TESTING AND EVALUATION OF THREE LIQUID COOLING
GARMENTS FOR USE DURING SPACEFLIGHT

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Victor S. Koscheyev, M.D., Ph.D, Sc.D. & Robert C. Serfass, Ph.D.

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ABSTRACT

Background: Extravehicular activity poses several dangers to astronauts. A major concern is the regulation of core temperature and thermal comfort in the context of an impermeable EMU microclimate and elevated energy expenditure rates for prolonged periods. **Purpose:** To identify the optimal features of each of three LCGs (MACS-Delphi, Russian Orlan, NASA LCVG) for maintaining core temperature and thermal comfort during exercise in mild (24 °C) and hot (35 °C) conditions. **Methods:** Four male and two female participants (aged 22-46 years) performed 10 trials (each with five 20-minute exercise stages and two rest stages) to account for all garment configurations (with/without hood) and temperature regimes. Metabolic (VO_2 , Ve , RER), temperature (core, skin), cardiovascular (HR, SBP, DBP, S_aO_2), local sweat rate, and skin wetness data were collected and analyzed during stages five (moderate exercise) and seven (rest). Whole body sweat rate and water flow parameters were collected pre- and post-trial. **Results:** Significant differences ($p \leq 0.05$) between garments were found for: skin temperature, HR, SBP, local and whole body sweat rate, and water flow rate. **Discussion:** There were several significant, yet few consistent, findings between the garments. Use of a cooling hood had no discernable effect. Amount of tubing coverage was related to whole body sweat rate while flow rate affected skin temperatures and local sweat rate. **Conclusion:** All three garments were similar in terms of regulating core temperature in a safe range (though not to the NASA standard of 37.2 °C) during physical exertion in moderate and hot environments. Future research is needed to identify the roles of adding a cooling hood and/or ventilation system to LCGs in addition to determining optimal water temperature, flow rate, tubing arrangement, and ergonomic design.

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CHAPTER 1: INTRODUCTION

It is estimated that 20-50% of the workforce in industrialized countries is subjected to hostile environments (Flouris & Cheung, 2006). Such hostile environments are characterized by exposure to contaminants (radiation, toxins, and corrosive substances), hypo- and hyperbaric conditions, and thermal extremes. Excess heat load is a situation that many humans find themselves in as a result of high environmental temperatures, protective clothing, and/or high energy expenditures. It is estimated that 5-10 million workers in the United States are exposed to heat stress annually (Furtado, Craig, Chard, Zaloom, & Chu, 2007). The human body is truly a marvel of evolutionary design in terms of its ability to tolerate (acutely) and adapt to (chronically) temperature extremes. Evidence for the thermal resiliency of humans is provided not only by the myriad climates that humans inhabit (from equatorial to polar regions), but also the case studies in the medical literature that document the extremes of human survival following accidental hypothermia and hyperthermia with recorded core temperatures of 14.4 °C and 47.0 °C, respectively (Taylor, 2006). In general, core body temperature is maintained within a very narrow range of 36.7 ± 0.3 °C (Taylor, 2006) even in the context of extreme temperatures due to behavioral and physiological temperature regulation (Pandolf, Sawka, & Gonzalez, 2001). It should be noted that many medical sources report “normal” core body temperature as 37.0 °C with a regular range of plus or minus up to one degree Celsius (Rhoades & Tanner, 2003).

Despite the ability of humans to adequately regulate heat balance in a range of thermal conditions, there are numerous situations in which thermal stress exceeds the body's

coping ability. Manned spaceflight represents one such situation. Astronauts and cosmonauts (for consistency, the term astronaut will be used from this point forward) represent a unique, albeit small, group that must endure numerous challenges to physiological homeostasis and physical health including microgravity, radiation exposure, biorhythm disturbances, and exposure to temperature and pressure extremes. To many, it may not be obvious that increased heat load is a problem that astronauts regularly face. In particular, extravehicular activity (EVA) represents a serious threat to health and safety due to thermoregulation impairments. The term EVA refers to activity performed outside of the confines of the safe haven that is the space capsule/station (e.g., International Space Station) or transport vehicle (e.g., space shuttle). Extravehicular activity takes place on planetary surfaces (e.g., walking on the moon) as well as in the vacuum of space that surrounds a space capsule or vehicle (e.g., spacewalk). While there are important differences between the two types of EVA, a common problem is an increased heat load due to the effects of elevated metabolic rates in the context of a protective (and impermeable) space suit that leads to a rise in the microclimate temperature in which the astronaut must operate. Extravehicular sorties often involve increased energy expenditure levels for prolonged periods of time (often measured in hours).

While the first EVAs performed in the 1960s may have been more for “show” as a result of the “space race” between the United States and the Soviet Union, in the year 2010 they are a necessity, not a luxury. Space station construction and maintenance require routine EVAs while in-flight external inspection, and possibly repair, of a transport vehicle like the space shuttle is now commonplace following the *Columbia* space shuttle disaster.

Despite what was essentially a termination of the Constellation Program by President Barack Obama on February 1, 2010 (this would have returned the United States to the moon by 2020), there seems to still be sufficient political and scientific inertia for a long-range goal of manned spaceflight to Mars. Exploration, and potential colonization, of extraterrestrial planetary surfaces will require, among other things, a significant amount of EVA. If past human ingenuity, curiosity, and endeavors are any indication of future behavior, then it would seem that it is not a matter of *if* humans will travel to Mars, but *when*. If that is the case, then the optimization of human safety and comfort during EVA will be a significant area of research and design in the coming years since the margin for error in spaceflight is already small and will presumably decrease as the missions take astronauts further from *terra firma*.

Thermal countermeasures in the form of ventilation- and liquid-perfused garments have been in existence since the 1940s and 1960s, respectively, and were first designed for pilots who routinely experienced thermal extremes (Nunneley, 1970). Agencies overseeing the early manned spaceflights of the 1960s saw the need for cooling countermeasures and incorporated ventilation-cooled garments. However, the cooling ability of ventilation alone was limited and it was not long before liquid cooling garments (LCGs) became standard equipment for spaceflight. The underlying principle of LCGs is rudimentary, yet effective, and simply involves the circulation of cool/cold water that perfuses the garment via a network of tubing. Direct contact between the skin and tubing promotes conductive heat transfer and exploits three important properties: 1) temperature gradients and the second law of thermodynamics, 2) fluidized flow of water, and 3) the

1. Water
 - a. Temperature
 - b. Flow rate
2. Tubing
 - a. Spatial configuration and total amount (length)
 - b. Material properties, diameter, shape, and flexibility
3. Garment
 - a. Material (fluid retention, durability, comfort)
 - b. Ergonomics (mobility, flexibility, sizing)
4. Cooling regime
 - a. Automatic or manual control
 - b. Constant or intermittent
5. Augmentation of heat transfer
 - a. Addition of cooling hood
 - b. Incorporation of ventilation system
6. Equipment
 - a. Hardware and power requirements
 - b. Equipment reliability, breakdown, and repair

Figure 1.1. Parameters of liquid cooling garments that require further investigation in terms of maximizing safety, comfort, and efficiency.

specific heat capacity of water. It should be noted that LCGs have numerous applications beyond aviation and spaceflight including occupational, athletic, and medical settings.

While the basic principles of LCGs have not changed in the nearly 50 years since the prototype was developed, the evolution of LCGs has focused on optimization of design. Many questions still surround the development of effective and efficient LCGs for use as a countermeasure to heat stress. The six categories listed in Figure 1.1 represent important questions regarding the development of LCGs that have yet to be adequately answered. As space agencies like NASA move forward in the planning stages for potential future missions to Mars, the optimization of LCG design has been identified as

a significant research focus. Proper management of thermal comfort and physiologic regulation (via LCGs) translate to enhanced subjective perception and increased safety, respectively, for astronauts and, as a result, these are areas of great interest as the research and design process moves forward.

The current study involves the testing and evaluation of three different LCGs, two of which are currently being used by the American and Russian space agencies. The Minnesota Advanced Cooling System (MACS-Delphi) was developed by researchers at the University of Minnesota (Twin Cities) and incorporates a physiologic design in which the tubing is strategically oriented to correspond to high-density tissue areas (i.e., bone). The Russian Orlan (Orlan) is currently used by Russian cosmonauts during spaceflight and also employs a physiologic design but instead focuses the tubing coverage on large areas of skeletal muscle. The third garment is the NASA Liquid Cooling Ventilation Garment (LCVG); the LCVG is currently used by NASA during spaceflight and is characterized not by selective tubing orientation, but by a focus on quantity of body coverage. The LCVG also has a ventilation component that is designed to augment heat transfer via convective and evaporative means (this option was not used during the current study for standardization purposes). It should be noted that the MACS-Delphi and Orlan have a cooling hood option (the LCVG does not) that covers the head for added heat extraction. The effectiveness of incorporating a cooling hood was also evaluated in this study. Testing and evaluation of the garments took place during simulated EVA (walking on a treadmill) in thermoneutral and hot environments.

Purpose

The purpose of this study is to identify the advanced features of each of three LCGs (MACS-Delphi, Orlan, LCVG) for maintaining core temperature and thermal comfort during intensive exercise in mild and hot conditions.

Hypothesis

The research hypothesis is that human heat balance can be supported during intensive physical exertion in mild and hot conditions by means of thermal regulation through different approaches to spacesuit design, with specific emphasis on the LCG component.

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CHAPTER 2: REVIEW OF LITERATURE

Since the purpose of this study is to evaluate the performance of three different liquid cooling garments (LCGs) in the context of simulated extravehicular activity (EVA) in thermoneutral and hot environments, it seems necessary to review several important topic areas. The topics that will be reviewed include: thermoregulation, the physiology of spaceflight and EVA, and cooling modalities. A recurring theme throughout the subsequent review will be the introduction of the topic of spaceflight and microgravity and how it relates to the corresponding subject matter.

Thermoregulation

Heat Balance

The human body has evolved to survive, and in many cases thrive, in a wide range of thermal environments. In modern times, the formal study of human thermoregulation dates back to at least 1775 where Charles Blagden's experiments involved baking himself and others in a heated room at temperatures reaching nearly 130 °C for 45 minutes. These early experiments yielded observations related to heart rate, circulation, and sweating (Blagden, 1775); this represents some of the earliest published work related to human thermoregulation. An understanding of the human body and the effects of various thermal conditions have come a long way in the past couple of centuries but much has yet to be learned about the complicated thermal relationship between the internal environment of humans and the external environment in which they must live. The following passage (Pisacane, Kuznetz, Logan, Clark, & Wissler, 2007) sums up the multifaceted nature of human thermoregulation:

Because of the complexity of the human thermoregulatory system, contributing components should be taken into account comprehensively in modeling. These include: 1) environment - atmospheric constituents, pressure, temperature, humidity, and [air or water] flow rate; 2) clothing - thermal conductivity and permeability; 3) anatomical characteristics - surface area, mass, body composition, heat capacity, gender, and age; 4) activity - workload, metabolism, oxygen uptake, respiratory heat loss, and acclimation; and 5) physiological response - shivering, sweating, vasoconstriction, vasodilation, blood flow rate, and heart rate. (p. A52)

The “modeling” referred to in the previous quote represents a technique used by some scientists to quantitatively assess various thermal parameters by using human body thermoregulatory simulators or so-called thermal manikins. While the pros and cons of thermal modeling are beyond the scope of this discussion, it suffices to say that there are myriad factors (including many not previously mentioned) that contribute to thermoregulation and heat balance that can make for precarious interpretations and erroneous assumptions.

An appropriate place to begin this discussion is at the level of thermal regulation and the means by which humans achieve thermal balance, even in extreme thermal conditions. The two primary means by which deep body temperature (i.e., core temperature) is maintained are behavioral and physiological regulation. Behavioral regulation has been described as involving “the conscious, willed use of whatever means are available to minimize thermal discomfort...[which]...appears to be proportional to core and skin temperatures” (Pandolf, Sawka, & Gonzalez, 2001). Examples of behavioral regulation in cold environments include wearing more clothing, increasing metabolic heat production by voluntarily increasing energy expenditure levels, or seeking shelter from the cold. Behavioral regulation in hot environments is often characterized by wearing less (or

light-colored) clothing, decreasing the intensity levels of physical work or exercise, and increasing fluid consumption. Behavioral regulation is not unique to humans and can be witnessed throughout the animal kingdom, though it is instinct (not conscious thought) that triggers the behavioral response in animals. Classic examples range from the huddling of groups of penguins during the long, cold, dark arctic winters in an attempt to maximize heat sharing and minimize exposed body surface area to hippopotamuses seeking refuge from the equatorial heat by bathing in watery mud holes to not only reap the cooling benefit of the water, but also to use the mud as an insulatory mechanism. Conversely, physiological regulation describes how the body responds (independent of a conscious thought process or volition) to various thermal stimuli in an attempt to maintain core temperature within a small range. In cold environments, a peripheral vasoconstrictor response is triggered that serves to decrease blood flow to the periphery, thus shunting warm blood to the deep veins reducing heat loss to the external environment. Other mechanisms of heat conservation in the cold include piloerection (i.e., goose bumps) and the initiation of shivering and chemical thermogenesis which serve to increase metabolic heat production which aids in maintaining core temperature. Hot environments elicit a decrease in metabolic rate (to decrease internal heat load) and, more notably, initiate cutaneous vasodilation and the sweating response in an attempt to transfer heat from the core to the periphery (via the circulating blood) at which point numerous heat transfer mechanisms are engaged (Pisacane et al., 2007). The four primary means by which heat transfer occurs are: 1) radiation - transfer of energy waves that are emitted by one object and absorbed by another, 2) convection - heat exchange that occurs between a solid medium and one that moves in a fluidized/flowlike manner (as in the air),

3) conduction - transfer of heat from a warm object to a cooler object, and
 4) evaporation - heat transfer from the vaporization of water (Armstrong, 2000). As it relates to evaporation, it should be noted that it is the only one of the four previously mentioned heat exchange mechanisms that only serves to transfer heat away from the body (i.e., convection, conduction, and radiation can transfer heat to the body or away from it). In terms of evaporation, each vaporized liter of water extracts 580 kcal from the body and transfers it to the environment; this water comes from the approximately two to four million sweat (eccrine) glands within the average person (McArdle, Katch, & Katch, 2010). Central to human thermoregulation is the heat balance equation which describes the thermal exchange between an individual's body and the environment (Fregly & Blatteis, 1996):

$$S = M - (\pm W_k) \pm (R) \pm (C) \pm (K) - E \quad [W \cdot m^{-2}]$$

S = rate of storage of body heat (+ for net gain)

M = rate of metabolic energy production (always +)

W_k = rate of work

(+ for work against external forces)

(- for eccentric/negative work)

R = rate of radiant heat exchange (+ for a gain)

C = rate of convective heat transfer (+ for a gain)

K = rate of conductive heat transfer (+ for a gain)

E = rate of evaporative heat transfer (- for net loss)

While a more detailed description of the complex nature of thermoregulation is beyond the scope of this discussion, such descriptions do exist elsewhere (Fregly & Blatteis, 1996; Pandolf et al., 2001). Additionally, a thorough review article has been written on the challenges to temperature regulation when working in hot environments (Taylor, 2006). The topic of acclimatization is particularly important for those subjected to chronically high heat loads and physical exertion; this topic is discussed in detail

elsewhere (Armstrong, 2000). It is important to note that prolonged exposure to microgravity (i.e., spaceflight) and simulated microgravity (i.e., bed rest) have been shown to negatively impact thermoregulation (Fortney et al., 1998; Greenleaf, 1989); however, more research is needed in this area to determine the mechanisms of such alterations in thermoregulation.

Temperature Measurement

Core body temperature is one of the three traditional “vital measures” in medicine (along with blood pressure and heart rate); skin temperature, though not used as frequently in the clinical setting as core temperature, does provide valuable insight into the thermal status of an individual. While measures of core and skin temperature are important in assessing overall thermal status for various medical and occupational applications, the issue of temperature measurement is fraught with controversy and lacks a standardized approach. Such unresolved issues relate to which site for core temperature measurement provides the most accurate reflection of overall deep body temperature, which skin sites should be measured and what is the best method for calculating an overall average skin temperature (using various mathematical weighting techniques), and what is the most accurate means by which to quantify overall average body temperature (i.e., as a combined function of various compartments) (Fregly & Blatteis, 1996; Pandolf et al., 2001; Shiraki & Yousef, 1987).

The measurement of rectal temperature can be logistically difficult for a multitude of reasons and may not be practical in all situations. While it is typically higher than

temperatures at other sites of core temperature measurement (i.e., esophageal, oral, and tympanic) and responds more slowly to rapid changes in core temperature, it is generally regarded as the standard for core temperature measurement (particularly in steady-state conditions) owing to its validity and stability (Fregly & Blatteis, 1996; Gagnon, Dorman, Ollie, Hardcastle, & Kenny, 2009). Insertion depth of the rectal probe is a frequent concern that a recent study sought to investigate. The study (Lee, Wakabayashi, Wijayanto, & Tochiara, 2010) involved simultaneous rectal temperature measurement at seven separate depths ranging from 4-19 cm beyond the external sphincter during bicycle exercise and subsequent recovery. The authors concluded that there were no systematic differences at depths greater than 10 cm which is in agreement with the common convention of requiring a minimum insertion depth of 10-13 cm but at odds with the conclusions of others that claim there is uniformity in terms of rectal temperature at depths ranging from 5-27 cm (Pandolf et al., 2001) and 5-20 cm (Fregly & Blatteis, 1996). It would seem that a conservative recommendation for rectal probe insertion depth is a minimum of 10 cm.

In terms of skin temperature measurement, Pandolf et al. (2001) cite three primary reasons for the measurement of skin temperature: 1) calculation of mean body temperature (in combination with other compartments) for heat storage determinations, 2) calculating radiative and convective heat exchange and skin conductance, and 3) determining the relationship between skin temperature and central thermoregulatory control mechanisms. Skin temperature measurement has several advantages and disadvantages. Skin is easily accessible for measurement and offers an almost real-time

indication of the current thermal conditions at the interface between the human body and the environment. However, individual skin sites alone are seldom useful for much beyond the regional level that is being measured. There are exceptions to this, one of which being the finger region. The hand has one of the most extensive blood vessel networks in the body which makes this area (specifically the finger) a candidate for skin temperature monitoring due to the thermal sensitivity and reactivity. The finger perhaps can be likened to the “canary in the coal mine” analogy as it relates to the status of the thermal environment. There exists experimental evidence that the thermal status of the fingers is highly correlated with heat content in the body and that the first indication of a forming heat deficit/surplus is manifested in this area (Coca, 2005; Koscheyev, Coca, & Leon, 2007). Automatic regulation of microclimate thermal control systems is a growing area of research due to the fact that manual control is often found to be sub-optimal. As Webb et al. (Webb, Troutman, & Annis, 1970) eloquently put it: “Man is a poor judge of his own thermal state.” However, effective automatic regulation first requires the identification of a reliable, valid, and easily measured indicator to act as a “thermostat.”

While individual skin sites can be of interest to some, mean skin temperature is generally considered a more utilitarian metric. However, there is no singly agreed-upon mathematical technique for arriving at an index that is representative of overall skin temperature. What is common to most averaging techniques is a weighting system based upon the percentage of body surface area that is represented by the skin region being measured. Perhaps the most well-known skin temperature weighting system for calculating mean skin temperature is the one created by Hardy and DuBois (Hardy &

DuBois, 1938) which divides the body into 12 regions with the following weighted proportions: head: 7%, hand: 4%, upper back: 9.5%, chest: 9.5%, lower back: 9.5%, abdomen: 9.5% , biceps: 9%, forearm: 7%, quadriceps: 9.5%, hamstring: 9.5%, front calf: 8.5%, and back calf: 7.5%. It should be noted that several weighting strategies exist ranging from a 15-site weighting formula based on partitional calorimetry (Winslow, Herrington, & Gagge, 1936) that has been validated (Mitchell & Wyndham, 1969) to a 4-site formula (Ramanathan, 1964). There are also approaches that deviate from the traditional body surface area percentage technique like that of basing regional weighting on the thermal sensitivity of the skin due to the observation that thermal receptors are not evenly distributed over the skin's surface (Nadel, Mitchell, & Stolwijk, 1973).

Finally, due to the fact that overall mean body temperature is a valuable source of information related to total-body heat balance and thermal status, there exist several weighting techniques that attempt to combine average skin (shell) temperature with average deep body (core) temperature. The traditional two-compartment model of core/shell weightings for hot, warm-temperate, and cool conditions are 0.9/0.1, 0.79/0.21, and 0.67/0.33, respectively (Sawka & Castellani, 2007). However, there is evidence that, even with a correction factor, estimating changes in mean body temperature based only on two compartments (shell and core) is inaccurate (Jay, Reardon, et al., 2007). Jay and colleagues (Jay, Gariepy, et al., 2007) have also investigated the incorporation of muscle temperature which represents a third compartment (in addition to shell and core). Their research indicates that the three compartment thermometry model used was superior to that of the traditional two-compartment model. It should be noted that they are not the

first to propose a three-compartment model using shell, core, and muscle temperatures (Nadel, Bergh, & Saltin, 1972; Snellen, 2000; Webb, 1998).

