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Quantitative Methods for Determining U.S. Air Force Crew Cushion Comfort

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14. ABSTRACT
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Peak seated pressures ranged from 1.22 - 3.22 psi. Oxygen saturation in the lower extremities decreased over the eight hours. Cognitive performance increased over time regardless of cushion with the exception of the dynamic cushion, which induced a decrease in performance for females. Muscular fatigue increased throughout the eight hours regardless of cushion, with the exception of the dynamic cushion which promoted muscular recovery. Subjective comfort levels declined over the eight hours. Subjective measures correlated with objective parameters for the static cushions. Trade-offs in performance and fatigue mitigation were apparent in the dynamic cushion which also highlighted differences between genders. These results will be used to develop cushion design guidelines, both to prevent deep vein thrombosis and to promote comfort for long-duration use.

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INTRODUCTION

The purpose of this study was to develop objective methods for determining and predicting human comfort in operational and prototype U.S. Air Force crew seat cushions. To achieve this, 4 main questions were addressed in this study: 1) Is there a measurable difference between cushion types in physical responses, namely seated pressures, and physiological responses, in particular muscle fatigue and lower extremity oxygen saturation, between cushion types? 2) Is there a measurable difference in cognitive performance between cushion types? 3) Is there a measurable difference in perceived comfort between cushion types? 4) What conclusions can be drawn regarding the existing correlations of the above physical, physiological, and performance parameters with perceived comfort?

This study is part of an overall effort to define seat and cushion parameters that will maximize comfort and performance without jeopardizing ejection safety. Previous work includes a pilot study done in 1999 in which 5 males were monitored for a 4-hour sit duration [1]. This study indicated the need for long-duration monitoring to gain a realistic understanding of the long-term effects on the operator's responses. The pilot study also led to improvements for the first 8-hour sit duration study conducted in 2003 in which a larger, more diverse subject panel was observed on 4 cushion types in an F-15 seat configuration [2]. The 2003 study highlighted the correlations that do exist in objective seated pressures and subjective comfort levels. The tools and measurement techniques employed in the current effort were selected based on the results from the first two studies. The current effort expanded upon the previous studies by introducing additional variables including dynamic cushion properties, increased measurement frequencies, and new measurement techniques. These techniques included monitoring the percent change in lower extremity blood oxygen saturation levels to provide an estimation of blood flow behavior and monitoring low back and shoulder muscular fatigue. Blood pooling was selected for monitoring due to periods of minimal to no motion in the leg in long-term flight which can lead to deep vein thrombosis (DVT). Muscular fatigue levels in the low back and shoulder were selected to be monitored due to the long-duration effects of low-level sustained contractions. Combined, these factors are suspected of being significant contributors of discomfort during seated long-term flight.

BACKGROUND

Ejection seat cushions in current U.S. Air Force aircraft are not optimized for comfort during extended missions. With combat bomber crew missions during Operation Enduring Freedom reaching over 40 hours in length, it has become increasingly important that crewmember seat comfort be improved. These improvements are critical to enhance both physical endurance and combat effectiveness.

Shortcomings of existing ejection seat cushions have been documented by researchers [3,4,5] and through interviews conducted with pilots and flight surgeons [6]. The most common complaints were buttock and lumbar spine soreness, tingling in the extremities, numbness and overall fatigue. The discomfort experienced during extended missions has several causes. The materials used in ejection seat cushions are not selected based on their comfort properties; but rather they are selected for their performance in limiting spinal injuries during ejection. Cockpit space restrictions associated with most ejection seat equipped aircraft severely restrict the seat occupant's ability to reposition during flight. Ejection seat dimensions and contours are fixed, causing accommodation problems, especially for large and small occupants. Previous research has shown that all of these problems can be addressed [3,5,7]. However, completely eliminating all occupant discomfort would likely require an entire seat system redesign or a limit in the duration of the mission. Oftentimes, the only component to which feasible, cost-effective modifications can be made is the ejection seat cushion.

Recent studies have shown that cushions made from various densities of Confor™ provide superior impact protection and improved occupant comfort [3,4,8,9] compared to foam rubber or polyurethane combinations. In fact, a replacement cushion was approved for use in the B-2 and other ACES II configurations based upon impact testing and an evaluation of cushions with different densities of Confor™ and various surface contours. However, in a recent evaluation of the replacement B-2 cushions, it was determined that no single cushion could be designed to accommodate the entire anthropometric range. It was recommended that individual cushions be fitted for each pilot [3]. Another technique that has been used extensively for wheelchair users is active stimulation incorporated within the cushion using pulsation or vibration devices. A qualification study was performed on a pulsating seat cushion and adjustable lumbar pad combination for U.S. Navy aircraft. The results showed no increased injury risk, but also highlighted the need for further research in this area [10].

