Local Pressure Application Effects on Neurological and Circulatory Function

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BACKGROUND: Pain and discomfort reported during sitting is a significant problem for aviators during prolonged missions. Previous work has determined that areas of local pressure exist during prolonged sitting in UH-60 seat systems; however, no work has examined the effects of this local pressure on measures of neurological and circulatory function.

METHODS: A total of 30 healthy subjects completed the study in which focal pressure was applied in three conditions (no pressure, pressure to the ischial tuberosity, and pressure to the posterior thigh). We applied pressure using a purpose-built pressure application system allowing subjects to sit in a position mimicking the sitting position in a UH-60 Black Hawk helicopter and measurements were taken before, during, and after pressure application. We measured neurological function with the soleus Hoffmann reflex and sural nerve conduction velocity, and circulatory function with dynamic infrared thermography.

RESULTS: We found a decrease in soleus Hoffmann reflex by 0.87 V and 0.52 V during pressure application at the posterior thigh and ischial tuberosity, respectively. No changes in nerve conduction velocity were found among the conditions during or after pressure application. Limb temperature increased 0.42–0.44°C during pressure application, but began to return to baseline once pressure was removed.

DISCUSSION: This study examined the development of neurological and circulatory alterations due to local pressure application in an aviation specific functional position. These results may be used in the development of future interventions to mitigate the negative effects of localized pressure in military aviators.

KEYWORDS: military, aviators, operational load-bearing.

Games KE, Lakin JM, Quindry JC, Weimar WH, Sefton JM. *Local pressure application effects on neurological and circulatory function*. Aerosp Med Hum Perform. 2018; 89(8):693–699.

Prolonged restricted sitting during long missions has been a challenge for aviators since World War II.[3] Seat designs have evolved from simple wooden seats to highly advanced, armored ejection seats; however, the problem of aviator discomfort negatively affecting mission performance has persisted despite changes to seat design.[3] Several studies have used seat interface pressure mapping devices[15,18,19] and subjective discomfort scales[15,18,19] in an attempt to elucidate the cause of aviator discomfort during flight and improve mission effectiveness. These studies demonstrate that prolonged restricted sitting in aircraft results in discomfort and high peak pressures.[15,18,19] The work examining the seat interface pressure revealed the onset of discomfort during prolonged restricted sitting but did not address the etiology of the reported discomfort and paresthesia.

The prevailing theory on the origin of discomfort and paresthesia during prolonged restricted sitting has been that areas of locally high pressure on the buttocks and posterior thigh compress the nervous and vascular tissue, resulting in discomfort, altered sensory function, and paresthesia. Previous work examining the UH-60 seat system supports this hypothesis, with evidence to suggest increased discomfort, decreased plantar sensory function, decreased downstream limb temperature, and increased tissue compression.[9–11] Physiological work on

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This manuscript was received for review in May 2016. It was accepted for publication in April 2018.

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DOI: https://doi.org/10.3357/AMHP.4675.2018

isolated nerves demonstrates that local pressure alters downstream nerve function[4,13] and impacts myelinated nerves more than unmyelinated nerves.[4] The sciatic nerve is highly myelinated and innervates the lower extremity.[12] The previous UH-60 seat system work, combined with the physiological data in isolated nerves, suggests that areas of locally high pressure on the sciatic nerve could create the reported symptoms of discomfort and paresthesia during prolonged sitting in aircraft. However, there is limited research examining this hypothesis during seated conditions in humans. Assessing the influence of local pressure application on nerve function and lower extremity blood flow would provide direct evidence that the hypothesized areas of local compression do, in fact, limit performance in a seated position, allowing for the development of interventions to decrease the burden on aviators.

It is essential to examine the effects of local pressure application in a seated position in order to test the hypothesis that local pressure application is responsible for alterations in nerve function and downstream blood flow. Therefore, the aim of the current study was to examine the neurological and vascular consequences of local pressure application to the buttock and posterior thigh. The goal of this current study was to better understand the mechanisms by which discomfort and temporary paresthesia arise during seated tasks in rotary-wing aircraft.

