Pressure Measurements and Comfort of Foam Safety Cushions for Confined Seating

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Introduction: Glider flights may require the pilot to sit for many hours in a cramped cockpit that allows little movement. Experiments were undertaken to evaluate the performance of different seat cushions in a glider simulator. ***Methods:*** Subjects were male glider pilots with a maximum height of 1.85 m (6.07 ft) who participated in simulated glider flights lasting 1.5 h. A pressure-mapping device was used to determine cushion performance. By analyzing 15 subjects we calculated the pressure threshold for comfort, above which fidgeting provided objective evidence of discomfort. To determine cushion performance relative to that threshold, 20 other pilots then sat on 5 different viscoelastic foam cushions in the simulator. ***Results:*** The time-averaged peak pressure below which no discomfort-induced fidgeting occurred was 8.8 kPa (1.28 psi). The highest peak pressure at which discomfort could be relieved by fidgeting was 11.0 kPa (1.6 psi). Of the five cushions tested, pressure remained below the discomfort threshold for almost all subjects for only one type of cushion. ***Discussion:*** The best-performing cushion had a layered structure made up of approximately 25 mm of Confor C47 foam with an overlay of approximately 13 mm of Confor C45. The other types of energy-absorbing cushions tested, either with or without a softer top layer, are unlikely to provide comfortable seating solutions for most pilots. We conclude that satisfactory cushions are available for this application and that they can be objectively evaluated using this technique.

Keywords: Seat comfort, viscoelastic foam, ischemia, glider, aircraft, energy-absorbing foam, pilot comfort.

GLIDER PILOTS OFTEN experience discomfort during long flights. In some cases this can be distracting and may compromise safety. In the UK, it was recommended that glider pilots use seat cushions containing a single layer of energy-absorbing viscoelastic foam (12). Glider pilots still experience discomfort with such cushions and it has been suggested that cushions with a layer of softer foam on top of the firmer foam might be better. Experience accumulated in the UK suggests that discomfort can still occur even when such two-layered foams are used.

In military aviation, early investigations into the comfort of safety cushions used a subjective discomfort scale (14, for example). Later, a study of the safety cushions used in ejection seats in the B-2A bomber (1) used pressure-mapping equipment to assess what caused pilot discomfort, while another study found that seat comfort could be objectively measured (15). It has been reported that although many military safety cushions are comfortable at first, they often became uncomfortable on long flights (9). Typically it takes at least 30 min for discomfort to become sufficient for a behavioral response to occur (13).

The physical discomfort experienced by seated individuals is due to ischemia in the compressed buttocks, when the pressure on the buttocks exceeds the opening pressure of the capillaries in the region. Ischemic pain is caused by the accumulation of metabolites, principally lactic acid (16), formed during anaerobic metabolism, and the release of chemicals from cells damaged by hypoxia. Early measurements of capillary blood pressure (6) indicated that it was of the order of 4.3 kPa (32 mmHg; 0.6 psi). Others have reported that the application of a constant pressure of 4.7 kPa (35 mmHg; 0.7 psi) or intermittent pressure up to 25.3 kPa (190 mmHg; 3.7 psi) produced no ischemic changes for up to 4 h, whereas a constant pressure of 9.3 kPa (70 mmHg; 1.4 psi) for 2 h produced irreversible cellular changes (5). Studies in man and experimental animals suggest that an external pressure appreciably above 4.3 kPa (32 mmHg; 0.6 psi) is likely to be needed to cause compressive closure of the capillaries in normal human tissue (3,10).

This, therefore, suggests that there is a threshold external pressure below which discomfort does not occur. We set out to test whether this concept is applicable to seated glider pilots and if so to determine this threshold. To make this relevant to actual flying we decided to determine what this typical value is in a cockpit where the pilot is making leg and thigh movements in moving the controls, but is also strapped down. We decided to measure the pressure pattern applied across the whole buttock/seat area by means of a pressure pad and to use the onset of fidgeting movements by the pilot, termed "butt flutter" by Cohen (1), as an objective indicator of the onset of discomfort. We performed two series of experiments to determine: 1) the peak pressure (i.e., the highest local pressure) below which capillary blood-flow in the buttocks would be maintained so that the pilot would experience no discomfort; and 2) the peak pressure that different energy-absorbing foam cushions delivered when used in a glider cockpit environment. This work

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was undertaken between November 2006 and December 2007.