METHODOLOGY

WORKSTATIONS

Two workstations were constructed utilizing ejection seat mockups and foot pedal assemblies modified to simulate the ACES II seat in the F-16 configuration (Figure 1). The seat was mounted such that the rail angle was 15° aft of vertical and the seat pan was inclined 4° from the horizontal. Horizontally adjustable foot pedestals were used for all tests.

Figure 1. Test Seat

SUBJECTS

The protocol was approved by the Wright Site Institutional Review Board and all test subjects consented to the study. Test subjects consisted of civilians. All subjects were pre-screened to ensure no pre-existing risk factors existed that may have increased the risk of DVT. Of 31 medically cleared subjects, 7 were unable to complete all test cells due to scheduling conflicts, 1 dropped out due to discomfort, and 1 was medically disqualified. The data presented in this paper represent 22 subjects, 9 female and 13 male, who completed all test cells. Subject height and weight fell close within the range of U.S. Air Force pilot anthropometry (Figure 2).

PRESSURE MEASUREMENT

Pressure and contact area measurements of the buttocks and upper thigh regions were obtained using the XSENSOR™ X2 Pressure Imaging System. The system consists of 2 thin mats containing a 36 x 36 array of sensors, data interface cable, data acquisition module, and PC software for data analysis. The sensor mats are extremely thin and pliable, enclosed in a nylon covering, and conform to the shape of any surface on which they are placed. The mats were placed on top of the seat cushion and against the back cushion. Subjects sat directly on top of the sensor mats. Similar pressure measurement systems have been used extensively over the past decade for medical, automotive, and manufacturing pressure evaluations

[11,12]. The XSENSOR™ software interface is highly user-configurable and allows for recording data over a span of

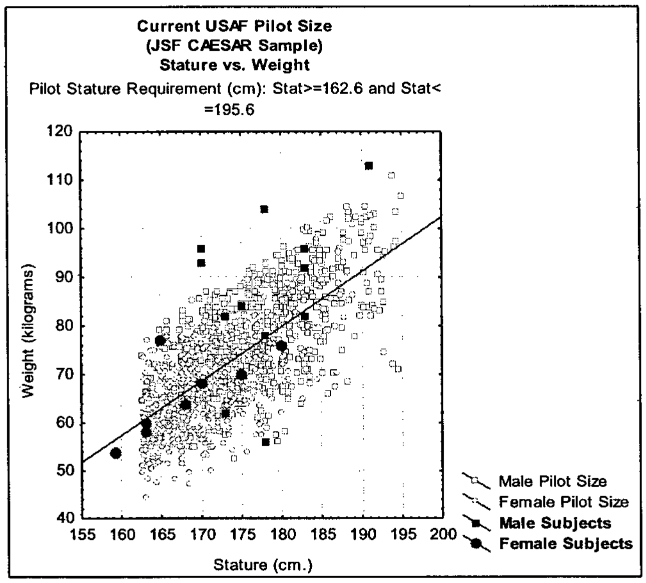


Figure 2. Test subject size plotted against U.S. Air Force pilot size.

time or as a still-frame snapshot in time. Subject pressure snapshots were taken at the beginning of each 8-hour test following a 6-minute settling period for the static cushions. For the dynamic cushion, a time record of the pressure and contact area distribution was collected for the entire 10-minute air flow cycle.

MUSCULAR FATIGUE

The median frequency of the left and right trapezius, erector spinae, and internal obliques was analyzed from the electromyography (EMG) signals that were collected using the DELSYS® hand-held Myomonitor® III data acquisition system. No measurable signal interference was detected due to contact between the subject's back and the back of the seat. The median frequency was used as a means to determine whether muscular fatigue in the shoulder and lumbar muscles induced by either cushion type, seated duration or both was present. The data acquisition system had the capability of acquiring 8 channels of data. Six signal-conditioning surface electrodes with a contact dimension of 10 x 1.0 mm were used. The electrodes required minimal skin preparation and, after being located via palpation, muscle sites were simply cleaned thoroughly with rubbing alcohol. EMG signals from the 6 electrodes were recorded at the start of each session and every 30 minutes for 10-second durations.