METHODS

Subjects

Participating in the study were 30 male volunteers (age = 21.7 ± 2.2 yr). Subjects met U.S. Army flight standards for anthropometry and body weight. Only male subjects were recruited for this study as requested by the funding agency. We screened subjects with an 18-point health questionnaire. Subjects reported no history of cardiovascular, neurological, or metabolic disease in the past 2 yr; no history of surgery or fracture in the lumbar spine or lower extremities in the past 2 yr; no current history of low back pain or lower extremity injury; and no current use of prescription or nonprescription pain relievers. All subjects provided signed written consent. The University's Institutional Review Board and the Institutional Review Board of the U.S. Army Medical Research and Materiel Command approved the study.

Equipment and Materials

The purpose-built pressure application device applied local pressure to locations on the posterior aspect of the upper leg of participants in a seated position.[10] It consisted of a step motor secured to an extendable metal rod and load cell with a 25.52 cm square round pressure application head. The unit was controlled using custom-written computer software and operated through a laptop computer (Dell Latitude D430, Dell Inc., Round Rock, TX). The wooden seat consisted of an 80.01 x 55.88 cm (height x width) seat back and a 50.80 x 55.88 cm (depth x width) seat pan. The seat pan was comprised of 14 removable slats, which allowed the pressure application head access to the area of interest while supporting the body mass of the participant. To reduce the edge pressure created by slat removal, a secondary cover was applied over the seat pan which allowed for a precision void to be created which was filled by the pressure application head, therefore minimizing unwanted edge pressure. The foot rest was a 91.44 x 50.80 x 35.66 cm (length x width x height) box with an adjustable crank lift to accommodate participants of different heights.

Local pressure was applied to the ischial tuberosity and the midpoint of the posterior thigh on the dominant lower extremity of participants.[10] A trained investigator palpated and marked the ischial tuberosity. We defined the midpoint of the posterior thigh as the halfway point between the greater trochanter and lateral epicondyle. The distance between the greater trochanter and the lateral epicondyle (determined by palpation) was measured using a tape measure (Medco Tape Measure, Patterson Medical Holdings Inc., Bolingbrook, IL). The distance between the medial and lateral borders of the thigh was measured in the same manner with the permanent marker line demarcating the midpoint of the femur along its polar axis. This test location was marked with permanent marker. The investigators visually confirmed the locations prior to pressure application. During the no pressure condition, the pressure application head was lowered below the threshold of the seat pan and all open slats were filled to create a flat seating surface.

Following preparation (e.g., application of electrodes) each day, we instructed subjects to sit on the pressure application chair barefoot with the appropriate slats removed and pressure application head correctly positioned. The participant sat upright and as far back in the chair as possible. The footrest was adjusted to the appropriate height and subjects' knees were positioned at the design eye point knee angle. Following positioning, subjects sat quietly in the seat system. After the rest period, we collected baseline measures of sural sensory nerve conduction velocity, soleus Hoffmann reflex, and dynamic infrared thermography. We applied local pressure at 44 kPa to one of the aforementioned locations (middle of the posterior thigh, ischial tuberosity, or no pressure) for a total of 10 min. The local pressure magnitude and duration was determined by previous work.[9–11] During the pressure application, the pressure application device maintained the set pressure within 5% of 44 kPa. Following 5 and 10 min of pressure application, follow-up measurements were taken. Additional follow-up measurements were collected during the recovery from the local pressure application period at time points of 5 and 10 min post pressure removal. The order of data acquisition remained the same for each session and for each participant. The investigators scheduled subjects no less than 24 h after completion of the session. We repeated this procedure for all three conditions.

