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Neck Muscle Fatigue Resulting from Prolonged Wear of Weighted Helmets under High G Acceleration

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Air Force Research Laboratory
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NOTICE AND SIGNATURE PAGE

AFRL-RH-WP-TR-2008-0085 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

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14. ABSTRACT
In search of guidelines for designing helmet-mounted systems without adding risk for additional pilot neck pain or injury, RHPG collaborated with the panoramic night vision goggle (PNVG) program office to begin this research. Neck muscles become fatigued as they work to stabilize the additional weight of helmet systems. The center of gravity (CG) of each individual helmet configuration varies according to the accessories attached. Neck strength measurements before and after high G simulations provided indications of muscle fatigue related to different helmets. Results show that volunteer test subjects tolerated the additional loads stabilized by their neck muscles when changes in CG are controlled. Questions remain unanswered concerning heavier helmets when CG cannot be controlled and how they might influence operational performance.

15. SUBJECT TERMS
Electromyography (EMG); Muscle Fatigue; High G Acceleration; Endurance; Neck Injury

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We are grateful for the collaboration with experts from other Air Force groups, the Army, Navy, and other international organizations through the NATO RTO who have provided insight and guidance throughout the research from concept and development to analysis of data. Their goal of reducing neck pain and injury is one we all share.

Members of the panoramic night vision goggle program office should be recognized and congratulated. They have been interested in providing the best product while minimizing negative effects on the warfighter. They stepped up with funding when necessary to complete the research. Part of the contribution came as a result of the work of Mr. Jim Barnaba whose efforts led to Major Pete Williams' assistance in data preparation. That assistance was very valuable to our program.

All these have helped obtain the basis for design criteria guiding development of new helmet-mounted systems giving our warriors the tools they need to excel.

Summary

Concern for neck pain and injury has been the primary motivation for this research. Pilot performance can be enhanced by the use of helmet-mounted systems but the additional weight, and the resulting changes in center of gravity, can make it difficult to maintain capabilities under high G acceleration. An added complication is that aircrews are often required to endure the weight longer as they respond to remote locations. This problem is not limited to the "fast movers". Rotary wing aircraft are commonly involved in long missions and their crew might wear even heavier helmets. Even fast moving boat crews experience neck stress as they bounce along turbulent waters.

This research was conducted to determine if a proposed new version of panoramic night vision goggles might be more fatiguing than those currently in use. Study of the results could lead to the establishment of design criteria for the proposed system, future systems, and upgrades of any system. Volunteer research subjects were exposed to a representative mission in which they encountered high G acceleration. As a result, they became fatigued. Evidence of neck muscle fatigue was derived from changes in muscle strength and endurance after the simulated missions. Use of electromyography (EMG) added another means to evaluate muscle activity as it changed in response to the demands placed on the neck muscles as they worked to stabilize the head and helmet system.

Results indicate that although subjects did indeed become fatigued, the increased weight of the proposed helmet, by itself, did not affect them more than the lighter helmet in use. However, the center of gravity of the heavier helmet was more neutral than the lighter helmet. The implication may be that additional weight may be tolerated as long as the CG is neutralized, possibly counterbalanced. In a long duration wear (7-8 hours), static program, Gallagher et al found that a 4.5 lb. helmet with forward CG (representative of NVG use) was significantly more uncomfortable on the subjects' neck and back than a 6.0 lb. helmet with the nominal CG shift (5). It is unknown how subjects exposed to sustained acceleration may have responded to a helmet system with both increased weight and an offset CG.

We are left with additional questions to answer. How would aircrews on extended, or multiple successive missions tolerate a helmet system which could not be configured with minimal CG offset? In the research completed here, no measurements were made during the high G centrifuge exposures. We therefore do not know how individuals might function. As they become fatigued, would they be able to perform actions requiring movements of the head? Targeting or anything requiring looking down into the cockpit might be problematic. Once new centrifuge facilities become available, consideration should be given to these questions.

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Introduction

The objective of this research protocol was to characterize human neck muscle response in subjects wearing helmets of varied mass properties (weight, Center of Gravity (CG), and Moment of Inertia (MOI)) while exposed to high G acceleration missions for durations up to 8 hours. Characterization of the muscular response was completed in terms of changes in neck strength, electromyography, and task performance expected to be affected by fatigue. The overall emphasis of this research was in regards to the effect on pilot fatigue during longer exposures due to the longer missions many aircraft are flying. Lessons learned from these results can help increase knowledge of neck pain and/or injury and lead to better design criteria for new helmet system development.

