G Protection When Adding Pressurized Sleeves and Gloves to a Representative G-Suit Ensemble

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BACKGROUND: In a previous study, pressurized sleeves and gloves were found to substantially diminish or eliminate G-induced arm pain. Since this equipment presumably acts similarly to a G suit for the arms and hands, it was hypothesized that higher inflation pressures might provide an additional increment of G protection.

METHODS: In a human-rated centrifuge, 15 well trained subjects using Combat Edge and ATAGS G-protective equipment were exposed to gradual and rapid onset relaxed G exposures as well as rapid onset straining and simulated aerial combat maneuver G exposures up to + 9 G_z with and without pressurized sleeves and gloves.

RESULTS: The pressurized sleeves and gloves did not show any improvement in G tolerance or endurance compared to the control. However, significantly lower heart rates (6–12%) and subjective effort (11%), along with slightly less peripheral vision loss, suggest a decreased work load when wearing the pressurized sleeves and gloves. A trend to shorter time on target in a tracking task was found with the pressurized sleeves and gloves, likely due to decreased mobility of the hands, thus affecting control stick input.

CONCLUSIONS: G tolerance and endurance were not improved by the pressurized sleeves and gloves. However, a lower heart rate and a decreased subjective effort level and peripheral vision loss indicated that the subjects did not have to work as hard with this equipment.

KEYWORDS: pressure sleeves, pressurized gloves, G protection, G suit.

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Pressure breathing during G (PBG) has been shown to substantially increase G endurance time and reduce fatigue.[5,7,9] This technique is now operational as the Combat Edge system in all U.S. Air Force F-15 and F-16 aircraft.[2] Furthermore, PBG in conjunction with extended coverage anti-G suits is currently in operation in the Finnish Air Force's F-18, the Swedish Air Force Gripen fighter aircraft, the USAF F-22 (Advanced Technology Anti-G Suit or ATAGS equipment), and in the European Consortium's Eurofighter. These systems substantially increase G tolerance and G endurance during high G exposures.[1,3,11]

In an earlier study, pressurized sleeves and gloves were developed for prevention of G-induced arm pain.[10] The sleeve and glove pressures started at +4 G_z and linearly increased to 40, 60, and 80 mmHg at +9 G_z. All three of these pressures were shown to substantially decrease or totally eliminate G-induced arm pain. In the conclusions of the study it was suggested that the pressurized sleeves may provide increased $+G_z$ tolerance. Since the pressurized sleeves and gloves presumably act in the same way as an ordinary anti-G suit, providing an external pressure to underlying legs and abdomen and forcing blood toward the heart but for the arms instead of the lower body region, we hypothesized that this equipment also would further improve G protection.

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METHODS

Subjects

Recruited from the Brooks City-Base human centrifuge subject panel (active duty military only) were 15 volunteers, including two women. Their average height was (mean ± SD) 172 ± 6 cm (range 165-183), average weight 75 ± 9 kg (range 61-91), and age 30 ± 7 yr (range 23-42). Centrifuge panel members are prescreened for appropriate health and fitness clearances. Panel members must complete introductory training on the centrifuge and demonstrate the capability to tolerate exposures up to +9 G_z when wearing standard G-protection ensembles. From a medical standpoint, potential panel members are included or excluded through a physical examination based on USAF Flying Class II/III standards, which screen for any medical issues precluding centrifuge exposure. By virtue of being voluntary members of the centrifuge panel, the subjects receive military incentive pay for their voluntary exposure to acceleration stress. The research protocol for this study was reviewed and approved by the AFRL Institutional Review Board prior to subject recruitment and the subjects gave written informed consent before participating. Female subjects provided a negative pregnancy test within 72 h prior to each of their centrifuge exposures.

The subjects' activity, food, and fluid intake the day prior to each test were ad libitum, except for alcohol, which was not allowed. In addition to standard G-tolerance training, the subjects were also trained on an F-16 tracking task, both at +1 G_z and up to +9 G_z. Before each centrifuge test session, standard sternal and biaxillary EKG electrodes were attached. The subjects were then dressed with Combat Edge and a counterpressure vest (for PBG), and ATAGS garments.