We used the subjects' dominant limbs for measurement of the sural sensory nerve conduction velocity. Disposable adhesive foam paired electrodes (EL500, Biopac Systems Inc., Goleta, CA) were placed 1 cm posterior and 1 cm inferior to the lateral malleolus and served as the active recording electrodes.[16] We placed a stimulating electrode (EL500, Biopac Systems Inc., Goleta, CA) 14 cm from the center of the active recording electrodes. A reference electrode (EL 503, Biopac Systems Inc.) was placed between the stimulating and recording electrodes.[16] The signal was differentially amplified (gain, 2000; low pass filter, 5 kHz; high pass filter, 10 Hz; sampling rate, 10,000 Hz; input impedance, 1000 MΩ; signal noise, 0.2) and digitally converted at 2000 Hz. Rectangular electrical pulses 0.1 ms in duration were delivered once every 3 s via transcutaneous stimulation (STMISOC, Biopac Systems Inc.) at an intensity sufficient to obtain a sensory response.[16] We delivered five stimulations at each time point during the local pressure application protocol. The peak negative potential was measured from the end of the stimulation artifact.[16] We averaged the latencies to obtain a mean sural nerve latency. The sural sensory nerve latency (milliseconds) was converted to nerve conduction velocity ($m \cdot s^{-1}$) by dividing the stimulating electrode to recording electrode distance (14 cm) by the sural sensory nerve latency (in milliseconds). We then standardized the nerve conduction velocity by converting centimeters into meters and milliseconds into seconds.

We chose to investigate the functionally dominant leg soleus muscle due to its location in the lower leg, importance in foot function, and ease of access in a seated position. The electrode sites for the soleus H-reflex were shaven to remove excess hair, abraded, and cleaned with isopropyl alcohol.[23] We placed disposable adhesive silver/silver chloride (Ag/AgCl) electrodes (EL503, Biopac Systems Inc.) on the soleus muscle 2 cm distal to the belly of the gastrocnemius muscle with an interelectrode distance of 2 cm. A ground electrode (EL 503, Biopac Systems Inc.) was placed on the ipsilateral medial malleolus. A stimulating electrode (EL 254, Biopac Systems Inc.) was placed over the posterior tibial nerve in the popliteal fossa of the posterior knee. We placed an 8-cm round dispersal pad above the patella on the ipsilateral quadriceps muscles. A series of 1.0-ms square wave stimuli were delivered via transcutaneous stimulation (STMISOC, Biopac Systems Inc.) at 10- to 20-s intervals while increasing stimulus intensity by 0.2 V until the soleus maximum H-reflex (H_{max}) and maximum M-wave (M_{max}) were found for each participant. We normalized the test stimulus to 25% of soleus M_{max}. Electromyographic (EMG) data were collected and the signal amplified using an EMG amplifier (EMG100C, Biopac Systems Inc.). The raw signal was differentially amplified (gain, 1000; common mode rejection ratio, 110 dB; input impedance, 1000 MΩ; signal noise, 0.2) and digitally converted at 2000 Hz.[22] The data were analyzed using AcqKnowledge Software (Biopac Systems Inc., Version 4.0). Seven repetitions were averaged for each time point.[22] During pressure application the electrodes, stimulator, and leads remained in place and connected to the data acquisition system. Data collection occurred during the same time of day for each session to eliminate diurnal effects on the H-reflex.

We used a digital infrared camera (FLIR T420, FLIR Systems Inc., Wilsonville, OR) to measure noncontact, superficial temperatures (°C) in the lower leg. The investigators captured anterior and lateral infrared images 1 m from the dominant leg of participants. The average temperature of the lateral and anterior ankle was analyzed using manufacturer specific analysis software (FLIR ExaminIR, version 1.40.12.44). Mean temperature values for regions of interest at the anterior and lateral ankle were measured using the Glamorgan Protocol.[1] The anterior ankle region of interest was comprised of the width of the ankle with upper and lower edges at the tip of the medial malleolus and the tip of the navicular bone, respectively.[1] The lateral ankle region of interest included the entire anterior to posterior thickness at the level of the lateral malleolus.[1]

Procedures

This study used a 3 × 5 factorial repeated measures design. The independent variables included location with three levels (ischial tuberosity, posterior thigh, and no pressure) and time with five levels (preapplication, 5 min into application, 10 min into application, 5 min postremoval, and 10 min postremoval). The dependent variables included mean sural sensory nerve conduction velocity, soleus H-reflex (mean peak-to-peak amplitude), and dynamic infrared thermography (lateral lower leg and anterior lower leg).