Physiology of Spaceflight and EVA

Spaceflight

The so-called Space Age was launched on October 4, 1957 with the Soviet Union's successful flight of *Sputnik*. That was followed shortly thereafter by the first human (Yuri Gagarin) to travel to outer space on April 12, 1961 and the rest, as they say, is history. While the ability to travel beyond the reaches of planet earth is nothing less than amazing, the most difficult part still lies ahead. It is an unfortunate irony that humans, by their mental constitution, are so very driven to explore space and yet, by their physical nature, are so ill-equipped to survive in it. Assuming that humans will be protected from such lethalties of outer space as ionizing radiation, space projectiles, and lack of oxygen, one of the greatest obstacles will be surviving in an environment devoid of gravity. Gravity is an obvious environmental parameter that humans are well-equipped to deal with. Microgravity, on the other hand, is not something that any bipedal mammal would be expected to have adaptive responses against on a chronic scale. Most humans do, however, experience effects similar to those induced by microgravity on a daily basis when lying in the horizontal position, as when sleeping. There are key differences, however, the most notable being that these bouts, while regularly occurring, are relatively short in duration and are interspersed with long durations of continuously fighting the force of gravity. Interestingly, patients with illnesses/ailments that cause them to be chronically bedridden suffer many of the same health sequelae as astronauts who spend

prolonged periods of time in space like the development of kidney stones (Cheung, 2010) and a decrease in bone mineral density (Smith & Heer, 2002). As a result, one the most valuable models for studying the effects of microgravity on humans is a modified bed rest condition (typically a negative 6-12° head-tilt position to account for fluid shifts). Some of the longest bed rest studies last 6-12 months; NASA continually conducts 90-day bed rest protocols at its facility in Galveston, Texas (Cheung, 2010).

In the case of spaceflight, a gravity-free environment creates several problems for humans. While many of these problems were predicted before manned spaceflight came to fruition, they were not of emergent concern in the early days of space travel because: 1) the focus of early research and design was, rightfully, on the technology to safely transport humans to and from space and 2) the duration of early spaceflights was, by and large, not thought to be sufficient to induce significant health-related complications. Problems that emerge as the result of prolonged exposure to microgravity typically can be traced to two physiological systems: cardiovascular and musculoskeletal. In the case of the cardiovascular system, a major deleterious effect is an impairment of the circulation whereas the lack of mechanical stresses on the bones, musculature, and connective tissues results in decreased strength, integrity, and function of the musculoskeletal system. It is important to note that the two systems are not independent of each other, on earth or in space, and that disruptions in any one physiological system typically have repercussions within another system or systems. For example, in microgravity, the forces generated by skeletal muscles are very low simply because there are no (or minimal) gravitational forces to overcome. As a result, the skeletal muscles

atrophy, particularly those that are used most regularly on earth like the large postural and locomotor groups of the lower extremity (Buckey, 2006). However, this also has an effect on the cardiovascular system (i.e., the heart) due to the fact that not as much oxygen is required by the musculature because the energy requirements are significantly reduced. A reduced oxygen demand will necessarily lead to a reduced cardiac output which ultimately results in deconditioning of the cardiac muscle tissue which may result in decreased pumping capacity and arterial pressure (Perhonen et al., 2001). Altered circulation (due to microgravity) resulting in reduced blood flow to certain areas is a second example that illustrates the interconnectedness of physiological systems. Specifically, in microgravity, blood tends to pool in the central regions of the body, not in the dependent areas like the lower limbs as evidenced on earth as a result of gravity (Rowell, 1993). For a thorough and detailed analysis of the effects of microgravity on the cardiovascular and musculoskeletal systems, the reader is directed to Fregly and Blatteis (1996). Additionally, there exist in-depth explanations of human circulation and its control (Rowell, 1993; Rowell & Shepherd, 1996). Another issue that warrants attention is the effects that an impaired circulation exerts on thermoregulation. Since much of the human body's capability to transfer heat lies within the fluidized flow of blood, it stands to reason that an impaired circulation will result in less-than-optimal thermoregulation.

EVA

The Soviet Union's Alexey Leonov conducted the first-ever EVA from the *Voskhod 2* spacecraft on March 18, 1965. He was outside of the craft for 12 minutes and nine seconds, connected by a 5.35 m tether (Abramov & Skoog, 2003). On March 11, 2001,

Americans Susan Helms and James Voss performed the longest EVA to date at nearly nine hours (8 hr 56 min). As a clarifying note, the Russian space program defines EVA as occurring when a cosmonaut is in a vacuum whereas NASA considers EVA to commence when the astronaut switches the extravehicular mobility suit (EMU) to battery power. When EVA durations are measured in hours, serious consideration must be given to issues related to thermal comfort and temperature regulation. Three elements act synergistically to create a situation for astronauts during EVA that can lead to heat overload, thermoregulatory collapse, and possibly death. Those elements are increased energy expenditure rates, high temperatures, and a microclimate that is impermeable within the EMU. In this day and age of space shuttles, space stations, and proposed space flights to the moon and beyond, EVA is a necessity. An important distinction must be made between the two primary types of EVA (this is not referring to the differences in how Russians and Americans define EVA). The lunar missions that made for television rating bonanzas in the 1970s were characterized by planetary EVA that involved walking around on the moon surface like a Louis and Clark expedition. Today's EVAs are less sensational and are characterized by long durations of remaining in the same spot and assuming the role of mundane mechanic.

Lighthearted analogies aside, there are very real differences in the two types of EVA. Surface EVA on an extraterrestrial body requires locomotion and dynamic movement whereas an EVA sortie to repair a broken solar array or inspect the heat shield on the space shuttle involves a large static component in the lower body and a sustained aerobic output in the upper body. All of the EVA experience on extraterrestrial surfaces comes

from the Apollo missions which began with Neil Armstrong's "giant leap for mankind" on July 20, 1969 and ended on December 14, 1972 with the departure from the lunar surface of astronauts Eugene Cernan and Harrison Schmitt. At the time, it was expected that American astronauts would return to the moon by the late 1980s (Portree & Trevino, 1997), but as of 2010 there still has not been a human on the moon or any other extraterrestrial surface and there is no firm plan in place to do so in the immediate future. There were 14 EVAs performed on the lunar surface for a total time of 80 hours and 43 minutes (Cintala, 2005). Although there were a relatively few number of lunar EVAs performed, valuable information was obtained related to metabolic rate during planetary EVA. The average energy expenditure during lunar surface EVA was 234 kcal/h which was much lower than the anticipated upper limits of 400-500 kcal/h. It was noted that metabolic rates during discrete activities were as high as 450 kcal/h for brief periods (Waligora & Kumar, 1995). This is very important data that aids in simulating the metabolic demands of EVA on earth to test space suit design (including the microclimate cooling system). Waligora and Kumar (1995) also determined that the average energy expenditure rate during the first 29 space shuttle EVA missions (1983-1995) was 194 kcal/h. The average metabolic rate for the Skylab EVAs (1973-1974) was 230 kcal/h (Cowell, Stocks, Evan, Simonson, & Greenleaf, 2002).

While the absolute rates of metabolism during EVA are important to know, the type of work being done must also be considered. Cowell et al. (2002) characterize present-day EVA "...mainly as upper body aerobic plus isometric work, and lower-body isometric work." Oxygen consumption rates between 0.65 and 0.8 l/min have been reported during

EVA by the Soviet and American programs (Cowell et al., 2002). It is important to consider that sustained isometric skeletal muscle contractions and prolonged upper body aerobic activity are very different than that to which most individuals (astronauts or otherwise) are accustomed. In particular, it is well-known that aerobic capacity is lower for upper body aerobic exercise than lower body aerobic exercise (with the exception of certain athletic and clinical populations). In arm exercise, the maximal oxygen uptake is about 70% of what is attained in leg exercise (Astrand, Rodahl, Dahl, & Stromme 2003). Additionally, arterial blood pressures and heart rates are higher during arm exercise compared to leg exercise at a given oxygen uptake or cardiac output (Astrand, Ekblom, Messin, Saltin, & Stenberg, 1965). Miles et al. and Pendergast provide two nice reviews of the cardiovascular responses to upper body exercise (Miles, Cox, & Bomze, 1989; Pendergast, 1989). This increased cardiac strain could have consequences on individuals who are already somewhat compromised by the deleterious effects of microgravity on the cardiovascular system. However, it has been shown that the rise in core temperature with exercise is not dependent on the skeletal muscle mass employed but, rather, it is dependent on the metabolic rate during exercise (Sawka, Latzka, & Pandolf, 1989).

Water Cooling

Optimal Water Temperature

In the world of thermoregulatory research, particularly heat stress, perhaps one of the most hotly debated (pun intended) topics is that of optimal water temperature for cooling. Water has been used for the purpose of cooling since antiquity and is obvious throughout the animal kingdom. The fluidized properties of water are particularly valuable in terms

of the numerous ways in which they can be utilized in the artificial management of the microclimate. Due to its specific heat capacity ($\sim 4.2 \text{ J}/(\text{g}\cdot\text{K})$), which is the second highest of any known substance (after ammonia which is $\sim 4.7 \text{ J}/(\text{g}\cdot\text{K})$), water may be the most efficient means by which to regulate heat transfer (insertion or extraction). Across the physiologically relevant spectrum of temperatures, the volume-specific heat capacity of water is 3400 times greater than that of air (Taylor, Caldwell, Van Den Heuvel, & Patterson, 2008). The potent effects that water exerts on the human body is illustrated by the fact that cool/cold water has 25 times the cooling effect on the human body than does air of a comparable temperature (Pandolf et al., 2001) which is why hypothermia is a concern in water temperatures that may seem mild. For example, the shivering threshold (also called critical temperature) normally occurs at a water temperature between $30\text{-}34^\circ\text{C}$ compared to an air temperature between $20\text{-}27^\circ\text{C}$ (Pandolf et al., 2001). Not only does water have a greater capacity to accept thermal energy, but this energy transfer will proceed at a much greater rate (Taylor et al., 2008) owing to the fluidity of water. The enhancement of heat transfer potential as a result of water's fluid nature is evidenced by higher convective heat losses and heat transfer coefficients during swimming compared with being motionless in the water (Nadel, Holmer, Bergh, Astrand, & Stolwijk, 1974).

The majority of the thermoregulatory research involving optimal water temperatures for cooling resides in the medical realm, specifically emergency medicine, as it relates to acute heat illness. There are two primary schools of thought regarding recommendations for water temperature in the context of reducing a core temperature that is indicative of

hyperthermia and portends thermoregulatory collapse. A summary of the opposing viewpoints was recently published (Taylor, Casa, & Kenny, 2010) and presents the contrasting views of the two sides of the debate. If the goal is to remove heat in the context of an elevated body temperature due to physical activity or heat illness, there are two theories. The first supports the notion that “colder is better.” This is evidenced by the ice bath regimens used in cases of heat illness. The idea is simple: the colder the water, the greater the thermal gradient between the water and the human body. The second law of thermodynamics states that “the entropy of an isolated system not in equilibrium will tend to increase over time, approaching a maximum value at equilibrium” which means that heat can *spontaneously* flow from a region of higher temperature to a region of lower temperature but not the other way around. The second law of thermodynamics also speaks to the nature of thermal gradients and that heat transfer will increase as the temperature gradient increases. The ice water bath technique is designed to maximize surface area coverage and the thermal gradient between the human body and the water in which it is immersed. Other techniques like ice-pack application, showering the body with water, fanning, and wet-towel application have been reviewed elsewhere (McDermott et al., 2009) as well as ice vest cooling (Lopez, Cleary, Jones, & Zuri, 2008). Ice water immersion remains the current recommendation for acutely treating exercise-induced hyperthermia (Casa et al., 2007; McDermott et al., 2009; Proulx, Ducharme, & Kenny, 2003).

While cold water immersion is still an accepted medical technique (if not “the” accepted technique) for managing acute hyperthermia, it is not without its critics. In terms of

optimally cooling the human body, there are some in the thermoregulatory community who believe cold water temperatures may be counterproductive, despite the large thermal gradients they produce (Taylor et al., 2010). One of the most potent physiologic self-defense mechanisms against cold that humans possess is a reflexive vasoconstriction of the peripheral vasculature. The primary means by which heat is transferred from the body “core” to the “shell” (or periphery), which is then dissipated to the environment, is via circulating blood. The peripheral vasoconstriction response during exposure to cold is simply the body’s way of minimizing heat loss; as the diameter of the conduits (i.e., arterioles) decreases, so too does the volume of blood flowing through them which decreases heat dissipation to the external environment and preferentially shunts the warm blood to the core region. Those who oppose the use of extreme cold temperatures for heat extraction base their objections on the idea that the increased thermal gradient produced by techniques like cold water immersion is not optimal due to the resulting vasoconstriction which reduces blood flow and, ultimately, heat transfer. The resulting contention is that cool or temperate water (as opposed to cold) would not be as likely to elicit the vasoconstriction response.

There is experimental evidence to support the idea of temperate water immersion in the management of acute heat illness. In a study designed to compare the amount of time it takes to lower core temperature from a hyperthermic state (induced in a controlled laboratory setting by exercise, heat, and a warm water-perfused garment) with different cooling regimes, it was demonstrated that temperate water was almost as effective as cold water. Specifically, all of the participants’ core temperatures were raised to 39.5 °C

followed immediately by one of three different cooling methods: air (20-22 °C), cold water immersion (14 °C), and temperate water immersion (26 °C). The times to reach a core temperature of 37.5 °C for air, cold water, and temperate water were 22.81, 2.16, and 2.91 minutes, respectively. While the authors conceded that there were statistical differences for each of the between-trial comparisons, they call into question the practical and clinical significance of a 45-second discrepancy between cold and temperate water immersion (Taylor et al., 2008). Critics contend that the study of Taylor et al. (2008), and its conclusions, are flawed for two reasons (Taylor et al., 2010). First, core temperature was assessed via esophageal temperature, not rectal temperature which has gained recognition as the best overall means (in terms of stability and validity) by which to measure deep body temperature (Gagnon, Lemire, Jay, & Kenny, 2010). It should be noted that some believe rectal temperature may not be appropriate in situations involving rapidly changing body temperatures such as during the treatment of hyperthermia (due to the lag in rectal temperature response time) and that esophageal temperature might be more appropriate because it is a good measure of the temperature of the blood that perfuses the hypothalamus and it reacts quickly to changes in the temperature of blood (Proulx, Ducharme, & Kenny, 2006). Secondly, very cold water (2 °C) has been shown to be superior in terms of cooling rates for high rectal temperatures as evidenced by cooling rates of 0.35 °C per minute for very cold water (2 °C) (Proulx et al., 2003) as compared to rates of 0.18 °C per minute and 0.10 °C per minute with water temperatures of 14 °C and 26 °C, respectively (Taylor et al., 2008). Taylor counters Kenny's criticism by suggesting that, in addition to the vasoconstriction that is likely elicited by cold water, potentially dangerous sequelae exist when humans are exposed to the shock of cold or very cold

water immersion, most notably supraventricular ectopic arrhythmias and reduced cerebral blood flow (Taylor et al., 2008).

The debate about a lack of vasoconstriction with temperate water versus a greater thermal gradient with cold water continues with contentions that the human body is not like a bowling ball (in terms of a known density and consistent overall material properties) and therefore should not be thought of as such (implying a blinding single-mindedness regarding the supremacy of maximizing thermal gradients for heat transfer). This is then countered with evidence supporting the theory that the cold-induced vasoconstrictor response is blunted in hyperthermic individuals (Taylor et al., 2010). The argument between the opposing sides and their respective viewpoints is ongoing so it would seem that the debate remains unsettled.

The challenge for researchers in the thermoregulation field is to elucidate the relationship between vasoconstriction, thermal gradient and heat exchange in terms of reconciling an appropriate/optimal balance between the three. This is a particularly important topic within the realm of microclimate cooling systems like LCGs.

LCGs

It is estimated that 20-50% of the workforce in industrialized countries is subjected to hostile environments (WHO, 1995). These environments are characterized by toxins, contaminants, and pollutants as well as thermal extremes. Many occupations are associated with high heat loads including the power, metal and ceramics industries;

firefighting; the military; etc. It is estimated that approximately 5-10 million workers in the United States are exposed to heat stress annually (Furtado, Craig, Chard, Zaloom, & Chu, 2007). Heat stress is interpreted the same by the body's thermoregulatory centers regardless of the source. Three potent contributors to heat stress are high environmental temperatures, high rates of energy expenditure, and increased thermal insulation. Any one of these factors acting alone can impart serious heat stress to the human body. For example, Roberts reports on a recent case study in which a middle-aged and well-trained man suffered from exertional heat stroke (measured rectal temperature of 40.7 °C) during a cool weather marathon in which the temperature ranged from 6 °C at the start to 9.5 °C at the time of the man's collapse just 10 meters from the finish line (Roberts, 2006). This is a testament to the heat generating capabilities of skeletal muscle, particularly when an individual is able to override the central governor that would normally cause that person to decrease the intensity of effort. In the aforementioned case, the man was attempting to qualify for the Boston Marathon (an elite event) and needed a finish time of three hours and 15 minutes or better (he was on pace to achieve that goal with no more than a couple of seconds to spare). The consequences of high ambient temperatures on thermal strain should be obvious and do not require further explanation. One of the common themes of occupations that take place in the hostile environments mentioned at the beginning of this section is protective equipment to minimize exposure to dangerous elements. The equipment, if well-designed, serves its functional purpose but comes at the cost of creating a microclimate defined by high temperatures and a limited ability to dissipate heat. This increased thermal insulation can be complicated by concomitantly high environmental temperatures and energy expenditure rates.

A microclimate management system was first developed in 1940 by Dr. Brian McArdle for use by World War II pilots who experienced *cold* stress. These first systems used gas ventilation as the primary means of heat transfer via convection. Water was proposed as a potential heat transfer medium in microclimate cooling systems in 1958 by Billingham (Billingham, 1959) and the prototype LCG was developed in 1962 at the Royal Aircraft Establishment in England (Burton & Collier, 1964). The underlying principle of LCGs is quite rudimentary and simply involves the circulation of cool/cold water through a network of tubing that perfuses the garment. The contact of the tubes with the skin promotes conductive heat transfer and exploits the second law of thermodynamics while also taking advantage of the unique properties of water (i.e., fluidized flow and specific heat capacity). Over the years, the fundamental principle upon which LCGs is based has not changed. However, the evolution of LCGs has sought to improve the garment design by optimizing heat transfer from the body.

The first cooling garment used during spaceflight incorporated a ventilation cooling system and was part of the Gemini spacesuit as well as the prototype Apollo suit. The limitations of ventilation as the sole mediator of heat exchange during EVA were quickly realized during the Gemini IX and XI missions. These limitations were manifested by fogged face plates, high heart rates (170-180 bpm), and astronaut fatigue that resulted in premature termination of EVA. The estimated heat production of 550 kcal/h (with spikes up to 900 kcal/h) was extremely high for the relatively mild activities being performed and the cooling garment quickly became overloaded and incapable of supporting thermal comfort (Nunneley, 1970). The subsequent EVAs performed with the ventilation garment

were significantly compromised in terms of the work performed as the astronauts had to work within the limits of the garment. By 1969, NASA had settled on a LCG design composed of 40 tubes with a water flow rate of 1.8 l/min and heat extraction capabilities of 400-500 kcal/h for use with the Apollo program. Later, NASA decided to revisit the ventilation cooling system but this time opted to incorporate it with the water-cooling component; this liquid cooling and ventilation garment (LCVG) design is still in use today. It should be noted that the NASA LCVG is one the three garments investigated in the present study.

More recent designs of LCGs have experimented with different design features so as to maximize the efficiency of heat transfer. For example, Koscheyev et al. have designed a LCG (MACS-Delphi) based on physiological principles (Koscheyev et al., 2007). Specifically, tubing is strategically oriented over high density tissue areas like the region of the upper back. Fat, muscle (high circulation), muscle (low circulation), and bone have the following thermal conductivities: 0.187, 0.533, 0.628, and 0.782 W/K/m, respectively. It is thought that efficiency can be maximized by minimizing the amount of tubing required without sacrificing heat transfer capabilities. The MACS-Delphi LCG is also being evaluated in the current study. A feature of the MACS-Delphi (and some other LCGs) is the option of a cooling hood that is theorized to exploit not only the large potential heat sink that is the cranium, but also the unusual vascular properties in the head that are highlighted by reduced (or absent) cold-mediated vasoconstrictor reflexes (Blair, Glover, & Roddie, 1961; Froese & Burton, 1957; Hertzman & Roth, 1942; Rasch, Samson, Cote, & Cabanac, 1991). Specific questions regarding cooling hoods relate to

water temperature, spatial configuration of tubing, and the potential negative consequences of the insulatory properties of hair.

There are numerous innovative design features currently being investigated like automatic thermal control based on physiologic responses and cues (Nyberg, Diller, & Wissler, 2000) and differences between intermittent versus regional cooling (Cheuvront, Kolka, Cadarette, Montain, & Sawka, 2003). This study seeks to evaluate the performance of different LCGs for the express purpose of providing recommendations for future designs to be implemented with the next generation of planetary EVA. However, LCGs have also found unique applications in sports in terms of performance enhancement (Booth et al., 2001; Cheung & Robinson, 2004; Wilson et al., 2002), in occupational settings (Furtado et al., 2007), and in medicine. For example, there have been encouraging results from research looking at the benefit of LCGs for clinical populations like multiple sclerosis patients (Meyer-Heim et al., 2007). Two excellent reviews have been written on the topic of LCGs that present detailed histories (Nunneley, 1970) and a clear vision of what direction the research needs to go in the future to optimize the design and performance of LCGs (Flouris & Cheung, 2006).

It is hoped that the results of the current study will contribute to the body of scientific knowledge on the topic of cooling strategies with specific emphasis on LCGs in a manner similar to that which the reviewed literature in this chapter has contributed to the understanding of important topics related to thermoregulation, the physiology of spaceflight and EVA, and cooling modalities.