OXYGEN SATURATION

Measuring the oxygen saturation of the tissues below the buttocks region is an important parameter in objectively determining the comfort and tolerance relationship of the subject. The Somanetics® Oximeter was used to collect oxygen saturation of the lower extremities while the subject was seated. The Oximeter monitors continuous changes in oxygen saturation of the blood. The measurement is made by noninvasively transmitting and detecting low intensity, near infrared light through sensors that are adhered to the skin surface over the bulk of the medial head of the gastrocnemius muscle. Oximeter readings were recorded continuously at a rate of 14 samples/min from the start of Hour 0 to the end of Hour 8.

COGNITIVE TASK BATTERY

At the start of each session and every 2 hours thereafter, each subject completed a 5-minute cognitive task battery as a measure of performance throughout the 8-hour session. SynWin, created by Activity Research Services, was used to obtain objective performance data. The battery consisted of 4 tasks which the subjects had to conduct simultaneously. The primary display is composed of 4 separated task quadrants: the upper left quadrant is a memory task, the upper right quadrant is an arithmetic task, the lower left quadrant is a visual monitoring task, and the lower right quadrant is an auditory monitoring task (Figure 3). The program reports a composite score and individual task scores for each 5-minute test. Subjects were trained on SynWin to a point where their scores reached a plateau and stabilized prior to starting their first 8-hour test session. SynWin has successfully been used as a measure of cognitive performance in a previous comfort evaluation [2] and has been used extensively at the Warfighter Fatigue Countermeasures Branch of the Air Force Research Laboratory.

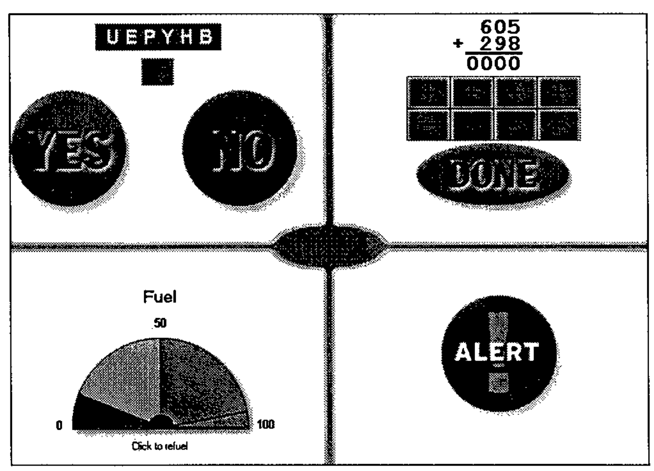


Figure 3. SynWin Task Battery

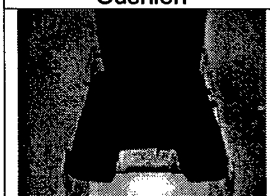
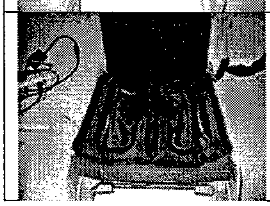
SUBJECTIVE SURVEY

Two subjective comfort surveys were completed by each subject every test session. The first was the Seated Comfort Survey which was administered at the start of each session and every two hours thereafter. The survey required subjects to rate the physical condition of the whole body on a 10-point scale, where 1 was equivalent to "feeling bad" and 10 was equivalent to "feeling great." It also required subjects to rate the discomfort or pain of individual body parts on a 12-point scale, where 0 was equivalent to no discomfort and 11 corresponded to maximal discomfort [13]. The second comfort survey was the End-of-Day Comfort Survey which was administered at the end of the 8-hour session after the subject stood up. This survey required the subjects to rate on a 12-point scale the discomfort, hot spots, or numbness of 11 body parts that became noticeable once they stood from the ejection seat mock-up. Both surveys were collected in order to compare the subjective comfort ratings to objective data.

TEST CELLS

The 4 cushion specimens that were chosen for use in this study were selected based on their material properties and the anticipation that they would provide a diverse range of objective and subjective results. The 4 cushions consisted of an operational ACES II cushion, a prototype from Oregon Aero, a cushion made in-house by combining Confor™ C-47 with a Soft Supracor Stimulite cover, and a dynamic cushion traditionally used to alleviate stresses induced by prolonged wheelchair sitting. Each cushion specimen represents a separate test cell and each subject completed one 8-hour test on each cushion (Table 1). Test cells were completed in Alphabetical order with the starting cell selected based upon a counterbalanced study method.

