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Cushion Effects During Low Frequency Jet Aircraft Vibration Exposure

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14. ABSTRACT
Objective: The purpose of this study was to compare the biodynamic, subjective comfort, and occupant performance effects of a prototype active air bladder cushion, a prototype contoured rate-sensitive foam cushion, and a standard flat aircraft cushion during exposure to low level vibration. **Methods:** Subjects were exposed to 30 minutes of low level F-15 aircraft vibration for each seat pan cushion while performing the Multi-Attribute Task Battery in the laboratory. Following the exposure, the subjects completed a questionnaire and survey on subjective comfort and support. **Results:** No clear trends were observed in performance. In general, all cushions showed similar results with respect to the subjective comfort of various body parts and the seat comfort and support ratings. There was an indication that the standard cushion was more firm than the prototypes. All cushions tended to be rated as too firm. This coincided with greater discomfort and less adequate support in the buttocks but adequate thighs/legs comfort and support. **Conclusions:** The transmissibility results indicated that the prototype cushions may provide beneficial dampening effects that could influence comfort and performance for exposures to higher level, higher frequency operational vibration.

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SUMMARY

The purpose of this study was to compare the biodynamic, subjective comfort, and occupant performance effects of selected prototype seat pan cushions and a standard cushion used in high performance military jets during exposure to low levels of vibration. This study supported the Air Force Research Laboratory (AFRL) 6.3 Technology Demonstration program, "Seat Interfaces for Aircrew Performance and Safety" [1]. The program was sponsored by the Vulnerability Analysis Branch of the 711th Human Performance Wing (711 HPW/RHPA). Two prototype cushions were selected from those tested under static conditions as part of the 6.3 effort. The first prototype cushion included rate-sensitive foam and an active air bladder. The second prototype cushion included a contoured layer of rate-sensitive foam. The standard ACES II cushion was a thin, flat foam cushion.

Level flight vertical axis (Z) vibration collected on the F-15 was recreated in the 711 HPW/RHPA human-rated single-axis vibration facility. Subjects performed the NASA Multi-Attribute Task Battery (MATB) during 30-minute exposures to the vibration while seated in a modified ACES II ejection seat with either a prototype seat pan cushion or the standard seat pan cushion. Following the exposure with each cushion, the subjects completed a Comfort Questionnaire and Body Parts Comfort Survey. The questionnaire and survey were used to assess subject comfort and provide an indication of which cushions the subjects preferred. Subjects were then briefly exposed to a flat acceleration spectrum for evaluating the transmissibility characteristics of the tested seat cushion at the occupant/seat interface.

Task performance showed no clear trends over the 30-minute periods and was found to be similar among the cushion configurations. This was expected due to the short exposure duration and relatively low vibration level. In general, all cushions showed similar results with respect to the subjective comfort of various body parts and the seat comfort/support ratings, although there was an indication that the standard cushion was more firm than the prototypes. All cushions tended to be rated as too firm. This coincided with the observations of greater discomfort and less adequate support in the buttocks, but adequate thighs/legs comfort and support.

Two distinct peaks were observed in the acceleration spectrum measured at the subject/seat interface. The first peak occurred around 8.5 – 9 Hz and was associated with a structural resonance in the aircraft. All cushions showed similar magnitudes at this peak. The second peak occurred around 26.5 – 27 Hz and was associated with a harmonic of the first peak. The standard cushion produced significantly higher peaks than the prototype cushions at this harmonic. The rate-sensitive foam prototype showed a significantly higher peak than the air bladder prototype at this harmonic. The vibration transmissibility results did show that the prototype cushions significantly increased the transmission of vibration to the subject in the vicinity of 4 to 5 Hz. These frequencies coincide with human whole-body vibration resonance in the vertical direction. At higher frequencies beyond 8 – 10 Hz, the prototype cushions dampened the vibration, the greatest dampening occurring with the air bladder cushion. While these findings were inconsequential with respect to performance and subjective comfort during low level vibration associated with jet aircraft, the results did indicate that the prototype cushions may provide beneficial dampening effects that could influence comfort and performance for exposures to higher level, higher frequency operational vibration.

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1.0 INTRODUCTION

World events have driven military tactical and strategic flight missions to record durations, exposing aircrews to a variety of operational stressors while being confined to restricted spaces. Sitting for long durations in these restricted spaces can severely limit lower body movement and have physiological as well as psychological consequences. Decreased blood flow, pooling of blood, edema, and tingling or numbness in the lower extremities have been associated with symptoms of fatigue, annoyance, and even pain when restricted to static postures for long durations [2]. According to [2], maintaining normal blood flow could minimize fatigue and improve flight performance.

Aircrews have historically complained of poor seat design. Until the 1990s, these complaints were primarily addressed through subjective data collected on the aircrew and did not necessarily lead to improved seat design [3]. As early as the 1950's, Hertzberg [4] attempted to collect more objective data by quantitatively measuring seated buttocks pressure, although attempts to improve seated comfort were still hit or miss. Once sensor technology improved in the 1990s, quantitative measurements of seated pressure were more common [3]. Guidelines were suggested for improving seat comfort and included the even distribution of seated pressure to minimize pressure hot spots and avoiding compression of the thighs that could interfere with circulation and lead to pain and numbness [3].

A more recent study, conducted by the 711 HPW/RH, focused on evaluating objective measures of seat comfort. Subjects were exposed to eight hours of static seating using four different seat pan cushions; two were fabricated entirely of rate-sensitive foams, one was layered with a combination of rate-sensitive foam and polyethylene, and one was layered with a combination of rate-sensitive foam and urethane honeycomb air cells [5]. In addition to measuring peak and average pressures and contact areas, subjects also completed a subjective survey and a cognitive performance task (Synthetic Work for Windows, SynWin, Activity Research Services). The highest peak pressure was observed with the current ACES II cushion fabricated with rate-sensitive foam and polyethylene. The average peak pressure data correlated well with the subjective ratings for buttocks discomfort, with the ACES II cushion rated the least comfortable. Mixed results were observed for task performance; the contoured rate-sensitive prototype and rate-sensitive plus air cells prototype showed some performance improvements (15% with air cell prototype), while the ACES II rate-sensitive cushion and non-contoured rate-sensitive prototype showed either no improvement or very slight degradation in performance.

Back in the 1970's, researchers evaluated the ability of active stimulation to promote blood circulation while in the seated posture. One design included the use of a pulsating-type seat cushion to maintain blood circulation and minimize fatigue. Subjects were tested for a three-hour period in a confined seated posture in the non-pulsating and pulsating modes [2]. Blood flow velocity measured at the foot showed the greatest reduction with the non-pulsating configuration. The pulsating cushion was also reported by the subjects to be more desirable and having less effect on fatigue.

A follow-on to the previous eight-hour study [5] included a therapeutic seat utilizing active stimulation via pulsating air [6]. Additional measurements included electromyography (EMG) of the low back and shoulders and oxygen saturation in the lower extremities. This study aimed to investigate the correlation between physical fatigue and cognitive performance [7]. As with the previous study, peak pressure correlated well with the subject ratings of both buttocks and thigh discomfort for the three static cushions. The highest peak pressure was measured with the pulsating cushion. This cushion was rated the most uncomfortable by the female subjects but not by the male subjects. The composite task scores (SynWin) showed the greatest improvement with this cushion for the males, but showed a degrading effect in the females. Muscle recovery was observed in the trapezius for all subjects with this cushion. For all cushions, there was a general trend for a decrease in blood oxygen saturation over time. The authors concluded that there may be trade-offs with performance and fatigue mitigation when using dynamic cushions [6, 7].

In 2006, the 711 HPW/RH initiated a series of studies to further evaluate and compare cushion designs and their ability to minimize discomfort during prolonged missions in jet aircraft. Subjects were seated in an F-16 cockpit mockup. The static comfort studies were 4 hours and 8 hours in duration. These studies included an ACES II operational seat cushion, a contoured rate sensitive foam prototype, and an air bladder cushion that inflated and deflated over time. One difference between this air bladder cushion and the one used in [6] was that the air tubes ran laterally across the seat pan cushion instead of fore-and-aft. In both the 4-hour and 8-hour experiments, seated pressure measurements were obtained 6 minutes into the study. In the 4-hour study, lower leg blood pooling was evaluated using a bioelectrical impedance analysis. In the 8-hour study, blood oxygen saturation was measured in the lower leg. In addition, the subjects completed a cognitive task battery every two hours. Both studies included an electronic comfort survey. The survey was conducted every hour in the 4-hour study and every 2 hours in the 8-hour study. Data analysis is near completion. The preliminary results for the comfort survey did show that the air bladder cushion was given the highest comfort rating among the male and female subjects during the 8-hour study.

In an effort to compare these cushions in a more operationally-relevant environment, a study was conducted that included exposure to operational vibration. The objective was to compare the biodynamic effects and subjective comfort of selected cushions used in the static studies while being exposed to low level vibration encountered in military jet aircraft. This report presents the results of the low level vibration study.

2.0 METHODS AND PROCEDURES

2.1 Facility, Equipment, and Instrumentation

All testing was accomplished in the Single-Axis Servo Hydraulic Human Vibration Facility located in Building 824, Area B, Wright-Patterson AFB, OH. The human-rated single-axis vibration table is capable of recreating operational exposures in the vertical or Z direction. A rigid seat (modified ACES-II ejection seat) with seat pan and seat back cushions was mounted on top of the single-axis platform.

The seat pan cushion configurations included a standard ACES-II cushion and two prototype ejection seat cushions. Figure 1 illustrates a subject sitting in the seat mounted on top of the

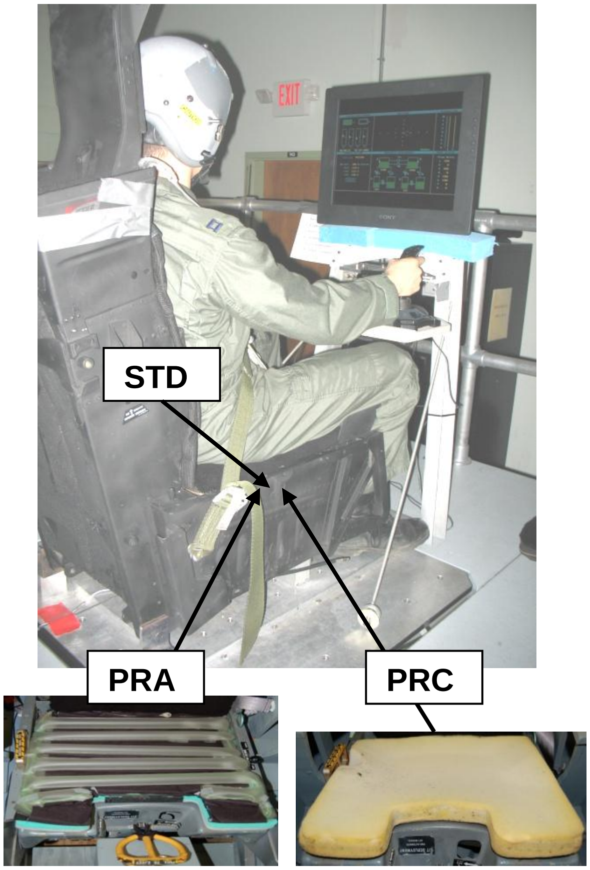

Figure 1 Subject Seated in Single-Axis Facility

vibration table with the standard (STD) seat pan cushion. Also shown are the prototype air bladder cushion (PRA) and prototype rate-sensitive foam cushion (PRC) with their covers removed. These prototype cushions were used in the 4-hour static study described above. The standard (STD) cushion was a thin, flat foam cushion encased in a fur-like material. The first prototype cushion (PRA) included a lower layer of stiff foam and rate-sensitive foam, and an upper layer of air bladders that slowly cycled air when activated (Figure 1). The cushion incorporated a small motor and battery pack to pump the air into the bladders once activated via a switch. The second prototype cushion (PRC) included a contoured layer of rate-sensitive foam (Figure 1). Both cushions were encased in fabric that included a thick, wool-like material on the top surface (not shown). A standard seat back cushion was used for all configurations. The seat back cushion was comprised of thin foam encased in fabric. A similar smaller cushion was attached to the seat back cushion via Velcro and was used for low-back support.