CHAPTER 3: METHODS AND PROCEDURES

Study Design

The purpose of this study was to identify the advanced features of each of three LCGs for maintaining core temperature and thermal comfort during intensive exercise in mild (24 °C) and hot (35 °C) conditions. The three garments evaluated were: 1) Minnesota Advanced Cooling Suit (MACS-Delphi), 2) Russian Orlan (Orlan), and 3) NASA Liquid Cooling Ventilation Garment (LCVG). It is important to note that two out of the three LCG designs (MACS-Delphi and Orlan) had the option of a cooling hood (which covered the head and neck) in addition to the full body coverage that was common to all three designs. Since it was deemed essential to evaluate all possible LCG configurations, five possibilities existed:

- 1) MACS-Delphi with hood
- 2) MACS-Delphi without hood
- 3) Orlan with hood
- 4) Orlan without hood
- 5) LCVG without hood

As the purpose of the study was not only to evaluate the LCGs in terms of exercise (i.e., simulated EVA) and garment design, but also to evaluate the LCGs under two different environmental conditions (hot and thermoneutral), 10 experimental conditions existed:

- 1) Thermoneutral, MACS-Delphi with hood
- 2) Thermoneutral, MACS-Delphi without hood
- 3) Thermoneutral, Orlan with hood
- 4) Thermoneutral, Orlan without hood
- 5) Thermoneutral, LCVG without hood
- 6) Hot, MACS-Delphi with hood
- 7) Hot, MACS-Delphi without hood
- 8) Hot, Orlan with hood
- 9) Hot, Orlan without hood
- 10) Hot, LCVG without hood

Using a crossover design, participants were each required to complete 10 trials in order to account for all possible experimental conditions. The order of the 10 experimental conditions for each participant was randomized and the start time of the trials ranged from early morning to early afternoon (6 a.m. - 2 p.m.). All testing occurred in the environmental chamber within the Laboratory for Health and Human Performance in Extreme Environments (LHHPEE) at the University of Minnesota. A medical doctor and an exercise physiologist were present for all experimental trials. All experimental testing took place between March 27, 2008 and July 15, 2008.

Specifications of LCGs

Each of the three LCGs (Figure 3.1) was made of spandex-type material. Specifically, the MACS-Delphi was made of spandex polyester (with the exception of the hood component which was made of spandex mesh) while the Orlan and LCVG were both made of spandex mesh (LCVG had a double layer of material). The masses of the garments (tubing filled with water) were as follows: MACS-Delphi with hood (1.43 kg), Orlan with hood (2.45 kg), and LCVG without hood (1.79 kg). The tubing used for the circulation of water was sewn or woven into the garment material (on the inside of the garment) so that the tubing surface was in direct contact with the skin. Table 3.1 summarizes the specifications of each garment used in this study as it relates to tubing coverage. It should be noted that the information in the table represents the MACS-Delphi with the hood option, the Orlan with the hood option, and the LCVG without the hood as no hood option exists with this garment.

Figure 3.1. The three liquid cooling garments used in this study.

Table 3.1

Specifications of Tubing Coverage as Defined by Length of Tubing in Meters and Relative Coverage (Percent of Total) by Anatomical Region

Region of Tubing Coverage	Garment		
	MACS-Delphi	Russian Orlan	NASA LCVG
Head / Neck	5.3 (9.0%)	7.1 (14.4%)	0 (0%)
Chest / Abdomen	11.7 (19.9%)	7.8 (15.8%)	14.2 (17.9%)
Back	5.7 (9.7%)	9.2 (18.6%)	12.2 (15.4%)
Thighs	22.3 (37.9%)	22.4 (45.4%)	37.8 (47.6%) [†]
Calves	3.9 (6.6%)	0 (0%)	
Upper Arms	0 (0%)	2.9 (5.9%)	15.2 (19.1%) [‡]
Lower Arms	10.0 (17.0%)	0 (0%)	
Garment Total	58.9 (100%)*	49.4 (100%)*	79.4 (100%)*

*Total percentage does not add up to 100.0% due to rounding

[†] Data only available for the combination of thigh and calf region

[‡] Data only available for the combination of upper and lower arm region

Participants

Recruitment

Male and female participants were recruited from the University of Minnesota (Twin Cities) and the surrounding area of Minneapolis and St. Paul, Minnesota via posted fliers, classroom advertisements, and word-of-mouth solicitation (see Figure A1). Inclusion criteria were as follows: 1) aged 20-50 years, 2) an aerobic fitness level sufficient to meet the experimental demands, and 3) a body size/type that could be accommodated by the available LCG sizes. Potential participants were excluded if they: 1) had any medically diagnosed disease/illness that could either be made worse by the experimental conditions (i.e., exercise and/or environmental conditions) or cause abnormal thermoregulatory responses that could confound experimental interpretations, 2) had any positive responses on a pre-screening exercise stress test, and/or 3) had reservations or doubts about being able to fulfill the experimental requirements. Participants signed an informed consent prior to the study (see Figures A2-A5). This study was approved by the Institutional Review Board of the University of Minnesota (Twin Cities). The number of participants (six) was determined based on the resources allocated from the granting agency.

Pre-Screening Procedures

Potential participants were instructed to report to the Laboratory of Physiological Hygiene and Exercise Science (LPHES) at the University of Minnesota for a pre-screening assessment. Participants first completed a medical history questionnaire (Figure A6) to identify possible risks of participating in the study (or the pre-screening assessment). Upon satisfactory completion of the medical history form, demographic

(date of birth, sex, and race) and anthropometric data were collected. Height was determined (without shoes) to the nearest 0.1 cm using a standard wall-mounted stadiometer and body mass was determined (to the nearest 0.1 kg) by having the participant stand on an electronic Tanita BWB-800S scale (Tanita Corporation of America Inc., Arlington Heights, IL) wearing only a T-shirt, shorts, and socks. Body composition data was collected using the sum of skinfolds method. While this method has been described in detail elsewhere (Maud & Foster, 2006; McArdle, Katch, & Katch, 2010; Thompson, 2010), a brief description of the process follows. A calibrated (length and tension) Lange skinfold caliper was used by the same trained exercise physiologist (JMW) to collect triplicate measures of the double thickness of subcutaneous fat (using a thumb-index finger pinch) at seven anatomically referenced points (abdomen, iliac crest, triceps, pectoralis, subscapularis, midaxilla, and thigh). The seven representative skinfold measurements (in millimeters) were then summed and factored into a sex- and age-specific regression equation (Jackson, Pollock, & Ward, 1978, 1980) to determine body density which was then used to determine percent body fat via appropriate race- and sex-specific regression equations (Maud & Foster, 2006; Siri, 1961). Body composition data was collected due to the nature of the relationship between subcutaneous fat and thermoregulatory dynamics (Fregly & Blatteis, 1996; Lemire et al., 2008).

Following the collection of demographic and anthropometric data, participants completed an exercise stress test to determine: 1) any risks associated with performing exercise at the intensity required for the experimental protocol and 2) aerobic fitness which was operationally defined as peak relative oxygen consumption. Prior to the commencement

of the stress test, participants signed an informed consent document specifically for the graded exercise test (per LPHES protocol). This was followed by the collection of resting data including blood pressure (stethoscope and sphygmomanometer) and heart rate/rhythm via a 12-lead Quinton 2000 ECG system (Cardiac Science Inc., Bothell, WA). Stress testing was administered by an exercise physiologist (JMW) and involved walking/jogging on a Trackmaster TMX22 treadmill (Full Vision Inc., Newton, KS) as the mode of exercise. Specifically, the Bruce treadmill protocol (Bruce, 1971) was used in conjunction with the continual monitoring of physiologic data including heart rate and rhythm, blood pressure, and oxygen consumption. These measures were recorded once per three-minute exercise stage in addition to a subjective interpretation of effort by the participant using the rating of perceived exertion scale designed by Borg (Borg, 1982). Heart rate and rhythm data were collected via a 12-lead ECG and blood pressure was manually assessed using a stethoscope and sphygmomanometer. Oxygen consumption was collected utilizing open-circuit spirometry via a computerized Medgraphics Ultima metabolic analyzing system (Medical Graphics Corp., St. Paul, MN). Breath-by-breath inspired and expired gases (volume and concentration) were collected via a Hans Rudolph 7900 Series face mask and headgear assembly (Hans Rudolph Inc., Shawnee, KS) fitted with a Medgraphics preVent® pneumotach (Medical Graphics Corp., St. Paul, MN) and delivered to the metabolic analyzer which was calibrated prior to each test. Specifically, the flow meter was calibrated with a known-volume standard (3-liter syringe) and the gas analyzer was calibrated with known concentrations of gases in the form of a “reference” gas (21% oxygen and 79% nitrogen) and a “calibration” gas (12% oxygen, 5% carbon dioxide, and 83% nitrogen).

Prior to the test, participants were informed that the workload would be continually increased every three minutes in the form of speed and grade/inclination and that the goal was to reach a state of maximal effort. Each participant was told what to expect over the course of the stress test in terms effort/exertion levels as well as the data collection process and was informed that he or she could terminate the test at any time for any reason as could the exercise physiologist administering the test. All stress tests were terminated at or near maximal exertion levels based upon the desire of the participants to stop. Following the termination of the stress test, participants were allowed to “cool down” which entailed walking at a slow speed with no inclination. Physiologic parameters (heart rate, heart rhythm, and blood pressure) were monitored during the recovery stage to ensure a normal post-exercise response (the recovery stage typically lasted five minutes). Participants were allowed to leave the laboratory once their physiologic values were at or near pre-exercise levels. The data collected during the stress test was forwarded to the cardiologist (ASL) who served as the medical director of the LPHES; he granted the final medical clearance required for participation in the study.

Selection

Four males and two females were selected to participate in the study. Descriptive data for the six participants are presented in Table 3.2. Participants were asked to refrain from vigorous exercise 24 hours prior to an experimental trial and were instructed to eat nothing larger than a “light meal” two hours prior to a trial.

Table 3.2

Descriptive Data for the Six Study Participants

Participant (Code)	Descriptor						
	Race	Sex (M/F)	Age (years)	Height (cm)	Weight (kg)	Body Fat (%)	VO ₂ Peak (ml/kg/min)
BZ	American Indian	M	22	163.5	68.6	8.3	40.0
CG	Caucasian	M	30	177.8	76.7	7.9	54.0
CR	Caucasian	F	26	171.5	64.2	18.6	47.2
CT	Caucasian	M	29	178.2	91.4	13.8	51.1
CX	Caucasian	M	25	187.0	86.5	6.3	50.8
CY	African American	F	46	163.8	61.5	17.8	38.0
Mean			29.7	173.6	74.8	12.1	46.9
± Standard Deviation			8.5	9.2	12.2	5.4	6.5

Experimental Protocol*Simulated EVA*

Exercise, in the form of walking on a Trackmaster TMX22 treadmill (Full Vision Inc., Newton, KS) at various workloads, was selected as the most appropriate method to simulate the metabolic, biomechanical, and psychological demands of planetary EVA. The protocol used in this study was similar to that used by NASA in previous ground-based EVA research as indicated by personal communications with NASA researchers. Specifically, the protocol was defined by seven 20-minute stages of varying energy expenditure levels (i.e., power output/workload), two of which were “rest” stages (rest occurred in the seated position). The protocol is illustrated in Figure 3.2.

Figure 3.2 Exercise protocol designed to simulate the demands of EVA.

Notes: T_{wi} = inlet water temperature; 1 W = 0.01433 kcal/min

It is important to note that two minutes were added following the completion of each 20-minute stage to accommodate experimental measurements and workload modulation. Since the protocol was based on energy expenditure defined in *absolute* terms, participants with lower body masses were required to work at higher *relative* intensity levels. While this necessarily resulted in an inequity in terms of relative exercise intensity, it served the purpose of standardizing absolute metabolic rate along with the associated heat liberation. Prior to each participant's first experimental trial, workload (in the form of treadmill speed and grade) for each stage was determined using the ACSM metabolic equations (Thompson, 2010) and the body mass of the participant. Specifically, the following metabolic regression equation for walking was used:

$$\text{VO}_2 \text{ (ml/kg/min)} = (0.1 \times S) + (1.8 \times S \times G) + 3.5$$

S = speed (meters per minute); G = grade (fractional grade)

Since the energy expenditure requirements for each stage were predetermined, the relative oxygen consumption that was estimated to correspond with a specific power output could be determined based on the known relationship between kilocalories and oxygen consumption (i.e., approximately 5 kcal of energy are liberated for each liter of oxygen consumed). Once the corresponding relative oxygen consumption was

determined, an appropriate workload (i.e., speed and grade) could be calculated (see Table 3.3 for participant-specific protocols).

As previously mentioned, differing body masses of the participants required that unique protocols be developed for each participant. While it was necessary to formulate protocols with different workloads (in the form of speed and grade) for given stages for the various participants, it was deemed critical to ensure that walking was always the mode of locomotion to negate the confounding effects introduced by the differences in gait pattern and mechanical efficiency of jogging/running. While it was assumed that the body masses of participants would fluctuate slightly over the course of all 10 trials, this fluctuation was not predicted to be significant and, therefore, the protocol was not changed between the first and last trials in the interest of standardization.

Table 3.3

Prescribed Treadmill Workloads Defined by Speed (Miles Per Hour) and Inclination (Percent Grade) for Each Participant

Participant (Code)	Stage						
	1 (mph; %)	2 (mph; %)	3 (mph; %)	4 (Rest)	5 (mph; %)	6 (mph; %)	7 (Rest)
BZ	2.0; 2.5	2.5; 2.5	3.4; 2.5	---	3.0; 12.5	2.5; 10	---
CG	2.0; 0.0	2.0; 2.5	3.0; 2.5	---	3.0; 10.0	3.0; 5.0	---
CR	2.0; 2.5	2.0; 5.0	3.0; 5.0	---	3.0; 15.0	3.0; 7.5	---
CT	1.7; 0.0	2.5; 0.0	2.5; 2.5	---	3.0; 7.5	2.5; 5.0	---
CX	2.0; 0.0	2.5; 0.0	2.5; 2.5	---	3.0; 10.0	3.0; 5.0	---
CY	1.7; 5.0	1.7; 7.5	2.5; 7.5	---	3.0; 15.0	2.5; 12.5	---

Environmental Conditions

All testing occurred in an environmental chamber that was a custom design involving the conversion of a walk-in refrigerator and the associated heating/cooling system. For the thermoneutral and hot conditions, the chamber temperature was set at approximately 24 °C and 35 °C, respectively. While humidity is a significant contributor to heat stress, the ability to control the humidity of the chamber was limited. The temperature and humidity of the chamber during the experimental trials were monitored and recorded with a calibrated Extech model RH390 digital psychrometer (Extech Corp., Waltham, MA).

Data Collection

Metabolic Data

Metabolic data was collected continuously over the course of each 154-minute trial. Specifically, indirect calorimetry was used to analyze, on a breath-by-breath basis, the inspired and expired gases of the participant via open-circuit spirometry. A Medgraphics CPX/D metabolic analyzing system with Breeze Ex version 3.06 software (Medical Graphics Corp., St. Paul, MN) was used to analyze the volume and concentration of inspired and expired air which was collected utilizing a Hans Rudolph 7900 Series facemask (Hans Rudolph Inc., Shawnee, KS) fitted with a Medgraphics preVent® pneumotach (Medical Graphics Corp., St. Paul, MN) which was connected to the metabolic unit by way of a tubing assembly. The metabolic analyzer was calibrated prior to each test similarly to that described previously in the “Pre-Screening Procedures” section. The inspired and expired air yielded the following variables of interest: relative

oxygen consumption (ml/kg/min), absolute oxygen consumption (l/min), respiratory exchange ratio (no units), energy expenditure (kcal/min), and ventilation (l/min).

The metabolic data collected during the middle 10 minutes of each 20-minute stage (i.e., minutes 5-15) were averaged and statistically analyzed. The first five minutes of metabolic data was not used due to the fact that steady-state exercise typically takes between three and four minutes to achieve (McArdle et al., 2010) and the dynamics of oxygen uptake kinetics during the initial minutes following the onset of a new workload is variable between individuals. It was therefore assumed that steady-state exercise was achieved by the fifth minute into a new stage. The last five minutes of data for each stage was similarly omitted from analysis for two reasons. First, participants were being asked questions (e.g., rating of perceived exertion, temperature perception, etc.) during the last five minutes of each stage which could have been a sufficient stimulus to alter metabolism via a psychophysiological response. Second, due to the nature of the exercise and environmental conditions, cardiac drift (Rowell, 1993) could potentially have begun to alter physiological responses (particularly in the hot conditions) after 15 minutes at a given exercise intensity.

It should be noted that metabolic data was not collected for the middle 10 minutes of the first rest period (stage four) which was done for two reasons. First, it was determined during pilot testing that the nature of the facemask and headgear assembly caused significant discomfort (particularly in the form of head pain) when worn continuously for 154 minutes. Second, due to the large amount of data collected over the course of 154

minutes and the limitations of the computer system integrated with the metabolic analyzer, it was necessary to collect the data for a single experimental trial in two separate computer files which required that data collection cease for several minutes in order to close one file and open a new one. It was determined that this data “void” was acceptable owing to the relative unimportance of the time period in question and also served the purpose of giving some relief to the participant from the facemask and headgear assembly midway through the trial. Therefore, the metabolic data used for the fourth stage analysis was an average of the data collected in the first and last five minutes of the 20-minute rest stage.

Temperature Data

Core temperature data was collected continuously over the course of each 154-minute trial via a YSI model 401 rectal probe (YSI Inc., Yellow Springs, OH) inserted 13 cm beyond the external anal sphincter (Fregly & Blatteis, 1996; Lee, Wakabayashi, Wijayanto, & Tochiara, 2010). Each participant was instructed how to properly insert the rectal probe (see Figure A7) on their own in a private room prior to each experimental trial. A medical-grade lubricant jelly was used for probe insertion and participants were instructed how to affix an external portion of the probe to the inner thigh (with medical tape) to prevent slippage during the trial. Core temperature data was sampled at 25.2-second intervals via a Keithly 2701 DMM data acquisition system (Keithly Instruments Inc., Cleveland, OH) that was integrated with a customized LabVIEW software program for data analysis. For the data analysis, core temperature data was averaged over minutes 10 to 20 of each 20-minute stage.

Skin temperature data was also collected continuously over the course of each 154-minute trial utilizing the same data acquisition/analysis system, sampling rate, and averaging procedure as those used for core temperature. Prior to each trial, five YSI model 409A skin temperature sensors (YSI Inc., Yellow Springs, OH) were affixed (with medical tape) to the participant's skin in a predetermined anatomical pattern as described below:

1. ear (mastoid process)
2. finger (4th digit, lateral border of distal phalanx)
3. chest (center of pectoralis major at mid-clavicular line)
4. thigh (middle portion of anterior thigh)
5. calf (gastrocnemius, midpoint of lateral side)

The skin temperature sensors are pictured in Figure A8.

Sweat Rate Data

Whole body sweat rate/fluid loss data was collected by weighing participants (to the nearest 0.1 kg) in a semi-nude state immediately before and after each trial using a NTEP Class III Tanita BWB-800A digital scale (Tanita Corporation of America Inc., Arlington Heights, IL). Participants did not ingest any fluids or food during the trials and none needed to urinate or defecate therefore a simple calculation involving the body mass measurement before and after was used to determine total body water loss during each trial.

Local sweat rates were determined by affixing (with medical tape) 3 layers of circular (4.25 cm diameter) absorbent grade #3 filter paper (Advantec MFS, Dublin, CA) in three locations. The filter paper (see Figure A9) was weighed on a Mettler H51 precision

analytical balance (Mettler-Toledo Inc., Columbus, OH) to the nearest 0.0001 g before and after each trial to determine relative sweat rates of the following three anatomic locations:

1. upper back (scapular region on the left side)
2. chest (upper portion of left pectoralis major at mid-clavicular line)
3. thigh (medial portion of right upper thigh in groin region)

Skin wetness was measured during each of the seven stages with a NOVA DPM 9003 skin impedance measurement device via a handheld NOVA DPM 9103 sensor probe (NOVA Technology Corp., Gloucester, MA). Skin surface hydration (i.e., wetness) was defined (using arbitrary units with a range of 90 to 999) as the instantaneous impedance reading upon probe application to the skin. Relative skin wetness was measured at the following four anatomic locations:

1. forehead (middle)
2. left hand (dorsal surface)
3. left hand (volar/palmar surface)
4. left ankle (lateral malleolus)

Cardiovascular Data

Heart rate data was collected continuously via a heart rate monitoring system (see Figure A10) that incorporated a T31 chest strap transmitter and S610i wristwatch receiver (Polar Electro Oy, Kempele, Finland). Heart rate data was sampled at one-minute intervals and stored in the wristwatch unit. Following each experimental trial, heart rate data was downloaded to a computer and analyzed with Polar Precision Performance version 4.01.029 software (Polar Electro Oy, Kempele, Finland). Heart rate data was

averaged over the middle 10 minutes of each 20-minute stage (i.e., minutes 5-15) for the same reasons as those indicated for the metabolic data.

Systolic and diastolic blood pressures were taken manually at the end of each stage by the same medical doctor (VSK) using a standard stethoscope and properly sized sphygmomanometer. No reliability testing was performed with this technique. However, the individual responsible for taking blood pressure measurements has extensive experience (40+ years) with exercise and resting blood pressure measurements so the reliability of the technique, and the accuracy of the data, were assumed to be within acceptable parameters.

Arterial oxygen saturation was measured at the end of each stage using a Nonin model 2500 pulse oximeter (Nonin Medical Inc., Plymouth, MN). The tip of the forefinger was the site of measurement.

Flow Rate Data

Water of a constant temperature (15 °C) was circulated through the LCGs using a Neslab RTE-111 refrigerated bath/circulator (Thermo Fisher Scientific Inc., Waltham, MA) connected via a network of tubing. As the various LCGs have tubing with differing diameters, it was deemed important to evaluate flow rate during each trial by performing a one-minute collection of water at the outlet point and weighing the collected water (to the nearest 0.01 kg) on a digital Ohaus DS4 scale (Ohaus Corp., Pine Brook, NJ) to determine volume and, hence, flow rate. Though this was a crude method to determine

flow rate, the error with such a technique was deemed insignificant for the purposes of this study.