Equipment

The Wyle human-rated centrifuge [formerly a U.S. Air Force Research Laboratory (AFRL) property at Brooks City-Base, TX] generates acceleration forces similar to those encountered during flight and air combat maneuvering. The 19.5-ft rotating arm produces centrifugal force and the free swinging action of the gondola orients the human subject such that the resultant G vector is aligned with the subject's z-axis, producing +G_z (produces an inertial force opposite to the acceleration).

The arm and hand pressurization device was comprised of sleeves with a full arm bladder extending from the pressure vest to the wrist, and pressure gloves with a bladder on the dorsal side.[9] The subjects had sleeves and gloves on both arms. The devices were connected to the mechanically controlled anti-G valve. The in-house developed modification of a G-valve regulator for the different required arm pressure levels was used and tested and calibrated before every experiment.

The subjects were seated in the centrifuge with an F-15 aircraft seat configuration (seat back angle 13°) for G tolerance (maximal G levels) and G endurance (time at the simulated aerial combat maneuver G profile) assessments. A CRU-93A (Combat Edge) breathing regulator capable of applying individually adjustable electronically controlled pressures provided the PBG. They also wore a HGU-55/P flight helmet, MBU-20/P oxygen mask, CSU-17/P counterpressure vest, ATAGS anti-G suit, parachute harness, life preserver connector block and flight boots. An adjustable G valve for the anti-G suit pressure in the ATAGS G-suit schedules was used in the first nine subjects. In the last six subjects the standard breathing regulator and G valve were used.

Procedures

The distance from the heart to the middle of the forearm for a short subject sitting in an F-15 seat was measured to be 14 cm, vs. 9 cm for a tall subject. This surprisingly small difference is due to the fact that the heart, in relation to the fixed hand positions for the control stick and throttle, is lower in the tall person with the seat down. We calculated that the arm sleeve pressure necessary to counteract the blood column from the middle of the arm to the heart level, i.e., heart level systolic blood pressure (PBG at +9 Gz), was 296 mmHg (5.71 psi) for a short subject and 319 mmHg (6.16 psi) for a tall subject. As these pressures are very similar, an approximate mean of 310 mmHg (equal to 6 psi) of the two values was used for all 15 subjects. Arm sleeve pressurization began at +2 G_z and linearly increased with G level to a maximum pressure of 310 mmHg at +9 G_z.

The subjects were exposed to two different conditions: 1) standard Combat Edge PBG, or PBG pressure in relation to the eye to heart blood column distance; and 2) the same PBG as in condition 1, but with the addition of pressurized sleeves and gloves. The eye to heart distance were measured before the centrifuge runs on a sitting subject from the eye level with the head in an upright position to the level of the fourth intercostal space at the sternal border. Calculations of the necessary blood pressures to avoid cerebral hypoxia were used for the different heart to eye distances (with compensation for intraocular pressure). In a subject with an eye to heart distance of 30 cm, calculations of the blood column heart to eye level indicated that an optimal PBG pressure of about 60 mmHg at +9 G_z was required (two of the nine subjects). Subjects with an eye to heart distance of less than 30 cm were exposed to a maximum PBG pressure of 44 to 56 mmHg (four subjects). Subjects with greater than 30 cm eye to heart distance were exposed to a maximum PBG pressure not exceeding 80 mmHg for safety reasons (three subjects). However, the different PBG pressures in the subjects were the same with and without pressurized sleeves and gloves for paired comparisons. In the first nine subjects, PBG was regulated with an in-house modified Combat Edge breathing regulator, where the sense line, which normally connects to the G valve, was connected to a transducer, with a Lab View program that controlled the breathing pressure according to the different calculated breathing pressures. For the six subjects later added to the study, we used the standard Combat Edge pressure breathing levels for all centrifuge runs. Pressurization began at +4 G_z and increased to a maximum of 60 mmHg at +9 G_z.