Background

Modern flight helmets have become platforms for many types of helmet-mounted devices (HMDs) used to give an advantage to the pilot using them. The HMDs enhance vision in darkness; provide aircraft altitude information, and sighting for weapons. Without this equipment, mission performance might not be possible under some adverse conditions.

Although the lightest materials available are used for the helmet systems, an additional load is still added in attempts to guarantee ejection safety / impact requirements. The weight and safety requirement go hand and hand with the design of these HMDS. The pilot's neck muscles must support the load as weight increases. The additional weight is not always added symmetrically so changes in center of gravity and moments of inertia occur. This is especially true for Night Vision goggles that are direct view devices which give a forward CG. Loads are best absorbed with the head in a "neutral" position aligned with the spinal column. Deviation from this position requires the muscles to work to stabilize the neck. The extensors tighten to pull the head back, resisting the tendency to be pulled toward the chest. These changes, when encountered under exposure to high G acceleration, may increase the risk of neck pain and injury.

Preliminary research in centrifuge tests has indicated that females required a high percentage of their maximal voluntary effort to stabilize heavy helmets and were unable to complete tracking tasks as weight increased (1). This could be attributed to less muscle mass found in females. Smaller males, in this study, did not appear to have the same types of problems.

Data collected during developmental testing of one helmet-mounted system in flight indicates that neck strength may decline over a series of daily exposures in high G aircraft (3), but aircrew were able to perform the mission. If this initial data is representative of a normal occurrence, it may mean pilots could experience neck muscle fatigue that might influence a pilot's ability to stabilize the head and helmet system. Mission performance might be adversely affected and ultimately increase the risk of injury during long duration / multiple missions.

The hypothesis for this research effort is that prolonged exposure to heavier helmet systems will lead to neck muscle fatigue. This fatigue can be identified by changes in neck muscle force in extension. Analysis of electromyography will show evidence to support fatigue through changes in signal amplitude and frequency. It is also expected that subject feedback might support the idea that pilots' performance is affected by muscle fatigue.

Impact

The impact related to this research should be similar to that described for the static long term fatigue protocol, #F-WR-2005-05-23-H (4). Without investigating human neck muscle response due to prolonged wear of weighted helmet configurations and its resultant experimental data, decisions concerning development and deployment of helmet mounted systems will be severely limited. If these systems are fielded without having been tested with human subjects, pilot safety, and performance may be compromised. Design criteria to guide manufacturers of helmet systems will continue to be inadequate for new and upgraded systems. In addition, these tests will provide the baseline for future model development that seeks to simulate a living human with active muscles, thus providing greater utility to modeling and simulations of the future. This study will aide in providing the information regarding safety, and performance of helmet mounted systems during long missions.

Methods

Equipment

Research testing was conducted on the Air Force Research Laboratory's Dynamic Environment Simulator (DES) centrifuge at Wright-Patterson AFB. The DES cab was configured to accommodate an approved seat. Rudder pedals, throttle, control stick, and other structures representative of an aircraft cockpit were also installed in the cab. Minimal instrumentation included audio and video monitoring equipment and EKG. In addition, ancillary noninvasive physiologic monitoring using electromyography (EMG) was provided to monitor muscle activity. Simulations were conducted in RHPG flight simulators.

Helmets were selected to represent those currently in use. One type represented a basic flight helmet with nothing additional mounted on it. It served as a control for comparison purposes. Two types of "heavy" helmets were evaluated. The first was based on the Joint Helmet Mounted Cueing System (JHMCS) and the second based on helmets with panoramic night vision goggles (PNVG / JHMCS integrated variant). The PNVG / JHMCS variant was weight representative; however the CG was more neutral, as if counterbalanced toward the CG of the head. Variable weight helmets (**Figure 1**) used in previous research by both RHPG and RHPA were modified for the simulation. Inertial properties of the helmet systems were adjusted to match the actual systems as closely as possible (**Table 1**). The weight range for the helmets was approximately 3.0 to 6.0 pounds. The helmet weight included the weight of the mask. The helmets were measured on a large ADAM manikin head with known mass properties to determine the existing head CG shift when the helmet of interest was worn. The CG data was recorded and reported with respect to the manikin head's anatomical coordinate system (Frankfort plane).

Selection of these helmets was done to allow researchers to determine how added weight and center of gravity (CG) changes affect muscle activity and might therefore affect pilot performance. The goal was to find how characteristics of any one type helmet might be associated with positive or negative performance indicators. Information could be passed on to developers for inclusion in the creation of design criteria which might be refined with these results.