Statistical Analysis

A three-factor (temperature x stage x garment) within subjects repeated measures ANOVA was used to identify differences in cardiovascular, temperature, metabolic, local sweat rate, and skin wetness values. As it relates to the aforementioned parameters, only the data collected during stages five (highest-intensity exercise) and seven (rest) were analyzed making “stage” a two-level factor along with temperature (i.e., 24 °C and 35 °C). Where significant main effects for garment were found by ANOVA, post-hoc contrasts were performed using independent two-tailed t-tests. In order to avoid the confounding effects of a hood (which was not an option for the LCVG), three post-hoc contrasts were performed on the three garments without the hood (i.e., MACS-Delphi-no hood vs. Orlan-no hood, MACS-Delphi-no hood vs. LCVG-no hood, and LCVG-no hood vs. Orlan-no hood) in addition to a hood/no hood contrast (i.e., MACS-Delphi-hood and Orlan-hood vs. MACS-Delphi-no hood and Orlan-no hood). All data undergoing ANOVA were tested for assumptions of sphericity using Mauchly’s sphericity test; Greenhouse-Geisser and Huynh-Feldt corrections were used in cases of departure from the assumption of sphericity. The ANOVA and post-hoc tests were performed using the statistical program R, version 2.9 (R: A Language and Environment for Statistical Computing, Vienna, Austria). Total body sweat rate and water flow rate were analyzed using independent 2-tailed t-tests with Microsoft Excel 2003 (Microsoft Inc., Redmond, WA). Statistical significance for all analyses was set at an alpha level of $p \leq 0.05$.

CHAPTER 4 - RESULTS

Cardiovascular

Table 4.1 summarizes the statistical analysis of the cardiovascular parameters. Means and standard deviations for the cardiovascular data are presented in Tables B1-B4. When comparing the three garments without a hood across stages five and seven and across the 24 °C and 35 °C conditions, systolic blood pressure was lower for the MACS-Delphi when compared to both the LCVG (123.29 vs. 126.92 mmHg; $p = 0.023$) and the Orlan (123.29 vs. 128.17 mmHg; $p = 0.004$). When comparing the MACS-Delphi and LCVG (both without a hood) across stages five and seven and across the 24 °C and 35 °C conditions, heart rate was lower for the MACS-Delphi when compared to the LCVG (103.36 vs. 106.66 bpm; $p = 0.039$). It should be noted that when a direct comparison was made between the hood and no-hood conditions for the MACS-Delphi and Orlan across both stages and temperature conditions (as a means to evaluate the effects of using a hood), heart rate was lower without the hood (103.67 vs. 106.36 bpm); however, this difference failed to reach statistical significance ($p = 0.059$). There were no statistically significant differences between the garments with regard to diastolic blood pressure and arterial oxygen saturation.

Metabolic

Table 4.2 summarizes the statistical analysis of the metabolic parameters. Means and standard deviations for the metabolic data are presented in Tables B5-B8. There were no statistically significant differences between the garments with regard to relative oxygen consumption, absolute oxygen consumption, respiratory exchange ratio and ventilation.

Core and Skin Temperature

Table 4.3 summarizes the statistical analysis of the core and skin temperature parameters. Means and standard deviations for the core and skin temperature data are presented in Tables B9-B14. When comparing the three garments without a hood across stages five and seven and across the 24 °C and 35 °C conditions, calf skin temperature was lower for the LCVG when compared to both the MACS-Delphi (28.71 vs. 30.80 °C; $p = 0.005$) and the Orlan (28.71 vs. 31.68 °C; $p = 0.008$). When comparing the MACS-Delphi and Orlan (both without a hood) across stages five and seven and across the 24 °C and 35 °C conditions, chest skin temperature was lower for the Orlan when compared to the MACS-Delphi (27.94 vs. 30.01 °C; $p = 0.025$). When comparing the three garments without a hood across stages five and seven and across the 24 °C and 35 °C conditions, femoralis skin temperature was lower for the LCVG when compared to both the MACS-Delphi (28.29 vs. 31.72 °C; $p = 0.001$) and the Orlan (28.29 vs. 31.09 °C; $p = 0.011$). There were no statistically significant differences between the garments with regard to core temperature or skin temperature for the ear or finger.

Local Sweat Rate

Table 4.4 summarizes the statistical analysis of the local sweat rate parameters. Means and standard deviations for the local sweat rate data are presented in Tables B15-B17. When comparing the three garments without a hood across stages five and seven and across the 24 °C and 35 °C conditions, local sweat rate in the groin was lower for the LCVG when compared to both the MACS-Delphi (0.14 vs. 0.29 g; $p = 0.017$) and the Orlan (0.14 vs. 0.25 g; $p = 0.015$). When comparing the three garments without a hood

across stages five and seven and across the 24 °C and 35 °C conditions, ANOVA for local sweat rate in the back indicated a statistically insignificant effect ($p = 0.066$) but post-hoc testing was suggestive (due to reduced statistical power caused by a small sample size) of the following: local sweat rate was higher for the MACS-Delphi when compared to both the LCVG (0.95 vs. 0.59 g; $p = 0.046$) and the Orlan (0.95 vs. 0.67 g; $p = 0.006$). There were no statistically significant differences between the garments with regard to local sweat rate in the chest.

Skin Wetness

Table 4.5 summarizes the statistical analysis of the skin wetness parameters. Means and standard deviations for the skin wetness data are presented in Tables B18-B21. There were no statistically significant differences between the garments with regard to skin wetness in the forehead, hand, palm, or ankle regions.

Water Flow Rate

Means and standard deviations for the water flow rate data are presented in Table B22. In terms of water flow rate through the garments, the air temperature (24 vs. 35 °C) did not significantly influence garment performance. While the MACS-Delphi (without hood) did exhibit a seemingly large difference in flow rates between the 24 °C and 35 °C conditions (333.40 and 236.33 ml/min, respectively), this difference was not statistically significant ($p = 0.085$). As it relates to flow rate between the various garments (without the hood option), there were significant differences in the absolute flow rate. When the three garments were compared (averaged across both temperature conditions), the

MACS-Delphi had a significantly lower flow rate than the LCVG (280.45 vs. 1985.91 ml/min; $p < 0.001$) and the Orlan (280.45 vs. 2385.75 ml/min; $p < 0.001$); additionally, the LCVG had a lower flow rate than the Orlan (1985.91 vs. 2385.75 ml/min; $p < 0.001$).

Whole Body Sweat Rate

Means and standard deviations for the whole body sweat rate data are presented in Table B23. In the 24 °C regime, whole body sweat rate was lower in the LCVG (no hood) condition compared to the Orlan (no hood) condition (0.45 vs. 0.63 kg; $p = 0.007$). Also in the 24 °C regime, it should be noted that, while there was a trend for whole body sweat rate to be lower in the LCVG (no hood) condition compared to the Orlan (hood) condition (0.45 vs. 0.75 kg), this difference was not statistically significant ($p = 0.055$). In the 35 °C regime, whole body sweat rate was lower in the LCVG (no hood) condition compared to the Orlan (no hood) condition (0.72 vs. 0.93 kg; $p = 0.004$), the MACS-Delphi (no hood) condition (0.72 vs. 0.95 kg; $p = 0.001$), and the MACS-Delphi (hood) condition (0.72 vs. 0.93 kg; $p = 0.002$). When the hooded conditions were compared to the non-hooded conditions (MACS-Delphi and Orlan) in both temperature regimes to determine if there was an effect for the hood, the statistical analysis revealed no significant differences.

Table 4.1

Univariate Repeated Measures ANOVA for Cardiovascular Variables

Variable	Numerator		Denominator		F	p
	SS	dF	SS	dF		
Heart Rate (bpm)	504	4	502	16	4.02	0.02*
Systolic Blood Pressure (mmHg)	720	4	337	20	10.69	<0.01*
Diastolic Blood Pressure (mmHg)	345	4	1164	20	1.48	0.25
Arterial Oxygen Saturation (%)	2	4	14	20	0.54	0.71

* significant at the alpha level $p \leq 0.05$

Table 4.2

Univariate Repeated Measures ANOVA for Metabolic Variables

Variable	Numerator		Denominator		F	p
	SS	dF	SS	dF		
VO ₂ - Relative (ml/kg/min)	7.1	4	17.2	16	1.66	0.21
VO ₂ - Absolute (l/min)	0.04	4	0.11	16	1.21	0.34
Respiratory Exchange Ratio (no units)	0.01	4	0.05	16	0.91	0.48
Ventilation (l/min)	57	4	217	16	1.05	0.41

Table 4.3

Univariate Repeated Measures ANOVA for Temperature Variables

Variable	Numerator		Denominator		F	p
	SS	dF	SS	dF		
Core Temperature - Rectal (°C)	0.22	4	2	20	0.57	0.68
Skin Temperature - Calf (°C)	151	4	236	20	3.21	0.03*
Skin Temperature - Chest (°C)	132	4	142	20	4.64	<0.01*
Skin Temperature - Earlobe (°C)	31	4	120	20	1.27	0.31
Skin Temperature - Femoralis (°C)	268	4	78	20	17.24	<0.01*
Skin Temperature - Finger (°C)	28	4	127	20	1.11	0.38

* significant at the alpha level $p \leq 0.05$

Table 4.4

Univariate Repeated Measures ANOVA for Local Sweat Rate Variables

Variable	Numerator		Denominator		F	p
	SS	dF	SS	dF		
Local Sweat Rate - Chest (Δ grams)	0.11	4	0.52	20	1.10	0.38
Local Sweat Rate - Back (Δ grams)	1.21	4	2.32	20	2.61	0.07
Local Sweat Rate - Groin (Δ grams)	0.20	4	0.21	20	4.60	<0.01*

* significant at the alpha level $p \leq 0.05$

Table 4.5

Univariate Repeated Measures ANOVA for Skin Wetness Variables

Variable	Numerator		Denominator		F	p
	SS	dF	SS	dF		
Skin Wetness - Forehead (arbitrary units)	55428	4	316229	20	0.88	0.50
Skin Wetness - Hand (arbitrary units)	9151	4	107122	20	0.43	0.79
Skin Wetness - Palm (arbitrary units)	84577	4	254430	20	1.66	0.20
Skin Wetness - Ankle (arbitrary units)	40863	4	226024	20	0.90	0.48

CHAPTER 5 - DISCUSSION

The purpose of this study was to identify the advanced features of three different liquid cooling garments in the context of simulated extravehicular activity (i.e., walking on a treadmill) in two separate temperature regimes (24 °C and 35 °C). Since two garments (MACS-Delphi and Orlan) allowed for the addition of a cooling hood, there were 10 potential experimental conditions. Each participant performed 10 trials (one for each potential garment and temperature combination). In terms of the ambient air temperature, the goal was to create two distinctly different environmental conditions, one thermoneutral (24 °C) and the other hot (35 °C). The environmental chamber in which all testing took place was a converted walk-in refrigeration unit that was customized for the express purpose of human testing in various temperature regimes. The crude nature of the testing chamber did not allow for precise control of air temperature and was not capable of modulating humidity; collectively, these two variables represent a potentially significant environmental heat stressor to humans (Armstrong, 2000). Despite the limitations of the chamber design, the overall averages of the 30 thermoneutral trials and the 30 hot trials were very close to the prescribed regimes at 25.0 °C (± 1.3 °C) and 35.6 °C (± 0.5 °C), respectively. For the 30 thermoneutral and 30 hot trials, the temperature ranged from 22.5-27.4 °C and 34.0-36.5 °C, respectively. The air humidity likely did not contribute to a significantly increased heat stress due to the fact that humidity was generally low in both the thermoneutral and hot conditions (28.5 and 18.4%, respectively). Although there were slight variations in ambient temperature between experimental trials, these were deemed inconsequential and the goal of creating two separate temperature regimes (i.e., thermoneutral and hot) was achieved.

The purpose of the exercise protocol was to model (using a treadmill) the energy expenditure profile used by NASA to simulate the metabolic demands of extravehicular activity (EVA). In particular, EVA on a planetary surface (e.g., the Moon, Mars, etc.) involves a significant increase in energy expenditure (Waligora & Kumar, 1995). As metabolic heat load increases in the context of increased energy expenditure in an enclosed and impermeable microclimate (i.e., space suit), the management of the resulting psychological and physiological milieu is of the utmost importance. The consequences of failing to properly regulate body temperature during EVA go far beyond discomfort, and can have catastrophic results. In order to estimate the treadmill speed and grade that would elicit the prescribed energy expenditure during various stages of exercise, a regression equation (Thompson, 2010) was used. A metabolic analyzing system was used to measure energy expenditure over the course of each experimental trial in order to record the actual energy expenditure levels across the various stages. The actual energy expenditure profile was quite close to the prescribed profile as seen in Table 5.1. Estimating energy expenditure from regression equations is often imperfect owing to the fact that there can be significant variability between and within individuals. However, the actual energy expenditures measured within this study were remarkably close to the predicted values which demonstrates a certain degree of utility to an equation that some have questioned in terms of validity and reliability. Despite the small variability in actual levels of energy expenditure for a given exercise stage, the goal of creating distinctly different energy expenditure rates (for different exercise stages) was achieved.

Table 5.1

*Prescribed vs. Measured Energy
Expenditure by Stage*

Stage	Energy Expenditure (Watts)	
	Prescribed	Measured*
1	250	269.2 ($\pm$ 8.4)
2	300	307.8 ($\pm$ 6.5)
3	400	389.0 ($\pm$ 10.9)
4	100 (rest)	110.4 ($\pm$ 7.8)
5	700	682.8 ($\pm$ 17.2)
6	500	488.1 ($\pm$ 13.9)
7	100 (rest)	99.0 ($\pm$ 5.8)

* Average of all 60 trials ($\pm$ standard deviation)

Of the seven stages that defined each trial, two stages were investigated in detail and statistically analyzed. The stages that were selected were stages five and seven. Stage five was selected as the most representative of the exercise stages (i.e., one, two, three, five, and six) because it was defined as the highest intensity (in terms of exercise and energy expenditure). Stage seven was selected due to the fact that it was a rest stage and reflected a recovery phase following the combined 40 minutes of stages five and six, the two stages of highest intensity exercise within the seven-stage protocol. The fact that the remaining stages (i.e., one, two, three, four, and six) were not statistically analyzed is not meant to minimize the importance of these stages. However, a detailed analysis of stages five and seven was believed to best evaluate the performance of the various garments.

Physiological Findings

Metabolism

Metabolism was assessed using a metabolic analyzing system and open-circuit spirometry. There were no differences in the four variables that were analyzed (i.e., relative oxygen consumption, absolute oxygen consumption, ventilation, and respiratory exchange ratio). The oxygen consumption data indicate that the participants were exercising at similar intensities during stage five over the course of the 10 trials. The goal of the study design was to standardize the exercise intensity for each individual and stage so as to minimize the confounding influence that different exercise intensities (for a given participant and stage) would have on thermoregulation. It is therefore concluded that any differences in the analyzed variables are not attributable to differing levels of energy expenditure. It is assumed that any observed differences are the result of the garment being used. However, there is the possibility that other factors confounded the results; this important topic is discussed later in the chapter. The similar respiratory exchange ratios indicate that substrate utilization (i.e., carbohydrate vs. fat) was the same for each participant throughout the 10 trials. This was the expected result for two reasons: 1) it would be unlikely to see significant differences in the respiratory exchange ratio without concomitant changes in oxygen consumption as both reflect exercise intensity (Brooks, Fahey, & Baldwin, 2005) and 2) most of the evidence for temperature-mediated alterations in substrate utilization is relegated to the other side of the thermal spectrum, namely in cold environments when carbohydrate usage is increased (Brooks et al., 2005; Pandolf, Sawka, & Gonzalez, 2001).

Skin and Core Temperature

There were no differences between the garments in terms of core/rectal temperature. This illustrates the collective effectiveness of the three garment types in terms of maintaining core temperature, particularly in the context of the increasing heat load that occurred during stage five (exercise). The average core temperatures for all five garment combinations were maintained in a very narrow range during stage five (highest intensity exercise) for both the thermoneutral and hot conditions (37.33 - 37.58 °C and 37.52 - 37.75 °C, respectively). The core temperature profiles for the different garments over the course of the entire 154-minute protocol were also quite similar in both the 24 °C (Figure 5.1) and 35 °C (Figure 5.2) regimes. Considering that normal core body temperature is 37.0 °C, the results suggest that the garments evaluated in this study were effective at attenuating the heat load generated by exercise and heat exposure. This is an important finding considering the fact that core temperature is traditionally one of the three vital measures (i.e., temperature, blood pressure, and heart rate) and its regulation is crucial for future space missions and the safety of astronauts performing EVA. As it relates to core temperature regulation, all three garment types performed similarly in both the thermoneutral and hot environments. This is perhaps the most salient finding of the current study because it provides evidence that water flow rate (through a garment) is not a critical factor. This finding is in contrast to the findings of Cadarette et al. in which the authors speculate that low flow rates (i.e., 0.4 l/min) hinder heat transfer due to an increased presence of air bubbles that block the coolant flow and reduce heat extraction (Cadarette, DeCristofano, Speckman, & Sawka, 1990). While the same air bubble

Figure 5.1. Average core (rectal) temperature profiles of the MACS-Delphi, Orlan, and LCVG across all stages during the 24 °C temperature regime.

Figure 5.2. Average core (rectal) temperature profiles of the MACS-Delphi, Orlan, and LCVG across all stages during the 35 °C temperature regime.

phenomenon was observed with the lowest flow rate garment in the present study (with a flow rate of ~ 0.3 l/min), the current findings are in agreement with the observations of others that flow rates above one liter per minute produce little improvement in cooling (Nunneley, 1970). The results of this study demonstrate that low flow rates (exhibited by the MACS-Delphi) can be as effective as high flow rates (exhibited by the LCVG and Orlan). The topic of water flow rate is further examined in the “Garment Design” section. In this study, core temperature was not significantly affected by the addition of a cooling hood. However, the effects of a cooling hood on psychological perception and thermal comfort have yet to be elucidated.

In contrast to the findings regarding core temperature, there were significant differences between the garments related to skin temperature. The LCVG caused a lower skin temperature in the calf region when compared to the MACS-Delphi and Orlan. This was not an entirely unexpected finding. The Orlan does not have any tubing coverage below the knee so the higher skin temperatures found in the calf region are presumably due to a lack of conductive heat exchange in the region of the lower leg. On the other hand, the MACS-Delphi does have tubing in both the upper and lower leg regions (22.3 and 3.9 m, respectively). There are two possible explanations for this finding (acting independently or in combination). First, the lower calf temperatures (relative to the MACS-Delphi) associated with the LCVG could be a result of differences in water flow rates between the garments. The average flow rate of the LCVG is nearly seven-fold greater than that of the MACS-Delphi. It is certainly within reason that such a discrepancy in flow rates could elicit significantly different effects on skin temperature. However, if this mechanism was,

in fact, responsible for the differences in skin temperatures between garments, then similar differences would be expected in all of the skin regions for which temperature was measured (similar differences were not found at all skin measurement sites). Second, the differences could be a result of the amount of tubing in the lower leg segment of the garments. The MACS-Delphi has a collective tubing length of 26.2 m in the lower extremity (i.e., thighs and calves) compared to a total length of 37.8 m in the same anatomic region of the LCVG. While the exact specifications for lower leg (i.e., below the knee) coverage of the LCVG garment are not available, it is reasonable to assume that the LCVG design covers a greater area of the lower leg region than that of the MACS-Delphi (i.e., 3.9 m) owing to the greater overall length of tubing in the collective lower extremity region. If there is, in fact, a greater amount of tubing coverage in the lower leg region of the LCVG, the lower calf skin temperatures in the LCVG could simply be the result of increased heat transfer (via conduction) due to increased skin surface area in contact with the water-cooled tubing network.

In terms of chest skin temperature, the Orlan elicited significantly lower temperatures than the MACS-Delphi. As discussed previously, a difference in skin temperatures between garments could be due to different water flow rates. In this case, there were vast differences between the Orlan and MACS-Delphi garments (2385.75 and 284.87 ml/min, respectively). Interestingly, and in contrast with the findings regarding the calf region, the garment with lesser absolute tubing coverage in a defined area elicited lower skin temperatures than the garment with greater coverage. The Orlan has 7.79 m of tubing length in the chest/abdomen region compared to 11.7 m for the same region of the

MACS-Delphi. If differences in water flow rate do not account for the differences in chest skin temperature, the explanation is less clear. One possible reason could be related to the tightness of the garments. Although not quantitatively measured, it was observed that the Orlan garment was generally the tightest fitting garment of the three, particularly in the chest/upper back region. It is possible that a tighter fit resulted in a greater surface area of tubing in direct contact with the skin. Obviously, a tighter fit would result in greater surface area contact than a looser fit if everything else was equal. This potentially could have resulted in greater heat transfer, despite less overall tubing length in the region. Another possible explanation has to do with the diameter of the tubing. Of the three garments, the MACS-Delphi has the smallest diameter tubing (inner and outer diameters of 2.4 and 4.0 mm, respectively) whereas the Orlan has the largest diameter tubing. If all else is equal, a larger diameter tube will have a greater surface area in contact with the skin than a smaller diameter tube. Perhaps the Orlan actually had a greater amount of tubing surface area in contact with the skin (by virtue of a greater tube diameter) than the MACS-Delphi and this increase in heat transfer potential outweighed the decrease in heat transfer potential associated with a lesser absolute length of tubing.

The final significant finding related to skin temperature occurred in the femoralis (thigh) region. The femoralis skin temperature was significantly lower with the LCVG than both the MACS-Delphi and Orlan. Water flow rate does not explain the observed difference because, while the LCVG had a significantly greater flow rate than the MACS-Delphi, the Orlan had a significantly greater flow rate than the LCVG. Tubing diameter does not explain the difference either because the tubing diameter of the Orlan is greater than that

of the LCVG. The most likely explanation has to do with amount (i.e., length) of tubing coverage since the MACS-Delphi and Orlan have virtually identical lengths of tubing in the thigh area (22.3 and 22.4 m, respectively). As was mentioned previously, the total amount of tubing in the lower extremity of the LCVG is 37.8 m. However, no distinction is made in the garment specifications for the length of tubing in the upper versus lower legs of the LCVG. The fact that the LCVG contains a much greater absolute length of tubing in the lower extremity compared to the MACS-Delphi and Orlan (37.8 vs. 26.2 m and 37.8 vs. 22.4 m, respectively) makes it reasonable to conclude that there is a much greater length of tubing in the thigh area of the LCVG compared to the MACS-Delphi and Orlan. If the LCVG does, in fact, have a greater length of tubing than the other two garments, then an increased surface area coverage (and accompanying increased potential for conductive heat exchange) would seem to be the most logical explanation for the significantly lower femoralis temperatures observed in the LCVG.