METHODS

There were 35 male pilots of height less than 1.85 m (6.07 ft) who participated in the study. Participants sat in a glider simulator consisting of a Grob Twin Astir cockpit and a screen served by three projectors. Participants did not wear parachutes but were strapped in by a two-point harness. In the first part of the study, in which we sought to determine the critical pressure below which discomfort was not manifested, 15 pilots took part. In second part, in which we assessed the effectiveness of different energy-absorbing foam cushions, 20 pilots participated.

We measured the pressure over the seating area with a Tekscan (Boston, MA) type 5315 seat sensor and we measured the force/pressure exerted by the seat belt with a Tekscan type 5101 I-Scan sensor. Test runs were recorded as movie files with sample frames taken at 1-s intervals. The sensors were also checked for repeatability and accuracy. After application of a load, the electronic output from the pressure-pads took about 3 min to stabilize. Once stabilized the final readings were repeatable within an accuracy of 3–4%. The temperature of the simulator room over the course of the tests varied from approximately 15° to 20°C.

The cushions tested consisted of viscoelastic energy-absorbing foams. The foams tested were:

1. Sunmate X-Firm, manufactured by Dynamic Systems, Inc. (Leicester, NC) and sold by a third party in the UK under the name Dynafoam Extra-Firm (SXF);
2. A layer of Sunmate Soft (Dynafoam Soft) on top of Sunmate X-Firm (SXF+SS);
3. A layer of Tempur Firm (T85-18, manufactured by Tempur-Pedic International, Lexington, KY) on top of Sunmate X-Firm (SXF+TF);
4. Confor C47 (manufactured by E-A-R Specialty Composites, Indianapolis, IN) (C47);
5. A layer of Confor C45 on top of C47 (CF47+CF45); and
6. The bare seat without any foam.

The underlying layers of Sunmate X-Firm and Confor C47 were 25 mm (1 in) thick. The overlaying SS, TF, and C45 were 11 mm, 10 mm, and 13.5 mm thick, respectively (all supplied as nominally 0.5 in).

To standardize the force exerted by the lap strap, some of which would be transmitted to the seat pressure sensor, we asked 10 of the pilots to sit in the simulator cockpit and to tighten the lap strap to their normal strap pressure/force. The average pressure/force across the sensor was 5.0 kPa/34.3 N (0.72 psi/7.7 $\text{lb} \cdot \text{f}^{-1}$). This was then used as the standard for the rest of the experiments; in each test the seat belt was tightened until the seat pressure sensor recorded 5.0 kPa/34.3 N (0.72 psi/7.7 $\text{lb} \cdot \text{f}^{-1}$).

To determine the maximum localized pressure that could be tolerated without discomfort developing, 15 pilots were each strapped into the cockpit and sat relatively immobile for 1.5 h. To alleviate boredom and to prevent them from becoming excessively focused on discomfort, the pilots were given a simple flight objective to complete in the time. This was a 230-km task in wave using realistic cloud and flight conditions. Pilots were prohibited from making 360° thermalling turns in order to minimize large rudder movements. This was intended to ensure a near-constant pilot position and to eliminate the nausea sometimes experienced by pilots in fixed-cockpit simulators. Pressure-map data were recorded at 1-s intervals.

We took care to eliminate changes in general overall seat pressure caused by such things as sporadic extreme movements of the feet on the rudder pedals that suddenly pushed a thigh onto or raised it from the front of the seat pan, or alterations in the position of the feet on the rudder pedals that suddenly lowered or raised the thighs from the seat. For each flight we calculated the time-averaged localized peak pressure ("mean peak pressure") from the pressure-pad. For each flight we also calculated the amplitude of the most frequent (i.e., typical) pressure-lowering fidget.