For the first nine subjects we calculated the optimal anti-G suit pressure for G protection to avoid cerebral hypoxia. A full coverage anti-G suit (ATAGS) based on the vertical heart-foot distance (from the fourth intercostal space to the foot resting on the pedal) for a short subject in the seat up and pedals up position and for a tall subject with the seat down and pedals down position was used. There were very limited differences of the heart to foot distances with adjustments of the seat and foot pedals for short and tall subjects (from 66 to 71 cm) because the foot pedal adjustments moved the pedals more forward or backward than upwards and downwards and the seats moved only very slightly up and down. The calculated pressure, with similar assumptions as above, only caused small changes in the G-suit pressure (from 670 to 690 mmHg at + 9 G_z). For the last six subjects, a maximum G-suit pressure of about 525 mmHg at +9 G_z was used. All anti-G suit pressures started at +2 G_z and followed a linear increase to the maximal pressure at +9 G_z. It is important to point out that since each of the 15 subjects was exposed to the same PBG levels and G-suit pressures in both of his/her experimental conditions, no bias was introduced that would void the paired statistical comparisons of the sleeve/no-sleeve conditions.

There were two test conditions. On one day the subject wore Combat Edge and ATAGS equipment and on a different day the subject wore the same equipment together with pressurized sleeves and gloves. The order of the conditions was randomized and balanced (half the subjects wore pressurized sleeves on the first day, the other half did not wear pressurized sleeves on the first day) to counter any potential biases due to learning or training effects.

The following G profiles were used on each test day:

A) Relaxed gradual onset ($0.1\ G \cdot s^{-1}$) run (GOR) to +9 G_z. End point criteria were subject-reported 100% loss of peripheral vision and/or 50% loss of central vision as determined by peripheral and central lights. In the centrifuge gondola a single central red light and two peripheral green lights were mounted on a horizontal bar 30 inches in front of the seated subject. The central light was directly on the subject's horizontal centerline of sight and the two peripheral lights were each at a 25° angle on either side of the central light. The maximum G level reached was recorded for analysis.

B) After a 5-min rest period at +1 G_z, a series of relaxed rapid onset ($6\ G \cdot s^{-1}$) runs (ROR) were started first at +3 G_z, and increasing by +1 G_z per run, to a maximum of +9 G_z. Each G exposure lasted 15 s or until vision end point criteria were reached. There was a 2-min rest period between exposures. If end point criteria were reached, the immediate lower G level was recorded as the maximal successful G.

C) After a 2-min rest period at +1 G_z, the subject continued the G-exposures starting one G level above the relaxed ROR maximal G, but with the execution of necessary muscle and respiratory straining (standard anti-G straining maneuvers or AGSM). After a 2-min rest period the next higher G level was tested. This process was repeated up to a maximum of +9 G_z or until vision end point criteria were reached. The highest G level was recorded for analysis.

D) After a 5-min rest period at +1 G_z a simulated aerial combat maneuver (SACM) G profile consisting of 10-s periods at approximately +5 G_z and +9 G_z (see below) was performed while using standard anti-G straining maneuvers. During this run, subjects simultaneously executed an F-16 tracking task wherein they used a control stick to track an aircraft displayed on a screen in front of them. The root mean square (RMS) of the deviations from the ideal distance to the target and the time on target (TOT) were computed continuously and stored in the computer.[2,3] This was done in combination with closed loop control of the centrifuge via the control stick. The control stick forces controlled the G level in the centrifuge gondola (similar to actively flying an aircraft by moving the control stick), which means that the subject was actively in control of the centrifuge speed and, thus, the G level. The SACM continued to exhaustion, the above mentioned visual end point criteria, or for a maximum of 15 peaks. The time duration (in seconds) of the ride was recorded for analysis.

The subjects also provided their subjective general discomfort levels after each ROR and the SACM exposures, and their subjective effort levels after the straining ROR and SACM exposures, by using a scale ranging from 0 (none) to 11 (maximal).[4] Heart rate was also recorded for analysis from each centrifuge exposure. Heart rate, effort level, light loss, RMS error, and TOT were all measured at a "common G level" during the centrifuge runs. A "common G level" was defined as the lowest maximum G level or for SACM exposures the longest duration attained by a subject across both experimental sessions, and was determined for each subject individually. It was necessary to measure heart rate, etc., at a common G level to avoid bias when comparing the conditions. For example, if a subject went to +6 G_z under one condition, and +9 G_z under the other, his/her heart rate, effort level, light loss, RMS, and TOT value might differ simply due to the additional stress of the higher G or longer SACM duration, not because of a difference caused by whether or not they wore pressurized sleeves and gloves. The subjects reported a percentage of light as a result of decreases in perceived brightness of the peripheral and central vision loss after each high G exposure.