Figure 1. Variable weight helmets

Table 1. Three helmets (based on LRG size)

Control (Basic 55/P), 3 lb	**CG (X) -0.18 IN. (Z) 1.09 IN.**
Current system, 4.5 lb	**CG (X) 0.10 IN. (Z) 1.02 IN.**
Projected 6 lb system	**CG (X) -0.02 IN. (Z) 0.79 IN.**

Neck strength tests were accomplished using a neck strength test fixture **(Figure 2)** based on an original neck strength device built by the Navy and loaned to AFRL/RHPG under a Memorandum of Understanding (MOU). Duplication of the fixture will allow data to be collected by both the Air Force and Navy, hopefully meaning a quicker resolution to neck pain and injury questions. Data collected is accessible by both parties of the MOU for the benefit of both parties. This data does/will provide a crucial set of missing data and criteria defining the tolerance of the neck to injury in high performance fixed and rotary-wing aircraft and designing guidelines essential to the development of HMD systems which accommodate males and females in both maneuvering and ejection acceleration exposures. This data is valuable to address concerns, not only related to Air Force and Navy fighters, but also rotary winged aircraft in the United States and foreign allies.

Figure 2. Neck Strength Test Fixture

Subjects

All individuals exposed to sustained acceleration under this protocol were volunteers from the AFRL Sustained Acceleration Stress Panel, which is composed of volunteer active duty Air Force members. These individuals qualified for the panel only after successfully completing extensive medical evaluations, training for exposures to high G in the DES, and in order to continue to participate, providing their ongoing informed consent. Informed consent was obtained prior to participation and as specified in the informed consent document, they must be cognizant of the phrase "if physical injury were to occur, it may result in my physical disqualification from flight or other special duty".

Test subjects included both male and female volunteers. Several candidates were selected to participate in the research in hopes of obtaining data from twelve males and twelve females. The goal was to select both female and male participants of varying sizes. They were protected by G-suits appropriate for the G level of the trial. They were trained to experience multiple G exposures and to provide verbal feedback regarding their physical and visual status throughout the profiles.

Members of the research panel are military volunteers who completed a training program and were successful in performing in G levels greater than they were to experience during the testing protocol, most up to 9 G. Subjects were selected and screened per protocol F-WR-2003-0027 - "General Protocol for Subject Selection, Indoctrination and Training for Dynamic Environment Simulator Studies." The ages of the panel were to fall within a range between 20 and 40 years. They were exposed to helmets of gradually increasing weight during training so they might adapt and become competent in performing centrifuge profiles while wearing the helmets.

Duration

In preparation for the long duration helmet exposures, subjects trained in the centrifuge starting with the basic helmet and gradually increasing weight. The goal for upper limit of weight was to be equal to the heaviest helmet to be tested. This gradual or incremental exposure was done using a modified helmet with a rail system that allows attachment of additional weight. With the basic helmet and after each increase in weight, a series of training runs was done. These runs began with 3.0 G for at least 10 seconds and increased in 0.5 G increments. Each person progressed at his/her own pace, moving up to the next higher G level only upon successful completion of a run. The intent was to prepare each participant for high G performance with helmets.

During the time subjects were preparing for the helmet exposures, they also began to practice simulator tasks. In addition, subjects were given questionnaires with questions to help determine if they had any history of strength training and, if so, a description or summary of the training. The questionnaire was be used, at the end of testing, to determine subject perception of fatigue. Any neck soreness was to be documented. Follow-up contact with subjects was attempted to inquire about delayed onset muscle soreness (DOMS) and to assess the duration of any soreness.

On test days, subjects prepared to spend most of an eight hour work day participating in research. The duration "under the helmet" was about 6 hours. The research required this availability so that long-term affects might be evaluated. Upon arrival, on each visit, subjects were provided with G protection and checked by the medical staff. They were briefed on the expectations for the day. Detailed plans, described in section 8d of the protocol, were made available for their reference.

Typical high G exposures included two mission profiles lasting up to 90 minutes. The exposures were designed based on acceleration data obtained from Nellis AFB Red Flag training. The profiles began with G warm - ups as if the subjects were performing a "G checkout" preparing for a mission. This "warm-up" was followed by a longer period of lower level G loads representing travel to a mission site. Higher G loads were encountered again as the "pilot" reached the mission environment and engaged the adversary. After completion of the engagement, the G levels dropped as the "aircraft" returned home. For purposes of this research, top G was limited to 7 ½ Gz. A pictorial representation showing one presentation of the data is shown in **Figure 3**. Similar daily exposures or routines took place at each visit or test day. Separate test days were required for each helmet system tested.