Subjects reported to the laboratory three times with a minimum of 24 h between sessions. Testing order was randomized (computerized random number generator, TI-83 Plus, Texas Instruments Inc., Dallas, TX) into three conditions completed on different days: pressure application (44 kPa) to the middle of the posterior thigh (condition A); pressure application (44 kPa) to the ischial tuberosity (condition B); and a no pressure condition (condition C). Functional leg dominance was determined on day 1 using: the step up test, the ball kick test, and the balance recovery test. Investigators recorded the anthropometric measures of arm length, crotch height, sitting height, height, and weight from the participants to ensure all subjects met Army flight status requirements.

Subjects sat in a custom-built pressure application seat for all data collection previously described by Games et al.[10] The seat's design applied pressure only to the test location while still supporting the participant's body weight. To reproduce sitting postures in the UH-60 helicopter, design eye point knee sitting angles were evaluated, collected using a goniometer (12.5″ International Standard Goniometer, Patterson Medical Holdings Inc., Bolingbrook, IL), and recorded using standard U.S. Army design eye point procedures.[5] The design eye point is an aircraft specific position for aviators that optimizes field of view and equipment access within the cockpit.[5] We replicated the knee angle by passively moving the participants' knees prior to the start of all data collection sessions and after each data collection time point. The 44-kPa pressure was applied to the test location (middle of the posterior thigh, ischial tuberosity, or no pressure) for 10 min; participants were asked to sit quietly with their head facing forward and hands resting on their laps. We collected data preapplication, 5 min into pressure application, 10 min into pressure application, 5 min postremoval, and 10 min postremoval.

Statistical Analysis

Data were collected via a tablet computer (iPad 2, Apple Inc., Cupertino, CA), transferred into a custom database (Microsoft

Excel 2010, Microsoft Corp., Redmond, WA), and analyzed using Statistical Package for Social Sciences version 19 (IBM SPSS Statistics 19, IBM Corp., Somers, NY). Descriptive statistics (mean ± SD) were calculated. Four 3 x 5 (location x time) factorial repeated measures ANOVAs were performed. Appropriate follow-up ANOVAs and dependent *t*-tests with Holm's sequential Bonferroni adjustments were performed. Significance levels were set a priori at $P \leq 0.05$.

RESULTS

A 3 x 5 (condition x time) repeated measures ANOVA analysis of the sural sensory nerve conduction velocity revealed no significant two-way interaction effect [Wilks' $\Lambda = 0.64$; $F(8,22) = 1.51$, $P = 0.208$; $\eta_p^2 = 0.35$]. No significant main effect of pressure application condition or time was found. These data indicate that local pressure application does not alter mean sural sensory nerve conduction velocity.

Mean peak-to-peak soleus Hoffmann reflex amplitudes demonstrated no significant two-way location x time interaction effect [Wilks' $\Lambda = 0.59$; $F(8,22) = 1.90$, $P = 0.110$; $\eta_p^2 = 0.41$]. However, significant main effects were found for pressure application condition [Wilks' $\Lambda = 0.74$; $F(2,28) = 4.68$, $P = 0.018$; $\eta_p^2 = 0.25$] and for time [Wilks' $\Lambda = 0.65$; $F(4,26) = 3.46$, $P = 0.021$; $\eta_p^2 = 0.34$). Follow-up tests for the significant main effect of pressure application condition revealed a significant decrease in Hoffmann reflex peak-to-peak amplitude during the posterior thigh condition compared to both the ischial tuberosity condition [$t(29) = -0.86$, $P = 0.007$] and the control condition [$t(29) = -0.51$, $P = 0.029$]. No significant difference was found between the ischial tuberosity and control condition [$t(29) = 0.34$, $P = 0.218$]. Follow-up pairwise comparisons for the significant main effect of time found a significant decrease in mean peak-to-peak amplitude at the 5-min postpressure application time point [$t(29) = 0.29$, $P = 0.028$] compared to baseline measurements. These data suggest that 5 min following the removal of pressure application mean peak-to-peak soleus Hoffmann reflex amplitudes are decreased (**Fig. 1**).

