Image Cover Sheet

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ORIGINAL RESEARCH

Extended-Coverage-Bladder G-Suits Can Provide Improved G-Tolerance and High Gz Foot Pain

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Method: An extended coverage bladder (ECB) G-suit was evaluated on the DCIEM centrifuge against the current service G-suit (CSU-15/P) in two separate series of experiments. The ECB G-suit covered approximately 85% of the lower body measuring from the umbilicus and all five bladders completely encircled each leg and the lower trunk. The CSU-15/P G-suit covered approximately 30% of the lower body and its five bladders were located only over the frontal aspect of each leg and the lower trunk. The first series of experiments involved five subjects from the highly experienced DCIEM A-team. A standard gradual onset rate (GOR) run was used and suit testing order was counterbalanced across subjects. ***Results:*** The test condition G-tolerances are listed as mean ± SEM; relaxed uninflated tolerances were 4.0 ± 0.14 for the CSU-15/P suit vs. 4.1 ± 0.09 for the ECB suit (ns, single tailed, paired *t*-test) while relaxed inflated tolerances were 4.7 ± 0.19 for the CSU-15/P suit and 5.5 ± 0.37 for the ECB suit ($p = 0.02$, single tailed, paired *t*-test). The straining tolerances were 8.1 ± 0.44 for the CSU-15/P suit and 9.0 ± 0.56 for the ECB suit ($p = 0.01$, single tailed, paired *t*-test) The second series involved nine subjects for the following three G-suit conditions; CSU-15/P, ECB with inflation limiters, and ECB with inflation limiters and foot bladders. Relaxed uninflated tolerances were 4.0 ± 0.13, 4.0 ± 0.08, and 3.9 ± 0.10 (ns) while straining inflated tolerances were 9.4 ± 0.48, 10.1 ± 0.38 and 10.6 ± 0.42, respectively ($p = 0.01$ between all three straining conditions, ANOVA with Scheffé F-test). The ECB G-suit with inflation limiters eliminated abdominal pain and discomfort. ***Conclusion:*** The ECB G-suit provides improved G-tolerance for both inflated relaxed and straining exposures. Foot bladders eliminated high Gz foot pain and improved straining G-tolerance by about half a Gz. The efficacy of ECB G-suits should be evaluated when used in conjunction with positive pressure breathing. While the ultimate G-suit has yet to be conceived and will no doubt be part of an integrated life support system, ECB G-suits are a step in the right direction in the evolution of life support garmentry.

UNTIL THE MID-1980s, virtually all of the world's air forces were still content to use G-suit designs that were conceived during the late 1940's. Although the inherent design limitations of these old G-suits were known since the 1970's, it wasn't until recently that serious research and development effort was expended on developing a new generation of G-suits.

At DCIEM, as well as in several other acceleration research laboratories, the most promising route to improved G-tolerance from G-suit design changes has been achieved by increasing G-suit bladder coverage area to almost full coverage of the lower half of the body (1,2,4–7). Given that the Frank's flying suit (the first G-suit ever built) was a full coverage G-suit, we have essentially come full circle in G-suit design thought.

The work reported here involves the specifics of two series of G-suit evaluations. The first series evaluated an extended-coverage-bladder (ECB) G-suit that was recently developed and built at DCIEM against the current service G-suit (CSU-15/P), which is currently used by fighter aircrew of the Canadian Forces. Because of the abdominal pain reported by the subjects in series 1 while wearing the ECB suit, this suit was modified for series 2 by adding inflation limiters to the abdominal bladders. Inflation limiters were also added to the thigh bladders in order to limit the inflated size of this G-suit because our CF-18 pilots reported that the relatively large inflated size of the CSU-15/P thigh bladder interfered with the movement of the throttle. It was decided to add foot bladders in a third condition in order to determine whether or not they would attenuate foot pain and/or improve G-tolerance.

METHODS

All subjects used in this study were fully informed of any hazards, gave their written informed consent, and knew that they were free to withdraw from the study at any time without prejudice. The protocol was approved by the DCIEM Human Ethics Committee.

Five subjects underwent G-tolerance assessment using each of two G-suits; the CSU-15/P and the DCIEM ECB suit. The CSU-15/P suit bladder area covers approximately 30% of the lower body measured from the umbilicus. The five bladders of this suit were located only over the frontal aspect of the lower trunk and each of the legs. The ECB suit covered approximately 85% of the lower body and completely encircled the lower trunk and each leg.