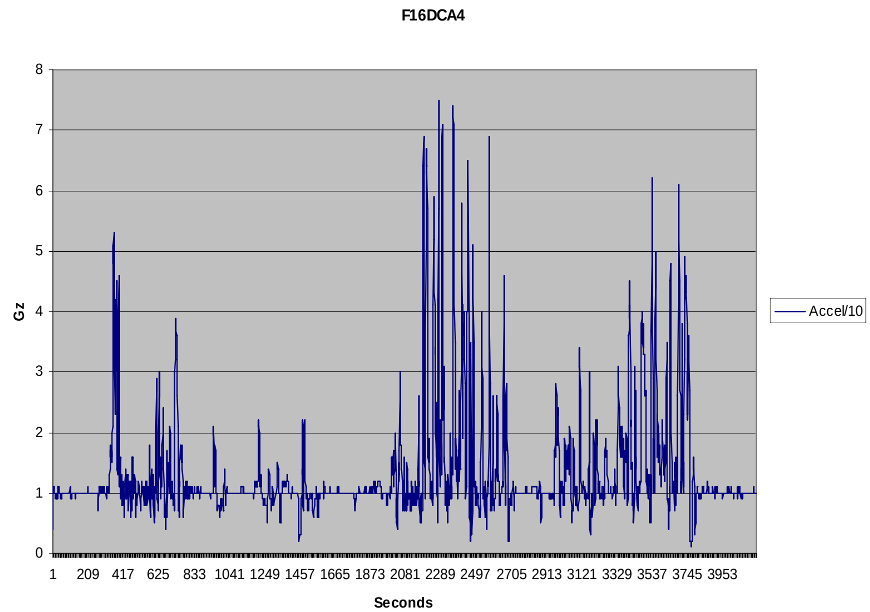


Figure 3. Representative G profile based on Operation Red Flag data

Description of experiment, data collection, and analysis

The research was set up under this protocol so subjects could prepare for a 10 step procedure (**Figure 4**). Basic anthropometrical data was gathered (stature, sitting height, weight, neck circumference, history of strength training, etc) during one visit. Computerized body scan technology was used to collect precise measurements from stationary subjects. This additional data was collected after an amendment to the protocol was approved. Not all subjects were scanned due to the timing of this addition and their departure from the area. The physical dimensions obtained will be used to search for correlations between such things as neck size (cross-section area) and neck strength. This work is awaiting results from a related study searching for the basis for these correlations.

The first step prepares the subjects for more intense neck muscle activity. Subjects perform a set of prescribed warm-up activities① to prepare the neck muscles for neck extension movements against resistance. The warm-ups followed illustrations from a specific set of exercises, defined in a Navy protocol. Once those exercises were complete, the subjects were seated in the neck strength testing fixture. A set of attempts to obtain maximal voluntary contractions (MVCs) describing subject ability to extend the neck and resist movement of the head in a forward direction came in step②. Surface electromyography electrodes were attached to the neck and upper shoulder area. They were held in place using an adhesive double-sided interface material. A head harness was fitted on the head to provide a secure attachment point for pulling against a load cell measuring force exerted.