To determine the mean peak pressure delivered by different energy-absorbing foam-cushions in a glider cockpit, 20 pilots sat in approximately the same position in the simulator, sitting in random order on each of the 5 cushions or the bare seat pan in turn. Pilots sat directly on the pressure pad, which was placed on top of the foam cushion being tested. For the first test, pilots made themselves comfortable and then their seated positions were recorded so that they could be subsequently repeated. Participants then applied the standard lap strap pressure for each test run. Recordings of the pressure pad output were taken at intervals of 1 s over 4 min, during which the pilots were asked to remain immobile.

Only the last 60 s of data were used from each recording. This ensured that the readings represented the stable environment. The mean peak pressure was calculated as the average of the peak pressures for each of the 1-s frames as determined from the Tekscan software. Statistical comparisons were made using Tukey's HSD test in order to account for multiple comparisons. Linear regression analysis was by Pearson's method. The study was carried out according to the principles of the Helsinki Declaration and participants gave their informed consent.

RESULTS

The mean height (± SD) of the pilots in this study was 1.76 ± 0.05 m. The mean body mass index (BMI) (± SD) of the pilots was 26.7 ± 3.94 $\text{kg} \cdot \text{m}^{-2}$ (range 20–37 $\text{kg} \cdot \text{m}^{-2}$). We found no significant correlation between height, BMI, weight, and mean peak pressure.

After about 40 min pilots began to make large fidgeting movements to relieve buttock pressure. These were clearly distinguishable from the background movements caused by moving the controls. In some cases we could detect these fidgeting movements before the pilots became aware of them. Pressure-relieving fidgets consisted of three broad categories: 1) shifting from one buttock to another; 2) raising both buttocks; and 3) clenching both buttocks.

Fig. 1 shows typical pressure-lowering fidget amplitude vs. mean peak pressure. Linear regression analysis

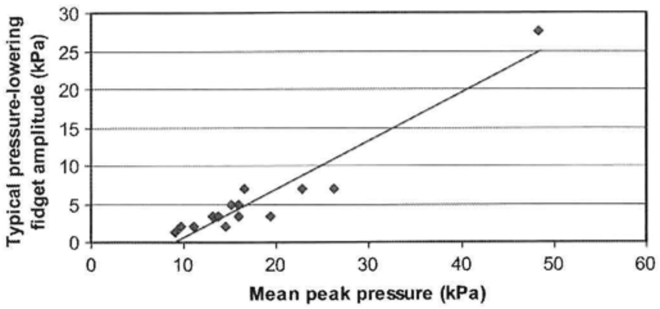

Fig. 1. Plot of amplitude of most-frequent (typical) pressure-lowering fidget vs. mean peak pressure.

revealed a significant correlation between the mean peak pressure and amplitude ($r = 0.954$, $P < 0.0001$). The x-axis intercept of the regression line, i.e., the mean peak pressure below which no discomfort-induced fidgeting will occur, was 8.8 kPa (1.28 psi).

Fig. 2 shows a plot of transiently achieved lowered pressure at the peak points (mean peak pressure minus typical pressure-lowering fidget amplitude) vs. mean peak pressure. The point on this line that corresponds to the mean peak pressure below which no fidgeting will occur (8.8 kPa; 1.28 psi) was determined by linear regression analysis using the cluster of the 10 lowest values ($r = 0.91$, $P = 0.0002$). This value (11.0 kPa; 1.6 psi) represents the highest mean peak pressure at which discomfort could be effectively relieved by the pilot fidgeting in the cockpit.

The results for the bare cockpit seat were eliminated from the comparisons because they were highly significantly different from all the others. Both SXF+SS and SXF+TF were significantly better than SXF alone and C47+C45 was significantly better than either SXF+SS or SXF+TF (in each case $P < 0.05$; Tukey HSD test).

Fig. 3 is a frequency plot of the different peak pressures for the different foams. Only C47+C45 enabled the majority of participants to remain below the critical mean peak pressure. The average mean peak pressure ± SD was 9.8 ± 1.0 kPa (1.42 ± 0.15 psi).