The table floor and seat base were instrumented with a triaxial accelerometer pack consisting of three miniature accelerometers (ENTRAN EGA 125-10D or EGAX-25) embedded in a Delrin cylinder. Triaxial accelerometer pads were placed between the subject and seat pan cushion and seat back cushion to measure the acceleration entering the human body at the points of contact with the seating system. The pads consisted of a rubber disk with a triaxial accelerometer pack mounted in the center. The seat pan pad was only used during the brief time required to collect the acceleration data. The seat back pad remained at the interface for the duration of the test session.

2.2 Vibration Signal Generation

The primary vibration exposure was a selected 20-second signal collected during level flight operations onboard the F-15 aircraft. The signal was generated at 1024 samples per second and continuously repeated, as necessary, to meet the exposure requirements for each test session as described below. In addition, the subjects were also briefly exposed to a 20-second constant bandwidth flat acceleration spectrum at 1.0 ms^{-2} rms in the frequency range from 1 to 80 Hz. This signal was also generated at 1024 samples per second and repeated as necessary for data collection. This signal was used to estimate the transmissibility characteristics of the tested seat pan cushion.

2.3 Acceleration Data Collection and Processing

At selected times during a test session, the seat pan acceleration pad was carefully placed between the subject and the seat pan or cushion surface. During the F-15 signal exposure, accelerations were collected for 20 seconds, low-pass filtered at 100-Hz (anti-aliasing), and digitized at 1024 samples/second. The subjects were then exposed to the flat acceleration spectrum and data were similarly collected for 20 seconds at 1024 samples/second.

The acceleration data were processed using the MATLAB® Signal Processing Toolbox (The Mathworks, Inc., Natick, MA) to estimate the constant bandwidth spectra. Using Welch's method, each 20-second time history was divided into two-second sub-segments with a 50% overlap. A Hamming window was applied to each sub-segment, and the resultant power spectral densities were averaged for the 20-second period. The root-mean-square (rms) acceleration, a_{rms}, was calculated from the power spectral densities at 0.5 Hz intervals.

The seat pan transmissibility was calculated as

$$H(\omega) = {P_{zZ}(\omega)}\Big/{P_{ZZ}(\omega)} \qquad 1$$

where P_{zZ} is the cross-spectrum between the input z (floor) and output Z (seat pan), and P_{zz} is the auto-spectrum of the input z. For this case, the ordinary coherence, $C(\omega)$, is estimated as follows:

$$C(\omega) = {\left|P_{zZ}(\omega)\right|^2}\Big/{P_{zz}(\omega)P_{ZZ}(\omega)} \qquad 2$$

where P_{ZZ} is the auto-spectrum of the output Z. The ordinary coherence indicates the extent to which the output is linearly related to the input. Values less than unity reflect the contribution of other factors (noise). The rms acceleration data were evaluated to see if any significant changes occurred in the input vibration spectra between cushion configurations, subjects, and test days. The transmissibility data were used to define and compare the vibration characteristics of each cushion configuration.

2.4 Performance Task and Comfort Assessments

During the tests, the subjects performed the Multi-Attribute Task Battery (MATB) [8]. MATB is a PC-based multi-component performance test battery created by NASA. Figure 1 includes a subject performing the task. Figure 2 shows a more detailed view of the task display. There were four tasks which the subjects conducted simultaneously. The tasks included a visual monitoring task with dials and lights (System Monitoring), a visual tracking task using a joystick (Tracking), a resource management task (Resource Management and Pump Status) and an

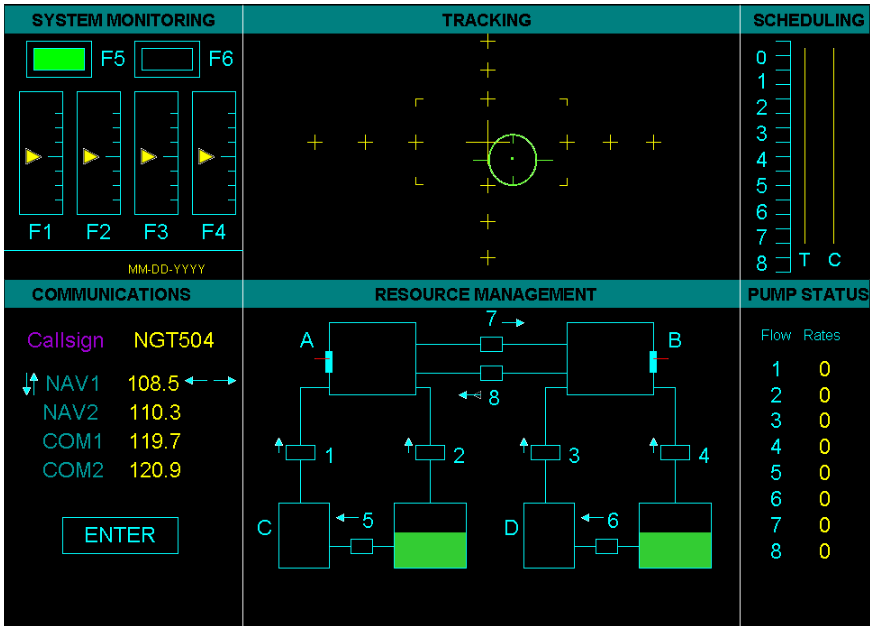

Figure 2 MATB Multi-Attribute Task Battery

auditory monitoring task (Communications). For this study, the Scheduling task was not performed. The joystick and keyboard-controlled tasks were generated onto a flat-panel display located in front of the subject (similar to one's desktop computer). The software package included the analysis of several parameters depending on the particular task. Among the tasks, there were approximately 31 parameters that could be evaluated at selected time periods during the exposure as well as over the entire test period. For example, response time and total errors were two parameters evaluated for the Communications task.

A Comfort Questionnaire designed by TNO Defence, Security and Safety [9] was used to assess subject comfort and provide an indication of which cushions the subjects preferred. The questionnaire was completed using the computer at selected intervals in the test session. The TNO Comfort Questionnaire included the local perceived discomfort (LPD) for various body areas and the seat ratings. The various body areas are depicted in Figure 3 [9]. The LPD rating used a 12-point scale ranging from 0 (no discomfort) to 11 (maximum discomfort). The results of the LPD ratings were combined for several areas. The neck consisted of areas P, Q, R, S, and T. The back combined the areas A, B, C, and D to L. The arms and shoulders included areas AA-KK, G, H, O, and M. The buttocks included areas LL and SS. The legs combined the areas of the upper legs (MM and TT) to the feet (ZZ, RR).

The seat ratings included the Overall Seat Impression, Seat Pan Firmness, Buttocks Support and Comfort, and Thigh/Legs Support and Comfort. The Overall Seat Impression was rated between 1 (bad) and 5 (good). The Seat Pan Firmness was rated on a 7-point scale ranging from -3 (too soft), 0 (just right) and +3 (too firm). The Buttocks and Thigh/Legs Support were also rated on a 7-point scale ranging from -3 (too little), 0 (just right), and +3 (too much). These ratings were transposed to a range of 0 to 6 for statistical analysis. The subjects rated the

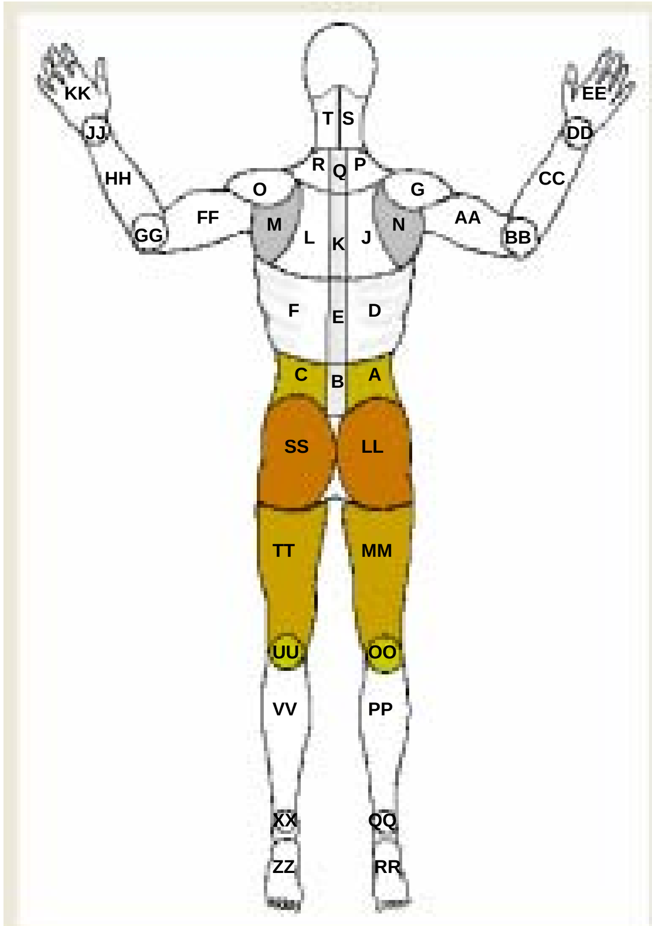

Figure 3 TNO Body Areas

Buttocks and Thigh/Legs Comfort on a scale from 1 (uncomfortable) to 5 (comfortable). Figure 4 shows an example of the seat rating portion of the questionnaire.

In addition to the TNO Comfort Questionnaire, a Body Parts Comfort Survey was conducted. In this survey, the subjects were asked to name, from a list posted in front of them, those body parts where they felt the low level vibration:

1. No Specific Location
2. Face
3. Head/Neck
4. Upper Back
5. Chest
6. Lower Back
7. Buttocks
8. Upper Legs
9. Lower Legs
10. Feet

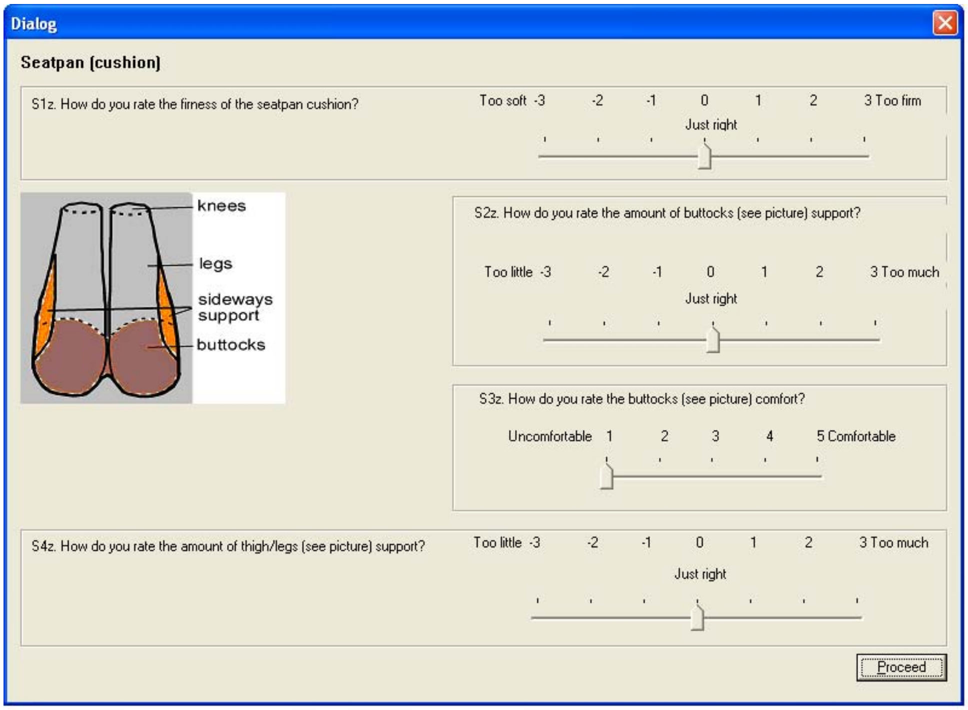

Figure 4 TNO Example Seat Rating

The subjects were then asked to rate the comfort according to the comfort reactions defined in the ISO 2631-1: 1997 [10] and posted in front of them:

1. Not Uncomfortable
2. A Little Uncomfortable
3. Fairly Uncomfortable
4. Uncomfortable
5. Very Uncomfortable
6. Extremely Uncomfortable

The locations and their ratings obtained from the posted list were combined and reduced to three general locations: no specific location, upper torso (including the face, head/neck, upper back, and chest), and lower torso (including the lower back, buttocks, upper and lower legs, and feet).