Table 1. Cushion Specimens/Cell Designation

Cushion	Cell & Description
	Cell A Current ACES II Cushion – Confor™ C-47 and Polyethylene with sheepskin cover
	Cell B Oregon Aero Prototype – Contoured C-47 with sheepskin cover
	Cell C Stimulite/Confor™ Blend – 1" C-47 with 1" soft Supracor Stimulite top layer and nylon cover
	Cell D Ergo Air ErgoDynamic™ Therapeutic Seating System 2000 with mechanical pumping action

SEQUENCE OF AN 8-HOUR TEST SESSION

The test conductor informed the subjects of the tasks and procedures. The subjects were prepped for and fitted with EMG and Oximeter sensors. Seat pan and back rest pressure mats were placed directly atop the test ejection seat cushion. The subjects were seated for a 6- or 10-minute settling period, depending on the cushion type, on the pressure mat and pressure measurements were taken. The pressure mats were then removed and this marked the beginning of the 8-hour session. The Oximeter data were started and continuously recorded until the end of the 8 hours. EMG data were collected for 10 seconds at time 0 and every 30 minutes thereafter. Additionally, at time 0, the first SynWin cognitive task session and the Seated Comfort Survey were administered; this was repeated at 2, 4, 6 and 8 hours. During each 8-hour test, subjects were instructed to complete basic isometric and stretching exercises for the legs every 30 minutes to mitigate the risk of deep venous thrombosis from prolonged periods of static seating. Subjects remained seated at all times during the 8-hour tests. Subjects were trained on the use of appropriate bladder relief devices, which were utilized as needed. At the end of the 8 hours, the Oximeter data collection was terminated and, once the subject stood up, the End-of-Day Survey was completed.

RESULTS

PRESSURE MEASUREMENT

The highest peak pressure averaged over all 22 subjects was measured on Cell D, the Ergo Air ErgoDynamic™ cushion, at 22.2 kPa (Figure 4). The highest peak pressures averaged over the 9 female subjects and averaged over the 13 male subjects were measured on Cell D at 21.1 kPa and 22.9 kPa. Averaged over all subjects, the lowest peak pressure was measured on Cell C, the Stimulite/Confor™ Blend, at 8.4 kPa. The lowest peak pressures averaged over the 9 females and the averaged over the 13 males were measured on Cell C at 7.1 kPa and 9.3 kPa, respectively. The remaining cushions, Cells A and B, had peak pressures between 10.9 and 11.6 kPa averaged over the female subset and 16.1 and 16.7 kPa averaged over the male subset.

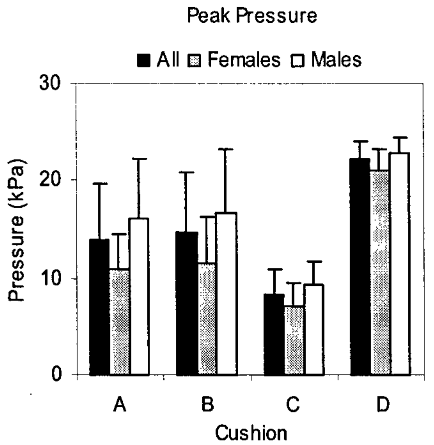


Figure 4. Peak Pressure Results – All Subjects

MUSCLE FATIGUE

As a measure of muscle fatigue, the median frequency of the EMG signal for the 6 monitored muscles was calculated for every 2-hour interval. These values were then compared to the base value at time zero to calculate the average percentage change in median frequency. The median frequency analyses of the lumbar muscles were contaminated due to the low signal-to-noise ratio. This essentially meant that these muscles exhibited no measurable activity.

The median frequency analyses indicated that fatigue over time was induced in the trapezius muscle for the three static cushions – Cells A, B, and C (Figure 5). However, some degree of muscle recovery was present in Cell D, the dynamic cushion, for both female (Figure 6) and male (Figure 7) subjects. Cell A induced the highest level of fatigue for all subjects.

