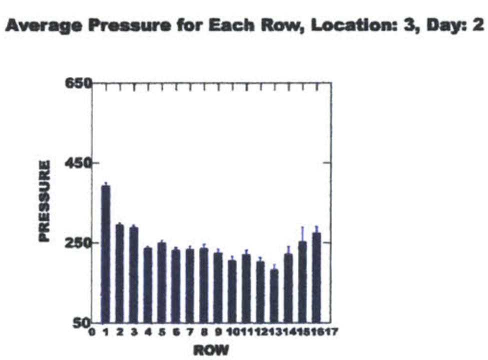
Pressure Measurements by Row and Location, Day: 2

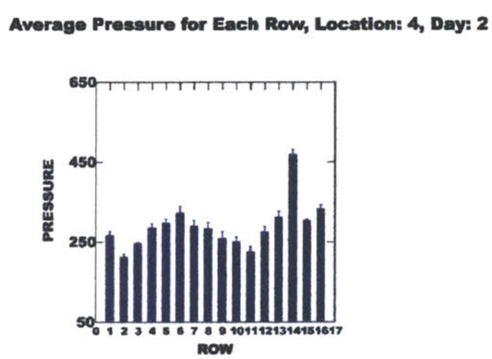




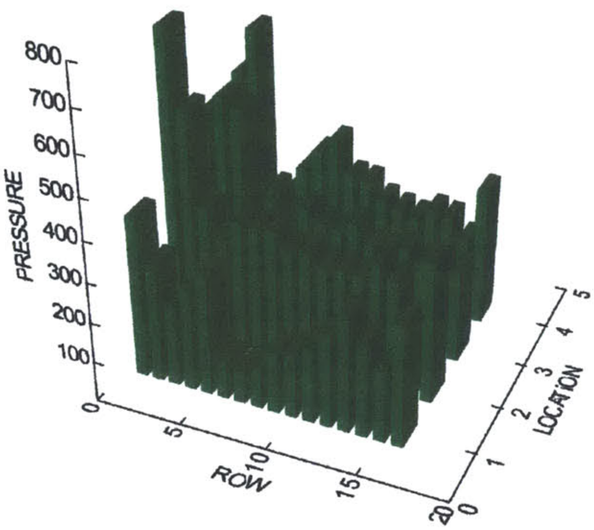




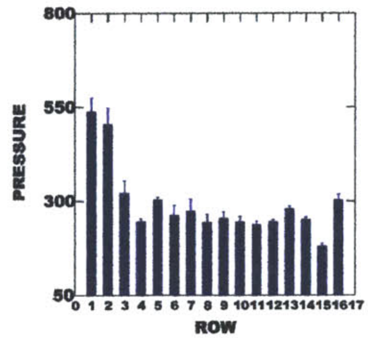




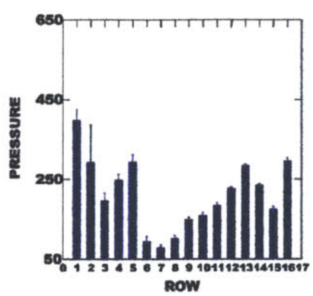
Pressure Measurements by Row and Location, Day: 3



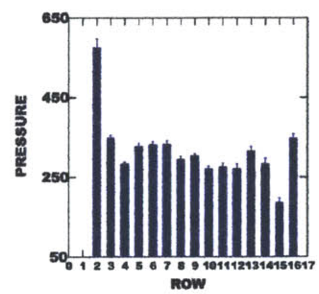
Average Pressure Measurements, Day: 3



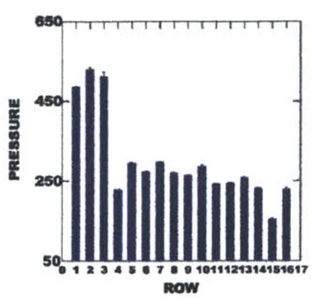
Average Pressure for Each Row, Location: 1, Day: 3



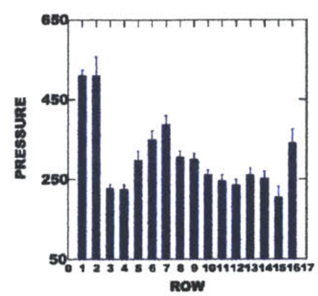
Average Pressure for Each Row, Location: 2, Day: 3



Average Pressure for Each Row, Location: 3, Day: 3



Average Pressure for Each Row, Location: 4, Day: 3



Appendix G: Preparing Body Scans for 3D Printing

Prepared by Mariel John

The Program that seemed to work the best to deal with .stl files was Magics 8.05. A demo version can be acquired via the internet, but you'll have to call the company to get the proper registration codes.