Cardiovascular Parameters

There were two very interesting findings related to systolic blood pressure and heart rate. The MACS-Delphi elicited a significantly lower systolic blood pressure response than both the LCVG and Orlan. While this finding is noteworthy, the mechanism of such a blood pressure response is unclear. Certainly, the regulation of systemic blood pressure is complicated, involves the interactions of numerous complex systems, and is not fully understood. It is accepted that, in a healthy individual, systolic blood pressure increases as energy expenditure (i.e., workload) increases and it does so in a roughly linear fashion. This increase in blood pressure with physical exertion is caused by a disproportionate

increase in cardiac output relative to the decrease in peripheral vascular resistance. It is not out of the realm of possibility that there is an interaction between blood pressure and temperature regulation, as both have a significant vascular component (particularly the smaller arterioles) in common. Perhaps the most significant contributor to heat balance within the human body lies in the reflex peripheral vasoconstriction and vasodilation associated with exposure to cool/cold and warm/hot environmental stressors, respectively. Exercise in hot environments presents an interesting physiological paradox as circulatory regulation (maintenance of blood pressure in the context of a reduced plasma volume) competes with temperature regulation (peripheral vasodilation to facilitate heat transfer). It should be noted, however, that muscle blood flow and circulatory regulation take precedence over temperature regulation during exercise in warm/hot environments (McArdle, Katch, & Katch, 2010). The findings associated with systolic blood pressure in this study may also be related to water flow rates and thermal gradients. In this study, all circulating water entered the garments at 15 °C. However, due to the significantly lower flow rates characteristic of the MACS-Delphi, the overall average water temperature within the garment was warmer, presumably due to the longer transit time. Conversely, the water within the garments with the high flow rates was, on average, cooler owing to more rapid transit times. This was substantiated quantitatively by continuous measurement of inlet versus outlet water temperatures during each trial. It is possible that systolic blood pressure was higher in the LCVG and Orlan due to a systemic peripheral vasoconstriction mediated by the greater thermal gradient between the skin and circulating water. This effect would be expected to be reflected in lower systemic skin temperatures in the LCVG and Orlan, but the data do not consistently support this.

However, the subjective thermal perception (data not presented) of participants show that, as a whole, participants felt more dramatic thermal changes (towards the cooler/colder end of the continuum) with the higher flow rate garments (i.e., LCVG and Orlan). While the objective (skin temperature) and subjective (thermal perception) data are conflicting, a peripheral vasoconstrictor response (due to a large thermal gradient) can not be ruled out as a possible mechanism for the difference in systolic blood pressure observed.

In addition to the systolic blood pressure response, there was also a significant difference in heart rates between the MACS-Delphi and LCVG. Heart rate was, on average, lower in the MACS-Delphi compared to the LCVG. As with the systolic blood pressure findings, an explanation for such a difference is not obvious. Heart rate is modulated by the autonomic nervous system and, like systolic blood pressure, it rises linearly with increasing workload intensity. The onset of physical exertion is characterized by an increasing sympathetic involvement accompanied by a withdrawal of the parasympathetic dominance that is present at rest. There is, however, one particular phenomenon that is exclusively related to heart rate modulation and exercise in the heat. Cardiac drift is a term that describes the common observation that heart rate gradually increases over time (tens of minutes to hours depending on exercise intensity) despite a constant, or even decreasing, intensity level. In theory, heart rate should remain relatively constant over time in the context of steady-state exercise at a given intensity. This is not the case when exercise is performed in hot, or even warm, environments for a prolonged period of time (i.e., greater than 30-60 minutes). The typical profile of prolonged exercise in the heat is one of a gradually, yet progressively, increasing heart rate. This is due to a

redistribution (and pooling) of blood as well as a decreased plasma volume which is the result of fluid loss, primarily in the form of sweat. On average, heart rate increases eight beats per minute for each liter of sweat-loss dehydration (McArdle et al., 2010). This phenomenon is illustrated by the relationship between cardiac output, heart rate, and stroke volume which is defined as: $[\text{cardiac output} = \text{heart rate} \times \text{stroke volume}]$. As plasma volume decreases, venous return to the heart decreases which causes a decrease in preload and myocardial contractility (i.e., Frank-Starling law of the heart) which ultimately results in a decreased stroke volume. If cardiac output remains unchanged (in theory cardiac output should not change if workload remains constant) and stroke volume decreases, the only option for maintaining cardiac output is an increase in heart rate (Rowell, 1993; Rowell & Shepherd, 1996). Certainly, by stage five (the exercise stage analyzed in detail), it would seem there was an adequate duration of exercise in the heat to potentially cause fluid losses in excess of the threshold required for cardiac drift. However, the fact that the findings indicate a significant difference in heart rate between the MACS-Delphi and LCVG without a concomitant difference in sweat-loss dehydration (the LCVG actually elicited *lower* whole body fluid losses than the MACS-Delphi) leads to the distinct possibility that another mechanism is responsible for the difference in heart rate between the two garments. The difference in garment weight is another possible factor to consider when attempting to explain the heart rate findings since the LCVG was heavier than the MACS-Delphi (1.79 vs. 1.43 kg, respectively). A heavier garment would necessarily require a greater energy expenditure during locomotion (in a gravity-dependent environment) and greater energy expenditures are usually reflected in higher heart rates. However, there are two factors that do not support the idea that the MACS-

Delphi resulted in a lower heart rate than the LCVG simply due to garment weight. First, there was no difference in metabolic variables (e.g., oxygen consumption) which would be expected to mirror the differences in heart rate. Second, the Orlan (2.45 kg) was heavier than both the LCVG and MACS-Delphi yet the heart rates between the MACS-Delphi and Orlan were not significantly different.

Local Sweat Rate

Local sweat rate was indirectly estimated by affixing absorbent filter paper to three regions of the body: the chest, upper back, and groin. Sweat rate was assessed on a relative scale by weighing the filter paper before and after each trial. The unit of measure (Δ grams) was used to indirectly assess sweat rate (i.e., a greater change in weight represents a greater sweat rate). This metric differs from the metabolic, cardiovascular, skin wetness, and temperature parameters in that it was a simple before-and-after measurement and represented the seven stages collectively as opposed to the selective analysis of stages five and seven. The reason for the measurement technique of placing absorbent patches on the body surface for the entirety of the trial, compared to that of skin wetness which was measured each stage, was due to the fact that all three regions of interest were covered by the garment which made it difficult to access on a regular basis throughout a trial. There were significant differences observed in the groin and back region. The local sweat rate in the groin was lower in the LCVG compared to the MACS-Delphi and Orlan. This result is in agreement with the finding that the femoralis skin temperature was also lower in the LCVG compared to the MACS-Delphi and Orlan garments. It is likely that the two findings are related due to the proximity of the two

anatomic sites of measurement (i.e., femoralis and groin) and the presumed link between skin temperature and sweat rate. As was discussed with regard to skin temperature, the most likely explanation is the greater length of tubing in the upper leg region of the LCVG compared to the MACS-Delphi and Orlan. It seems reasonable to conclude that a more extensive network of tubing in a given anatomic region results in lower sweating rates in that region.

In the upper back, the local sweat rate for the MACS-Delphi was greater than that of both the LCVG and Orlan. The upper back is known to be a region of high sweat rates (Cotter, Patterson, & Taylor, 1995; Machado-Moreira, Smith, Van Den Heuvel, Mekjavic, & Taylor, 2008) which is likely attributable to the combination of the several large skeletal muscle groups (e.g., latissimus dorsi, trapezius, rhomboideus major, etc.) and large bone structures (i.e., clavicles, ribs, and vertebrae). This collectively represents a large mass of dense tissue that acts as a heat sink during times of increasing heat load due to the density of the involved tissues. It is interesting that the MACS-Delphi had a higher sweat rate in this region because the MACS-Delphi was specifically designed with physiology in mind as evidenced by the selective focus of tube coverage on high density tissue areas like that found in the upper back (Koscheyev, Coca, & Leon, 2007; Koscheyev, Coca, Leon, & Dancisak, 2002). However, an inspection of the garment specifications reveals one possible explanation for the current findings. The MACS-Delphi has 5.69 m of tubing length in the back region whereas the Orlan and LCVG have 9.19 and 12.2 m of tubing length, respectively, in the same region. So, it is possible that the lower surface area coverage is the cause of the higher sweat rate. Another possibility for the higher sweat

rate in the back with the MACS-Delphi is the lower flow rate associated with that garment which has already been discussed. Finally, the MACS-Delphi has the smallest diameter tubing which not only affects flow rate but also dictates surface area coverage independent of length. Any of the aforementioned factors (i.e., tubing length, flow rate, and/or diameter) could explain the higher sweat rate in the back region with the MACS-Delphi.

Skin Wetness

Skin wetness was measured using a skin impedance probe. The device used arbitrary units so the analysis focused on relative differences between the four anatomic sites: forehead, hand (dorsal), hand (volar), and ankle. This measure was different from local sweat rate in that all four sites represented skin regions not covered by any garment. Differences in skin wetness would represent a more systemic effect of a garment (or garments) as the garment, or its tubing network, was not in direct contact with the skin site. There were no differences in any skin wetness variables during stages five and seven indicating that all of the garments performed similarly. This suggests that either: 1) there were no systemic effects, at least as they apply to the four measured sites, for any of the garments related to skin wetness; or 2) there was a systemic effect but it was equal between the different garments.

Whole Body Sweat Rate

Whole body sweat rate was determined simply by weighing in the semi-nude state before and after each experimental trial. Participants did not consume any solids or liquids

during the experimental trials so the assumption that body mass change reflected whole body sweat rate was straightforward with the exception of not accounting for fluid lost in the form of water vapor during exhalation (this component was deemed inconsequential for the purposes of this study). Some of the most consistent findings of the present study relate to whole body sweat rate with the LCVG demonstrating a favorable effect compared the MACS-Delphi and Orlan as illustrated by the attenuation of whole body water loss via sweating. This effect can most likely be explained by the fact that the LCVG had a greater total amount of tubing (79.4 m) than the MACS-Delphi (58.9 m) or Orlan (49.4 m). Flow rate may have also exerted an influence but overall tubing length would seem to be the predominant factor as the flow rate for the Orlan was significantly greater than that of the LCVG. It can be assumed that the garment with the greatest overall length of tubing will be in contact with the greatest body surface area. This greater body cooling (in terms of area) would presumably exert the greatest overall skin cooling and would certainly have an effect on the sweating response. This finding is particularly important in the context of heat stress since dehydration beyond certain thresholds exacerbates, or even perpetuates, heat-related dysfunction (Armstrong, 2000). Further, this idea is of specific relevance to astronauts during extended EVA since the current protocol only provides 947 ml of water per EVA sortie (Cowell, Stocks, Evan, Simonson, & Greenleaf, 2002) despite the fact that astronauts require about one to three liters of water for every five to six hours of EVA (Greenleaf, 1989). It seems logical that every effort should be made to conserve water in a situation like EVA that is highlighted by a growing whole body water deficit over a period of several hours.

Garment Design

Two primary characteristics that differentiate liquid cooling garments are: 1) the diameter of the tubing and 2) the coverage of the tubing network across the body. It is important to note that both absolute coverage (amount of tubing in direct contact with the skin) and location of coverage (regions of the body in which tubing is in contact with the skin) are considered important questions regarding garment design that have yet to be fully answered (Flouris & Cheung, 2006). The rate of water flow through the garment is an important consideration. Flow rate is determined, in large part, by the diameter of the tubing (i.e., larger diameter tubes can accommodate a greater flow rate than smaller diameter tubes). Common sense may indicate that, if cooling a heated body via conduction using cool/cold water circulated through tubing in contact with the skin, a higher flow rate is more effective at transferring heat from the body and, hence, results in a lower core temperature. In other words, the greater the volume of water being circulated through the garment per unit time, the greater the heat transfer. The results of the present study do indicate that heat flow (i.e., heat extraction) was lowest in the garment with the lowest flow rate (i.e., MACS-Delphi). However, it was not the garment with the greatest flow rate (i.e., Orlan) that resulted in the greatest heat extraction; the greatest heat extraction occurred in the garment with a flow rate in-between the highest and lowest flow rates (i.e., LCVG).

The results suggest that overall heat extraction is not the sole determinant of core temperature since all three garments elicited similar core temperatures despite different flow rates and heat extraction rates. As has already been discussed, the different flow

rates may have exerted an influence on skin temperatures at various locations but this was neither consistent nor systemic. This is an important finding since core temperature is arguably the most important physiological variable in terms of comfort, health, and safety in the context of EVA. This supports the analogy posed by Taylor in which he asserts that the human body is not a “bowling ball” of uniform density, known material properties, and easily quantifiable proportions which lends itself exclusively to common engineering assumptions and first-principles thermodynamics (Taylor, Casa, & Kenny, 2010). The fact that the human body does not have homogenous composition and uniform thermal conductivity highlights the difficulty in attempting to model and predict heat transfer within a dynamic body that is highlighted by multiple interconnected systems, different tissue types, and heat transfer facilitated by both conductive and convective (mass) flow (Taylor et al., 2010).

The coverage of the tubing is an important consideration in the design of a cooling garment. This study investigated three garments, each of which has unique tubing arrangements. The LCVG design focuses on absolute surface area and is indiscriminate in coverage as it relates to the potential for heat transfer via the underlying tissues. The focus on sheer coverage is evidenced by the total amount of tubing incorporated in the LCVG (79.4 m) compared to that of the MACS-Delphi and Orlan (58.9 and 49.4 m, respectively). The MACS-Delphi and Orlan designs have more strategic physiologic orientations of tubing based on specific types of tissue. The Orlan design focuses tube distribution primarily in areas of large amounts of muscle mass, presumably to more effectively remove heat from areas of significant heat generation during physical exertion

(i.e., skeletal muscles). The MACS-Delphi is also physiologically designed, with primary emphasis on high density tissue (i.e., bone). The tubing arrangements of the three garments evaluated in this study range from seemingly random to very strategic. The results of this study indicate that there may be some merit to increased quantity of coverage (at the expense of quality of coverage) if the goal is lowering skin temperature as is seen in the lower calf and femoralis skin temperatures with the LCVG. However, these findings must be balanced with the need to preserve thermal comfort (subjective perception) as well as regulate core temperature. Core temperature was regulated similarly between all three garments despite the fact that the LCVG had the greatest heat extraction (which was accompanied by lower perceived thermal comfort).

The addition of a cooling hood is another design option for cooling garments. In this study, two of the garments had a hood option (i.e., MACS-Delphi and Orlan). The rationale behind incorporating a hood is to augment conductive heat exchange. Use of the head for heat exchange is thought to be a potentially effective strategy owing to the large amount of heat released from this region as well as its unique vasculature. The head can be thought of as the body's "chimney" because it is capable of transferring large amounts of heat due to the dense tissue (i.e., cranium) and the large blood vessels that supply it. A large proportion of the body's heat loss occurs via the head (Froese & Burton, 1957; Rasch, Samson, Cote, & Cabanac, 1991), particularly in extreme thermal environments like the cold, making it an attractive site for purposeful heat removal by means of a cooling hood. Anecdotal observations certainly reveal a tendency for many people to focus first on the head when it comes to cooling off with a wet towel or water in hot

environments. This instinctual reflex should not be overlooked. The head also has the distinction of containing a dense network of blood vessels that are less prone to cold-induced vasoconstriction (Blair, Glover, & Roddie, 1961; Froese & Burton, 1957; Hertzman & Roth, 1942; Rasch et al., 1991). There currently exists a great debate as to the optimal temperature of water for the purpose of lowering core temperature by means of whole body cooling (e.g., emergency medicine for heat illness) (Taylor et al., 2010). Some believe the greater the thermal gradient, the greater the conductive/convective heat transfer so “the colder the better” is the mantra. Others caution against this approach citing the reflex vasoconstriction that accompanies rapid application of cold to the body’s outer shell. The belief is that a large thermal gradient is of limited usefulness in the context of reduced skin blood flow due to vasoconstriction. The vasculature of the head may allow for the application of cold to very cold water and, hence, a large thermal gradient and potential for substantial heat transfer from a large heat sink without concern for a marked vasoconstrictor effect. The results of this study did not show any added effect of the hood despite the reports of participants that overall thermal comfort was higher with the hood which is in agreement with previous findings (Simmons, Mundel, & Jones, 2008). The use of a hood is also a contentious debate with astronauts because the addition of a hood is seen by many as an unnecessary discomfort from an ergonomic standpoint. Caution is urged when making conclusions based on the current cooling hood findings because: 1) the participants all had hair which certainly acted as an insulator and barrier to heat transfer and 2) the temperature of the water was set at 15 °C and not decreased to lower temperatures in the head region so it is not possible to determine if the hood would have been effective at lower temperatures.

Limiting Factors

There were several limiting factors in this study, many of which were unavoidable due to the experimental design. The first limitation is the small sample size (i.e., six participants). The major disadvantage of such a small sample size is the reduced statistical power to detect differences between groups. However, this research was meant to serve more as a pilot study and, from the beginning, the funding agency dictated that there be a small sample size owing to budgetary constraints. The detailed data collection of numerous variables and the fact that each participant performed 10 separate experimental trials allowed for the achievement of the study's primary goal which was to evaluate the performance of three different liquid cooling garments and identify the advanced features of each.

Another limitation was the population used. The study population consisted of volunteers recruited from the Twin Cities area of Minnesota and, more specifically, the campus of the University of Minnesota. Not unexpectedly, the majority of participants were students. The primary concern with the population used is the similarity to the typical profile of present-day astronauts (for whom this research is based). In particular, the average age of the participants in this study was 29.7 years whereas the average age of active-duty astronauts is between 42-43 years (Harm et al., 2001). This discrepancy in age is not deemed to be a significant factor as there are only subtle differences in thermoregulatory physiology between the third and fifth decades of life for healthy, fit individuals (Havenith, Yoshimitsu, & Kenney, 1995; Kenny, Gagnon, Dorman, Hardcastle, & Jay, 2010). Additionally, men and women were recruited for the study since females represent

more than one-fifth (22.3% as of August 2001) of the active astronaut population in the United States (Harm et al., 2001). Men and women were pooled together as a single group in terms of data analysis (i.e., separate comparisons of men and women were not performed) due to the methodological and statistical power limitations imposed by small sub-group analysis (i.e., four males and two females). While differences in core temperature between sexes has been suggested to be related to differences in physical characteristics (not due to differences in whole-body thermoregulatory responses) (Gagnon, Dorman, Ollie, Hardcastle, & Kenny, 2009), it has been noted that systemic differences in thermoregulation do exist in terms of sweat rate (Gagnon, Jay, Lemire, & Kenny, 2008) and sweat distribution (Havenith, Fogarty, Bartlett, Smith, & Ventenat, 2008) which could confound the interpretation of the present results.

The issue of physical fitness of the study participants was of paramount concern due to: 1) the strenuous physical requirements of the experimental trials, 2) the relationship between thermoregulation and physical fitness, and 3) the above-average physical fitness profile of astronauts. The average peak oxygen consumption for men and women in this study was 42.6 and 49.0 ml/kg/min, respectively. This index of physical/aerobic fitness for the study population is higher than the reported average peak oxygen consumption for active-duty male and female astronauts of 36.5 and 44.2 ml/kg/min, respectively (Harm et al., 2001). However, when adjusted for age, both groups scored in a similar range for peak oxygen consumption between the 70th and 75th percentile on population-based normative data for American adults (Thompson, 2010).

Body composition was also an important factor due to the relationship between adipose tissue and heat transfer dynamics (i.e., the insulative properties of adipose tissue). The study participants were, on average, leaner than the typical astronaut. Females in this study had an average body fat percentage of 18.2% while males averaged 9.1%. This compares to the average astronaut profiles for women and men of 20.8 and 17.6% body fat, respectively (Harm et al., 2001). This difference between the body composition profiles of the study population and the typical astronaut is not deemed a practical difference as it relates to thermoregulation and heat transfer dynamics. This conclusion was reached after a review of the findings of Lemire et al. in which it was found that body adiposity did not affect core cooling rates in active individuals under 25% body fat rendered hyperthermic by exercise (Lemire et al., 2008).

An obvious limitation of the current study is the fact that all testing occurred in an Earth-based, gravity-dependent environment (i.e., not in microgravity). There was no way to circumvent this limitation, barring performing the experiments in outer space which was not practical. This is a very important point owing to the significant effects that microgravity exerts on the circulation. In microgravity, blood tends to pool in the central regions of the body as opposed to the dependent regions (i.e., lower extremities) which is the hallmark of an upright posture on the Earth's surface (Rowell, 1993). The importance of this is underscored by the fact that circulating blood is the predominant facilitator of heat transfer in the context of an elevated core temperature. However, the circulation profiles between gravity-dependent and gravity-independent environments are greatest at rest. In microgravity, the increase in cardiac output with physical exertion and the

accompanying muscle actions (and vascular muscle pump) leads to a circulation profile that more closely resembles that of a gravity-dependent environment. In fact, it has been shown that circulation can be enhanced to the lower limbs during head-down tilt simply by warming the upper body and thighs (Koscheyev, Leon, Coca, & List, 2004). Therefore, while caution must be used when interpreting ground-based experiments with spaceflight applications, it seems likely that the results of this study can be reasonably applied to spaceflight, particularly as it relates to physical activity.