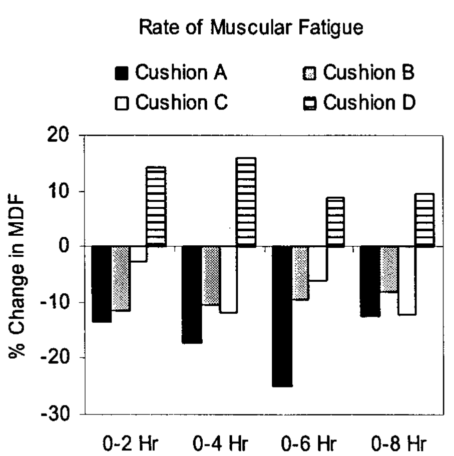


Figure 5. Trapezius Muscle Fatigue – All Subjects

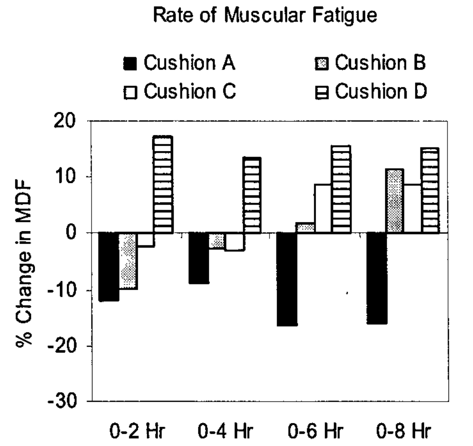


Figure 6. Trapezius Muscle Fatigue – Females

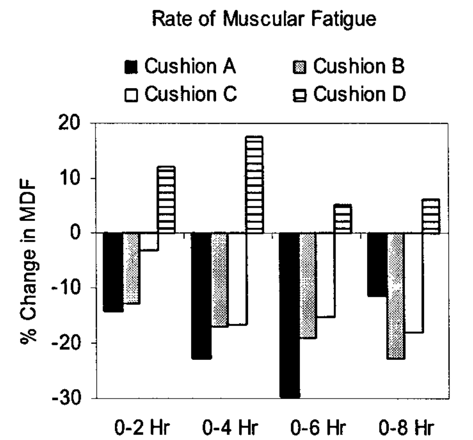


Figure 7. Trapezius Muscle Fatigue – Males

OXYGEN SATURATION

An average of 5-minute periods of the lower extremity oxygen saturation data was calculated at every 2-hour interval and compared to baseline. Regardless of cushion, the general trend for all 22 subjects was a decrease in the oxygen saturation level over time (Figure 8). This trend remains consistent when the data are divided by gender; with the exception of a 1.66% increase from baseline for females on Cell A (Figure 9). Although there were no statistically significant differences between cells for female subjects, males had a significantly higher decrease in oxygen saturation on Cell C as compared with Cells A and B (Figure 10).

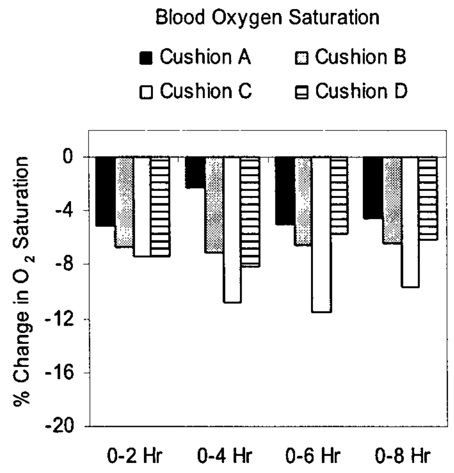


Figure 8. Oxygen Saturation – All Subjects

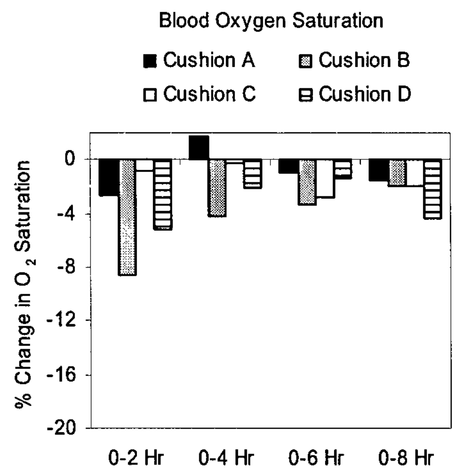


Figure 9. Oxygen Saturation – Females

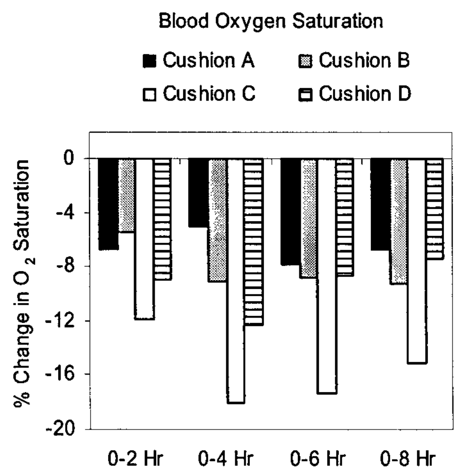


Figure 10. Oxygen Saturation – Males

PERFORMANCE TASK

The performance data from the SynWin task were analyzed to determine the percent improvement or degradation between the initial assessment at the beginning of each 8-hour test and the scores of every 2-hour assessment. The general trend for all 22 subjects was an improvement in performance between the initial assessment and each 2-hour assessment (Figure 11). For all cells except Cell D, subjects exhibited a steady increase in performance up to the 6-hour mark, after which there existed a slight decline. For Cell D, the performance of the male subjects increased over the 8-hour session (Figure 13); however, the performance of the female subjects decreased throughout the 8 hours (Figure 12).