Anterior ankle temperatures revealed no significant two-way interaction [Wilks' $\Lambda = 0.71$; $F(8,22) = 1.10$, $P = 0.395$; $\eta_p^2 = 0.28$] for anterior ankle skin temperature. A significant time main effect was found [Wilks' $\Lambda = 0.20$; $F(4,26) = 1.10$, $P < 0.001$; $\eta_p^2 = 0.79$]; however, no significant effect of location was found [Wilks' $\Lambda = 0.98$; $F(2,28) = 0.29$, $P = 0.75$; $\eta_p^2 = 0.02$]. Follow-up pairwise comparisons for the main effect of time revealed a significant increase in temperature at 5 min into pressure application [$t(29) = -0.42$, $P < 0.001$] and 10 min into pressure application [$t(29) = -0.24$, $P = 0.002$]. These data indicate that superficial skin temperature at the anterior ankle is increased during the first 10 min of the protocol. Lateral ankle temperature revealed a nonsignificant two-way interaction [Wilks' $\Lambda = 0.88$; $F(8,22) = 0.37$, $P = 0.992$; $\eta_p^2 = 0.12$]. A significant main effect of time was found [Wilks' $\Lambda = 0.17$; $F(4,26) = 31.2$, $P < 0.001$; $\eta_p^2 = 0.82$], but no significant effect of location was present [Wilks' $\Lambda = 0.96$; $F(2,28) = 0.45$, $P = 0.63$; $\eta_p^2 = 0.03$]. Follow-up pairwise comparisons found a significant increase in lateral ankle skin temperature at 5 min into pressure application [$t(29) = -0.44$, $P < 0.001$] and at 10 min into pressure application [$t(29) = -0.26$, $P < 0.001$]. As with the anterior skin temperature data, these data suggest that skin temperatures at the lateral ankle are increased during the first pressure application.

DISCUSSION

This study investigated the effects of 44 kPa of pressure application at three locations (control, ischial tuberosity, posterior thigh) on measures of lower extremity nervous system and vascular system function. The most notable results from this study were that mean peak-to-peak Hoffmann reflex amplitudes decreased when pressure was applied to the posterior thigh. Peak-to-peak amplitude during posterior thigh pressure application was 0.87 V lower than H-reflex amplitudes at the ischial tuberosity and 0.52 V lower than H-reflex amplitudes during the control conditions. This study examined the Hoffmann reflex in a functional position when pressure was applied to the ischial tuberosity and posterior thigh. Previous research examining the effects of local pressure application on Hoffmann reflex amplitude while in the prone position produced different results.[20] Previous work found a 17% increase in H-reflex amplitude following 9 min of pressure application of 28 kPa to the posterior thigh.[20] The authors hypothesized that cutaneous stimulation during the pressure application created an increase in the α-motoneuron pool excitability.[20] Work examining the effects of pressure stimuli on soleus H-reflex amplitudes during locomotion found that H-reflex amplitudes are inhibited when mechanical pressure is applied to the plantar aspect of the foot.[2] Cutaneous stimuli at the heel resulted in significant facilitation of the soleus H-reflex while cutaneous stimulation at the third metatarsal resulted in significant inhibition of soleus H-reflex.[21] Work at other locations in the lower extremity does appear to support location dependent cutaneous stimuli changes to H-reflex output.[20] We suspect the differences between the results of previous work and the current study are a result of participant position (prone vs. upright sitting), pressure application magnitude (28 kPa and 44 kPa), and H-reflex amplitude normalization procedures (50% H_{max} vs. 25% M_{max} test stimulus). We chose to use 44 kPa of pressure in the present study because previous work in our laboratory suggests a magnitude of 28 kPa of local pressure application is not great enough to elicit the symptoms of discomfort and temporary paresthesia.[10] Participant position and stimulation intensity have both been shown influence the H-reflex outputs.[17,24]

An inhibition of the soleus H-reflex amplitude could have significant performance implications for rotary-wing aviators. To safely operate the aircraft, rotary-wing pilots must use all four limbs simultaneously. The feet operate the antitorque pedals of the aircraft.[6] If there is a decreased α-motoneuron output as found in the present study, the muscle force output may be