G-tolerance assessment sessions were conducted on 2

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separate days. The G-suit testing order was counterbalanced across subjects in an effort to separate out any effects due to practice. A gradual onset rate (GOR) run profile, having an onset rate of 0.1 $G \cdot s^{-1}$, was used for all runs. The rationale for using GOR is discussed below. A warm-up run was performed by each subject at the start of each session. Following the warm-up run, each subject performed three relaxed runs with the G-suit uninflated and an additional three runs with the G-suit inflated. The final profile of either session was a single maximum effort straining run with G-suit inflated to the standard schedule for a high flow Alar G-valve. The subjects were all very experienced centrifuge riders and each chose the most reliable personalized criterion light-loss endpoint, which ranged from the normal 100% peripheral light loss to full visual black-out. All subjects were able to titrate their relaxed centrifuge run end-points reproducibly to within 0.1 G. In this second series, nine subjects were assessed for relaxed and straining G-tolerance over three conditions: a) the regular CSU-15/P suit; b) the modified ECB suit (fitted with abdominal and thigh bladder inflation limiters); and c) the modified ECB suit complete with foot bladders. Here all three conditions were counterbalanced across subjects and the GOR profile used in series 1 was also used in this series. A high flow Alar valve was used throughout this study and pressurized the G-suits according to the following schedule ($P_{g\text{-suit}} = 1.5\ (G_z - 2)$ psi).

RESULTS

The G-tolerance values for series 1 are plotted in **Fig. 1**. The relaxed G-tolerances with uninflated G-suits were 4.0 ± 0.14 (CSU-15/P) vs. 4.1 ± 0.09 (ECB) (ns, single tailed, paired *t*-test). The relaxed G-tolerances with inflated G-suits were 4.7 ± 0.19 (CSU-15/P) vs. 5.5 ± 0.37 (ECB) ($p = 0.02$, single tailed paired *t*-test) while straining tolerances were 8.1 ± 0.44 (CSU-15/P) vs. 9.0 ± 0.56 (ECB) ($p = 0.01$, single-tailed, paired *t*-test). The single tailed paired *t*-test was used because we decided that a larger coverage bladder G-suit had no possibility of degrading G-tolerance. This type of G-suit would either not change G-tolerance, or improve it. Severe foot pain was reported by two subjects while wearing the ECB G-suit. Further, four subjects complained of abdominal pain/discomfort while wearing the ECB G-suit.

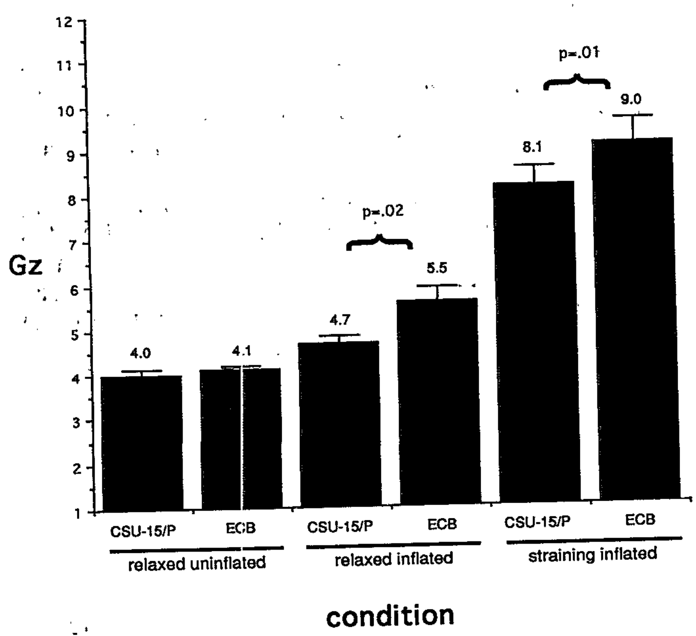

Fig. 1. Plot of G-tolerance for each of the CSU-15/P and ECB G-suits over the three conditions of series 1.

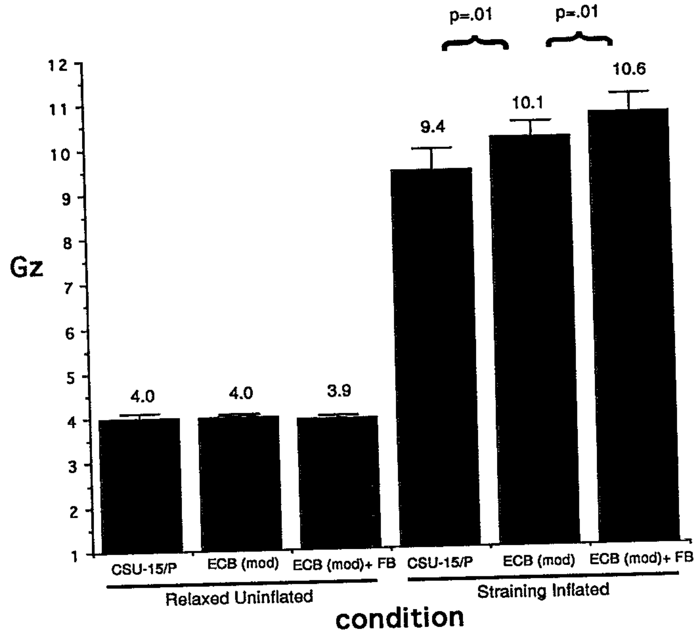

Fig. 2. Plot of relaxed uninflated and straining inflated G-tolerances for each of the three G-suit configurations of series 2.