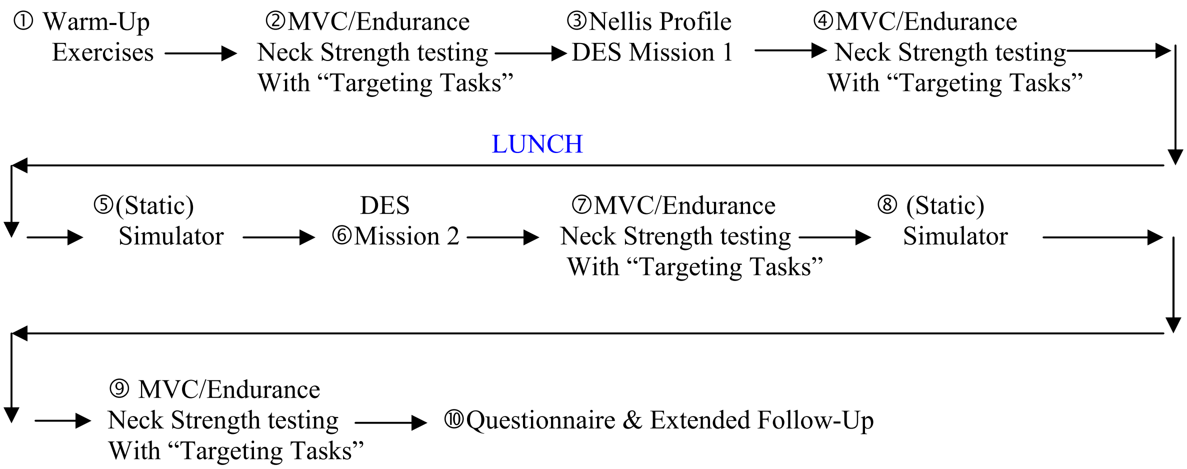


Figure 4. Diagram of testing procedure sequence

The harness was left loosely in place until just prior to testing, avoiding prolonged pressure that might lead to headaches. Once ready, it was tightened securely so it would not slip during testing. Attachment of a strap finished the connection between harness and force measuring load cell. Three pulling attempts or neck extensions of four seconds each were accomplished, pulling against the load cell with 45 seconds rest between each attempt. Subjects were instructed to avoid jerking into the strap and to ease into it over the first seconds as they began to pull. The endurance portion of the test followed, based on 70% of the greatest effort made in the three MVC attempts. Subjects were encouraged to sustain the necessary effort to maintain the 70% level of max. pulling effort or force for as long as they were able. The intent of this testing was to determine how long subjects could sustain (endure) the muscular effort. Software provided visual guidance for the correct level of exertion. A goal line appeared horizontally on a computer monitor placed in front of the subjects. Parallel limit lines provided a range of acceptable exertion around the goal. Each volunteer subject was instructed to increase force exerted against the strap until the indicator reached the area between limit lines and maintain it there as long as possible. All neck extensions were substantially static efforts as the neck muscles held the connection strap tight at the beginning and kept it tight against a load cell. Throughout the testing, subjects were restrained to insure correct alignment of the body with the axis of pull against the load cell. Exertion was intended to be provided entirely by the neck - without assistance from any other part of the body.

A non-physical task was administered next. Subjects were asked to do a target recognition task (**Figure 5 and 6**)②. This served as a baseline reference for comparison of later task efforts after long duration exertions. Subjects were asked to identify the presence or absence of a target among a field of distractors. Correct responses including hits, false alarms, misses, and correct rejections plus response time were data items measured. This task was evaluated for evidence of performance changes in later research data runs. The task was repeated at the end of each centrifuge profile. The intent of the task was to identify changes in performances after time and help determine if fatigue might influence pilot performance.

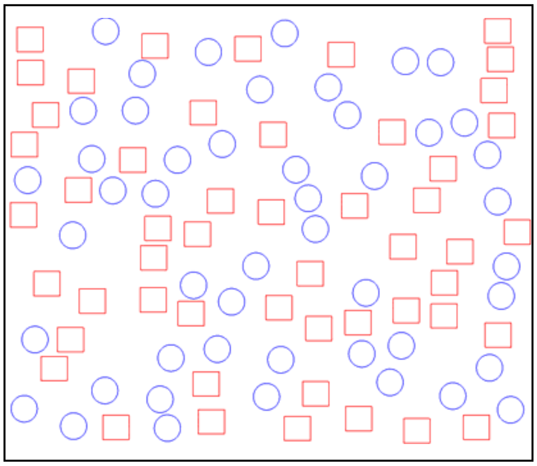


Figure 5. Screen shot with no target.

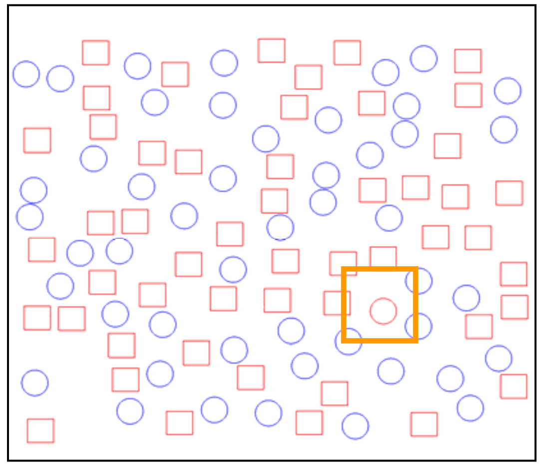


Figure 6. Screen shot with target (lower right).