2.5 Testing Procedures

2.5.1 Subject Clothing and Restraint

The subjects wore BDUs during the training sessions (including boots) and wore a flight suit during the formal tests (including boots). All subjects wore a P-55 helmet equipped with headphones for hearing the verbal commands in the MATB tasks. During all tests, the subjects were lightly restrained in the seating system using a lap belt and double shoulder harness and asked to maintain an upright posture with the back in contact with the seat back.

2.5.2 Training

Four training sessions were conducted prior to formal testing. During the first training session, subjects were familiarized with the vibration facility, the exposure signals, and the performance tasks. The remaining training sessions exposed the subjects to two 10-minute sets of MATB while being exposed to the F-15 vibration signal. Following each set, the subjects completed the TNO Comfort Questionnaire. Training was considered sufficient when the MATB task scores reached a baseline level between training sessions after a five-minute warm up. This occurred within the four training sessions.

2.5.3 Formal Test Sessions and Testing Sequence

During each test session, two seat configurations were tested: the ACES-II seat with one of the two prototype seat pan cushions (PROTO), and the ACES-II seat with the standard seat pan cushion (STD). Both configurations included the standard seat back cushions described previously. Prior to initiating the test session, there was a 5-minute task warm-up period where the subject performed the MATB task without vibration. The subject was then exposed to the F-15 level flight vibration (F15LF) with either the PROTO or STD seat configuration. The subject performed MATB for 30 minutes. Following this 30-minute period, the vibration was stopped and the subject was asked to complete the TNO Comfort Questionnaire and Body Parts Comfort Survey. Once completed, the subject lifted part way out of the seat just enough to attach the seat pan acceleration pad to the seat. The vibration table was then activated and there was a brief exposure (less than 1 minute) to the F15LF and the flat spectrum (FLAT) signals for data collection in the initial seat configuration. This procedure was done to avoid introducing any effect of the seat pad on the subjective assessment of the seat cushion during the vibration exposure. Following the collection of acceleration data, the system was shut down. The subject was escorted from the seat and allowed to stretch their legs and arms while the seat was reconfigured with the second cushion configuration. The subject was seated and lightly restrained. There was another 5-minute warm-up period where the subject performed the MATB task without vibration. The subject was then exposed to the F15LF signal and performed the MATB task for another 30 minutes. The vibration was stopped and the subject completed the questionnaire and survey. The seat accelerometer pad was again installed, the table activated, and accelerations collected during brief exposures to the F15LF and the FLAT signals. The seat back acceleration pad was attached to the seat back cushion for the duration of the test session.

There was a total of 6 formal test sessions (2 prototype cushions, PRA and PRC). Table 1 includes the testing scheme. One-half of the subjects were exposed once to test session TEST A and twice to test session TEST B. The other half was exposed once to test session TEST B and twice to test session TEST A. This varied the presentation of the cushions with each subject being tested a total of three times with the PROTO configuration and three times with the STD configuration. A 48-hr rest period was required between vibration test sessions.

Table 1. Test Session Scheme (per prototype cushion configuration)

TEST A				
SEAT CONFIG.	TIME	EXPOSURE	TASK	ACCELERATION
PROTO	-5–0 Min	None	MATB	No
PROTO	0-30 Min	F15LF	MATB	No
PROTO	~5 Min	None	Questionnaire	No
PROTO	20 Sec	F15LF	None	Yes
PROTO	20 Sec	FLAT	None	Yes
Change Seat Configuration				
STD	-5-0 Min	None	MATB	No
STD	0-30 Min	F15LF	MATB	No
STD	~5 Min	None	Questionnaire	No
STD	20 Sec	F15LF	None	Yes
STD	20 Sec	FLAT	None	Yes
TEST B				
STD	-5–0 Min	None	MATB	No
STD	0-30 Min	F15LF	MATB	No
STD	~5 Min	None	Questionnaire	No
STD	20 Sec	F15LF	None	Yes
STD	20 sec	FLAT	None	Yes
Change Seat Configuration				
PROTO	-5-0 Min	None	MATB	No
PROTO	0-30 Min	F15LF	MATB	No
PROTO	~5 Min	None	Questionnaire	No
PROTO	20 Sec	F15LF	None	Yes
PROTO	20 sec	FLAT	None	Yes
PROTO: Selected Prototype Seat Configuration STD: Standard Seat Configuration F15LF: F-15 Level Flight Exposure FLAT: Flat Vibration Spectrum				

3.0 RESULTS

All Figures and Tables referred to in this section are located in Appendix A. The Repeated Measures Analysis of Variance and Bonferroni Comparison Test were used to determine significant differences ($P < 0.05$).

3.1 Acceleration Spectra and Transmissibility

Figure A-1 illustrates the seat base vertical acceleration spectra (acceleration entering the seating system) during exposure to the F-15 signal (F15LF) for four subjects in the various cushion configurations. The spectra for the standard cushion (STDA) and the first prototype (PRA) were collected during the same test session. The spectra for the standard cushion (STDC) and second prototype cushion (PRC) were collected during the same test session. The figure also includes the acceleration spectra of the original F-15 input signal. For the data shown, the overall seat base rms acceleration ranged from 0.25 – 0.28 ms^{-2} rms as compared to the original F-15 signal at 0.17 ms^{-2} rms. The base accelerations did show somewhat higher peak magnitudes as compared to the original signal, as shown in Figure A-1. The figure does show that the base accelerations were similar among the subjects and seat configurations. The distinct peak observed around 8.5 – 9 Hz (PEAK 1) has been associated with F-15 buffeting during high angle-of-attach maneuvers, although the acceleration magnitudes associated with these maneuvers are quite a bit higher than during level flight [11]. A second distinct peak was observed around 26.5 – 27 Hz (PEAK 2) and was assumed to be a harmonic of the first aircraft aerodynamic resonance mentioned above. A broader peak was observed to be centered around 40 Hz. It was not clear what contributed to the generation of this peak that was also observed in the original F-15 input signal.

Figure A-2 illustrates the seat pan vertical acceleration spectra (acceleration entering the subject at the cushion/occupant interface) for the same four subjects in the various cushion configurations mentioned above. The figure suggests that there were minimal differences in the frequency location of the spectral peaks (which also coincided with the input signal), but some differences in the magnitude of the spectral peaks among the subjects. For the data shown, the overall seat pan rms acceleration ranged from 0.15 to 0.30 ms^{-2} rms. Regardless, the figure does show differences in the magnitudes of certain peaks depending on the configuration.

Figure A-3 illustrates the mean seat pan acceleration magnitudes ± one standard deviation associated with PEAK 1 and PEAK 2 for each of the cushion configurations for the three repetitions (REP 1, REP 2, and REP 3). It is emphasized that STDA and STDC are the same cushion. Figure A-3a shows very little differences in the acceleration rms magnitudes among the cushions for the 8.5 – 9 Hz peak (PEAK 1). However, the statistical analysis showed that the peaks for STDC and PRC were significantly greater than PRA for REP 1. PEAK 1 for STDC was significantly greater than PEAK 1 for PRA for REP 2. There were no significant differences in the magnitude of PEAK 1 among the cushions for REP 3. There were no significant differences in the magnitude of PEAK 1 among the three repetitions for any specific cushion configuration. In contrast to PEAK 1, Figure A-3b strongly suggests differences in the acceleration rms magnitudes among the cushions for the 26.5 – 27 Hz peak (PEAK 2). The statistical analysis showed no significant differences between the two standard configurations (STDA and STDC) for all three repetitions. The PEAK 2 magnitude was significantly higher for STDA, STDC, and PRC as compared to PRA for all three repetitions. The PEAK 2 magnitude was significantly higher for STDA and STDC as compared to PRC except for REP 2, where STDA was equal to PRC. In summary, PRA showed the lowest magnitude for PEAK 2 among all of the cushion configurations, as reflected in the seat pan acceleration spectra (Figure A-2). There were no significant differences in the magnitude of PEAK 2 among the three repetitions for any specific cushion configuration.

Figure A-4 illustrates the mean vertical (Z/z) seat pan transmissibility among the subjects for REP 2, including the magnitude ratio, phase, and coherence, for each cushion configuration. Similar results were also observed for REPs 1 and 3 conducted on different days. The magnitude ratio showed a distinct peak in the vicinity of 4 – 5 Hz. This peak was associated with whole-body resonance of the human body and was expected. Figure A-4a does show that the prototype cushions tended to amplify the low frequency vibration associated with this resonance region as compared to the standard cushion (STDA and STDC). In contrast, at higher frequencies beyond about 8 - 10 Hz, the prototype cushions tended to dampen the vibration, the greatest dampening occurring with PRA. Figure A-4b shows the rapid phase shift occurring between the input at the seat base and the output at the seat pan in the vicinity of whole-body resonance as expected. The prototypes showed greater phase shifts at higher frequencies associated with the dampening behavior. Figure A-4c shows relatively high values for the coherence at low frequencies (greater than 0.8) below 20 Hz. The coherence, particularly for PRA, was lower at higher frequencies, suggesting that noise was contributing to the response. This can occur when there is a very low level of vibration being transmitted to the occupant.

Figure A-5 illustrates the mean frequency location and magnitude ratio associated with the peak vertical seat pan transmissibility among the subjects for each cushion configuration. Table A-1 lists the mean values. The frequency location of the peaks primarily occurred at 4.5 or 5 Hz. There were no significant differences observed in the frequency location of the peak magnitude ratio among the cushions for any of the repetitions. There were no significant differences in the frequency location of the peak for any specific cushion configuration across repetitions. As observed in Figure A-5b, there were significant differences in the magnitude ratio of the peak transmissibility responses among the cushions. Both PRA and PRC showed significantly higher peaks as compared to the standard configurations (STDA and STDC). PRA showed a significantly higher peak than PRC for REP 2. The only significant effect of repetition occurred with PRA; the peak during REP 2 was greater than the peak during REP 1.

3.2 Multi-Attribute Task Battery (MATB)

Figures A-6 through A-11 illustrate the results for selected parameters of the MATB. It is emphasized that the parameters associated with the time to complete a response are provided as mean values for each subject over the 30-minute test session and include the standard deviation. This standard deviation reflects the extent of the variability in the subject's response over that time period. The results that are plotted in the figures include the mean among the subjects for the individual mean response time, as well as the mean among the subjects for the individual standard deviation or variation in the response time over the 30-min period. The standard deviation is also provided for these means among the subjects. For the mean tracking error, the MATB software does not calculate a standard deviation over the 30-min period. This deviation is valuable in that it would reflect the variability in the subject's tracking error over the length of the task, as mentioned above for the response time. For this parameter, the mean tracking error and standard deviation were calculated for each subject using the tracking error generated by the software over the smallest time increment (1 min). Therefore, 30 data points were used for these calculations. Figure A-6 reflects the mean response time (s), variation (s), and number of errors for the communications task. Figure A-7 reflects the mean response time (s), variation (s), and number of errors for the dials response task. Figure A-8 reflects the mean response time (s), variation (s), and number of errors for the lights response task. Figure A-9 reflects the mean of the total number of system monitoring errors including the failed attempts and time outs (combined dials and lights). Figure A-10 reflects the mean of the combined deviations of Tanks A and B from 2500 units. Figure A-11 reflects the mean tracking error and the mean tracking error variation (rms in pixel units) among the subjects.