Statistical Procedures

From tables in Cohen,[8] it was determined that a sample of 15 subjects would provide a power of 0.80 for detecting a moderate difference (i.e., a difference that is 0.8 SDs of the difference in magnitude) when performing paired comparisons at the 0.05 two-tailed alpha level. For each of the recorded outcome measures, the sleeve condition was compared with the no-sleeve condition using a Student's paired *t*-test. Some of the measures were not normally distributed and a second set of analyses (nonparametric Wilcoxon's signed rank tests) were therefore run to aid with overall interpretation of results. The Wilcoxon tests make no assumption about the underlying distribution of the data.

RESULTS

The values for the lowest and highest calculated and used PBG levels at +9 G_z for the first nine subjects were 44 mmHg and 80 mmHg. The maximal PBG level used was 80 mmHg for safety reasons and only one subject was calculated to have a higher PBG level. The average PBG level for the first nine subjects were 62 mmHg and for the added six subjects it was always 60 mmHg.

For every outcome measure, the *t*-test and Wilcoxon test were in agreement (i.e., when one test was significant, so was the other), with one exception (discussed later). Consequently, only the *t*-test results, along with descriptive statistics, are shown in **Table I, Table II,** and **Table III**.

There were no statistical differences between the no-sleeve and sleeve conditions in the maximal G levels reached during any of the GOR or ROR exposures (Table I). During the GOR, 9/15 reached +9 G_z with no sleeves and 10/15 with sleeves and during ROR with straining all subjects reached +9 G_z with no sleeves and 14/15 with sleeves. In addition, the average duration (ride time) of the straining SACM runs did not differ statistically between the sleeve and no-sleeve conditions. During the SACMs only 1 of the 15 subjects reached the maximum 15 peaks at +9 G_z and he accomplished that during both conditions.

Significant differences between the sleeve and no-sleeve conditions were found for all four common heart rate measurements at the common highest G level or longest SACM duration (Table II). In each case, heart rate was significantly higher under the no-sleeve condition than under the sleeve condition. In addition, perception of effort and peripheral light loss during the SACM were both higher in the no-sleeve condition than in the sleeve condition (Table III).

With respect to the SACM tracking task, the *t*-tests found no evidence of differences between the two test conditions for either RMS of the deviation from the ideal tracking path or TOT (Table III). However, a visual inspection of the results showed that the RMS and TOT means appeared slightly better under the no-sleeve condition, and the Wilcoxon test showed a significantly higher TOT when not wearing the sleeves ($P = 0.036$).

Finally, differences in discomfort levels were not remarkable between the sleeve and no-sleeve conditions for either of the ROR exposures or for the SACM exposure and are, therefore, not summarized in this paper.

DISCUSSION

Pressurized sleeves and gloves did not lead to improved G tolerance or endurance as hypothesized, but did result in a statistically significant reduction of heart rate in all G-exposures. This was accompanied by a lower reported effort level and less peripheral light loss during the SACM profiles.

Our hypothesis was that pressurized sleeves and gloves would improve relaxed G tolerance or straining endurance and perhaps both. We could not verify this hypothesis. However, in a study by Tripp et al.,[12] a retrograde inflation anti-G suit with capstan sleeves provided superior G endurance when compared to a standard CSU-13 B/P G suit alone, or to a retrograde inflation G suit alone. The beneficial effect of arm pressurization reported in their study was statistically significant on a +4.5 to +7 G_z SACM, but we failed to achieve similar significance on our +5 to +9 G_z SACM. They also showed that the equipment combination with capstan-pressurized sleeves was the most comfortable of those tested. This contrasts with our unchanged comfort levels in the comparison with and without pressurized sleeves and gloves. In a study by Wood and Lambert,[13] they reported no improvement in G tolerance with arterial occlusion unless used with an antiblackout suit affording good (2-G) protection, in which instance an additional 0.5-G improvement was gained. In our study, a full coverage anti-G suit with PBG with already very high G protection was used, and an additional gain in G protection could, probably, be expected to be even lower.