DISCUSSION

For some time glider seats have been covered with viscoelastic foam to provide protection to the pilot's spine in the event of a heavy landing or crash. The original experiments on glider cushions compared one type of viscoelastic foam (SXF) with ordinary furniture foam and closed-cell plastozote and concluded that a single layer of SXF provided better protection than the others (11). Such cushions became standard in UK gliders. Nevertheless, pilots found that these cushions often became uncomfortable on long flights, even when a layer of softer foam was added on top of the firmer foam. The studies we report here were intended to test some newer energy-absorbing foams for comfort. In order to do this we needed to develop a method for assessing comfort. We have shown that the method we used is relatively simple and reliable and suitable for comparing the comfort of different foams and combinations of foams.

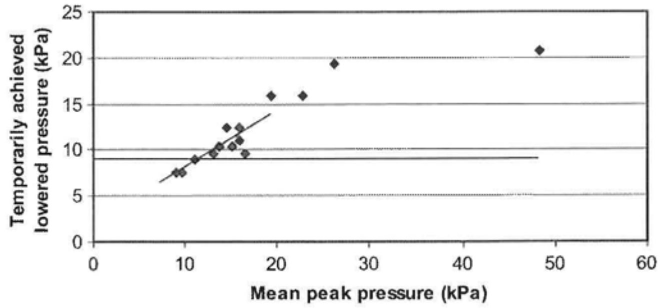

Fig. 2. Plot of temporarily achieved lowered pressure at the peak points (mean peak pressure minus typical, pressure-lowering fidget) vs. mean peak pressure. A horizontal line shows the pressure at which no discomfort-induced fidgeting will occur. A sloping line shows where the plot intersects that value.

Our study was limited to a small number of male pilots selected from a single large gliding club in the UK. However, our results may not be applicable to female pilots; further experiments would clarify this. On the other hand, compared to tests carried out by military authorities, our sample was large enough to be representative and we, therefore, have confidence in our conclusions. A survey of 196 pilots at Lasham found that their mean height was 1.77 ± 0.05 m. In terms of height, therefore, our sample was not appreciably different from the Lasham population of male pilots as a whole, despite the fact that we set an upper limit of 1.85 m. As we found no significant correlation between pilot weight, height, BMI, and the mean peak pressure generated by an individual's anatomy, the 20 pilots involved in our study appear to be typical of pilots at Lasham and, by extension, the general gliding population of UK male pilots with heights below 1.85 m (6.07 ft). According to World Health Organization criteria, the mean BMI of

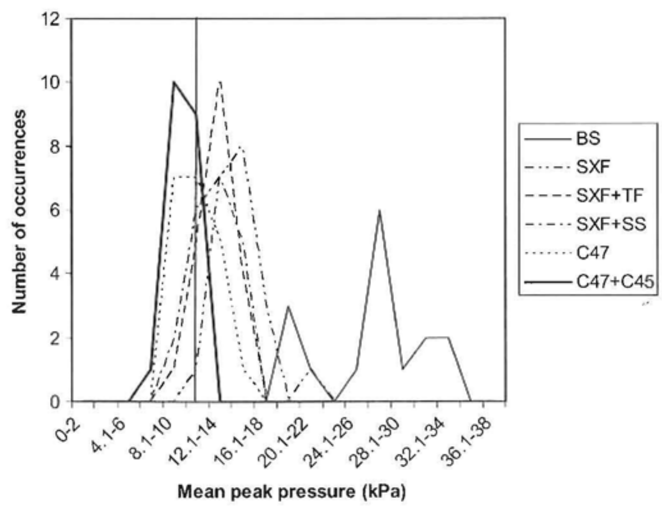

Fig. 3. Frequency distribution of mean peak pressures achieved by the different energy-absorbing foam combinations tested. A line indicates the critical mean peak buttock pressure. Although this graph is a histogram, for clarity the midpoints of the histogram bars have been joined by straight lines for each foam.

our sample (26.7 kg · m^{-2}) implies that our study pilots were somewhat overweight, the upper limit of the 'normal' range being 25 kg · m^{-2} (17). However, by the same criteria, the UK male population as a whole is overweight, so that our population is representative of UK males. Lasham Gliding Society makes up approximately 10% of the UK glider pilot population. Our study, therefore, represents a significant sample and we have no reason to consider our sample to be atypical.