For any of the parameters listed above, the overwhelming majority showed no significant differences among the cushion configurations for any of the three reps. The exceptions included the variation in the 30-min response time for the communications task where PRA was significantly greater than STDA and PRC for REP 3 only (Figure A-6b), the variation in the 30-min response time for the dials response task where PRC was significantly greater than PRA for REP 2 only (Figure A-7b), the 30-min response time for the lights response task where PRA was significantly greater than PRC for REP 3 only (Figure A-8a), and the 30-min system monitoring error where PRA was significantly greater than STDA for REP 3 only (Figure A-9). The only significant differences among the three reps for any selected cushion occurred for the 30-min lights response time with PRC where REP 2 was greater than REP 3 (Figure A-8a). The figures do show that these differences were quite small.

While the 30-min performance effects compared among the cushions and reps were minimal, there were some interesting observations when comparing selected parameters. Among those tasks where the response time and error were measured (communications, dials, and lights), the dials response time tended to be the highest (compare Figures A-6a, A-7a, and A-8a), the variation in the dials response time over the 30 minutes tended to be the highest (compare Figures A-6b, A-7b, and A-8b), and the dial response errors tended to be the greatest (compare Figures A-6c, A-7c, and A-8c). As illustrated in Figure A-7b, the mean variation in the dial response time is almost as high as the mean response time. The communications response error, dials response error, and lights response error also showed large variability among the subjects as reflected in the standard deviation (Figures A-6c, A-7c, and A-8c). The system monitoring error (Figure A-9), tanks deviation from 2500 (Figure A-10), and the variation in tracking error over the 30 minute period (Figure A-11b) also showed large variability among the subjects as reflected in the standard deviation. These large standard deviations strongly suggested that the level and quality of performance differed among the subjects.

In order to determine if the variation in a parameter that occurred over the 30-minute period for any subject showed a definitive trend (i.e., response time increased with exposure time), the data were plotted in 3-min increments. Observation of the data showed no clear trends in any of the parameters during the 30-minute exposures.

3.3 Body Parts Comfort Survey and TNO Comfort Questionnaire

Figure A-12 depicts the results of the Body Parts Comfort Survey. The figure includes the mean comfort rating at each body region for each cushion configuration and each rep. The number of subjects who responded that they felt the low level vibration in the respective body region is also given (bottom of graph). The figure shows that the vibration was felt the most in the lower torso which included the combined responses for the lower back, buttocks, legs, and feet. Only two subjects indicated that they felt the vibration in the upper torso and specifically with the PRA cushion. The ratings indicated that the subjects considered the comfort of the respective body regions to range from Not Uncomfortable (1) to A Little Uncomfortable (2) (refer to Section 2.4). The highest rating given was Uncomfortable (4) and occurred for the lower torso. STDA received this rating from two subjects for one of the reps. PRA received this rating from one subject for one of the reps. In addition, STDA received a rating of Fairly Uncomfortable (3) from two subjects for one of the reps. PRA received this rating from one subject for one of the reps. STDC received this rating from three subjects for one of the reps, and PRC received the rating from one subject for one of the reps. The more severe comfort ratings were not consistent among the three reps for any of these subjects. For the lower torso body parts, the mean rating among the three reps was calculated for each subject for each cushion configuration. These values were used in a one-way repeated measures ANOVA to see if there were trends in the ratings among the cushions for the lower torso. The highest mean among the subjects occurred with STDA followed by PRA, with PRC showing the lowest mean. The only significant difference occurred between STDA and PRC. The red lines in the lower torso plots in Figure A-12 reflect the mean of the combined rep data. Figure A-12 does suggest that the ratings were particularly higher for STDA. Given that STDA and STDC were the same standard cushion, it was speculated that the tendency for lower ratings for STDC and PRC may have been due to the STDC/PRC tests being conducted after the STDA/PRA tests (due to cushion availability).

For the Local Perceived Discomfort (LPD) portion of the TNO Comfort Questionnaire, responses greater than zero were only provided for the back, buttocks and legs. Among the four cushion configurations (PRA, STDA, PRC, STDC) and three reps, there were only 39 responses among four of the subjects that were greater than 0 (default rating). The ratings greater than zero ranged from 1 to 6, with one subject giving a rating of 9 for the back during one of the reps with STDA. For the remaining responses, the highest ratings of discomfort and the most responses were given for the buttocks region. The highest LPD rating for buttocks discomfort (combined left and right buttocks in Figure 3) was 6 (STDA, PRA, STDC). The highest LPD rating for the thigh/legs discomfort (combined left and right upper legs to the feet in Figure 3) was 4 (STDC, PRC).

Figures A-13 through A-16 illustrate the results of the TNO seat ratings and include the Overall Seat Impression (Figure A-13), Seat Pan Firmness (Figure A-14), Buttocks Support and Comfort (Figure A-15), and Thigh/Legs Support and Comfort (Figure A-16). For the Overall Seat Impression, there were no clear trends observed among the cushions for the three reps. The ratings fell primarily between 3 and 4, indicating a neutral to good impression of the cushions. The only significant effect indicated that PRA was rated higher than STDA during Rep 2. The most notable difference in the seat ratings was associated with the Seat Pan Firmness (Figure A-14). For Reps 2 and 3, the seat pan was rated as being more firm with STDA as compared to PRA. For Rep 2, STDC was also rated more firm than PRC. These results were significant. Additional observations indicated that all cushions tended to be too firm (Figure A-14); the majority of ratings fell above 3 (indicated with a red line). All cushions tended to provide too little buttocks support (Figure A-15a); the majority of ratings fell below 3 (indicated with a red line). The comfort rating for the buttocks was quite variable among the subjects (Figure A-15b). Thigh/legs support tended to be adequate with less variability among the subjects as compared to buttocks support (Figure A-16a). Thigh/legs comfort also tended to be rated higher for comfort as compared to the buttocks, ranging between 3 and 5. The only significant effect occurred for thigh/legs comfort. PRC was considered to have greater thigh/legs comfort as compared to STDC (Figure A-16b).

4.0 DISCUSSION

This study sought to compare the biodynamic effects and subjective comfort of prototype and standard aircraft seat cushions during exposure to low level vibration encountered during the operation of military jet aircraft. In order to re-create a more operationally-relevant workload, each subject continuously performed a complex multi-task (MATB) for each 30-minute period. The biodynamic characteristics of the prototype cushions were of particular interest. Both prototypes amplified low frequency vibration near whole-body resonance and dampened higher frequency vibration above 8-10 Hz to a greater extent as compared to the standard cushion. For the F-15 level flight exposure, this resulted in very little effect on the aircraft resonance peak at 8.5 - 9 Hz among the cushions, but did result in greater dampening of higher frequency aircraft resonance peaks with the prototypes. While the levels of vibration during F-15 level flight were relatively low, and appeared to be inconsequential relative to the assessment of comfort and task performance, the cushions may have an influential effect during exposure to higher levels of vibration. For exposures that include substantial low frequency vibration, the amplification of the vibration at the seat pan could results in substantial motions in the upper torso. For example, using a rigid seat with no cushion, the transmission of vertical vibration to the head can be greater than three times the input in the vicinity of whole-body resonance and can reach around two times the input between 8 and 10 Hz. Substantial head pitching can also result during low frequency vertical vibration [12]. The major concern for military operations would be undesirable visual performance effects and possibly manual performance effects that could be amplified with the use of the prototype cushions. In contrast, military rotary-wing, propeller-driven, and tilt-rotor aircraft have substantial vibration above 10 Hz that is primarily associated with the blade passage frequency. For these types of exposures, the prototype cushions may provide beneficial dampening effects that could influence comfort and performance.

This study used the NASA Multiple Task Battery (MATB) as opposed to the SynWin task battery that was used in previous static studies [5,6,7]. Preliminary SynWin data collected during 1.5 hours of exposure to propeller aircraft vibration suggested that the task scores were influenced by the self-paced math task and difficult to interpret across subjects. In addition, the objective of the current study was to create a more realistic operational environment. MATB included tasks that were designed to be more relevant to operational activity and would expose the subjects to a continuous workload. The results showed no clear effect of exposure length or cushion configuration on any of the tasks and associated parameters evaluated in this study. These findings were not unexpected given the relatively short exposure durations (30 min) and low level of vibration. Studies have shown the effects of vibration on various aspects of cognitive performance (learning and memory) [13, 14]. These studies exposed subjects to 16 Hz sinusoidal vibration at various acceleration magnitudes ranging from 1.0 to 2.5 ms^{-2} rms. The length of one of the studies was 30 minutes [13]. These exposures were substantially higher than the exposure used in this study (approximately 0.3 ms^{-2} rms at the seat pan for the F-15 level flight). At the time this paper was written, it was not known whether higher levels of operational vibration would show significant changes in performance relative to the static condition and relative to the length of the exposure.

This study showed that, in general, all of the cushion configurations produced similar seat ratings using the TNO Comfort Questionnaire. The one exception was for seat pan firmness, where the tendency was for greater firmness with the standard cushion as compared to the prototypes. In general, all cushions tended to be rated as too firm. It is interesting that this coincided with the relatively higher ratings for comfort in the thigh/legs as compared to the buttocks, and the tendency for less than optimal buttocks support as opposed to adequate thigh/legs support. This would suggest that these firmer cushions provided less than optimal buttocks support while providing adequate thigh/legs support and comfort. The ratings between body locations were not statistically compared.

It would be interesting to evaluate the possible relationships between seat pan firmness and buttocks and thigh/legs support using seated pressure measurements. Although the previous studies also used the TNO Comfort Questionnaire, both appeared to only use the Local Perceived Discomfort (LPD) ratings for the buttocks [5,6,7], and thigh [6]. The buttocks LPD ratings were less than 4 on the scale of 0 – 11 in [4]. The LPD ratings for both the buttocks and thighs were less than 2 in [6]. In these studies, there was a positive correlation between the peak pressure measurement and the highest discomfort. As mentioned previously, in this study, the highest LPD rating and most responses were given for the buttocks; with a maximum rating of 6.

5.0 CONCLUSIONS

In general, both prototype cushions and the standard cushion used in this study showed similar results with respect to a. task performance, b. the subjective comfort of various body parts, and c. seat ratings, although there was an indication that the standard cushion was more firm than the prototypes.

All cushions tended to be rated as too firm. This coincided with the observations of greater discomfort and less adequate support in the buttocks but adequate thighs/legs comfort and support.

The vibration transmissibility results indicated that the prototype cushions may provide beneficial dampening effects that could influence comfort and performance for exposures to higher frequency operational vibration.