A second targeting task completed the test battery. In this task, subjects were seated in a cockpit simulator, wearing the helmet. A "CyVisor" was placed over the eyes as a pair of goggles or flight visor. This visor was opaque, confining the user's vision to the inside and blocking sight of the room outside. Used with a computer program, this program allowed images of target aircraft to be projected within the visor as if the subject was following them outside the cockpit (**Figure 7**). Turning the head allowed a person to acquire a target initially outside their field of view. A set of crosshairs with a pointer, seen within the visor, provided indications of the direction to search for successive targets.

Figure 7. Target acquisition task

Instructions called for the volunteer subjects to perform the visual task as quickly as possible. The task placed them in a simulated aircraft that continued to fly straight and level automatically. The out-the-window scenery was displayed to them through the CyVisor. Once subjects were ready, investigators started the task. During task execution, subjects were responsible for visually acquiring each target. To acquire a target aircraft, it was necessary to move the head in such a way that the center crosshairs of the visual display aligned with the target aircraft for four consecutive seconds. It was apparent when the target had been acquired as it disappeared from view.

After each target was acquired, the task required the subject to return to looking forward to locate a standard target there before being prompted to search for another "off boresight" target. A series of additional targets was presented, requiring the searcher to look all around the cockpit for targets. The targeting task called for subjects to track and acquire 24 targets distributed equally to each side of the cockpit. There was a 2 degree window for target acquisition. Targeting crosshairs had to be held within that window for four seconds to acquire the target and trigger another.

In the operational environment, the ability to turn the head, locate targets, and perform mission requirements while using helmets enhanced by the addition of specialized equipment is important. Subjects were advised their efforts would help researchers learn how long-term exposures might affect performance.

When data collection for the test measurements was complete, subjects dressed in G suits in preparation for the first centrifuge test③. Helmets were adjusted to fit each individual comfortably and to minimize slippage during exposure to high G centrifuge runs. Investigators assisted them through the high G acceleration profile prepared from Operation Red Flag data. The Mission 1 profile began with G warm-up maneuvers typically done at the start of flight, shortly after take off. The middle part of the profile presents low G loads to the subject as they travel toward the mission. Upon engagement, the mission profile shows the highest G loads as the crew meets the adversary.

As the first DES step in the protocol ends, subjects return to another round of neck strength testing④. This testing provided data showing how one session on the centrifuge might affect the volunteer subjects. The procedures were completed as in step②. When the evaluation was finished, subjects were given opportunity for lunch before moving to the static simulators⑤. Helmets and G protection gear was retained for this phase of testing. Time in the static simulator extended the duration subjects wore the helmets while taking part in realistic simulations.

Subjects left the static simulator for another DES mission⑥. This mission was also based on Nellis data similar to mission 1 in step③. The same profile was used. G loads were again limited to prevent exposure above +7 ½ Gz. Subjects were guided through a repeat exposure to G warm-ups, low G travel time, and then higher G engagement.

Afterward, as soon as possible to preserve any fatigue effects, subjects exited the DES and returned to neck strength testing⑦. This was the routine procedure used to increase the likelihood of capturing any evidence of changes in muscle activity, strength, endurance, or targeting success. The second endurance test using the same maximal reference obtained for baseline at the beginning of the test day was used in each subsequent endurance test. This procedure was intended to determine if subject capabilities change after a day of work including two missions with extended G loads. A second set of MVC determinations were also performed.

Another target recognition task followed the MVCs. Here, subjects were again asked to identify targets⑦ on a series of displays. Each test was conducted, as much as possible, like the baseline testing of each morning to reduce variability. As in step②, subject volunteers attempt to recognize targets among distractors on a series of visual displays. Target acquisition testing with CyVisor completed the test battery after this new exposure.

To complete the day of testing, subjects sat in the static simulator. The simulations provided allowed the subjects to pass time without high G exposure but giving investigators additional time with the subjects wearing the helmet. No data was collected in this stage.

The final neck strength testing of the day in step ⑨ followed the static simulation. This final data was collected after the non-challenging static simulations to provide investigators with material to determine if subjects might recover from any fatigue shown immediately after the high G acceleration or if continual wear of the helmets add to fatigue. Four sets, or pairs, of MVC/Neck strength testing with target recognition and target acquisition tasks were completed over the course of a test day. Each set provided an opportunity to evaluate changes related to events preceding them. In the final step⑩, questions were asked the subjects to determine perceived effort at various points in the ten step procedure. Investigators were interested in task difficulty, neck muscle soreness, and comments related to possible fatigue effects over the course of activities. For consistency, these were collected in a manner based upon the surveys and Borg scales described in the Navy protocol.