Participants in this study performed treadmill exercise in order to simulate extravehicular activity (EVA). The primary aim was to approximate the overall power output of EVA and reproduce the associated energy expenditure by walking at various speeds and inclinations on a treadmill. There are two important implications of this experimental design. First, astronauts performing EVA must wear a protective space suit that significantly alters the biomechanics of movement for any given task (e.g., walking on the lunar surface) (Carr & Newman, 2007a, 2007b). However, since the experimental protocol used in this study was designed to replicate the overall energy expenditure of EVA (which takes into account such factors as altered biomechanics), the issue of performing the experimental protocols without donning a suit/garment that approximates the biomechanical effects created by a space suit is not seen as a major limitation. Of greater importance is the nature of the work performed during EVA. In particular, all present-day EVA involves so-called “spacewalks” which are characterized by free movement outside of the protective confines of a space station or transport vehicle (e.g., space shuttle) for the purposes of equipment repair or construction. The physical

requirements for EVA differ significantly based on the specific type of activity. For example, walking on the lunar surface involves locomotion and primarily uses the larger muscle mass of the lower body. This is in stark contrast to the less efficient physical requirements of a spacewalk. The longest spacewalks last between eight and nine hours in duration and the vast majority of this time is not spent moving from one place to the next, but rather involves maintaining a stationary position in which the musculature of the upper body is significantly engaged. The disproportionately small muscle mass of the upper body, combined with its fatigability and long periods in static positions (i.e., isometric muscle actions), makes this type of physical exertion much different than that of locomotion. So, while the overall energy expenditure (on an absolute scale) may be similar between a spacewalk and a moonwalk, the muscular requirements are quite different. This beckons the question as to whether or not thermoregulatory mechanisms respond differently based on the type of physical exertion (dynamic lower body activity versus static upper body activity) if the absolute energy expenditure is the same between the two types. Evidence has been provided that suggests that the rise in core temperature with earth-based exercise is not dependent on the skeletal muscle mass utilized but, rather, it is dependent on the metabolic rate during exercise (Sawka, Latzka, & Pandolf, 1989). However, no known research has addressed this question in the context of microgravity. If there is, in fact, a difference in the thermoregulatory profile between the two types of EVA, then caution must be used when applying the findings of the current research (employing dynamic lower body exercise) to present-day EVA (characterized by static upper body activity).

In terms of the spacing of the 10 experimental trials for each participant, there were several instances of less-than-ideal conditions. The envisioned study design involved participants coming to the laboratory at seven-day intervals, primarily to avoid fatigue (psychological and physiological) and remain within the individuals' circaseptan biorhythms. This would have meant each participant complete the required 10 trials in 10 weeks. However, due to time constraints on behalf of the participants, most completed the required 10 trials in a much shorter period of time than originally planned (the shortest time to complete all 10 trials was 32 days in the case of participant CX). It was deemed more important to get each participant through all 10 trials (even if it meant shorter intervals between trials) than not completing all 10 trials. As an extreme example of less-than-ideal spacing between trials, participant CX performed four trials on four consecutive days and, on two other occasions, performed two trials on consecutive days. This was unavoidable as this particular individual needed to complete all 10 trials before leaving for military obligations for an extended period of time. While ensuring that each participant completed all 10 trials allowed for a more complete data set, it does have potential consequences. First, those participants that had short intervals between trials (some as short as 24 hours) were more likely to have suffered from fatigue which could have had wide-ranging effects from cardiovascular to thermoregulatory to psychological. The potential effects of fatigue are too numerous to list, but it suffices to say that fatigue could have confounded the results of those experimental trials that were performed by participants who were not fully recovered from the previous trial. Along those lines, participants were instructed to abstain from vigorous exercise and physical activity for at

least 24 hours prior to a scheduled trial. The degree of compliance with this directive is unknown and remains a potential confounding factor.

The second concern with multiple trials performed in close proximity to one another is the potential for a training effect and/or heat acclimatization. The participants in this study were subjected to long periods of time performing exercise in a hot environment. The experimental portion of this study took place during the end of spring and beginning of summer in what can be considered a mid-latitude city (i.e., ~45° latitude) which meant it was unlikely that participants had already been heat acclimatized to any significant degree. Those participants that had a combination of short intervals between trials and were randomly assigned to more than one “hot” trial during that time were more likely to have undergone some degree of heat acclimatization. The timeline of heat acclimatization differs depending on the variable. Heart rate (decrease), rectal temperature (decrease), and sweat rate (increase) adaptations are 95% complete after 3-6, 5-8, and 8-14 days, respectively (Armstrong, 2000). It is possible that some physiological variables could have changed over time due to heat acclimatization but the magnitude of these changes likely did not systematically change the results of this study due to the fact that numerous consecutive days of exercise in the heat is required for significant changes to occur. Of additional concern is the issue of a training effect. It is conceivable that certain parameters changed over the course of the 10 trials due to a training effect. Since all participants were physically fit, it is unlikely that any major training effect occurred for what was light to moderate exercise (for most). However, the possibility does exist that a training effect did occur for some participants over the course of the 10 trials due to the

fact that there was no familiarization period (a common practice in exercise studies to minimize training effects) prior to the study. Additionally, if walking was not a common activity for a participant, it is possible that there was a training effect. If a training effect occurred, it would most likely have affected cardiovascular and metabolic parameters as these systems can exhibit rapid adaptation (e.g., a decrease in exercise heart rate can occur in a matter of days).

Finally, garment sizing was an issue with some participants. As only one size of each garment was available, great pains were taken to select participants that would properly fit into the garments. However, a perfect fit was not always achieved. This was most notable in the two female participants for which the garment did not always have a tight fit in all body regions, particularly in the torso. This problem was addressed by fastening an elastic belt around the torso in order to maximize garment contact with the skin. Having a properly fitted garment (properly fitted to all body regions) is crucial to maximizing tubing contact with the body and being able to fully exploit the heat transfer capabilities of the garment; this issue has been noted as one of the challenges that needs to be addressed in future LCG design (Flouris & Cheung, 2006). The opposite problem occurred with some of the larger participants in that the garment was quite tight in some instances. While this most likely did not affect heat transfer, it could have had negative ergonomic and biomechanical consequences. It is therefore recommended that each garment used in spaceflight be specifically tailored to the individual that will be wearing the garment.

Garment Evaluation

MACS-Delphi

The MACS-Delphi is characterized by an exceptionally low water flow rate. This rate is seven to eight times lower than the LCVG and Orlan. This low flow rate is presumably compensated for by the strategic orientation of tubing over high-density tissue (i.e., bone) and, thus, core temperature is maintained at levels similar to those of the LCVG and Orlan. It is possible that replacing the current tubing with tubing of a greater diameter may enhance the effectiveness of the garment. The fact that local sweat rates in the upper back were higher with the MACS-Delphi (compared to both the Orlan and LCVG) indicate that higher flow rates may be necessary for adequate heat extraction in large areas of high-density tissue that serve as significant heat sinks. On the other hand, a systematic analysis of skin temperatures across both temperature regimes and all seven experimental stages revealed less fluctuation and greater stability of skin temperatures with the MACS-Delphi which may offer benefits in terms of subjective thermal comfort. The spandex polyester material that makes up the MACS-Delphi allows for free movement and less restriction than the other two garments evaluated. The hood option makes the MACS-Delphi adaptable to different thermal conditions and/or personal preferences. Of the three garments evaluated, the MACS-Delphi had the greatest number of mechanical problems illustrated by occasional water leaks at manifold joints and tubing connections during testing. An equipment failure like this within an EMU during an EVA could have serious repercussions. However, the source of this sort of malfunction is easily identifiable and the design flaw can readily be fixed prior to use during spaceflight.

Orlan

The Orlan had the greatest water flow rate of the three garments as a result of the large-diameter tubing. This may seem like an advantage but it might represent a case of the garment being *too* effective at removing heat which can lead to the perception of thermal discomfort and elicitation of the vasoconstrictor response, thus attenuating heat transfer from the core to the periphery. The tubing arrangement in the back is of a vertical design which has deleterious ergonomic consequences highlighted by a hindrance in forward flexion of the spine (see Figure C1). The Orlan, when filled with water, is the heaviest (2.45 kg) of the three garments evaluated which may or may not have negative consequences in a microgravity environment. Of the three garments, the Orlan exhibited the greatest wear-and-tear, particularly in the groin region (see Figure C2). The tubing of the Orlan is intertwined into a thick textile mesh that can damage the skin as a result of chronic rubbing of polymer fibers (see Figure C3) and did so in the cases of two different participants during testing. A bacterial infection (e.g., staph infection) caused by a skin abrasion can have potentially disastrous consequences during spaceflight in which medical treatment is rudimentary and the chances of spreading a contagious agent are markedly increased. The hood, while seen as a beneficial option, is limited by the fact that the tubing only covers the crown of the head which may limit its effectiveness.

LCVG

The LCVG has no vertical expansion during forward and backward inclination which illustrates a potential impediment to optimal biomechanics and free movement. The LCVG had the most extensive tubing network in terms of length, but the arrangement

seems random with the designers perhaps opting for quantity of coverage over quality of coverage. However, it seems likely that it was this emphasis on quantity of coverage that led to the current findings that the LCVG was superior to the MACS-Delphi and Orlan in terms of reducing whole body fluid loss via a decreased sweating response. The high flow rate of the LCVG has the same potential negative consequences as the Orlan related to a cooling rate that decreases thermal comfort and potentially triggers a vasoconstrictor response. This was most obvious when going from an exercise condition to a rest condition for both the LCVG and Orlan. It is difficult to ascertain exactly what the independent and combined effects of a high flow rate and expansive tubing are with regard to thermal comfort and temperature regulation. It may represent a double-edged sword in that the extensive tubing network and high flow rate that serve to attenuate whole body and local sweating rates (particularly in the lower extremity) might also promote a reduction in skin temperatures (also evidenced in the lower extremity) beyond the thresholds of thermal comfort and critical temperature required to elicit a vasoconstrictive reflex. This is an interesting dilemma and one that requires further investigation. The LCVG was unique among the three garments studied in that it had a double layer of textile that was designed to serve the purpose of absorbing sweat. Participants reported that this was not effective and that this lack of a wicking ability caused negative subjective perceptions, most notably that of a feeling like “swimming in sweat.” Additionally, it was noted by investigators that donning and doffing the LCVG was made more difficult due to the second layer of material.

Practical Applications

The use of LCGs is not a new practice with regard to spaceflight and, in fact, LCGs have been utilized during spaceflight for almost as long as humans have been traveling to space. The need for such a thermal countermeasure may not be obvious to those outside of the space community but a cursory examination of the threats to heat balance during spaceflight (with specific emphasis on EVA) reveals a potentially deadly situation in the absence of thermal regulation beyond that which humans innately possess (i.e., physiologic thermoregulation). However, the implications of maintaining thermal balance and comfort transcend that of the relatively unique and small group of space traveling humans. The results of the current study have applications to the occupational, athletic, and medical settings including worker comfort and safety, athlete performance and recovery, and patient health and rehabilitation, respectively.

Future Research

Future research is needed to answer many of the questions that still exist regarding the optimization of LCG design (see Figure 1.1) nearly 50 years after the prototype LCG was created. A major topic of future research should focus on spatial configuration of the tubing network. The results of the present study indicate that selective placement of tubing over high-density tissues may be an efficient means by which to extract heat from the body. Advanced imaging technologies like infrared thermography should be employed to identify the regions with the highest heat content and used in conjunction with other factors (e.g., local sweat rate, local vascular supply, etc.) to determine the most effective tubing placement for efficient heat removal.

The investigation of supplemental cooling strategies like a cooling hood and ventilation system also seems like a logical next step. Certainly, the unique vascular properties in the blood vessels of the head, combined with the significant amount of high-density tissue and heat flow to the region, provide a potentially significant means by which to extract heat. Incorporating a ventilation system within a LCG is not a new idea but it has yet to be explored with many of the current LCG designs.

The relationship between temperature and comfort is not well-understood. Increased temperature is commonly associated with the perception that work is harder (Maw, Boutcher, & Taylor, 1993) but there are a wide variety of responses in terms of subjective perception to a given thermal stimulus indicating that more research is needed to better understand the psychophysiological mechanisms regulating human comfort. Along those same lines, the issue of whether to automatically or manually regulate temperature and/or flow through a LCG is complicated by the fact that no physiological metric has been identified that accurately and consistently reflects overall body temperature (necessary for automatic regulation) in addition to the common observation that humans are not always the best judge of their thermal status (necessary for manual regulation).

Finally, it would seem that valuable data could be obtained from pilot studies (or case studies) of garment performance during actual EVA. This sort of data collection has probably already taken place (perhaps not on a large scale) and, if such information exists, it should be pooled together for systematic analysis by engineers, physiologists, psychologists, ergonomists, and apparel designers.

CHAPTER 6 - CONCLUSION

Cooling garments that use water as the facilitator of heat transfer have been in existence for several decades. Two of the garments examined in this study (LCVG and Orlan) are currently being used by astronauts in outer space for the purposes of maintaining thermal comfort and temperature regulation. Clearly, the underlying principles of water-cooled garments are sound and have been demonstrated to be effective at achieving the stated thermal regulation goals. It would seem that, in the interest of both efficiency and safety, the next logical step in the evolution of cooling garments should be in the direction of determining such critical parameters as optimal water temperature, flow rate, and tubing arrangement. This study did not address the issue of water temperature so no conclusions can be made with regard to that topic. However, it can be gleaned from the results of this study that a low flow rate (e.g., MACS-Delphi) can be as effective at maintaining core temperature in the context of an increasing heat load as higher flow rates (e.g., Orlan and LCVG). A lower flow rate also offers the potential benefit of greater thermal comfort due to a less harsh cooling regime and a decreased likelihood of eliciting a vasoconstrictor reflex. Further research into the optimal tubing arrangement seems warranted due to the obvious efficiency-related benefits of less tubing, less water, and less weight as well as the physiological and psychological benefits of determining the optimal means by which to regulate core temperature (for safety) and skin temperature (for comfort).

While each of the three garments evaluated was able to regulate core temperature such that thermal comfort and elevated energy expenditures could be sustained for a prolonged period in thermoneutral and hot environments, the cooling ability of the garments fell

short of the goal of maintaining core temperature at or below 37.2 °C (a major goal of NASA). The results of this study indicate that additional means of cooling may need to be incorporated within the extravehicular mobility unit (EMU) if serious consideration is to be given to future missions involving planetary EVA. A cooling hood and air ventilation system are two such countermeasures that could augment heat transfer in the context of an increased heat load. The results of this study do not support the notion of incorporating a cooling hood but caution must be used when interpreting these results. First of all, the fact that all of the study participants had hair (some with long, thick hair) could confound the results due to the obvious insulating effect of hair and concomitant decrease in conductive heat transfer. Secondly, the lack of a significant cold-induced vasoconstrictor response of the head vasculature suggests that cold or very cold water could be circulated through the hood portion of a LCG which would increase the thermal gradient between the skin and water/tubing, thus increasing heat extraction capability. Although the topic of gas ventilation was not explored in this study, the benefits of added heat transfer due to evaporative and convective heat exchange mechanisms could have a synergistic effect (in terms of thermal comfort and temperature regulation) when combined with the conductive exchange of heat that is characteristic of LCGs. A primary recommendation is to repeat the current study, but on a larger scale, so as to confirm or refute the present findings as well as to enable researchers to draw out the more subtle aspects that may have been masked by a small sample size and, hence, reduced statistical power. One such illusive question deals with understanding conductive and convective mass heat flow through a [human] body that is not uniform in material properties, composition, or density making first-principles thermodynamic analysis problematic.

Each garment evaluated has certain advantages which need to be exploited as space programs plan for longer-duration missions involving EVA on planetary surfaces like those of the Moon and Mars. Temperature regulation and thermal comfort are two obvious areas of critical importance upon which this study was heavily focused. However, concerns related to human factors and ergonomics have been raised by the findings in this study as they relate to skin abrasion from chronic rubbing of certain areas, restriction of movement that negatively influences biomechanical profiles, and overall fit and durability of the garments. Ergonomic efficiency of cooling garments should be a major area of further study owing to the fact that these garments represent the first of many layers that must be donned by astronauts culminating in the EMU. It is logical to assume that a less-than-optimal biomechanical/ergonomic profile created by the first layer will only be compounded by the requisite donning of additional protective equipment.

Future research should focus on the above recommendations as well as exploring new and novel technologies and strategies for maximizing physiologic/thermal regulation and minimizing inefficiency in the interest of human health, safety, and comfort. It is not a matter of *if* humans will return to the Moon or walk on Mars, it is a matter of *when*. The protection of astronauts working in the harshest of environmental conditions so far away from *terra firma* requires that they be outfitted with nothing less than the best equipment, substantiated by empirical research performed by a multidisciplinary team (i.e., physiologists, engineers, apparel designers, psychologists, ergonomists, etc.). This can only be achieved by more trial-and-error research and out-of-the-box thinking similar to that which freed humans from their earthly bonds a generation ago.

REFERENCES

- Abramov, I. P., & Skoog, I. A. (2003). *Russian spacesuits*. London, England: Springer.
- Armstrong, L. E. (2000). *Performing in extreme environments*. Champaign, IL: Human Kinetics.
- Astrand, P.-O., Rodahl, K., Dahl, H.A., & Stromme, S.B. (2003). *Textbook of work physiology*. Champaign, IL: Human Kinetics.
- Astrand, P.-O., Ekblom, B., Messin, R., Saltin, B., & Stenberg, J. (1965). Intra-arterial blood pressure during exercise with different muscle groups. *Journal of Applied Physiology*, 20(2), 253-256.
- Billingham, J. (1959). Heat exchange between man and his environment on the surface of the moon. *Journal of the British Interplanetary Society*, 17, 297-300.
- Blagden, C. (1775). Experiments and observations in a heated room. *Philosophical Transactions of the Royal Society of London*, 65, 111-123.
- Blair, D. A., Glover, W. E., & Roddie, I. C. (1961). Cutaneous vasomotor nerves to the head and trunk. *Journal of Applied Physiology*, 16(1), 119-122.
- Booth, J., Wilsmore, B. R., Macdonald, A. D., Zeyl, A., Storlien, L. H., & Taylor, N. A. S. (2001). Whole-body pre-cooling does not alter human muscle metabolism during sub-maximal exercise in the heat. *European Journal of Applied Physiology*, 84, 587-590.
- Borg, G. A. (1982). Psychological bases of perceived exertion. *Medicine and Science in Sports and Exercise*, 14, 377-381.

- Brooks, G. A., Fahey, T. D., & Baldwin, K. M. (2005). *Exercise physiology: Human bioenergetics and its applications* (4th ed.). Boston, MA: McGraw Hill.
- Bruce, R. A. (1971). Exercise testing of patients with coronary heart disease. *Annals of Clinical Research*, 3, 323-332.
- Buckey, J. C. (2006). *Space physiology*. New York, NY: Oxford University Press.
- Burton, D. R., & Collier, L. (1964). *The development of water conditioned suits*. Technical note ME-400, Royal Aircraft Establishment, Farnborough.
- Cadarette, B. S., DeCristofano, M. S., Speckman, K. L., & Sawka, M. N. (1990). Evaluation of three commercial microclimate cooling systems. *Aviation, Space, and Environmental Medicine*, 61, 71-76.
- Carr, C. E., & Newman, D. J. (2007a). Space suit bioenergetics: Cost of transport during walking and running. *Aviation, Space, and Environmental Medicine*, 78(12), 1093-1102.
- Carr, C. E., & Newman, D. J. (2007b). Space suit bioenergetics: Framework and analysis of unsuited and suited activity. *Aviation, Space, and Environmental Medicine*, 78(11), 1013-1022.
- Casa, D. J., McDermott, B. P., Lee, E. C., Yeargin, S. W., Armstrong, L. E., & Maresh, C. M. (2007). Cold water immersion: The gold standard for exertional heatstroke treatment. *Exercise and Sports Sciences Reviews*, 35(3), 141-149.
- Cheung, S. S. (2010). *Advanced environmental exercise physiology*. Champaign, IL: Human Kinetics.

- Cheung, S. S., & Robinson, A. M. (2004). The influence of upper-body pre-cooling on repeated sprint performance in moderate ambient temperatures. *Journal of Sport Sciences*, 22, 605-612.
- Cheuvront, S. N., Kolka, M., Cadarette, B. S., Montain, S. J., & Sawka, M. N. (2003). Efficacy of intermittent, regional microclimate cooling. *Journal of Applied Physiology*, 94, 1841-1848.
- Cintala, M. J. (2005, November). *Science on the moon: EVA considerations*. Overview paper presented at the Exploration EVA Conference, Houston, TX.
- Coca, A. (2005). *Control and prediction of body thermal status through the dynamic of finger heat flux/temperature* (Doctoral dissertation, University of Minnesota).
- Cotter, J. D., Patterson, M. J., & Taylor, N. A. S. (1995). The topography of eccrine sweating in humans during exercise. *European Journal of Applied Physiology*, 71, 549-554.
- Cowell, S. A., Stocks, J. M., Evan, D. G., Simonson, S. R., & Greenleaf, J. E. (2002). The exercise and environmental physiology of extravehicular activity. *Aviation, Space, and Environmental Medicine*, 73(1), 54-67.
- Flouris, A. D., & Cheung, S. S. (2006). Design and control optimization of microclimate liquid cooling systems underneath protective clothing. *Annals of Biomedical Engineering*, 34(3), 359-372.
- Fortney, S. M., Mikhaylov, V., Lee, S. M. C., Kobzev, Y., Gonzalez, R. R., & Greenleaf, J. E. (1998). Body temperature and thermoregulation during submaximal exercise after 115-day spaceflight. *Aviation, Space, and Environmental Medicine*, 69(1), 1-5.