6.0 REFERENCES

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APPENDIX A

Table A-1. Mean Cushion Transmissibility Peaks ± One Standard Deviation

CUSHION	REPETITION 1		REPETITION 2		REPETITION 3	
	Frequency (Hz)	Magnitude Ratio	Frequency (Hz)	Magnitude Ratio	Frequency (Hz)	Magnitude Ratio
STDA	4.94±0.56	1.03±0.03	5.50±1.49	1.03±0.03	4.94±1.15	1.03±0.04
PRA	4.50±0.38	1.29±0.14	4.75±0.46	1.41±0.08	4.38±0.35	1.37±0.102
STDC	4.86±0.38	1.07±0.05	5.00±0.58	1.09±0.04	4.57±0.53	1.05±0.03
PRC	4.79±0.39	1.30±0.06	4.71±0.64	1.25±0.08	4.93±0.67	1.26±0.12

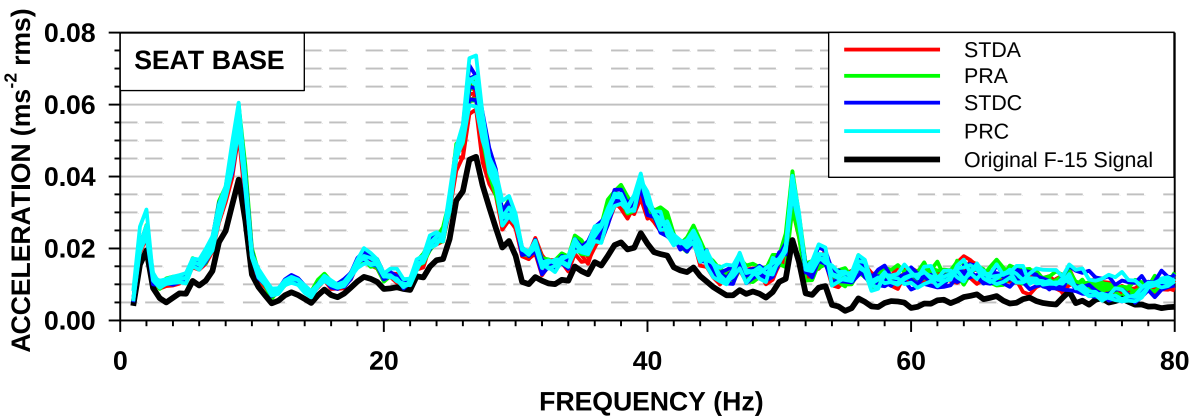

Figure A- 1 Seat Base Vertical Acceleration Spectra

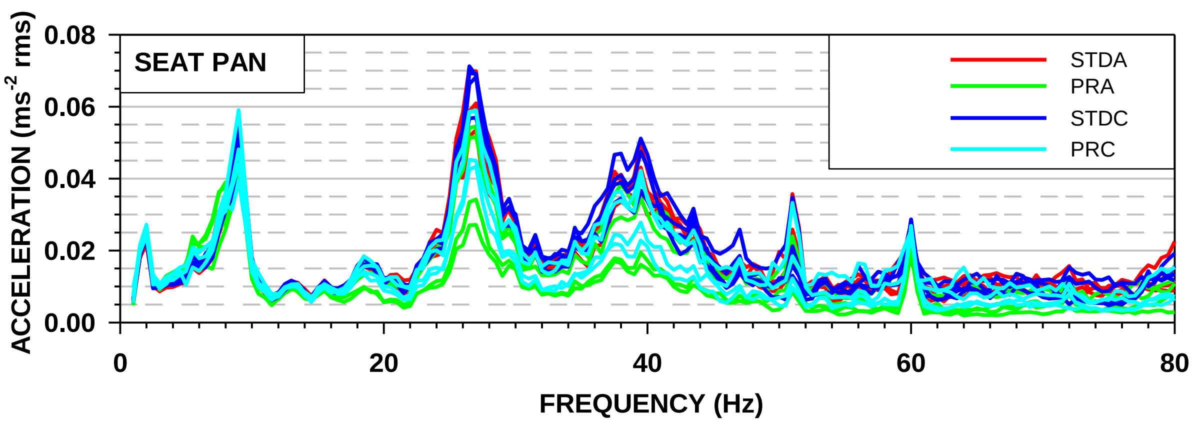

Figure A- 2 Seat Pan Vertical Acceleration Spectra

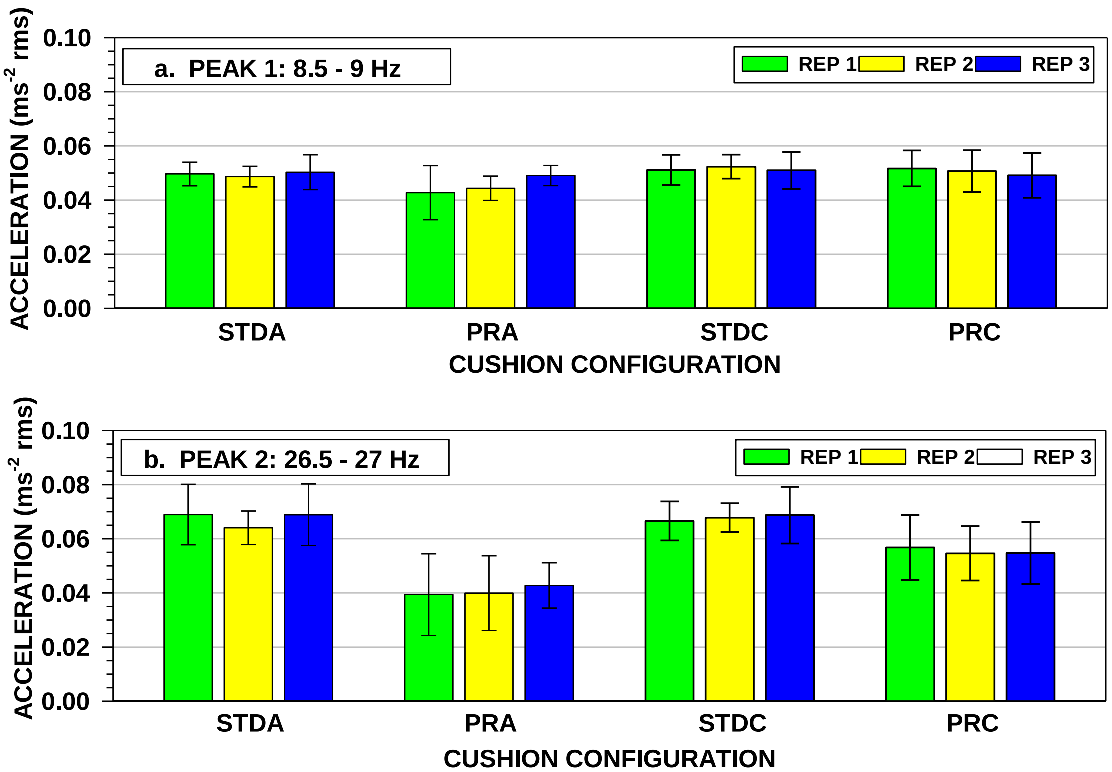

Figure A- 3 Mean Seat Pan Acceleration Peaks ± One Standard Deviation, a. PEAK 1: 8.5 – 9 Hz, b. PEAK 2: 26.5 – 27 Hz

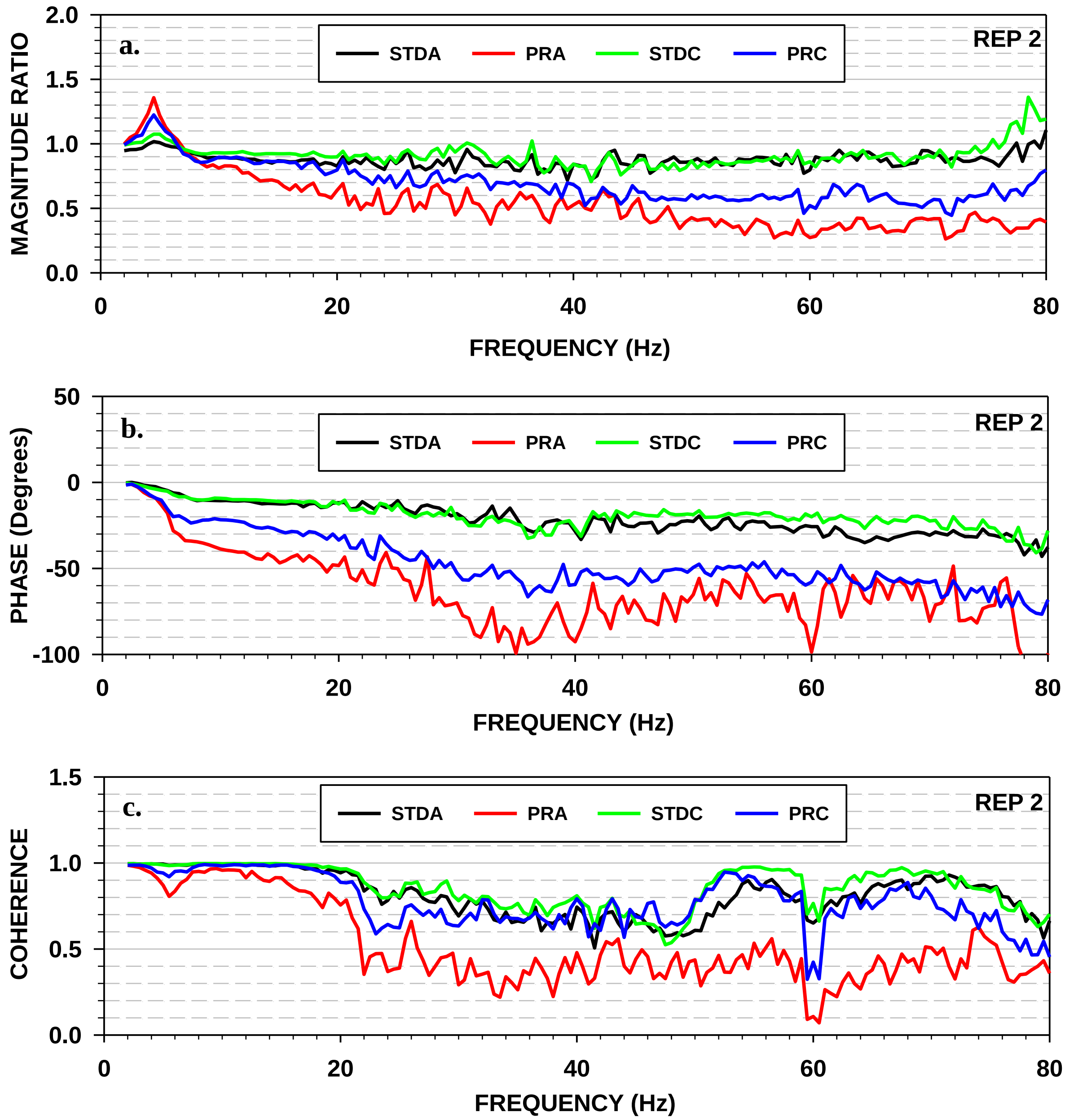

Figure A- 4 Vertical Seat Pan Transmissibility, a. Magnitude Ratio, b. Phase, c. Coherence