When working with this program, I have run into problems when trying to convert units. Generally your .stl will open in mm and it is best to leave it in those units throughout the entire process.

Adding Thickness

1. Go to Edit and click on select surface.
2. Click on the object you want to add thickness to. The entire object (inside and outside) should turn green.
3. Go to Tools and click on Offset Part.
4. Choose Global, Add Thickness, Internal, Avoid self-intersecting triangles. Starting with a thickness of about 6.25mm works well. Click ok.
5. The object should now appear to have a thickness.
6. Go to Edit and click on select surface.
7. Click on the inside surface of the object. Now only the inside should turn green.
8. Go to Tools and click Offsett Part.
9. This time choose External, Local, Add Triangles, Avoid Self intersecting triangles, again a thickness of about 6.25mm should be used. Click ok.
10. Now the Object should have a thickness of about .5 inches.

To Cut The Object

1. Go to Tools and choose Cut and Punch
2. You can use either a straight cut or a complex cut. The complex cut is better when

the plane is not aligned properly for your purposes.

3. If you are using a straight cut, click on the strait tab and choose a plane to work with. To see where each plane is, you have to click on it in the upper box on the left side of the screen. Use the arrows to move it around. When it is in the correct location, choose cut and that line will now be a separation between the two pieces.
4. If you are using complex cut, you click on Ind and use the mouse to put a point on each side of the object so a line is drawn where you want the cut to be made. Now choose cut.
5. You can repeat this as many times as necessary to make the object into pieces that will fit in a 3D printer.
6. One problem that arises in this procedure is that the program will name things as parts that don't really exist. The best way to see what is actually a part of your object and what is unnecessary is to go to the box on the left that has all of the parts listed, and click on the circle under color. Give each of them a unique color, and as you go along, if you see one of your pieces turn the color you have just chosen, rename that piece (in the same box on the left where you are controlling the color) so that you remember what it is. Once you know what your pieces are, you can save them.
7. When saving, you will want to go to Save Part As and it will automatically try to get you to save each part. You should save only the pieces you want and cancel the others.
8. Now you can close the project you've been working with. Be sure to choose no when it asks you to save the parts you haven't saved.
9. To see each part individually, choose load part and open the part you would like to see. Unload will get rid of it. While you are looking at your part you may want to measure it to be sure it is the correct size. To do this, choose the measuring tool on the left side of the screen and click on point to point. Now it will allow you to measure from one point on your part to another.

APPENDIX H: EXPOSED SURFACE AREA OF THE T^X SUIT

Mariel John, July, 2003

Average (50%) Male
Height: 178.4 cm
Weight: 81.5 kg
Chest Height: 40.6 cm
Chest Width: 40.9 cm
Head Circumference: 57.6 cm
Ankle Height: 13.8 cm
Ankle Width: 9.8 cm
Foot Length: 27.2 cm

Average (50%) Female
Height: 162.8 cm
Weight: 59.7 kg
Chest Height: 25.8 cm
Chest Width: 36.1 cm
Head Circumference: 55.2 cm
Ankle Height: 11.2 cm
Ankle Width: 8.8 cm
Foot Length: 24.1 cm

Measurements were taken from NASA: Anthropometric Source Book Vol. I: Anthropometry for designers pg. III-86, July 1978

The total surface area of a male 178.4 cm tall and 81.5 kg is 2.00 m^2.
The total surface area of a female 162.8 cm tall and 59.7 kg is 1.64 m^2.
SoftSlide Medical Computations
Dubois and Dubois equation used:
Log Area = Log Height x 0.725 + Log Weight x 0.425 + 1.8504

To find the surface area the Space Suit would cover, the surface area of the head, chest and feet were approximated and then subtracted from the total surface area.