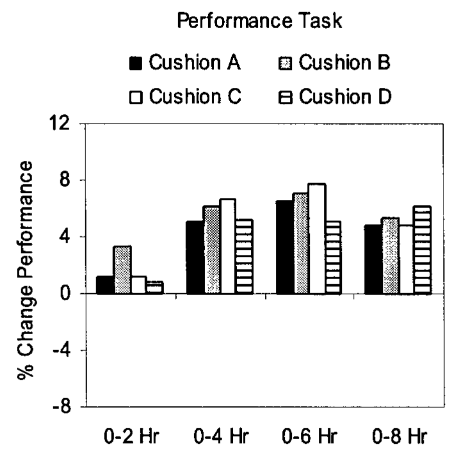


Figure 11. Performance Task Results – All Subjects

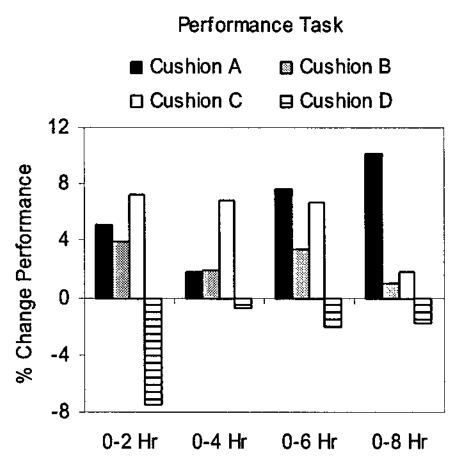


Figure 12. Performance Task Results – Females

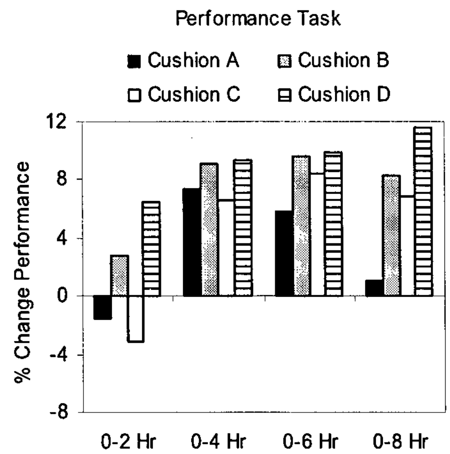


Figure 13. Performance Task Results – Males

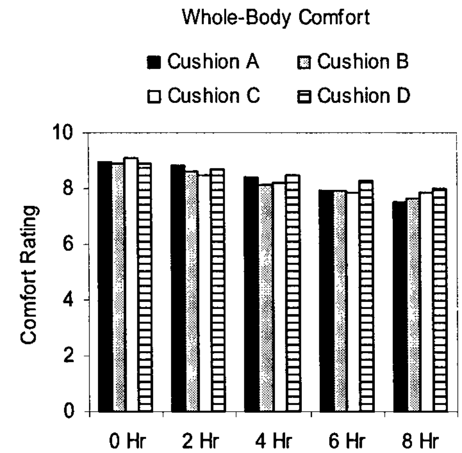


Figure 14. Whole-Body Survey Results – All Subjects

SEATED COMFORT SURVEY RESULTS

A subjective physical condition level for the whole body was reported at every 2-hour interval. All subjects experienced a decline in comfort regardless of cushion over the 8 hours (Figure 14). This trend was true for both female and male subjects; however, females typically reported lower levels of comfort than their male counterparts.

Of the ratings of discomfort for the individual body parts, the survey responses for buttock and thigh discomfort were chosen for reporting because of the direct relationship of the buttocks and thighs to the seat pan cushion and the high frequency of subject complaints in that area. In general, females rated higher levels of buttock discomfort for all cushions. The average survey results for buttock discomfort for all subjects showed that Cells A and D were the least comfortable (Figure 15). This relationship was slightly different within the female and male subsets. Females rated Cells A and D as least comfortable, while males rated Cell B as uncomfortable as Cells A and D.