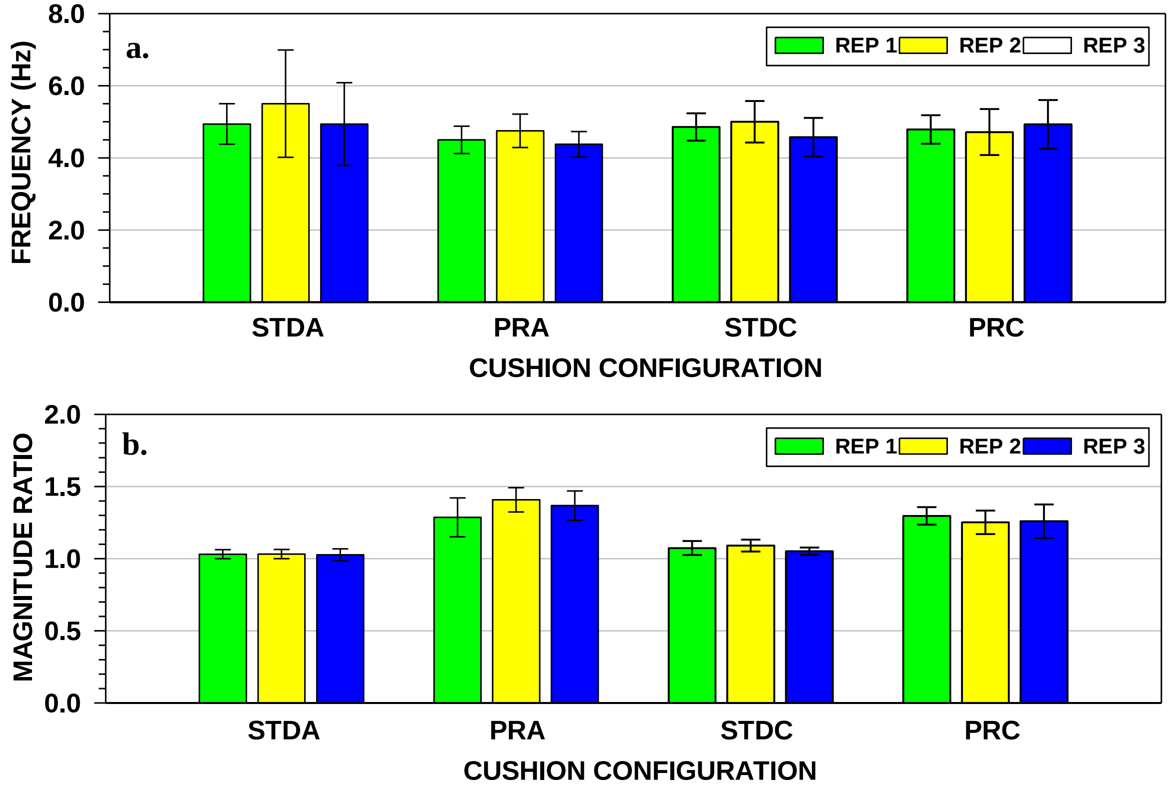

Figure A- 5 Mean Vertical Peak Transmissibility ± One Standard Deviation, a. Frequency Location, b. Magnitude Ratio

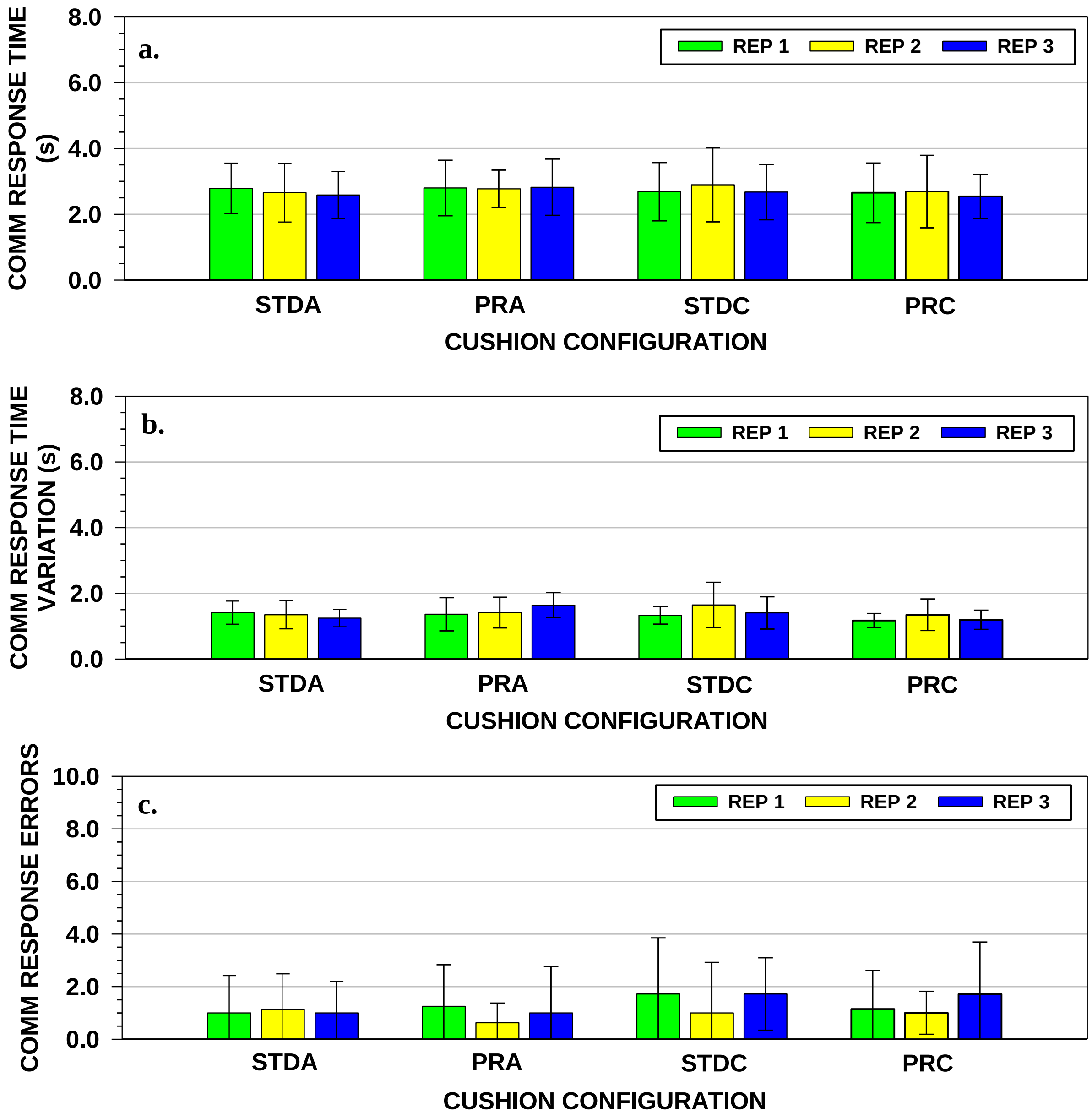

Figure A- 6 Mean 30-Minute Communications ± One Standard Deviation, a. Response Time, b. Response Time Variation, c. Number of Response Errors

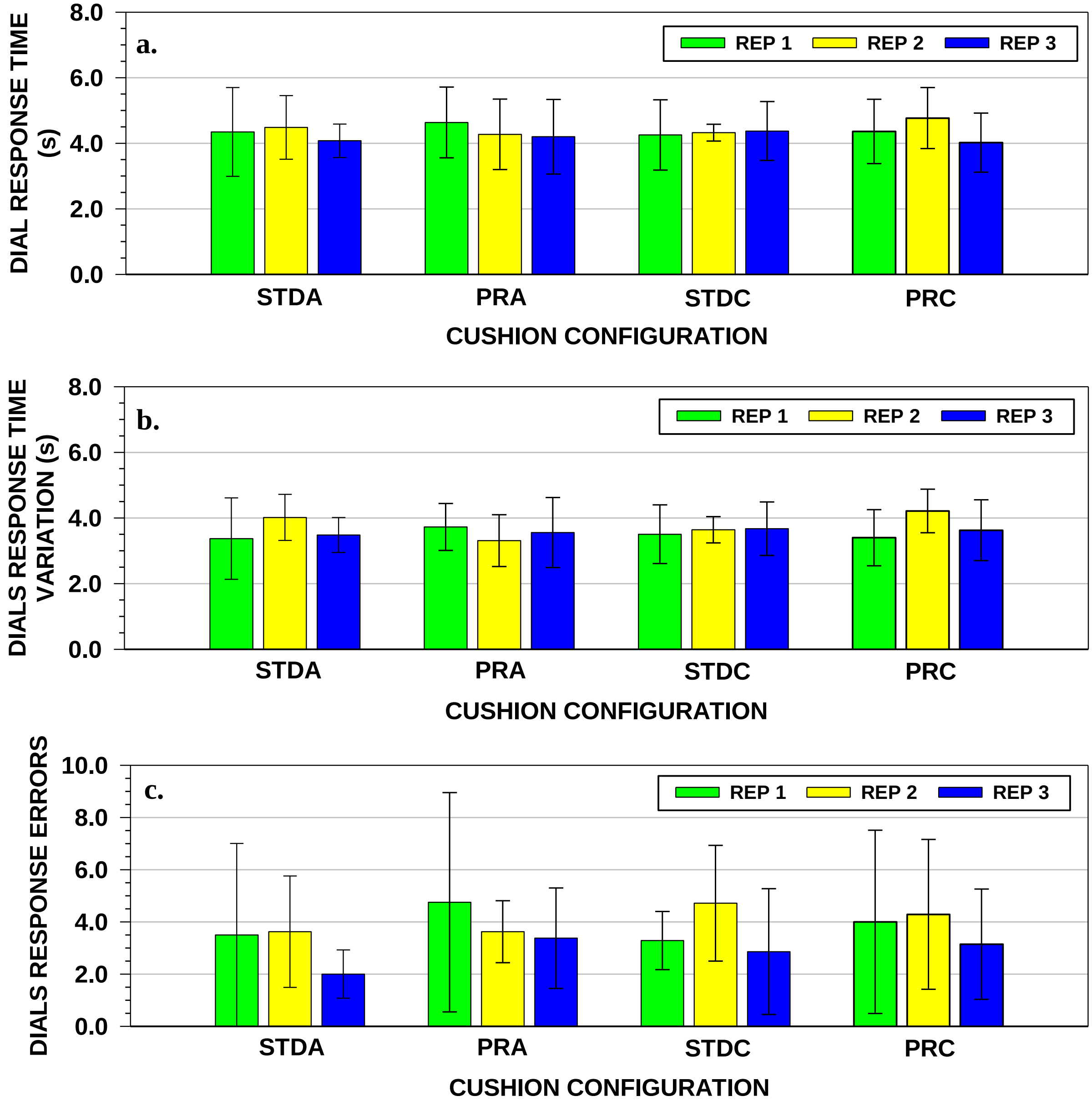

Figure A- 7 Mean 30-Minute Dials ± One Standard Deviation, a. Response Time, b. Response Time Variation, c. Number of Response Errors