The chest was approximated by a rectangle.
Average Male:
40.6 cm * 40.9 cm = 1660.54 cm^2 = .17 m^2
Average Female:
33.7 cm * 36.1 cm = 1216.57 cm^2 = .12 m^2

The head was approximated with a cylinder.
Average Male:
57.6 cm * 24.3 cm + 2*((57.6 cm/ (2*pi))^2)*pi = 1927.72 cm^2 = .19m^2
Average Female:

55.2 cm * 25.8 cm + 2*((55.2/(2*pi))^2)*pi = 1909.11 cm^2 = .19 m^2

The feet (stacked together) were approximated with a rectangular prism.
Average Male:
2*(13.8 cm*9.8 cm + 27.2cm*13.8cm + 9.8cm*27.2cm) = 1554.32 cm^2 = .15 m^2
Average Female:
2*(11.2cm*8.8cm+24.1cm*11.2cm+8.8cm*24.1cm) = 1161.12 cm^2 = .12 m^2

This means that the percentage of the total human body surface area that each portion encompasses is as follows:

Average Male	Average Female
Chest: 8.5%	Chest: 7.3 %
Head: 9.5%	Head: 11.6%
Feet: 8%	Feet: 7.3%
Remainder: 74%	Remainder: 73.8%

APPENDIX I: MATLAB CODES

```
% H_MCP.m
% Bradley Pitts 08.18.03
% Model of hybrid-MCP concept for a circular cross section and an isotropic garment

clear all

warning off

% Declare unchanging parameters
global R wi p tE t_c E_c

% Set parameter values
R = 0.0619; % cross section radius [m]
wi_R = linspace(0.1,3,50); % width of channel [m]
wi_ = R.*wi_R;
p = 27579.029; % channel pressure [Pa]
L = 1; % ratio of garment to pipe circumpherence
tE_ = linspace(1.18*10^2,72*10^5,50);
t_c = 2*10^(-3)*0.0254; % thickness of the material [m]
E_c = 0.16*10^9; % modulus of bladder material (LDPE liner grade) [Pa]

% Setup optimization parameters
OPTIONS = optimset('fmincon');
OPTIONS = optimset('Display', 'off');
optimset(OPTIONS, 'MaxFunEvals', 40000);

% Run loop to determine surface points
for j = 1:50;
  for i = 1:50;
    tE = tE_(j);
    wi = wi_(i);

    % Set initial guess
    r_init = R;
    a_init = 0;
    rho_init = 0;
    beta_init = wi/(2*R);
    theta_init = beta_init;
    alpha_init = beta_init;
    w_init = wi;
    init_vec = [r_init; a_init; rho_init; theta_init; beta_init; alpha_init; w_init];

    % Perform optimization
    [solution_vec, arg2, arg3, arg4] = fmincon('norm_vec', init_vec, -
eye(length(init_vec)), zeros(size(init_vec)), [], [], [], [], 'get_equations', OPTIONS);
```

```
    % Display solution vector
    %solution_vec

    % Check solution
    %disp('These should all be zero!');

    [C, CE] = get_equations(solution_vec);
    %CE

    % Calculate MCP on cross section
    r_sol = solution_vec(1);
    %T = p*r_sol; % tension in garment
    %MCP = T/R; % MCP on cross section
    n(j,i) = r_sol/R; % pressure distribution efficiency

  end
end

surfc (tE_,wi_R,n)
zlim([0.5 1])
```

FUNCTION [C, CE]

```
function [C, CE] = get_equations(solution_vector)

global R wi p tE t_c E_c

r = solution_vector(1);
a = solution_vector(2);
rho = solution_vector(3);
theta = solution_vector(4);
beta = solution_vector(5);
alpha = solution_vector(6);
w = solution_vector(7);

% Equation 1
CE(1) = R*sin(theta) - r*sin(beta) + rho*(sin(beta) + sin(theta));

% Equation 2
CE(2) = a - R*cos(theta) + sqrt((R*cos(theta) - a)^2 + (R*sin(theta))^2)*cos(alpha);

% Equation 3
CE(3) = r*beta + rho*(theta + pi - beta) + R*theta - w;

% Equation 4
```

```
CE(4) = p*r/(tE) - ((r-R)*beta + a*sin(beta))/(pi*R);

% Equation 5
CE(5) = (a*sin(beta))^2 - ((r-R)*cos(beta) + a)^2 - ((r-R)*sin(beta))^2;

% Equation 6
CE(6) = rho^2 -(R*cos(theta) - (r-rho)*cos(beta) - a)^2 - (R*sin(theta) - (r-rho)*sin(beta))^2;

% Equation 7
CE(7) = w - wi*(1+p*rho/(t_c*E_c));


% Set inequality constraints to nothing
C = [];
```