Prior to each exposure, subjects were asked to complete brief medical evaluations that included a history, blood pressure, heart rate and a heart, lung and neurological exams. This exam is repeated following each exposure as well. History consists of the following questions: hours of sleep, time of last meal, alcohol consumption in the last 24 hours, use of medications and a detailed menstrual history (females only). This evaluation is standard practice for all human subjects exposed to G in the DES.

If abnormalities would have been detected on the pre-exposure medical evaluation, subjects may have been prohibited from riding in the DES. This determination is at the discretion of the physician serving as medical observer. All rings and scarves were removed prior to entering the DES cab. The brief medical evaluation following exposures to ensure that the subject had recovered adequately from the physiologic stress of G exposure.

Results

Twelve subjects participated in this experiment (8 males, 4 females). Subject 5 was unable to finish due to scheduling conflicts. Subject 1 was missing too much data to be included in any analysis. Subject descriptive characteristics are shown in **Table 2**.

Table 2. Experimental Subjects.

Subject	Gender	Height (in)	Weight (lb)
1	M	69	175
2	M	71	158
3	M	70	175
4	F	69	155
6	F	65	165
7	M	67	140
8	M	73	189
9	M	72	200
10	M	68	145
11	F	64	127
12	M	68	125
13	F	62	130

The research experiment involved use of three helmets with different weights (3.0, 4.5, 6.0 lb). Each subject wore one of the helmets over the course of approximately six hours. On two additional days, the subjects wore each of the remaining helmets. Half of the subjects wore the 3.0 lb helmet first, followed by the 4.5 lb helmet and lastly the 6.0 lb helmet. The other half wore the 4.5 lb helmet first, followed by the 3.0 lb helmet and lastly the 6.0 lb helmet. During the six hours, the subjects performed each of four tasks at four different times (referred to as segments A, B, C, and D). The four tasks in order were: (1) MVC, (2) endurance at 70% of segment A MVC, (3) a target recognition task, and (4) a target acquisition task. The main purpose of the statistical analysis was to determine if performance varied among the helmets both overall (i.e., main effect) and across segments (i.e., helmet*segment interaction). The key to this research was to determine if any significant helmet*segment interactions would imply a greater performance decrement over time due to use of a heavier helmet.

The analysis was divided into two parts. The first part examined the 'big picture'. This included predetermined primary dependent variables from each task. The second part examined secondary dependent variables including possible effects of height and weight.

The primary dependent variables were:

(1) MVC
(2) Endurance time at 70% of segment A MVC
(3) Time to find a red circle among field of red (squares) and blue (circles) distractors
(4) Total time to acquire 24 peripheral and 24 centered targets

The first analysis performed was a comparison of segment A which was considered a pre baseline. Note that the helmet was not on for MVC and endurance while the harness was in place. This pre baseline was to indicate representative subject performance before any helmet effect. What can be concluded from this analysis is whether baselines used for the helmets were similar. For instance, the 6.0 lb helmet was used only on day 3. If segment A means for day 3 were significantly higher or lower than the days used for the other helmets, there may be a ceiling or floor effect which could make percent changes an unfair comparison among the helmets. Preliminary analyses used gender and helmet as fixed factors. Subjects were considered a random factor nested in gender. There was a significant main effect of gender for median capture time ($p = 0.0322$) with means as follows: male mean = 2.91s, female mean = 2.54s. The gender main effect or gender*helmet interaction was insignificant ($p \geq 0.2121$). Therefore, gender was not used as a factor for final analysis of segment A since with 7 males and 4 females the design was unbalanced. This imbalance creates concerns, including generation of means (i.e., do you average gender means or average across all 11 subjects). **Figure 8** contains means across the 11 subjects along with the F-test p-value for main effect of helmet (subject*helmet interaction used as error term).