As with the buttock discomfort ratings, females rated Cells A and D as the most uncomfortable cushions for the thighs. Males rated Cells B and C as the most uncomfortable for the thighs (Figure 16).

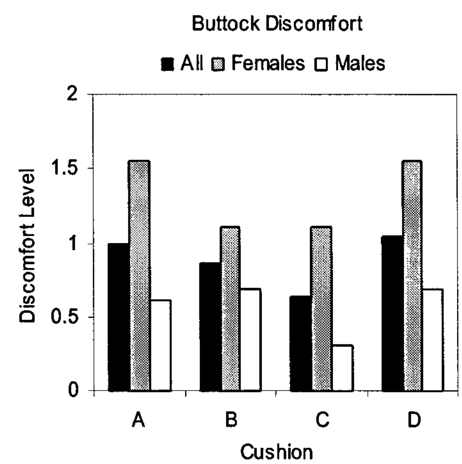


Figure 15. Seated Buttock Survey Results

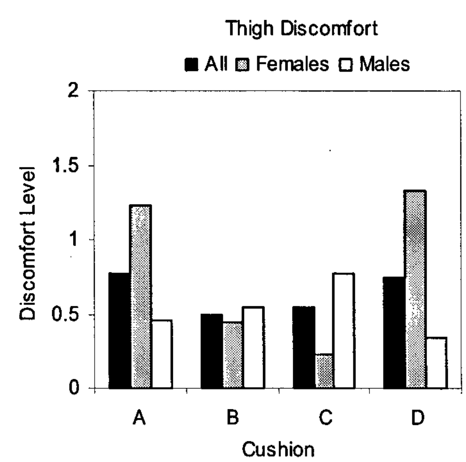


Figure 16. Seated Thigh Survey Results

END-OF-DAY COMFORT SURVEY RESULTS

The End-of-Day Comfort Survey was administered after the 8-hour session was complete immediately after the subject had stood up from the ejection seat. As with the Seated Comfort Survey, females reported the highest discomfort for Cell D for both the buttocks and the thighs. The cushion that the females found the most comfortable, Cell C, was the one that males rated as the most uncomfortable for both the buttocks and the thighs (Figures 17 and 18).

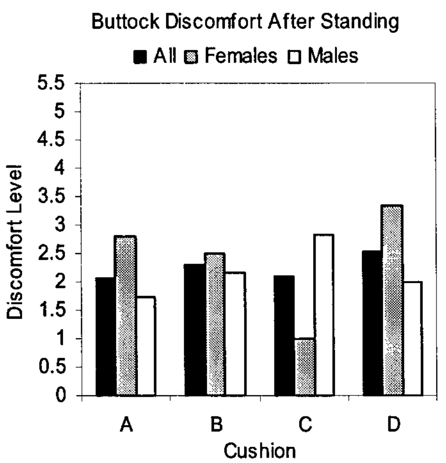


Figure 17. End-of-Day Buttock Survey Results

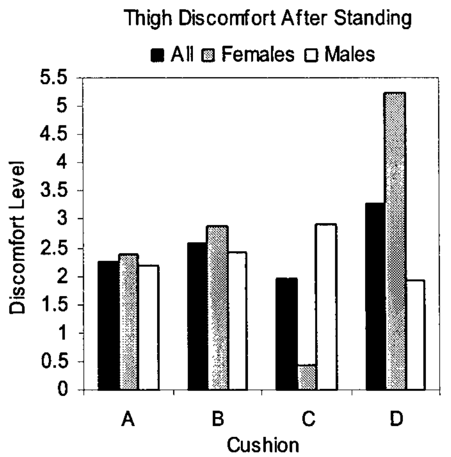


Figure 18. End-of-Day Thigh Survey Results

DISCUSSION

Current operational and prototype cushions were tested using objective and subjective methods to determine comfort characteristics. Peak pressure, muscle fatigue, lower extremity oxygen saturation, performance scores, and survey data were collected over the course of 8-hour sit tests.