- Fregly, M. J., & Blatteis, C. M. (1996). *Environmental physiology*. New York, NY: Oxford University Press.
- Froese, G., & Burton, A. C. (1957). Heat losses from the human head. *Journal of Applied Physiology*, 10(2), 235-241.
- Furtado, A. L., Craig, B. N., Chard, J. T., Zaloom, V. A., & Chu, H.-W. (2007). Cooling suits, physiological response, and task performance in hot environments for the power industry. *International Journal of Occupational Safety and Ergonomics*, 13(3), 227-239.
- Gagnon, D., Jay, O., Lemire, B., & Kenny, G. P. (2008). Sex-related differences in evaporative heat loss: The importance of metabolic heat production. *European Journal of Applied Physiology*, 104, 821-829.
- Gagnon, D., Dorman, L. E., Ollie, J., Hardcastle, S., & Kenny, G. P. (2009). Core temperature differences between males and females during intermittent exercise: Physical considerations. *European Journal of Applied Physiology*, 105, 453-461.
- Gagnon, D., Lemire, B., Jay, O., & Kenny, G. P. (2010). Aural canal, esophageal, and rectal temperatures during exertional heat stress and the subsequent recovery period. *Journal of Athletic Training*, 45(2), 157-163.
- Greenleaf, J. E. (1989). Energy and thermal regulation during bed rest and spaceflight. *Journal of Applied Physiology*, 67(2), 507-516.
- Hardy, J. D., & DuBois, E. F. (1938). The technique of measuring radiation and convection. *Journal of Nutrition*, 15, 461-475.

- Harm, D. L., Jennings, R. T., Meck, J. V., Powell, M. R., Putcha, L., Sams, C. P., et al. (2001). Invited review: Gender issues related to spaceflight: A NASA perspective. *Journal of Applied Physiology*, *91*, 2374-2383.
- Havenith, G., Fogarty, A., Bartlett, R., Smith, C. J., & Ventenat, V. (2008). Male and female upper body sweat distribution during running measured with technical absorbents. *European Journal of Applied Physiology*, *104*, 245-255.
- Havenith, G., Yoshimitsu, I., Luttikholt, V., & Kenney, W. L. (1995). Age predicts cardiovascular, but not thermoregulatory, responses to humid heat stress. *European Journal of Applied Physiology*, *70*, 88-96.
- Hertzman, A. B., & Roth, L. W. (1942). The absence of vasoconstrictor reflexes in the forehead circulation. *American Journal of Physiology*, *136*, 692-697.
- Jackson, A., Pollock, M., & Ward, A. (1978). Generalized equations for predicting body density of men. *British Journal of Nutrition*, *40*, 497-504.
- Jackson, A., Pollock, M., & Ward, A. (1980). Generalized equations for predicting body density of women. *Medicine and Science in Sports and Exercise*, *16*, 606-613.
- Jay, O., Reardon, F. D., Webb, P., Ducharme, M. B., Ramsay, T., Nettlefold, L., et al. (2007). Estimating changes in mean body temperature for humans during exercise using core and skin temperatures is inaccurate even with a correction factor. *Journal of Applied Physiology*, *103*, 443-451.
- Jay, O., Gariepy, L.M., Reardon, F. D., Webb, P., Ducharme, M. B., Ramsay, T., et al. (2007). A three-compartment thermometry model for the improved estimation of changes in body heat content. *American Journal of Physiology - Regulatory, Integrative and Comparative Physiology*, *292*, R167-R175.

- Kenny, G. P., Gagnon, D., Dorman, L. E., Hardcastle, S., & Jay, O. (2010). Heat balance and cumulative heat storage during exercise performed in the heat in physically active younger and middle-aged men. *European Journal of Applied Physiology*, 109, 81-92.
- Koscheyev, V. S., Coca, A., & Leon, G. R. (2007). Overview of physiological principles to support thermal balance and comfort of astronauts in open space and on planetary surfaces. *Acta Astronautica*, 60, 479-487.
- Koscheyev, V. S., Coca, A., Leon, G. R., & Dancisak, M. J. (2002). Individual thermal profiles as a basis for comfort improvement in space and other environments. *Aviation, Space, and Environmental Medicine*, 73(12), 1195-1202.
- Koscheyev, V. S., Leon, G. R., Coca, A., & List, N. (2004). Enhancing circulation to lower limbs during head-down tilt by warming upper body and thighs. *Aviation, Space, and Environmental Medicine*, 75(7), 596-602.
- Lee, J.-Y., Wakabayashi, H., Wijayanto, T., & Tochihara, Y. (2010). Differences in rectal temperatures measured at depths of 4-19 cm from the anal sphincter during exercise and rest. *European Journal of Applied Physiology*, 109, 73-80.
- Lemire, B., Gagnon, D., Jay, O., Dorman, L. E., Ducharme, M. B., & Kenny, G. P. (2008). Influence of adiposity on cooling efficiency in hyperthermic individuals. *European Journal of Applied Physiology*, 104, 67-74.
- Lopez, R. M., Cleary, M. A., Jones, L. C., & Zuri, R. E. (2008). Thermoregulatory influence of a cooling vest on hyperthermic athletes. *Journal of Athletic Training*, 43(1), 55-61.

- Machado-Moreira, C. A., Smith, F. M., Van Den Heuvel, A. M. J., Mekjavic, I. B., & Taylor, N. A. S. (2008). Sweat secretion from the torso during passively-induced and exercise-related hyperthermia. *European Journal of Applied Physiology*, 104, 265-270.
- Maud, P. J., & Foster, C. (2006). *Physiological assessment of human fitness* (2nd ed.). Champaign, IL: Human Kinetics.
- Maw, G. J., Boutcher, S. H., & Taylor, N. A. S. (1993). Ratings of perceived exertion and affect in hot and cool environments. *European Journal of Applied Physiology*, 67, 174-179.
- McArdle, W. D., Katch, F. I., & Katch, V. L. (2010). *Exercise physiology: Nutrition, energy, and human performance* (7th ed.). Philadelphia, PA: Lippincott Williams and Wilkins.
- McDermott, B. P., Casa, D. J., Ganio, M. S., Lopez, R. M., Yeargin, S. W., Armstrong, L. E., et al. (2009). Acute whole-body cooling for exercise-induced hyperthermia: A systematic review. *Journal of Athletic Training*, 44(1), 84-93.
- Meyer-Heim, A., Rothmaier, M., Weder, M., Kool, J., Schenk, P., & Kesselring, J. (2007). Advanced lightweight cooling-garment technology: Functional improvements in thermosensitive patients with multiple sclerosis. *Multiple Sclerosis*, 13, 232-237.
- Miles, D. S., Cox, M. H., & Bomze, J. P. (1989). Cardiovascular responses to upper body exercise in normals and cardiac patients. *Medicine and Science in Sports and Exercise*, 21(5), S126-S131.

- Mitchell, D., & Wyndham, C. H. (1969). Comparison of weighting formulas for calculating mean skin temperature. *Journal of Applied Physiology*, 26(5), 616-622.
- Nadel, E. R., Bergh, U., & Saltin, B. (1972). Body temperatures during negative work exercise. *Journal of Applied Physiology*, 33, 553-558.
- Nadel, E. R., Holmer, I., Bergh, U., Astrand, P.-O., & Stolwijk, J. A. (1974). Energy exchanges of swimming man. *Journal of Applied Physiology*, 36, 465-471.
- Nadel, E. R., Mitchell, J. W., & Stolwijk, J. A. (1973). Differential thermal sensitivity in the human skin. *Pflugers Archives*. 340, 71-76.
- Nunneley, S. A. (1970). Water cooled garments: A review. *Space Life Sciences*, 2, 335-360.
- Nyberg, K. L., Diller, K. R., & Wissler, E. H. (2000). Automatic control of thermal neutrality for space suit applications using a liquid cooling garment. *Aviation, Space, and Environmental Medicine*, 71(9), 904-913.
- Pandolf, K. B., Sawka, M. N., & Gonzalez, R. R. (2001). *Human performance physiology and environmental medicine at terrestrial extremes*. Traverse City, MI: Cooper Publishing Group.
- Pendergast, D. R. (1989). Cardiovascular, respiratory, and metabolic responses to upper body exercise. *Medicine and Science in Sports and Exercise*, 21(5), S121-S125.
- Perhonen, M. A., Franco, F., Lane, L. D., Buckey, J. C., Blomqvist, C. G., Zerwekh, J. E., et al. (2001). Cardiac atrophy after bed rest and spaceflight. *Journal of Applied Physiology*, 91, 645-653.

- Pisacane, V. L., Kuznetz, L. H., Logan, J. S., Clark, J. B., & Wissler, E. H. (2007). Thermoregulatory models of space shuttle and space station activities. *Aviation, Space, and Environmental Medicine*, 78(4), A48-A55.
- Portree, D. S. F., & Trevino, R. C. (1997). *Walking to Olympus: An EVA chronology*. Monographs in Aerospace History Series #7. Washington D.C.: NASA Headquarters.
- Proulx, C. I., Ducharme, M. B., & Kenny, G. P. (2003). Effect of water temperature on cooling efficiency during hyperthermia in humans. *Journal of Applied Physiology*, 94, 1317-1323.
- Proulx, C. I., Ducharme, M. B., & Kenny, G. P. (2006). Safe cooling limits from exercise-induced hyperthermia. *European Journal of Applied Physiology*, 96, 434-445.
- Ramanathan, N. L. (1964). A new weighting system for mean surface temperature of the human body. *Journal of Applied Physiology*, 19, 531-533.
- Rasch, W., Samson, P., Cote, J., & Cabanac, M. (1991). Heat loss from the human head during exercise. *Journal of Applied Physiology*, 71(2), 590-595.
- Rhoades, R. A., & Tanner, G. A. (2003). *Medical physiology* (2nd ed.). Philadelphia, PA: Lippincott Williams and Wilkins.
- Roberts, W. O. (2006). Exertional heat stroke during a cool weather marathon: A case study. *Medicine and Science in Sports and Exercise*, 38(7), 1197-1203.
- Rowell, L. B. (1993). *Human cardiovascular control*. New York, NY: Oxford University Press.

- Rowell, L. B., & Shepherd, J. T. (1996). *Exercise: Regulation and integration of multiple systems*. New York, NY: Oxford University Press.
- Sawka, M. N., & Castellani, J. W. (2007). How hot is the human body? *Journal of Applied Physiology*, 103, 419-420.
- Sawka, M. N., Latzka, W. A., & Pandolf, K. B. (1989). Temperature regulation during upper body exercise: Able-bodied and spinal cord injured. *Medicine and Science in Sports and Exercise*, 21(5), S132-S140.
- Shiraki, K., & Yousef, M. K. (1987). *Man in a stressful environment: Thermal and work physiology*. Springfield, IL: C.C. Thomas.
- Simmons, S. E., Mundel, T., & Jones, D. A. (2008). The effects of passive heating and head-cooling on perception of exercise in the heat. *European Journal of Applied Physiology*, 104, 281-288.
- Siri, W. (1961). Body composition from fluid spaces and density: Analysis of methods. In J. Brozek & A. Henschel (Eds.), *Techniques for measuring body composition* (pp. 223-244). Washington D.C.: National Academy of Science.
- Smith, S. M., & Heer, M. (2002). Calcium and bone metabolism during spaceflight. *Nutrition*, 18, 849-852.
- Snellen, J. W. (2000). An improved estimation of mean body temperature using combined direct calorimetry and thermometry. *European Journal of Applied Physiology*, 82, 188-196.
- Taylor, N. A. S. (2006). Challenges to temperature regulation when working in hot environments. *Industrial Health*, 44, 331-344.

- Taylor, N. A. S., Caldwell, J. N., Van Den Heuvel, A. M. J., & Patterson, M. J. (2008). To cool, but not too cool: That is the question - immersion cooling for hyperthermia. *Medicine and Science in Sports and Exercise*, 40(11), 1962-1969.
- Taylor, N. A. S., Casa, D. J., & Kenny, G. P. (2010). Immersion treatment for exertional hyperthermia: Cold or temperate water? *Medicine and Science in Sports and Exercise*, 42(7), 1246-1252.
- Thompson, W. R. (2010). *ACSM's guidelines for exercise testing and prescription* (8th ed.). Philadelphia, PA: Lippincott Williams and Wilkins.
- Waligora, J. M., & Kumar, K. V. (1995). Energy utilization rates during shuttle extravehicular activities. *Acta Astronautica*, 36(8-12), 595-599.
- Webb, P. (1998). *Heat storage during exercise, especially in muscle*. Paper presented at the 8th International Conference on Environmental Ergonomics, San Diego, CA.
- Webb, P., Troutman, S. J., & Annis, J. F. (1970). Automatic cooling in water cooled space suits. *Aerospace Medicine*, 41, 269-277.
- Wilson, T. E., Johnson, S. C., Petajan, J. H., Davis, S. L., Gappmaier, E., Luetkemeier, M. J., et al. (2002). Thermal regulatory responses to submaximal cycling following lower-body cooling in humans. *European Journal of Applied Physiology*, 88, 67-75.
- Winslow, C. E. A., Herrington, L. P., & Gagge, A. P. (1936). A new method of partitioned calorimetry. *American Journal of Physiology* 116, 641-655.
- World Health Organization. (1995). *Global strategy on occupational health for all: The way to health at work*. Geneva, Switzerland: World Health Organization.

APPENDIX A

Recruitment Ad

Comparison of Three Cooling Garments Developed for Space Activities

Subjects between the ages of 25-45 are needed for a research study at the University of Minnesota comparing three different liquid cooling garments developed for extravehicular activity during space missions. The total time commitment for the study is 6 experimental sessions approximately 10 days apart lasting approximately 2 ½ hours. Subject payment is \$25 for each session and a bonus of \$150 for completing all 6 sessions, for a possible total payment of \$300. For further information, please contact Dr. Victor Koscheyev at 625-8827 or send an e-mail to extreme@umn.edu.

Figure A1. Recruitment advertisement for solicitation of study participants.

February 25, 2008

CONSENT FORM

TEST AND EVALUATION OF LIQUID COOLING GARMENTS

You are invited to participate in a study comparing five different liquid cooling garments developed for extravehicular activity during space missions. You were selected as a possible participant in this study because you volunteered to come for an evaluation as a result of speaking with one of the investigators or responding to notices placed on bulletin boards at the University or in the *Minnesota Daily* newspaper. You have also been selected for consideration because you are between the ages of 25 and 45, in excellent physical condition, and not taking any type of medication other than birth control pills for females. We ask that you read this form and ask any questions you may have before agreeing to be in the study.

This study is being conducted by Victor S. Koscheyev, MD, PhD, ScD, research physiologist, Department of Integrative Biology and Physiology, University of Minnesota (principal investigator), and Gloria R. Leon, PhD, psychologist, Department of Psychology, University of Minnesota (co-principle investigator).

Potential Conflict of Interest

Dr. Koscheyev and Dr. Leon are co-inventors, along with the University of Minnesota, on a patent awarded for one of the garments studied in this investigation (the MACS-Delphi). Dr. Koscheyev and Dr. Leon also have a financial and business relationship with Trans-Ocean Technology and Business, Inc.(TOTBI). This arrangement has been disclosed and managed through the University of Minnesota conflict review process.

Study Purpose

The purpose of this investigation is to compare the physiological functioning and comfort perception of subjects in different liquid cooling garments (developed for current space purposes) while subjects are engaged in physical exertion levels comparable to what might be encountered during space activities. The optimal features of each of the garments will be identified to provide information helpful for future designs.

Study Procedures

If you agree to participate we will ask you to do the following: undergo an initial screening session consisting of a brief health examination (including health/medical history), measurement of height, weight, resting heart rate, resting blood pressure, resting electrocardiogram (12-lead ECG), skinfold thickness, and a graded exercise test on a treadmill. If you are selected for the study we will measure your internal and skin surface temperatures in experimental sessions lasting approximately 3 hours. Each session consists of seven 20-minute stages; you will be exercising for five of the stages and resting in the other two. During Stages 1-3 you will be exercising at a level consistent with brisk walking or slow running, with a 2 minute standing rest interval between Stages 1 and 2. Stage 4 consists of a 20-minute seated rest period. Stages 5 and

Figure A2. Informed consent document (page 1 of 4).

6 are exercise stages consisting of walking and/or running, with a 2 minute rest interval after Stage 5. Stage 7 is a 20-minute seated rest period. Each exercise stage is defined by different levels of physical exertion or "intensity" levels. The lowest intensity level can be expected to be walking at approximately 1.5-2.0 miles per hour with no inclination (equal to an energy expenditure of about 3.5 calories per minute). The highest intensity level could require that you run at speeds up to 6-7 miles per hour (i.e. a mile pace of ~8.5 to 10 minutes) with no inclination or walking 3-4 miles per hour up an inclination of 5-15% grade (equal to an energy expenditure of about 10 calories per minute). There will be no consumption of food during the testing session. During each session you will wear one of the five cooling garments through which cool water will circulate. At baseline the water temperature in the garment will be at a comfortable level (33°C/91°F). Water temperature circulating through the tubing of the garment will then be lowered to 15°C/59°F for the duration of the session to maintain your comfort under the different levels of exercise. Body surface temperature measurements will be made by means of sensors taped to your skin. Sensors will be placed to make contact with 9 sites on the skin surface (forehead, earlobe, neck, chest, forearm, hand/finger, foot, calf, and thigh). A specially designed finger sensor ring will be placed on the third fingertip of each hand. Male subjects will also have a skin sensor placed underneath/behind the scrotum. Rectal temperature will be monitored by a sensor/probe that you will be shown how to insert by yourself. Ear temperature will be monitored by placing a sensor in the ear.

Temperature (skin and core) and heart rate will be measured continuously. Oxygen consumption will also be measured continuously by a mask you will wear covering your nose and mouth. Perception of heat and cold sensations and physical comfort level, evaporative sweat rate, and blood pressure will be measured at the end of each stage of the session. Evaporative sweat rate will be measured by briefly placing a small flat monitor on your forehead, wrist/hand, and ankle. Sweat rate will also be measured by taping small absorbent papers on the upper back, chest, and upper thigh regions.

You will wear one of five cooling garments at each session. Five sessions will be conducted with the temperature/humidity conditions in the environmental chamber at 21-24°C (70-75°F), humidity, 40-65%. Five sessions will be conducted with chamber conditions at 32-35°C (90-95°F), humidity 20-45%. The sessions will be spaced approximately 7 days apart.

Risks of Study Participation

Potential risks from your participation in this study are minimal but include the following:

1. Abnormal changes in blood pressure, heart rate, heart rhythm, or the sensation of dizziness while doing the graded exercise stress test or the experimental treadmill exercise. Very rare instances of heart attack have occurred in these and other forms of moderate to strenuous exercise activities. Every effort will be made to minimize possible problems by the preliminary health evaluation and constant surveillance during testing. The stress testing and/or the experimental session will be terminated if you desire to stop or if the trained personnel administering the testing deem it necessary in the interest of your health and safety. Equipment and trained personnel are available to deal with unusual situations should they arise.

Figure A3. Informed consent document (page 2 of 4).

2. Although extremely rare (less than 1 per 10,000 exercise tests with middle-aged people), there is a risk of death from a heart attack from a previously unknown heart condition.
3. Feelings of discomfort due to the chilling of the water circulating through the garment tubing system.
4. Discomfort in using the rectal probe.
5. Skin irritation caused by electrodes placed on the skin or the connective wires.
6. Fatigue during the treadmill run.

Benefits of Study Participation

This research does not provide any direct benefit to the subject.

Study Costs/Compensation

If you are selected for this study and agree to participate, you will receive \$25 for each of the 10 experimental sessions. If you decide to stop the session for any reason, you will still be paid the full \$25. If you complete all 10 sessions, you will be paid a bonus of \$250, for a possible total of \$500.

Research-Related Injury

In the event that this research activity results in an injury, treatment will be available, including first aid, emergency treatment, and follow-up care as needed. Care for such injuries will be billed in the ordinary manner to you or your insurance company. If you think that you have suffered a research-related injury let the study investigators know right away.

Confidentiality

The records of this study will be kept private. Any information obtained in connection with this study that can be identified with you will remain confidential and will be disclosed only with your permission. In any written reports or publications, no one will be identified or identifiable by name. Only the investigators and NASA personnel will have access to the information collected.

Voluntary Nature of the Study

Your signature at the bottom of the next page indicates that you have decided to participate in this study and that you have read and understand the information in this consent form. Your decision not to participate in this study will not affect your present or future relations with the investigators or the University of Minnesota. If you decide to participate, you are free to withdraw consent and discontinue participation at any time without affecting this relationship.

Figure A4. Informed consent document (page 3 of 4).

Contacts and Questions

The researchers conducting this study are Dr. Victor Koscheyev and Dr. Gloria Leon. You may ask questions you have now or, if you have questions later, **you are encouraged to** contact Dr. Koscheyev at (612) 625-8827 or Dr. Leon at (612) 625-9324. If you have any questions or concerns regarding the study and would like to talk to someone other than the researchers, **you are encouraged to** contact the Fairview Research Helpline at telephone number (612) 672-7692 or toll free at 866-508-6961. You may also contact this office in writing or in person at Fairview University Medical Center – Riverside Campus, #815 Professional Building, 2450 Riverside Avenue, Minneapolis, MN 55454.

You will be given a copy of this form to keep for your records.

Statement of Consent

I have read the above information. I have asked questions and have received answers. I consent to participate in the study.

Printed Name of Subject _____

Date _____

Signature of Subject _____

Date _____

Printed Name of Investigator _____

Date _____

Signature of Investigator _____

Date _____

Figure A5. Informed consent document (page 4 of 4).

AHA/ACSM Health/Fitness Facility Preparticipation Screening Questionnaire

Assess your health needs by marking all *true* statements.

History

You have had:

- ☐ A heart attack
- ☐ Heart surgery
- ☐ Cardiac catheterization
- ☐ Coronary angioplasty (PTCA)
- ☐ Pacemaker/implantable cardiac defibrillator/rhythm disturbance
- ☐ Heart valve disease
- ☐ Heart failure
- ☐ Heart transplantation
- ☐ Congenital heart disease

Symptoms

- ☐ You experience chest discomfort with exertion.
- ☐ You experience unreasonable breathlessness.
- ☐ You experience dizziness, fainting, blackouts.
- ☐ You take heart medications.