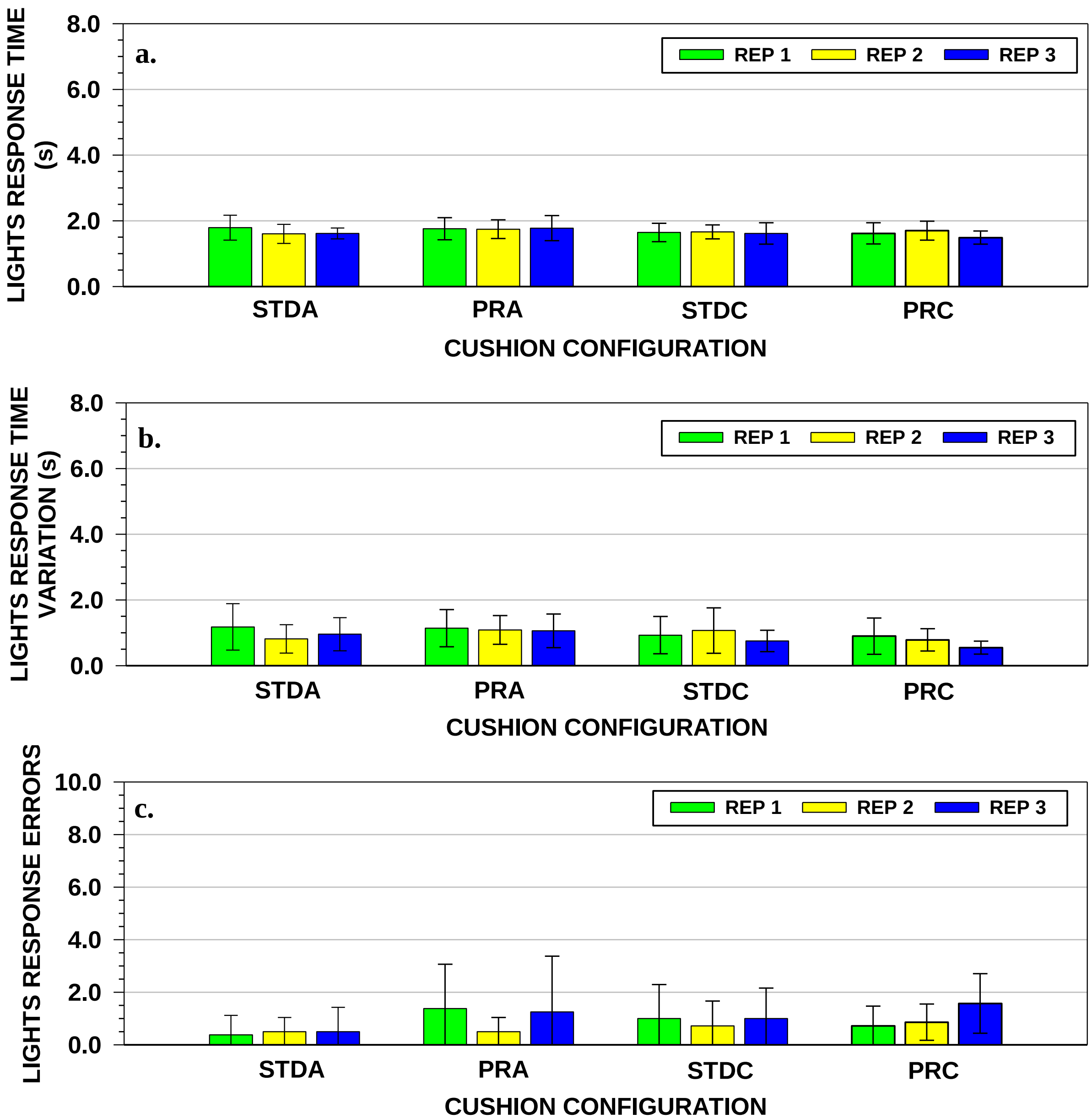

Figure A- 8 Mean 30-Minute Lights ± One Standard Deviation, a. Response Time, b. Response Time Variation, c. Number of Response Errors

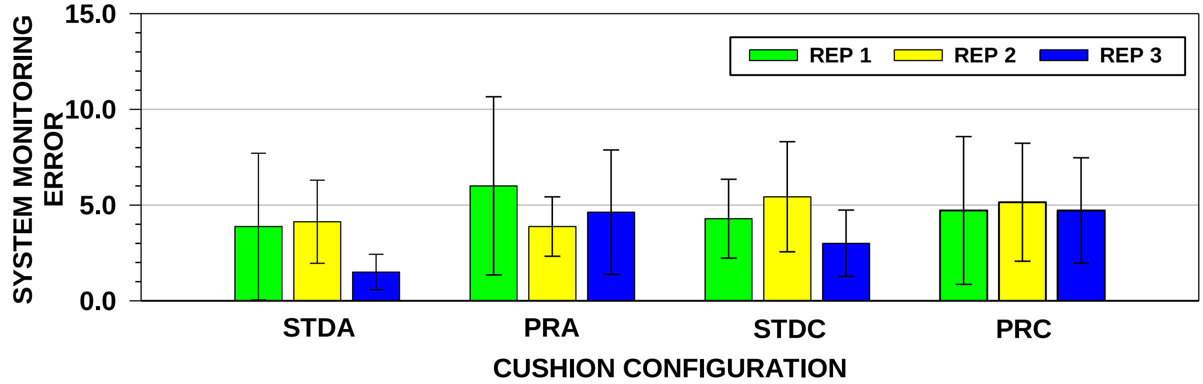

Figure A- 9 Mean 30-Minute System Monitoring Error ± One Standard Deviation

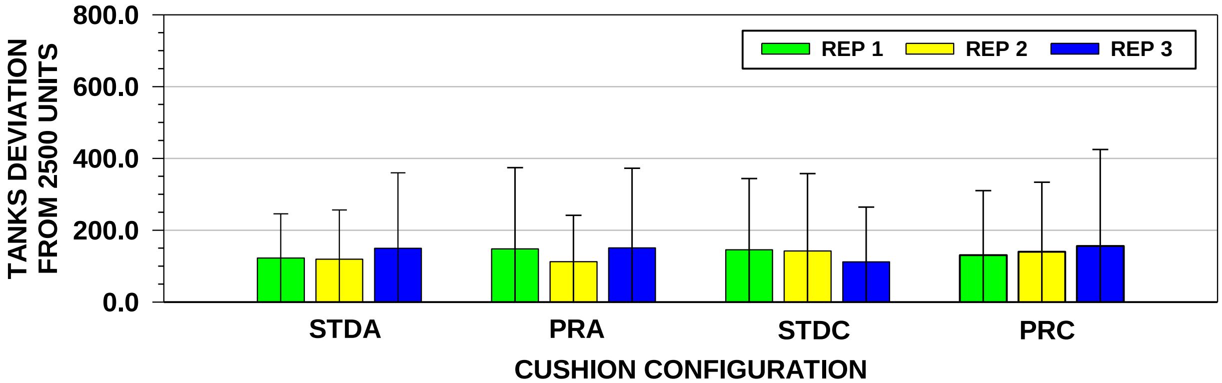

Figure A- 10 Mean 30-Minute Tanks Deviation from 2500 Units ± One Standard Deviation

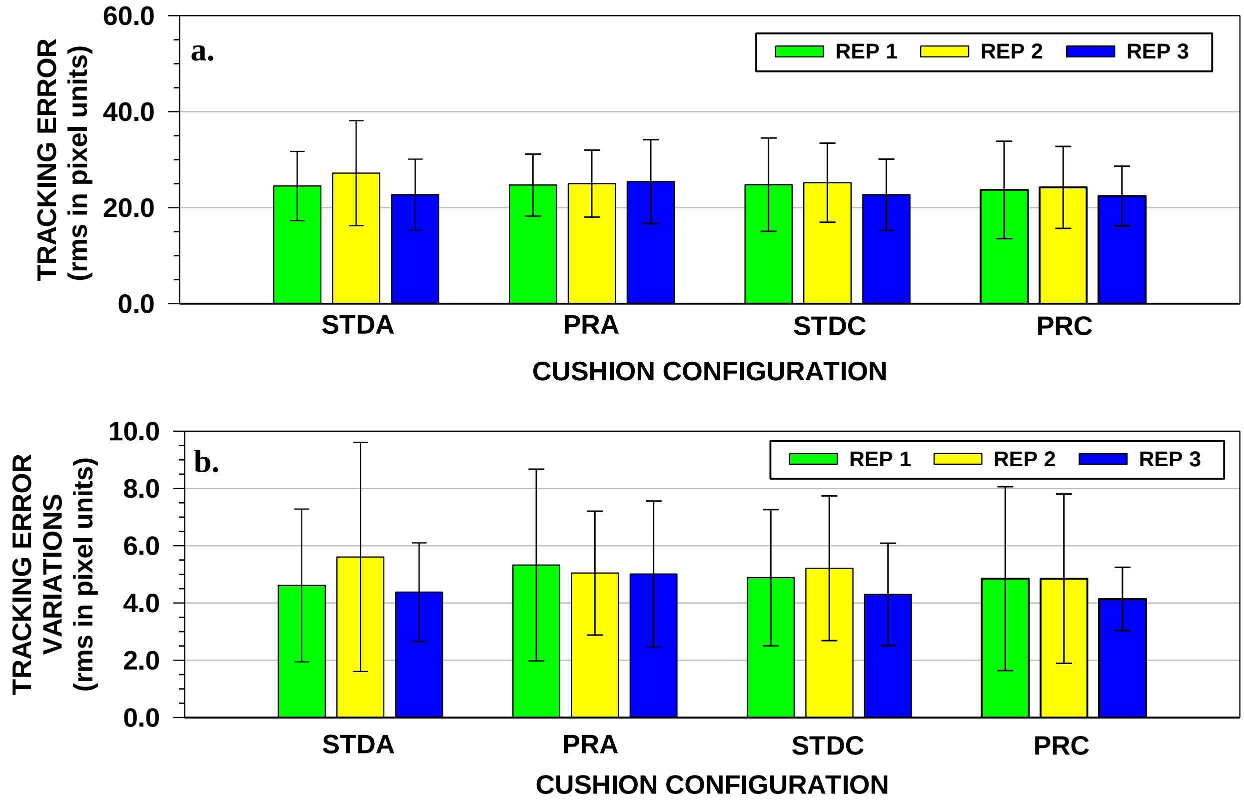

Figure A- 11 Mean 30-Minute Tracking ± One Standard Deviation, a. Tracking Error, b. Tracking Error Variations

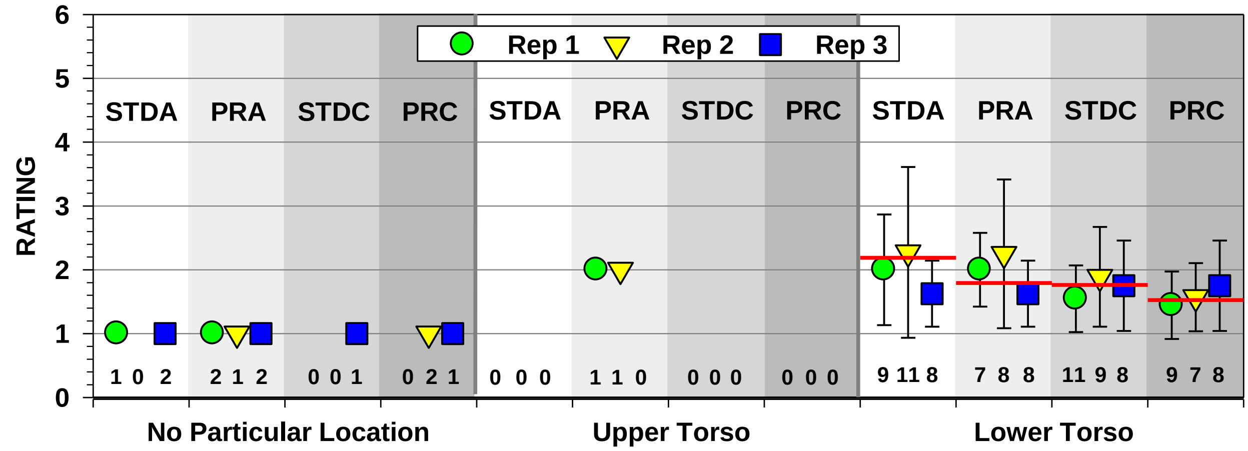

Figure A- 12 Mean Combined Body Parts Rating ± One Standard Deviation. Values at bottom indicate number of subjects included in rating. Red bars indicated mean across reps.