Peak pressure was measured using the XSENSOR™ X2 pressure measurement system. As in the cushion evaluation conducted by Stubbs et al. [2], it was expected that cushions with the lowest peak pressure points would show similar positive characteristics in other subjective and objective tests and that cushions with the highest peak pressure points would show similar negative characteristics in the other tests. For the static cushions, this proved to be the case for the correlation between average peak pressure and subjective discomfort survey ratings for the buttocks and thighs. Cell A, the current operational ACES II cushion, exhibited high peak pressure values and was rated as the least comfortable in buttocks and thigh discomfort among the static cushions. Cell C, the Stimulite/Confor™ blend cushion, exhibited the lowest average peak pressure as well as the lowest buttocks and thigh discomfort rating while seated among all cushions for both female and male subjects. The dynamic cushion did not follow this same trend. Cell D, the ErgoDynamic™ cushion, elicited the highest peak pressure among all cushions for all subjects, but was not rated as the most uncomfortable by males. Females, on the other hand, reported very high levels of seated and end-of-day discomfort with Cell D. Positive correlation was also noted between the performance task data and the highest peak pressure for the static cushions, which is in agreement with previous study [2]. Among the static cushions, Cell C showed the greatest improvement in the composite task score over 8 hours. The dynamic cushion, Cell D, showed the greatest improvement of all cushions for the male subjects, but showed a decrement in scores throughout the 8-hour session for females. The results of the performance task suggest that static cushion comfort does not have a negative impact on subject performance; however, low dynamic cushion comfort may be detrimental to performance. The wide difference between genders on the comfort responses to the dynamic cushion is probably in part due to the pressure exerted by the cushion and the changes over time. The pressure changes may be providing a level of relief to the males but not to the females. Comfort on dynamic cushions may be highly dependent upon gender-related anthropometric variations and this should be further investigated.

The three static cushions also elicited similar responses in levels of trapezius muscle fatigue. Trapezius muscle fatigue was exhibited throughout the 8-hour session for male subjects for all three static cushions. Cell A induced the highest rate of muscle fatigue for both males and females. Cell A is the only cushion that fatigued the females throughout the entire 8-hour session. Cells B and C were fatiguing up to the 4-hour mark, after which recovery was present. The dynamic cushion elicited a unique response for both males and females due to the fact that no fatigue, and potentially recovery, occurred at every 2-hour interval. No measurable activity was present for the lumbar muscles. This may be due to the lack of constraints placed on the assumed posture of the subjects. Restricting the motion as is typical in aircraft such as the F-16 should induce fatigue due to the low levels but constant activity that would be required of the lumbar muscles to maintain a restricted posture. More realistic aircraft scenarios with appropriate mobility restraints will be investigated in future studies. Restraining the posture will not only affect fatigue in the lumbar musculature but will also affect the trapezius muscles because these muscle are more indicative of head and neck positioning which can be influenced by the overall body position.

Although minimal changes of oxygen saturation and no differences between cushions were found for female subjects, males exhibited significantly decreased levels of oxygen saturation for all cushions, especially for Cell C. This cushion, although eliciting the lowest average peak pressure, had the highest levels of discomfort in the buttocks and thighs for the male subjects after standing. Due to the low pressures, male subjects may have felt that minimal movement was necessary to maintain comfort. This is supported by the low levels of oxygen saturation measured in male subjects for this cushion. This illuminates the necessity for additional objective measures of comfort other than the traditional measure of seated pressures. Although pressure issues are of utmost importance, if a cushion is composed of such materials that little to no movement is necessary to remain comfortable this may prove to be detrimental because motion and maintaining proper blood flow are necessary to mitigate long-term effects, such as the discomfort that the male subjects felt after standing. An automated dynamic cushion may help to alleviate this problem because motion under the buttocks will be forced and blood circulation will be maintained. It must be noted that monitoring oxygen saturation in the lower extremities is a relatively new modality for determining blood flow and pooling patterns and Oximeter data collection and processing techniques must be further investigated.

The difference in cushion properties and preferences between genders was a finding of interest in this study and will be examined in future studies. The differences could potentially be related to anthropometric and weight distribution variations between genders and their respective interactions with varying cushion materials.

CONCLUSION

In total, 88 eight-hour test sessions were completed. As in previous findings, peak pressure correlated well with comfort ratings for the static cushions where higher pressures elicited higher discomfort. However, low peak pressures may cause less fidgeting and promote blood pooling which can induce discomfort after a long bout of sitting. Static cushions also seem to have no benefit in muscle fatigue mitigation. Due to the concern with long periods of static sitting causing deep vein thrombosis and pressure sores, investigations of dynamic cushions must continue. Dynamic cushions indicated that there may be trade-offs in performance and fatigue mitigation, but further studies must be done to understand the implications of dynamic stimulation on both female and male operators. No incidence of injuries occurred in any subject at any time during this study. These findings will be used in developing cushion design guidelines that will maximize performance and comfort without jeopardizing ejection safety.

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