Other areas for further research include the effect of covering materials on the comfort and safety of different types of energy-absorbing foams, and the effects of temperature. This latter is important because the cockpits of gliders are unheated and as they fly at a range of altitudes the temperature inside the cockpit can range from well below 0°C to near or even above body temperature (37°C). The study we report here used foams that had not been previously evaluated for gliders. It would, therefore, be worth investigating how the characteristics of these energy-absorbing foams change in response to different ambient humidity levels and to verify the manufacturers' claims of stability during long-term exposure to sunlight and air. It is also known that tissue ischemia, and hence discomfort, can be produced by excess shear on the skin in addition to direct compression (2). This occurs when the skin is subjected to a "hammock" effect, for example when the individual is seated on a thick layer of soft foam. However, thick seat cushions are usually impracticable for gliders because of the small cockpits. In addition, thick soft cushions can increase the risk of spinal damage during a heavy landing or crash. Unpublished studies from the aerospace industry suggest that at thicknesses approaching 50 mm (2 in), energy-absorbing foam induces other dynamic behavior and becomes unsuitable (various personal communications). We did not, therefore, investigate thicker energy-absorbent cushions, nor have we tested other foams from other manufacturers. This would be a valuable topic for further research using the method we have developed.

A military study that assessed the comfort and safety of ejection seat cushions reported that perception of comfort can change considerably as a function of the number of hours of continuous use (7). Furthermore, no particular cushion, whatever the material of which it is composed, could be expected to fit the entire anthropometric range of pilots. A study undertaken in 2006 monitored oxygen levels in the legs at the level of the medial head of the gastrocnemius muscle (8). This found that a cushion that generated low mean peak pressures (corresponding to the levels of our findings) caused less fidgeting and hence subsequent relaxed immobility in male pilots. This resulted in blood pooling in the legs which ultimately—and paradoxically—led to discomfort. However, this is unlikely to occur in gliding because there are constant movements of the legs in actuating the rudder pedals during flight.

In a separate experiment (4) we compared in particular the energy-absorbing properties of the C47+C45 with the SXF and SXF+SS cushions, SXF being the recommended safety foam for gliders in the UK. We found that the C47+C45 option was significantly better than standard SXF (usually known in the UK as Dynafoam Extra-Firm). This suggests, therefore, that the extra comfort provided by this combination of foams (C47+C45) does not compromise safety. For the C47+C45 cushion, the mean peak pressure 1 SD above the mean was 9.8 kPa + 1.0 kPa = 10.8 kPa (1.57 psi). Given that our sample of pilots was typical of the UK male gliding population, this implies that approximately 84% of pilots would be below the critical mean peak pressure and would be comfortable on this cushion option. In the tests, only 1 pilot out of the 20 exceeded the critical value for the C47+C45 cushion. An equivalent calculation for SXF+SS implies, by contrast, that some 84% of pilots would ultimately become uncomfortable. A similar outcome applies to SXF+TF.

Seating is only one of the areas that contribute to the discomfort experienced in many glider cockpits during the course of long flights. Areas needing further study include:

- Excessive lateral forces in the tibiofemoral joints due to the position of the instrument panel and the aerodynamic shape of cockpits;
- Strain to the lateral ligaments of the ankle joints caused by the feet needing to be angled unnaturally to actuate rudder pedals;
- Lack of support in the lumbar region; and
- Uncomfortable parachute/body interfaces.

We, therefore, conclude that for male pilots to remain comfortable in a confined cockpit, seat cushions should generate a mean peak buttock pressure of no more than 11.0 kPa (1.6 psi). By reference to this, an energy-absorbing cushion made up of approximately 25 mm ("1 in") of Confor C47 foam with an overlaying thickness of approximately 13 mm ("0.5 in") of Confor C45 is likely to provide a comfortable solution for the majority of glider pilots.

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