*If you marked any of the statements in this section, consult your physician or other appropriate healthcare provider before engaging in exercise. You may need to use a facility with a **medically qualified staff**.*

Other health issues

- ☐ You have diabetes
- ☐ You have or asthma other lung disease.
- ☐ You have burning or cramping in your lower legs when walking short distances.
- ☐ You have musculoskeletal problems that limit your physical activity.
- ☐ You have concerns about the safety of exercise.
- ☐ You take prescription medication(s).
- ☐ You are pregnant.

Cardiovascular risk factors

- ☐ You are a man older than 45 years.
- ☐ You are a woman older than 55 years, you have had a hysterectomy, or you are postmenopausal.
- ☐ You smoke, or quite within the previous 6 mo.
- ☐ Your BP is greater than 140/90.
- ☐ You don't know your BP.
- ☐ You take BP medication.
- ☐ Your blood cholesterol level is >200 mg/dL.
- ☐ You don't know your cholesterol level.
- ☐ You have a close blood relative who had a heart attack before age 55 (father or brother) or age 65 (mother or sister).
- ☐ You are physically inactive (i.e., you get less than 30 min. of physical activity on at least 3 days per week).
- ☐ You are more than 20 pounds overweight.

*If you marked two or more of the statements in this section, you should consult your physician or other appropriate healthcare provider before engaging in exercise. You might benefit by using a facility with a **professionally qualified exercise staff** to guide your exercise program.*

☐ None of the above is true.

You should be able to exercise safely without consulting your physician or other healthcare provider in a self-guided program or almost any facility that meets your exercise program needs.

Balady et al. (1998). AHA/ACSM Joint Statement: Recommendations for Cardiovascular Screening, Staffing, and Emergency Policies at Health/Fitness Facilities. *Medicine & Science in Sports & Exercise*, 30(6). (Also in: ACSM's *Guidelines for Exercise Testing and Prescription*, 7th Edition, 2005. Lippincott Williams and Wilkins <http://www.lww.com>)

www.acsm-msse.org/pt/pt-core/template-journal/msse/media/0698c.htm

Figure A6: Medical history questionnaire.

Figure A7. Rectal probe used for core temperature measurement.

Figure A8. Sensors used for skin temperature measurement.

Figure A9. Filter paper used for measurement of local sweat rates.

Figure A10. Chest strap transmitter for heart rate monitor, alcohol (for sterilization), and lubricant (for rectal probe).

APPENDIX B

Table B1

Means and Standard Deviations of Systolic Blood Pressure[†] by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	131.00 (± 5.18)	131.67 (± 4.27)	119.50 (± 7.79)	115.33 (± 4.50)
MACS-Delphi (no hood)	133.67 (± 4.63)	128.67 (± 5.32)	117.50 (± 4.72)	113.33 (± 5.47)
LCVG (no hood)	138.00 (± 6.57)	136.33 (± 4.80)	117.33 (± 6.41)	116.00 (± 12.20)
Orlan (hood)	133.33 (± 4.68)	138.33 (± 7.94)	123.67 (± 10.46)	124.67 (± 9.00)
Orlan (no hood)	137.67 (± 4.27)	140.00 (± 5.06)	117.33 (± 5.47)	117.67 (± 7.31)

Note: data are presented as means (± standard deviation)

† Systolic blood pressure expressed in mmHg

Table B2

Means and Standard Deviations of Diastolic Blood Pressure[†] by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	80.67 (± 3.72)	75.00 (± 3.03)	77.67 (± 8.71)	73.33 (± 3.93)
MACS-Delphi (no hood)	82.00 (± 8.20)	81.67 (± 7.53)	77.67 (± 4.08)	78.33 (± 8.14)
LCVG (no hood)	82.00 (± 13.39)	78.33 (± 4.46)	79.33 (± 3.27)	79.33 (± 7.34)
Orlan (hood)	82.33 (± 7.09)	79.00 (± 8.83)	79.33 (± 5.89)	83.67 (± 10.98)
Orlan (no hood)	83.33 (± 3.01)	80.67 (± 6.65)	82.33 (± 5.85)	79.67 (± 7.94)

Note: data are presented as means (± standard deviation)

† Diastolic blood pressure expressed in mmHg

Table B3

Means and Standard Deviations of Arterial Oxygen Saturation[†] by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C [§]	35°C
MACS-Delphi (hood)	95.83 (± 0.41)	95.50 (± 1.05)	97.83 (± 0.41)	97.00 (± 1.10)
MACS-Delphi (no hood)	96.50 (± 1.38)	95.83 (± 1.17)	97.83 (± 1.03)	96.17 (± 1.17)
LCVG (no hood)	96.67 (± 0.82)	95.50 (± 0.84)	97.83 (± 0.98)	96.83 (± 1.33)
Orlan (hood)	95.83 (± 1.17)	96.17 (± 0.75)	97.83 (± 0.75)	96.83 (± 1.33)
Orlan (no hood)	95.50 (± 0.55)	95.83 (± 0.75)	97.83 (± 1.63)	97.00 (± 0.89)

Note: data are presented as means (± standard deviation)

[†] Arterial oxygen saturation expressed as a percent

[§] All means in the Stage 7 (24°C) column are identical (i.e., reported values are not errors)

Table B4

Means and Standard Deviations of Heart Rate[†] by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	129.28 (± 22.17)	136.60 (± 22.76)	70.66 (± 13.61)	77.72 (± 15.67)
MACS-Delphi (no hood)	131.38 (± 28.79)	135.56 (± 21.38)	69.14 (± 21.93)	77.38 (± 17.55)
LCVG (no hood)	134.82 (± 23.58)	140.08 (± 24.86)	73.28 (± 19.18)	78.48 (± 18.42)
Orlan (hood)	137.88 (± 21.51)	143.90 (± 22.81)	74.62 (± 15.41)	80.22 (± 17.14)
Orlan (no hood)	131.32 (± 18.88)	137.12 (± 19.67)	69.84 (± 13.83)	77.62 (± 17.47)

Note: data are presented as means (± standard deviation)

[†] Heart rate expressed in beats per minute

Table B5

Means and Standard Deviations of Relative Oxygen Consumption[†] by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	24.94 (± 4.98)	25.85 (± 4.12)	3.83 (± 0.68)	3.56 (± 0.81)
MACS-Delphi (no hood)	24.70 (± 4.41)	25.55 (± 4.19)	3.60 (± 0.62)	3.58 (± 0.27)
LCVG (no hood)	26.03 (± 5.05)	25.54 (± 4.38)	4.11 (± 0.70)	3.83 (± 0.71)
Orlan (hood)	26.00 (± 4.78)	26.59 (± 4.54)	3.77 (± 0.50)	4.04 (± 0.42)
Orlan (no hood)	24.81 (± 3.95)	25.97 (± 3.83)	4.01 (± 0.98)	3.39 (± 0.45)

Note: data are presented as means (± standard deviation)

† Relative oxygen consumption expressed in ml/kg/min

Table B6

Means and Standard Deviations of Absolute Oxygen Consumption[†] by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	1.89 (± 0.22)	1.97 (± 0.13)	0.30 (± 0.06)	0.28 (± 0.07)
MACS-Delphi (no hood)	1.87 (± 0.13)	1.94 (± 0.16)	0.28 (± 0.04)	0.28 (± 0.06)
LCVG (no hood)	1.96 (± 0.09)	1.92 (± 0.10)	0.31 (± 0.05)	0.30 (± 0.09)
Orlan (hood)	1.98 (± 0.05)	2.01 (± 0.15)	0.29 (± 0.03)	0.31 (± 0.04)
Orlan (no hood)	1.90 (± 0.26)	1.98 (± 0.22)	0.31 (± 0.06)	0.26 (± 0.06)

Note: data are presented as means (± standard deviation)

† Absolute oxygen consumption expressed in l/min

Table B7

Means and Standard Deviations of Respiratory Exchange Ratio by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	1.02 (± 0.07)	0.98 (± 0.07)	0.91 (± 0.05)	0.89 (± 0.07)
MACS-Delphi (no hood)	1.03 (± 0.09)	0.99 (± 0.04)	0.91 (± 0.07)	0.90 (± 0.03)
LCVG (no hood)	1.00 (± 0.06)	0.95 (± 0.08)	0.93 (± 0.05)	0.83 (± 0.04)
Orlan (hood)	1.03 (± 0.06)	0.96 (± 0.06)	0.94 (± 0.01)	0.84 (± 0.05)
Orlan (no hood)	1.01 (± 0.07)	0.98 (± 0.05)	0.91 (± 0.07)	0.90 (± 0.04)

Note: data are presented as means (± standard deviation)

† Respiratory exchange ratio expressed as an index of VCO_2/VO_2

Table B8

Means and Standard Deviations of Ventilation[†] by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	53.63 (± 5.45)	57.73 (± 10.52)	9.49 (± 1.89)	9.14 (± 1.80)
MACS-Delphi (no hood)	57.19 (± 10.95)	55.25 (± 4.74)	8.78 (± 1.37)	8.96 (± 1.88)
LCVG (no hood)	59.09 (± 12.71)	54.97 (± 9.46)	10.37 (± 1.22)	8.87 (± 2.46)
Orlan (hood)	60.33 (± 10.28)	58.18 (± 9.40)	9.61 (± 1.17)	9.21 (± 0.97)
Orlan (no hood)	54.53 (± 5.59)	56.05 (± 7.45)	9.72 (± 2.21)	8.79 (± 1.53)

Note: data are presented as means (± standard deviation)

† Ventilation expressed in l/min

Table B9

Means and Standard Deviations of Core (Rectal) Temperature[†] by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	37.33 (± 0.56)	37.73 (± 0.33)	37.31 (± 0.62)	37.58 (± 0.35)
MACS-Delphi (no hood)	37.45 (± 0.30)	37.71 (± 0.27)	37.24 (± 0.40)	37.74 (± 0.26)
LCVG (no hood)	37.58 (± 0.44)	37.52 (± 0.54)	37.56 (± 0.40)	37.59 (± 0.56)
Orlan (hood)	37.37 (± 0.52)	37.75 (± 0.36)	37.43 (± 0.42)	37.56 (± 0.23)
Orlan (no hood)	37.44 (± 0.29)	37.63 (± 0.38)	37.21 (± 0.34)	37.48 (± 0.41)

Note: data are presented as means (± standard deviation)

† Core temperature expressed in degrees Celsius

Table B10

Means and Standard Deviations of Skin (Femoralis) Temperature[†] by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	32.99 (± 1.30)	32.29 (± 1.54)	32.04 (± 1.94)	32.63 (± 1.39)
MACS-Delphi (no hood)	31.23 (± 2.51)	32.41 (± 1.08)	31.14 (± 2.05)	32.12 (± 2.28)
LCVG (no hood)	29.02 (± 1.88)	28.69 (± 1.31)	26.71 (± 1.69)	28.73 (± 1.33)
Orlan (hood)	30.62 (± 1.92)	32.42 (± 1.10)	31.76 (± 2.13)	33.47 (± 0.90)
Orlan (no hood)	31.68 (± 1.35)	31.29 (± 1.73)	30.74 (± 3.34)	30.67 (± 3.34)

Note: data are presented as means (± standard deviation)

† Skin temperature expressed in degrees Celsius

Table B11

Means and Standard Deviations of Skin (Chest) Temperature[†] by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	30.81 (± 2.49)	31.60 (± 1.93)	30.28 (± 1.89)	30.34 (± 1.60)
MACS-Delphi (no hood)	29.61 (± 1.87)	31.45 (± 1.94)	28.55 (± 1.77)	30.45 (± 2.38)
LCVG (no hood)	30.18 (± 2.35)	29.10 (± 2.95)	27.77 (± 2.43)	29.69 (± 2.91)
Orlan (hood)	27.79 (± 1.35)	28.42 (± 2.15)	27.63 (± 3.13)	29.30 (± 3.02)
Orlan (no hood)	28.49 (± 2.12)	29.37 (± 2.35)	27.40 (± 2.52)	26.52 (± 2.65)

Note: data are presented as means (± standard deviation)

† Skin temperature expressed in degrees Celsius

Table B12

Means and Standard Deviations of Skin (Finger) Temperature[†] by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	31.15 (± 1.79)	35.28 (± 1.44)	31.66 (± 1.78)	35.49 (± 0.92)
MACS-Delphi (no hood)	30.23 (± 3.59)	34.90 (± 0.74)	32.35 (± 1.66)	35.83 (± 0.65)
LCVG (no hood)	30.10 (± 4.42)	34.57 (± 1.90)	29.55 (± 3.02)	34.72 (± 2.28)
Orlan (hood)	30.81 (± 4.12)	34.98 (± 1.25)	31.55 (± 2.30)	34.41 (± 1.62)
Orlan (no hood)	31.55 (± 2.70)	33.54 (± 5.37)	30.82 (± 2.96)	33.41 (± 4.99)

Note: data are presented as means (± standard deviation)

† Skin temperature expressed in degrees Celsius

Table B13

Means and Standard Deviations of Skin (Ear) Temperature[†] by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	33.07 (± 2.50)	34.73 (± 0.54)	32.24 (± 2.47)	34.09 (± 0.33)
MACS-Delphi (no hood)	34.14 (± 0.73)	35.40 (± 0.98)	33.64 (± 1.03)	34.43 (± 2.72)
LCVG (no hood)	34.65 (± 0.53)	35.98 (± 0.37)	34.07 (± 1.25)	35.04 (± 1.16)
Orlan (hood)	33.95 (± 0.75)	35.58 (± 0.47)	31.74 (± 5.01)	33.69 (± 3.20)
Orlan (no hood)	34.08 (± 0.86)	34.36 (± 2.66)	33.37 (± 1.14)	33.80 (± 2.51)

Note: data are presented as means (± standard deviation)

† Skin temperature expressed in degrees Celsius

Table B14

Means and Standard Deviations of Skin (Calf) Temperature[†] by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	28.09 (± 2.47)	30.77 (± 1.50)	28.75 (± 2.62)	32.20 (± 2.21)
MACS-Delphi (no hood)	28.48 (± 2.31)	31.94 (± 1.64)	29.59 (± 2.16)	33.20 (± 2.25)
LCVG (no hood)	27.42 (± 1.36)	29.04 (± 1.47)	28.61 (± 1.56)	29.78 (± 2.42)
Orlan (hood)	30.15 (± 4.60)	32.62 (± 1.80)	30.77 (± 4.75)	33.09 (± 2.01)
Orlan (no hood)	30.27 (± 3.03)	32.18 (± 3.23)	31.36 (± 2.95)	32.92 (± 2.71)

Note: data are presented as means (± standard deviation)

† Skin temperature expressed in degrees Celsius

Table B15

*Means and Standard Deviations of Local Sweat Rate[†]
(Groin) by Suit and Temperature*

Suit	Temperature	
	24°C	35°C
MACS-Delphi (hood)	0.21 (± 0.19)	0.18 (± 0.11)
MACS-Delphi (no hood)	0.30 (± 0.22)	0.27 (± 0.30)
LCVG (no hood)	0.11 (± 0.11)	0.16 (± 0.16)
Orlan (hood)	0.15 (± 0.12)	0.15 (± 0.10)
Orlan (no hood)	0.24 (± 0.26)	0.26 (± 0.13)

Note: data are presented as means (± standard deviation)

† Local sweat rate expressed in Δ grams

Table B16

*Means and Standard Deviations of Local Sweat Rate[†]
(Back) by Suit and Temperature*

Suit	Temperature	
	24°C	35°C
MACS-Delphi (hood)	0.74 (± 0.52)	1.06 (± 0.53)
MACS-Delphi (no hood)	0.55 (± 0.29)	1.35 (± 0.72)
LCVG (no hood)	0.39 (± 0.21)	0.78 (± 0.27)
Orlan (hood)	0.77 (± 0.59)	1.00 (± 0.59)
Orlan (no hood)	0.59 (± 0.30)	0.75 (± 0.45)

Note: data are presented as means (± standard deviation)

† Local sweat rate expressed in Δ grams

Table B17

*Means and Standard Deviations of Local Sweat Rate[†]
(Chest) by Suit and Temperature*

Suit	Temperature	
	24°C	35°C
MACS-Delphi (hood)	0.63 (± 0.60)	0.88 (± 0.69)
MACS-Delphi (no hood)	0.74 (± 0.64)	0.93 (± 0.60)
LCVG (no hood)	0.58 (± 0.69)	0.82 (± 0.59)
Orlan (hood)	0.69 (± 0.55)	0.88 (± 0.57)
Orlan (no hood)	0.67 (± 0.57)	0.82 (± 0.64)

Note: data are presented as means (± standard deviation)

† Local sweat rate expressed in Δ grams

Table B18

Means and Standard Deviations of Skin Wetness[†] (Hand) by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	583.33 (± 70.64)	646.33 (± 87.87)	154.00 (± 52.31)	218.33 (± 156.39)
MACS-Delphi (no hood)	521.33 (± 113.85)	663.00 (± 76.70)	141.67 (± 31.25)	230.33 (± 86.74)
LCVG (no hood)	497.33 (± 110.15)	699.00 (± 89.36)	149.67 (± 57.79)	222.00 (± 52.35)
Orlan (hood)	509.67 (± 130.60)	696.00 (± 127.62)	159.17 (± 49.10)	260.33 (± 92.48)
Orlan (no hood)	593.00 (± 79.55)	674.00 (± 57.58)	151.67 (± 49.01)	231.67 (± 49.97)

Note: data are presented as means (± standard deviation)

† Skin wetness expressed in arbitrary units

Table B19

Means and Standard Deviations of Skin Wetness[†] (Ankle) by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	515.67 (± 125.71)	623.33 (± 87.65)	202.00 (± 28.06)	350.00 (± 107.99)
MACS-Delphi (no hood)	430.00 (± 130.77)	680.67 (± 108.45)	233.00 (± 106.96)	311.33 (± 119.09)
LCVG (no hood)	454.00 (± 98.66)	595.67 (± 144.45)	177.67 (± 84.33)	297.00 (± 166.29)
Orlan (hood)	522.83 (± 61.44)	629.67 (± 124.41)	237.33 (± 46.23)	355.67 (± 89.56)
Orlan (no hood)	505.00 (± 87.99)	582.33 (± 127.38)	228.00 (± 95.61)	309.33 (± 35.46)

Note: data are presented as means (± standard deviation)

† Skin wetness expressed in arbitrary units

Table B20

Means and Standard Deviations of Skin Wetness[†] (Forehead) by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	561.67 (± 125.66)	629.33 (± 116.73)	238.33 (± 97.93)	363.33 (± 92.13)
MACS-Delphi (no hood)	489.17 (± 53.54)	682.33 (± 84.98)	203.33 (± 75.69)	399.33 (± 143.42)
LCVG (no hood)	543.67 (± 161.02)	680.83 (± 146.59)	199.67 (± 108.18)	309.33 (± 163.13)
Orlan (hood)	600.00 (± 134.86)	754.00 (± 141.42)	240.67 (± 149.82)	334.33 (± 122.95)
Orlan (no hood)	603.67 (± 173.57)	722.00 (± 8.67)	264.33 (± 129.04)	356.00 (± 118.98)

Note: data are presented as means (± standard deviation)

† Skin wetness expressed in arbitrary units

Table B21

Means and Standard Deviations of Skin Wetness[†] (Palm) by Suit, Temperature and Stage

Suit	Stage 5 (Exercise)		Stage 7 (Rest)	
	24°C	35°C	24°C	35°C
MACS-Delphi (hood)	367.00 (± 198.83)	516.33 (± 152.23)	140.67 (± 66.63)	184.33 (± 105.52)
MACS-Delphi (no hood)	335.67 (± 154.94)	546.67 (± 104.79)	154.00 (± 65.73)	161.00 (± 68.84)
LCVG (no hood)	471.67 (± 183.50)	636.67 (± 153.10)	171.33 (± 96.04)	199.67 (± 99.11)
Orlan (hood)	338.00 (± 122.27)	542.00 (± 139.39)	153.67 (± 74.20)	189.33 (± 105.02)
Orlan (no hood)	439.50 (± 154.66)	530.33 (± 105.70)	162.67 (± 104.03)	187.33 (± 113.06)

Note: data are presented as means (± standard deviation)

† Skin wetness expressed in arbitrary units

Table B22

Means and Standard Deviations of Water Flow Rate[†] by Suit and Temperature

Suit	Temperature	
	24°C	35°C
MACS-Delphi (hood)	361.00 (± 90.88)	325.17 (± 88.04)
MACS-Delphi (no hood)	333.40 (± 89.82)	236.33 (± 76.56)
LCVG (no hood)	2041.83 (± 126.49)	1918.80 (± 93.09)
Orlan (hood)	2502.40 (± 299.04)	2149.20 (± 309.00)
Orlan (no hood)	2406.83 (± 322.12)	2364.67 (± 119.24)

Note: data are presented as means (± standard deviation)

† Water flow rate expressed in milliliters per minute

Table B23

Means and Standard Deviations of Whole Body Sweat Rate[†] by Suit and Temperature

Suit	Temperature	
	24°C	35°C
MACS-Delphi (hood)	0.58 (± 0.16)	0.93 (± 0.10)
MACS-Delphi (no hood)	0.57 (± 0.10)	0.95 (± 0.10)
LCVG (no hood)	0.45 (± 0.10)	0.72 (± 0.08)
Orlan (hood)	0.75 (± 0.32)	0.88 (± 0.17)
Orlan (no hood)	0.63 (± 0.08)	0.93 (± 0.12)

Note: data are presented as means (± standard deviation)

[†] Sweat rate expressed in kilograms

APPENDIX C

Figure C1. Limitation of forward flexion in the Orlan due to vertical tubing arrangement.

Figure C2. Results of wear-and-tear in the crotch region of the Orlan.

Figure C3. Skin abrasions in the upper thigh and crotch area of two different participants following trials with the Orlan.