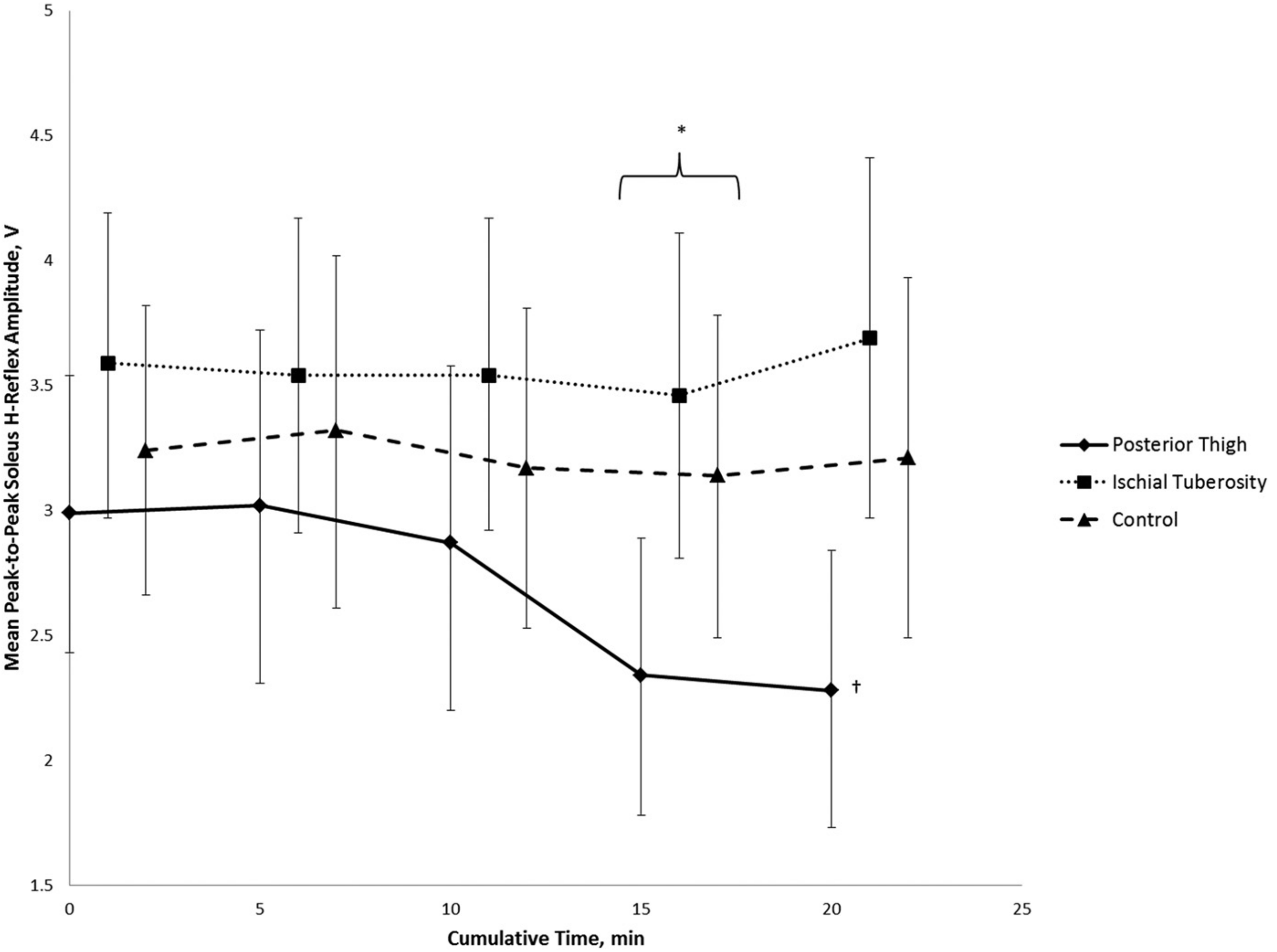

Fig. 1. Soleus Hoffmann reflex mean peak-to-peak amplitudes at each of the conditions across the pressure application and recovery period. min: minute; V: volts; * = $P < 0.05$ across time; † = $P < 0.05$ between conditions; error bars represent 95% confidence interval.

diminished. The diminished α-motoneuron output requires that more motor units be recruited in order to maintain muscle force output. Over the course of a sortie, the increased motor unit recruitment may lead to fatigue, diminishing the aviator's ability to operate the aircraft. Failure to effectively operate the antitorque pedals results in loss of helicopter control,[6] injury, equipment damage, or death. The results of the current project are supported by previous work which found that prolonged restricted sitting results in a decreased sensitivity to point pressure at the plantar aspect of the fifth metatarsal.[11] The skin of the plantar aspect of the fifth metatarsal is part of the S1 nerve root dermatome,[12] which is also responsible for motor control of several lower extremity muscles, including the soleus.[14] Future work should examine if soleus H-reflex amplitude is decreased during a prolonged (4-8 h) restricted sitting bout, and the influence of diminished α-motoneuron output on the recruitment of additional motor units during a prolonged task (e.g., operating antitorque pedals).