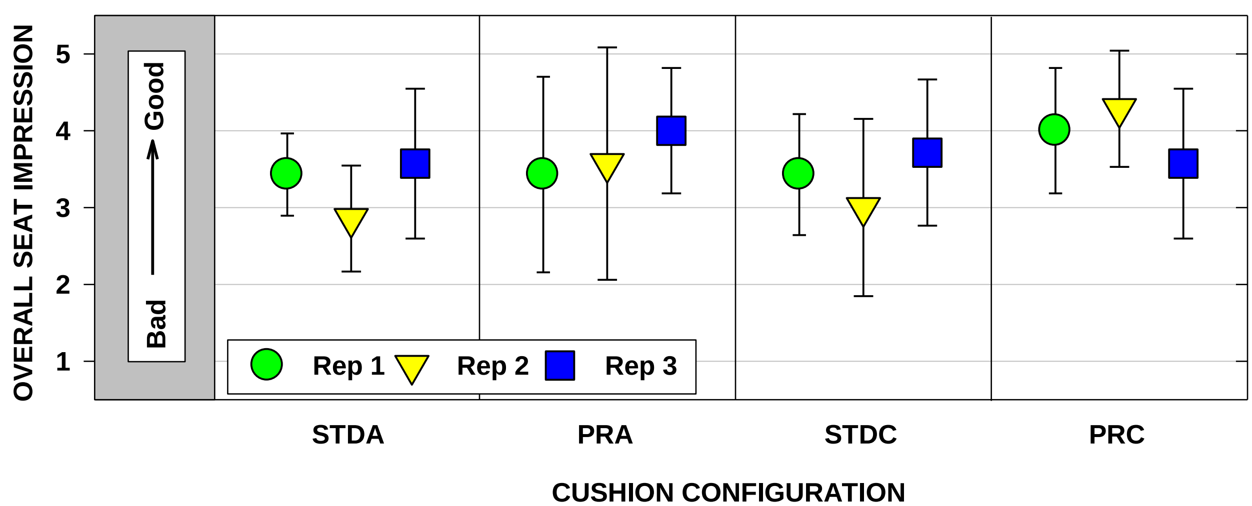

Figure A- 13 Mean Overall Seat Impression ± One Standard Deviation

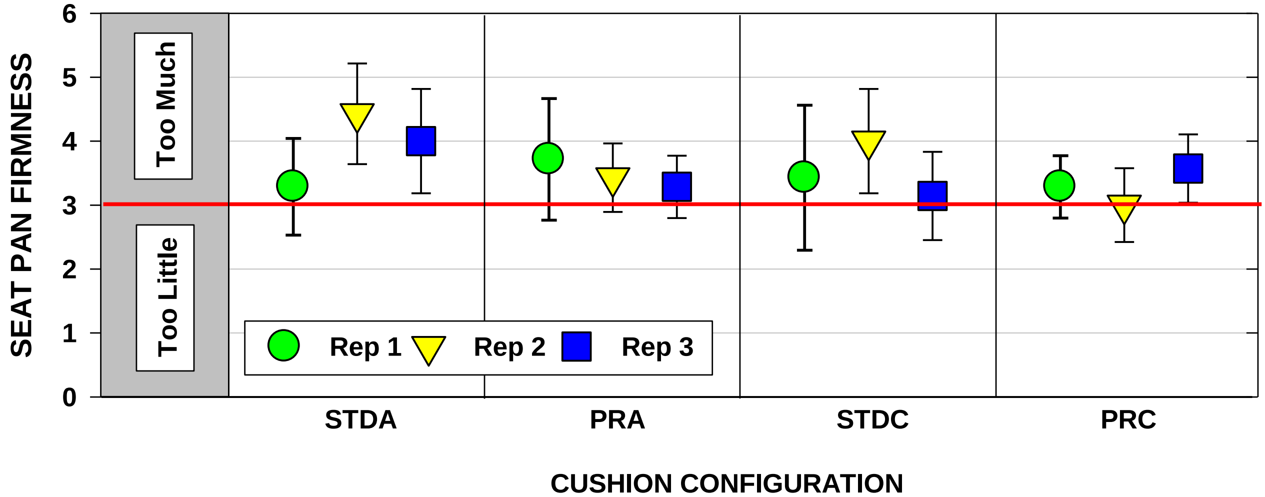

Figure A- 14 Mean Seat Pan Firmness ± One Standard Deviation

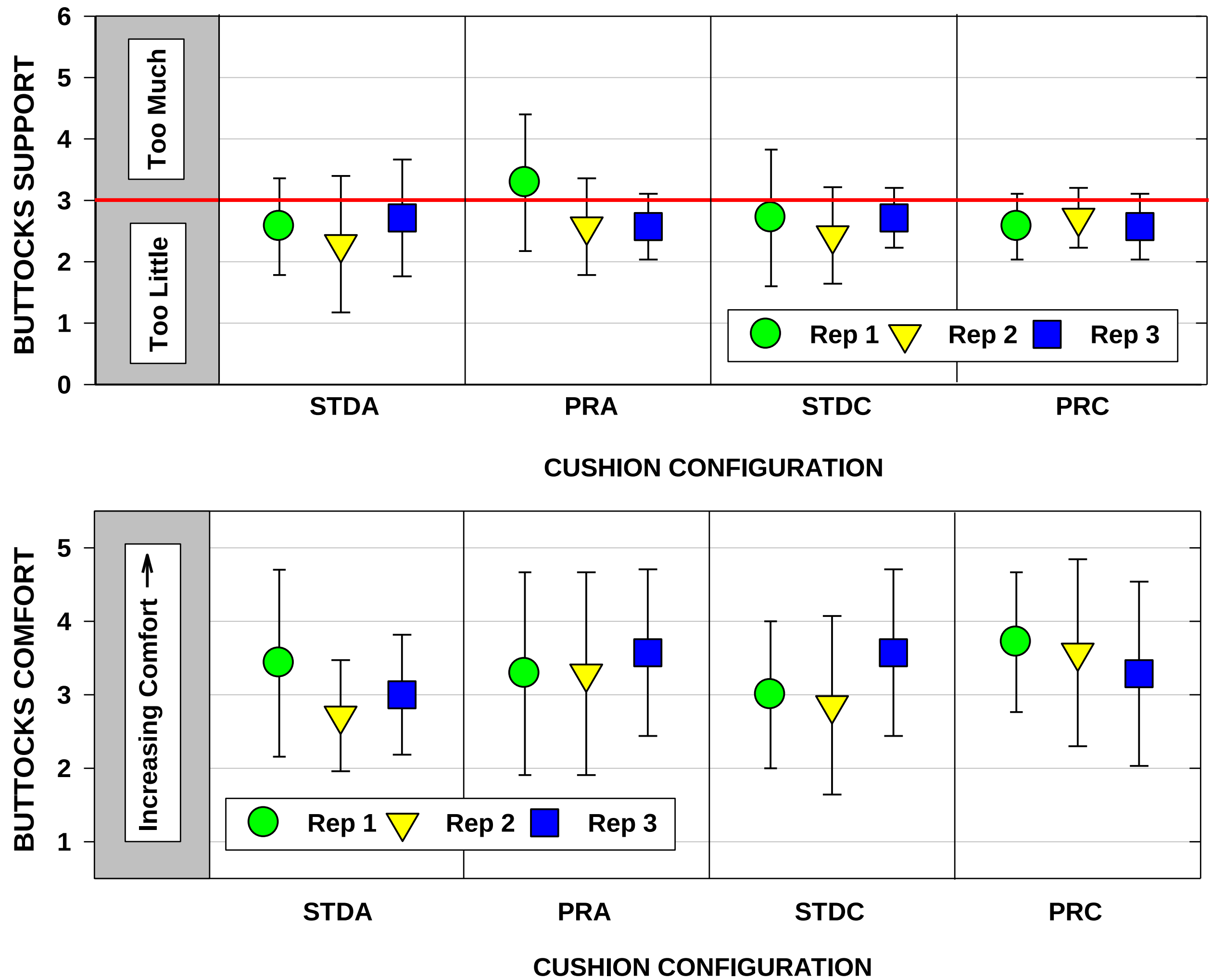

Figure A- 15 Mean Buttocks Support and Comfort ± One Standard Deviation

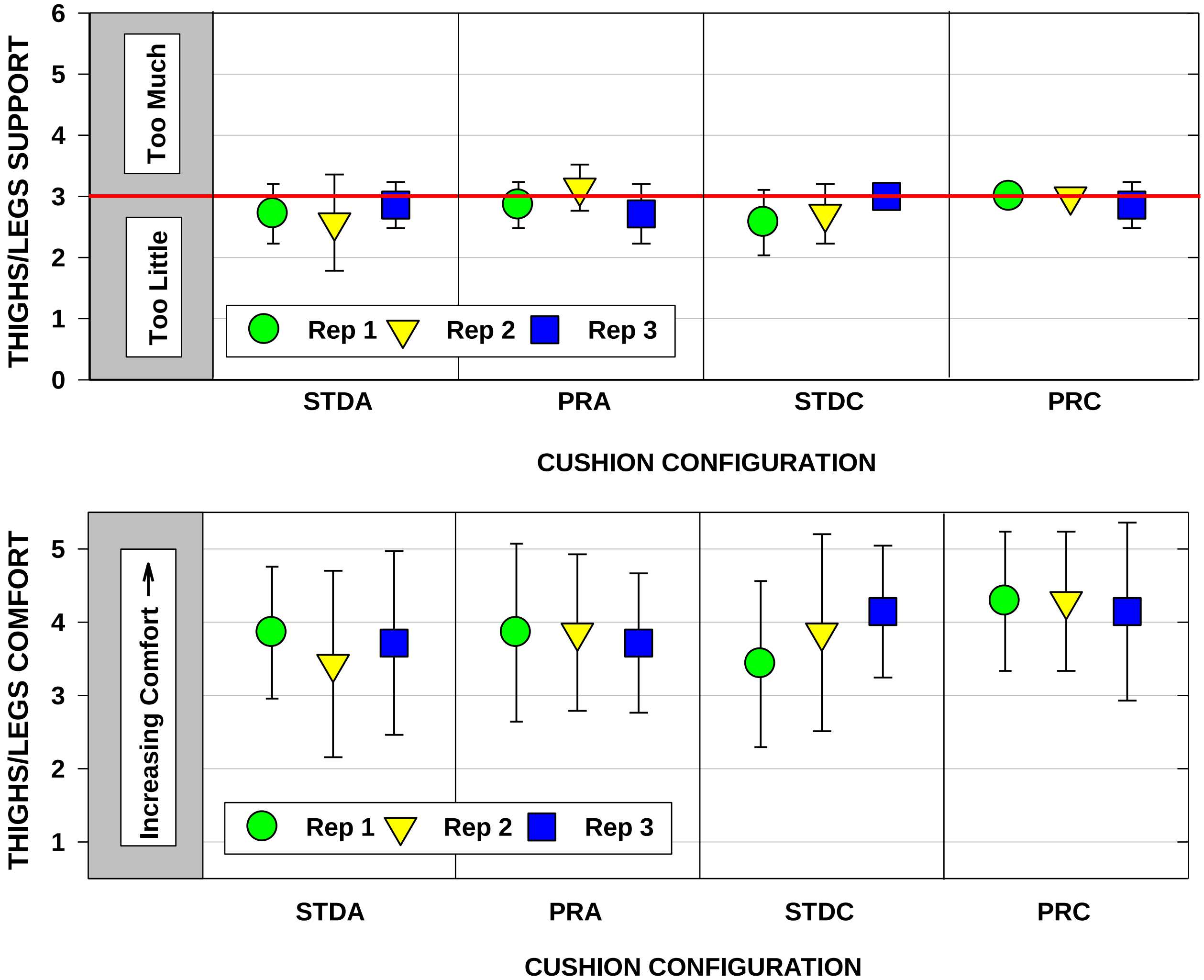

Figure A- 16 Mean Thighs/Legs Support and Comfort ± One Standard Deviation

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

a_{rms}	Root-Mean-Square Acceleration
$H(\omega)$	Seat Pan Transmissibility
$P_{zZ}(\omega)$	Cross-spectrum (acceleration) between input z and output Z
$P_{zz}(\omega)$	Auto-spectrum (acceleration) of input z
$C(\omega)$	Ordinary Coherence
$P_{ZZ}(\omega)$	Auto-spectrum (acceleration) of output Z

ACES II	Advanced Concept Ejection Seat II
BDU	Battle Dress Uniform
EMG	Electromyography
F15LF	F-15 level flight vibration
FLAT	Flat acceleration spectrum
LPD	Local Perceived Discomfort
MATB	Multi-Attribute Task Battery
PRA	Prototype Air Bladder Cushion
PRC	Prototype Rate-Sensitive Foam Cushion
PROTO	Prototype
REP	Repetition
Rms	Root-Mean-Square
STD	Standard Cushion
STDA	Standard cushion tested in same session as PRA
STDC	Standard cushion tested in same session as PRC
SynWin	Synthetic Work for Windows
TNO	Netherlands Organization for Applied Scientific Research