In an earlier study[10] we tested pressurized sleeves and gloves for protection against acceleration-induced arm pain, and found that 40 to 80 mmHg at +9 G_z caused a substantial decrease in, or totally eliminated, G-induced arm pain. In the current study, however, we used a much higher maximal sleeve and glove pressure (310 mmHg at + 9 G_z), which may have offset comfort improvements noted in the capstan and arm pain examples above.

The inflation schedule for the sleeves did make concessions to comfort in that it did not seek maximum theoretical effect: in the F-15 seat the arms and hands, at or slightly below heart level, are at the base of a hydrostatic column much shorter than that from the foot to the heart. We modeled our inflation pressure to approximate blood column caused pressure at the mid-forearm of 44 mmHg/G (0.86 psi/G), beginning at 2 G, to a maximum of 310 mmHg (6.0 psi) at 9 G. Theory here sought to allow blood flow but prevent its accumulation. Better performance could have been achieved with higher pressures on a more aggressive schedule, one which collapsed the major arteries, increased peripheral resistance and thus central arterial pressure, diverting more cardiac output cephalad. Pragmatic considerations of comfort and mobility, which get worse with higher inflation pressures, led us to adopt the lower schedule. A limitation in this study was that we did not directly measure the pressure in the arm bladders, but we calibrated the regulator

Table I. Maximal G Levels During Relaxed GOR and ROR, Straining ROR, and Maximal Duration Times During SACM With and Without Pressurized Sleeves and Gloves.

	DESCRIPTIVES		STUDENT'S PAIRED *t*-TEST RESULTS			
VARIABLE CONDITION	MEAN	SD	SD OF DIFF	*t*	DF	*P*-VALUE
GOR—relaxed G						
No sleeve	8.3	1.2	0.6	−0.32	14	0.751
Sleeve	8.4	1.2				
ROR—relaxed G						
No sleeve	6.7	1.6	0.8	−1.87	14	0.082
Sleeve	7.1	1.7				
ROR—straining G						
No sleeve	9.0	0.0	0.3	1.00	14	0.334
Sleeve	8.9	0.3				
SACM durations						
No sleeve	195	82	56	−1.54	14	0.145
Sleeve	217	83				

Table II. Heart Rates (bpm) During Relaxed GOR and ROR, Straining ROR, and SACM With and Without Pressurized Sleeves and Gloves.

	DESCRIPTIVES		STUDENT'S PAIRED *t*-TEST RESULTS			
VARIABLE CONDITION	MEAN	SD	SD OF DIFF	*t*	DF	*P*-VALUE
GOR—relaxed HR						
No sleeve	127	15	11	2.67	14	0.018
Sleeve	119	20				
ROR—relaxed HR						
No sleeve	113	20	14	3.66	14	0.003
Sleeve	100	15				
ROR—straining HR						
No sleeve	145	16	10	4.43	14	<0.001
Sleeve	133	15				
SACM HR						
No sleeve	155	17	15	3.69	14	0.002
Sleeve	141	22				

giving the pressure daily before every experiment. The sleeve pressure inflation delay would be about the same for every subject, but a higher pressure might have caused a very minor delay compared to a lower pressure.

Even though we did not find an improvement in G tolerance or endurance, using the same methodology to verify the G protection as in many earlier studies, the heart rate for all the tested G conditions was significantly lower by 6–12% for the relaxed G profiles and by 8–9% for the G profiles using the AGSM with the pressurized sleeve condition. Furthermore, the effect was consistent, with 80% or more of the subjects exhibiting a lower heart rate during the pressurized sleeve condition for each of the four G profiles. The lower heart rate suggests that less effort may be required to withstand the high G forces, especially during the SACM.[6] This hypothesis is supported by the fact that the subjective effort level was significantly lower by 11% with the pressurized sleeves and gloves during the SACMs, when vigorous AGSMs were needed to achieve maximum ride time. Heart rate reductions of this type were likely unnoticed by the subjects, with the only perceptible increase in protection being slight but significant improvements in peripheral vision reported at common duration SACM points when using the pressurized sleeves.