The results for the sural nerve conduction velocity found that 44 kPa of local pressure application at the ischial tuberosity or posterior thigh does not change the conduction velocity compared to a control condition. This study explored the effects of proximal local pressure application on distal peripheral nerve conduction velocity in the lower leg (sural sensory nerve) of humans. Other work has demonstrated that acute compression of isolated nerves decreases nerve conduction velocity and alters nerve function.[4,7,13] However, the previous work applied focal pressure between the stimulation site and the recording site.[4,7,13] We hypothesized that if nerve conduction velocity is tested across the segment at which the pressure is applied (ischial tuberosity and posterior thigh), nerve conduction velocity and function would be altered, particularly at the posterior thigh location due to the path of the sciatic nerve along the posterior aspect of the thigh. Testing this hypothesis would be difficult due to methodological limitations of nerve conduction studies at the sciatic nerve, but other neurological tests like the H-reflex provide valuable information, as shown in this present study.

Our results for anterior and lateral ankle skin temperatures indicate that anterior (0.42°C) and lateral superficial skin temperature (0.44°C) significantly increases during the first 5 min of pressure application. Superficial skin temperature at the anterior ankle begins to decrease 10 min after the beginning of the protocol, but is still significantly greater than baseline measurements (29.52°C compared to 29.28°C). Lateral ankle superficial skin temperature also begins to decrease after 10 min. These changes are likely the result of inactivity of the lower extremity muscles and decreased venous return, which caused pooling of the blood in the lower leg. Venous pressure is normally very low.[8] It is likely that the interface pressure between the buttocks and firm surface of the local pressure application apparatus was sufficient to occlude venous return; however, this was not measured. The flow into the venous system is exclusive from the arterial system. After 3 to 5 min of inactivity, the venous system is filled and serves as a reservoir for blood.[8] We suspect that the first 5 min of sitting resulted in an increase in temperature because the venous system was filling with warm arterial blood. Heat exchange from the lower leg to the environment then occurred via thermal radiation. Previous research found a similar pattern with both 44 and 36 kPa applied to the posterior thigh and ischial tuberosity across a 10-min pressure application period.[10] Our previous work also found that superficial skin temperature at the anterior and lateral ankle decreased by 2.78–2.85°C across a 4-h time period. During the prolonged restricted sitting study, we measured temperature once every 30 min; thus, any changes within the 30-min data collection periods were not analyzed.[11] Future research should collect data more frequently in order to examine the effects of prolonged sitting in an effort to determine if there is a pattern of temperature increases followed by decreases as we observed in this study.

The results of our study suggest that 44 kPa of local pressure application decreases motoneuron pool excitability, increases superficial anterior and lateral ankle skin temperature, but does not alter sural nerve conduction velocity. These differences were greater when pressure was applied to the posterior thigh compared to the ischial tuberosity. These data support the local pressure hypothesis and serve as a call to action for an in-depth investigation of the redesign of the UH-60 seat system to maintain crashworthiness, but decrease the burden of the negative effects prolonged mission length and local pressure apply to aviators which may affect situational awareness and mission efficacy. Future work should investigate neurological and circulatory deficits of prolonged sitting due to areas of locally high pressure in aviators and in combination with the known vibration of the rotors. Additionally, research should compare the current seat system to novel seat systems to identify potential design changes that could improve situational awareness and mission efficacy through the removal of distracting, painful stimuli.

ACKNOWLEDGMENTS

Funding provided by Department of Defense program number W911NF-11-D-0001: “Volunteer Investigations for Mounted and Head-Supported Mass in Dismounted Operations.”

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