The G-tolerance values for series 2 are presented in **Fig. 2**. The relaxed G-tolerances with uninflated G-suits were 4.0 ± 0.13 (CSU-15/P), 4.0 ± 0.08 modified ECB, and 3.9 ± 10 (modified ECB plus foot bladders). There was no difference in relaxed G-tolerance with uninflated G-suits across any of the suit configurations. The straining G-tolerance values for inflated suits were 9.4 ± 0.48 (CSU-15/P), 10.1 ± 0.38 (modified ECB), and 10.6 ± 0.42 (modified ECB plus foot bladders). Analysis of variance revealed a significant main effect of G-suits during the inflated straining runs and post hoc analysis (Scheffé) revealed that the modified ECB suit was better than the CSU-15/P ($p < 0.01$) and that the modified ECB suit with foot bladders provided more protection than the modified ECB suit without foot bladders ($p < 0.01$). None of the nine subjects in this series experienced any foot pain at high Gz when wearing foot bladders. Similarly, no subjects reported any abdominal pain or discomfort with the inflation limiters on the abdominal bladder. The inflation limiters in the abdominal and thigh bladders did not adversely impact G-tolerance.

DISCUSSION

At the Annual Scientific Meeting of the Aerospace Medical Association in Toronto (May 1994), several attendees asked questions about using gradual onset rate (GOR) acceleration profiles for assessment of protection afforded by G-suits. The general consensus was that GOR runs were not operationally relevant and therefore should not be used to assess protection afforded by G-suits. Rapid onset rate (ROR) runs were thought to be the appropriate acceleration profiles for this type of investigation.

Whinnery (9) described a theory of acceleration tolerance in which Stoll's (8) G_z time tolerance curve is partitioned into neurologic and cardiovascular components. Whinnery's theory characterizes the traditional single-point level-tolerance, duration tolerance, as well as cardiovascular and neurologic tolerance and the unique contributions of each of these subsets to operational G_z tolerance. According to Whinnery's classification, neurologic tolerance is measured in the centrifuge by ROR runs, cardiovascular tolerance is measured by GOR runs, level tolerance can be measured by either ROR or GOR runs, and duration tolerance is measured by sustained G or simulated aerial combat maneuvering (SACM) runs. In the fighter operations environment, different phases of aerial combat maneuvering make each of the various types of tolerance more important at different times. Since centrifuge investigations that would try to replicate operational tolerance with all of its subsets would be impractical at best, investigators are left to choose which of these types of G-tolerance they will use in their investigations. GOR runs were chosen for this study because the end-points are highly repeatable by our very experienced subjects, and the G-tolerance data generated are continuous in nature and therefore normally distributed and easily analyzed by parametric statistics. ROR runs don't provide such exact tolerance end-points and the interval data generated by ROR runs are not normally distributed and must be analyzed by less rigorous non-parametric statistics.

The first series demonstrated that the ECB G-suit provides almost one extra G_z of protection relative to the standard CSU-15/P, but this first version of the ECB suit caused significant abdominal pain or discomfort, and severe foot pain was experienced by two out of five experimental subjects during the upper G_z range of their straining runs. In fact one of these subjects stated that he would have been able to go to a higher G level except that his straining run end-point was definitely pain-limited.

In the second series, inflation limiters added to the ECB suit eliminated the abdominal pain and discomfort and maintained a similar protection advantage relative to the CSU-15/P. Further, the foot bladders improved G protection by 0.5 G_z and eliminated foot pain. Of note, another study in this laboratory (3), using ROR runs and a very sophisticated objective end-point provided by a device measuring ear opacity similar to the system used by Earl Wood in the 1940's (10), also found that these foot bladders provided the same 0.5 G of increased protection.

Part of the reason for this foot pain is that in a 20-ft radius centrifuge that is running at 10 G_z with respect to heart level, there is a 2 G_z gradient from head to toe, such that eye level G_z is approximately 9.5 G_z while foot level G_z is approximately 11.5 G_z. A shorter radius centrifuge would have an even greater head-to-toe G_z gradient. As the centrifuge radius increases, the G gradient decreases. Certainly, in an aircraft where to all intents and purposes the radius in any turn is "infinitely long," there is no G-gradient and pilots may not experience pain until reaching 11 or 12 G_z.

CONCLUSION

The ECB G-suit provides almost one extra G of protection more than the CSU-15/P. Inflation limiters eliminated abdominal pain and discomfort without compromising G-tolerance. Foot bladders eliminated foot pain and provided an extra 0.5 G_z of protection. Should there be a need to further exploit the high G_z capability of some modern fighters into the realm of possible foot pain, foot bladders are an effective means to eliminate or attenuate such pain, and the foot bladders provide an extra half G_z of protection in the process.

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