In retrospect, our decision to use PBG and a full coverage suit gave us the best G protection currently available in the operational fighter community, both in the control case and when we added the pressurized sleeves and gloves. The cardiovascular support available from our baseline ensemble may have been so good that adding pressurized sleeves and gloves could not improve G protection more than marginally and could not be detected with the method used for evaluating the G protection. If we had used a legacy five-bladder G suit without PBG, the pressurized sleeves and gloves might well have shown an effect similar to what we hypothesized.

Given that modest reductions in heart rate accompanied every exposure condition, something other than cardiovascular support may now be limiting G tolerance and endurance: the decision to stop on a 5-9 SACM normally results from fatigue to the point of incipient G-LOC, or G-related discomfort (arm/leg/neck pain). Respiratory fatigue may limit endurance at the AGSM and although PBG theoretically reduces the work required, it is still substantial, and the use of equivalent PBG schedules suggests the opportunity for similar outcomes. Ventilation/perfusion disturbances, manifest as pulmonary atelectasis and decreased arterial saturation, would have likely been similar in both cases, especially in combination with pressure breathing, and could signal similar outcomes regardless of ensemble. We know only that atelectasis clears rapidly after exposure; we do not know if it has acute effects in repetitive G-on-G exposures like a SACM, and the relationship it might have to perceptions of fatigue. Stoppages from subject discomfort can come from a variety of reasons, sometimes equipment related, but we did not have any such stoppages here.

We also note that some of our data is biased by a +9-G_z exposure limitation. Many of our relaxed or straining ROR peaks might have otherwise gone to +10, +11, or +12 G_z, and the

Table III. Effort Levels (Scale of 0 to 11) During Straining ROR and SACM, Peripheral and Central Light Loss (PLL and CLL in %), Root Mean Square Error (RMS), and Time on Target (TOT) during SACM.

	DESCRIPTIVES		STUDENT'S PAIRED *t*-TEST RESULTS			
VARIABLE CONDITION	MEAN	SD	SD OF DIFF	*t*	DF	*P*-VALUE
ROR strain effort						
No sleeve	3.8	2.2	1.4	0.36	14	0.726
Sleeve	3.7	2.5				
SACM effort						
No sleeve	7.0	3.1	1.4	2.18	14	0.047
Sleeve	6.2	3.2				
SACM PLL						
No sleeve	30	36	30	3.13	14	0.007
Sleeve	6	16				
SACM CLL						
No sleeve	5	14	14	1.33	14	0.204
Sleeve	0	0				
SACM RMS						
No sleeve	0.6	0.1	0.4	−1.51	14	0.154
Sleeve	0.7	0.4				
SACM TOT*						
No sleeve	130.4	66.2	38.8	1.71	14	0.110
Sleeve	113.3	61.5				

* Note that, while the *t*-test was not significant, the Wilcoxon signed rank test (not shown) indicted a significantly higher TOT during the no-sleeve run of the SACM ($P = 0.036$).

benefits of arm and hand pressurization might have emerged in greater relief at higher G levels. For example, Burns et al.[6] evaluated various protective equipment combinations on brief exposures to levels as high as +12 G_z. In this environment a full coverage G suit with PBG performed best, but less capably than at +9 G_z, suggesting that additional venous return from the arms or an increased arterial pressure by the pressurized sleeves would have a more visible and possibly significant effect on G tolerance and endurance at higher G levels.

Finally, we found a slight trend to a longer time on target when not wearing the sleeves. The Wilcoxon test showed a significant difference ($P = 0.036$), with 10 of the 15 subjects exhibiting a longer TOT when not wearing the pressurized sleeves. The tracking task was used to evaluate if an operational performance indicator was improved by the pressurized sleeves and gloves.[3] Instead of an improvement, we found a trend to the opposite. This deteriorating effect in the performance by the pressurized sleeves and gloves may possibly be explained by the pressurized gloves interfering with hand movements, causing a decreased mobility of the hand, restricting the control stick input.

In conclusion, this study could not find an improvement in G tolerance or endurance with the use of pressurized sleeves and gloves. However, a lower heart rate, a decreased subjective effort level, and a decreased peripheral vision loss indicated that there was evidence of improved physiological protection with the sleeves and gloves condition.

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