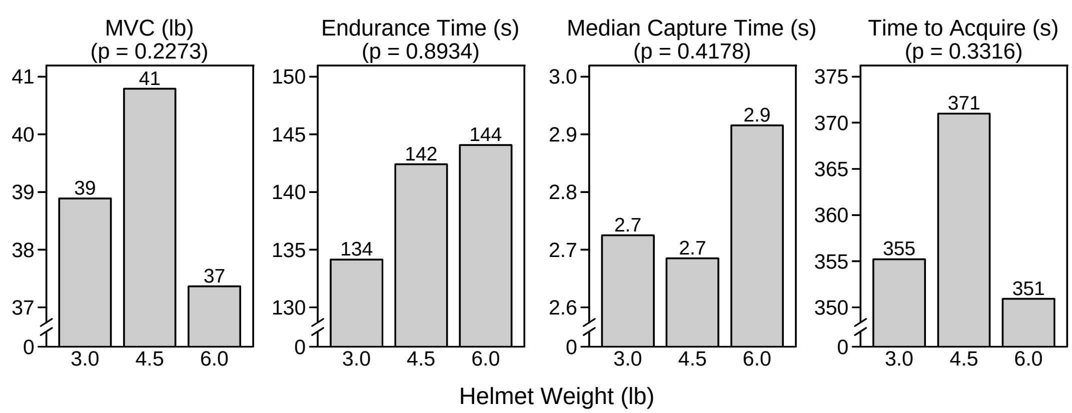


Figure 8. Means for Segment A. Above each panel is the F-test p-value comparing the three helmets. Note that the helmets had not been used for Segment A for MVC and Endurance. Testing was done with a harness before putting the helmet on.

Table 3 contains the minimum, mean, and maximum values for segment A across subjects (n = 11). Minimum and maximum values across helmets give a good indication of the range of values for each task.

Table 3. Minimum, mean, and maximum values for segment A (n = 11).

Variable	Helmet Weight (lb)	Minimum	Mean	Maximum
MVC (pounds)	3.0	28.11	38.89	58.22
	4.5	24.04	40.79	62.70
	6.0	20.62	37.36	56.84
Endurance Time (seconds)	3.0	32.48	134.14	347.49
	4.5	31.51	142.40	439.75
	6.0	30.24	144.08	432.81
Median Capture Time (seconds)	3.0	1.79	2.72	3.28
	4.5	2.00	2.68	3.56
	6.0	2.42	2.92	3.50
Time to Acquire (seconds)	3.0	308.11	355.22	432.00
	4.5	328.44	371.00	413.47
	6.0	298.67	350.91	454.81

For each subject, the percent change from segment A to segments B, C, and D were determined. Preliminary analyses use gender, helmet, and segment as fixed factors. “Subject” was considered a random factor nested in gender. Again, there were no significant main effects of gender ($p \geq 0.0796$) or significant interactions involving gender ($p \geq 0.1232$). Gender was not used as a factor in final analyses. **Table 4** contains results of repeated measures analyses of variance. Note that there was a missing value estimated so that the Greenhouse-Geisser adjustment could be made (Subj 9, MVC, 4.5 lb, segment D).

Table 4. Results from repeated measures analyses of variance.
Dependent Variable: percent change from segment A.

Dep. Variable	Source	df	SS	dfe	SSe	F	*p*	G-G *p*	G-G Ep
MVC	Helmet	2	2.32E+02	20	7.26E+03	0.32	0.7298	0.6894	0.8242
	Segment	2	1.61E+03	20	1.17E+03	13.74	0.0002	0.0003	0.9052
	Helmet*Segment	4	3.74E+02	40	2.64E+03	1.42	0.2456	0.2612	0.6418
Endurance Time	Helmet	2	4.18E+03	20	2.53E+04	1.65	0.2167	0.2187	0.9418
	Segment	2	6.07E+03	20	5.45E+03	11.14	0.0006	0.0028	0.6864
	Helmet*Segment	4	1.76E+02	40	1.08E+04	0.16	0.9558	0.8802	0.5854
Median Capture Time	Helmet	2	7.25E+03	20	1.58E+04	4.59	0.0228	0.0291	0.8686
	Segment	2	1.64E+02	20	6.88E+03	0.24	0.7904	0.6834	0.6152
	Helmet*Segment	4	1.89E+03	40	1.60E+04	1.18	0.3342	0.3285	0.5173
Time to Acquire	Helmet	2	6.47E+02	20	2.45E+03	2.64	0.0964	0.1240	0.6379
	Segment	2	3.74E+02	20	4.02E+02	9.32	0.0014	0.0018	0.9375
	Helmet*Segment	4	1.68E+02	40	9.72E+02	1.73	0.1627	0.1834	0.7359

Figure 9 contains mean percent change across subjects. Two-tailed t-tests were used to determine whether any particular mean percent change was significantly different from 0 ($p \leq 0.05$).

Table 5 and **Table 6** contain main effect means and minimum significant difference (MSD) values from the Bonferroni paired comparison procedure for helmet and segment respectively. The MSD is the smallest difference in means that can be considered significant using a family-wise error level of 0.05 and a per comparison error level of 0.05/3 = 0.0167. **Figure 10** contains main effect means. Two-tailed t-tests were used to determine whether any particular mean percent change was significantly different from 0 ($p \leq 0.05$).

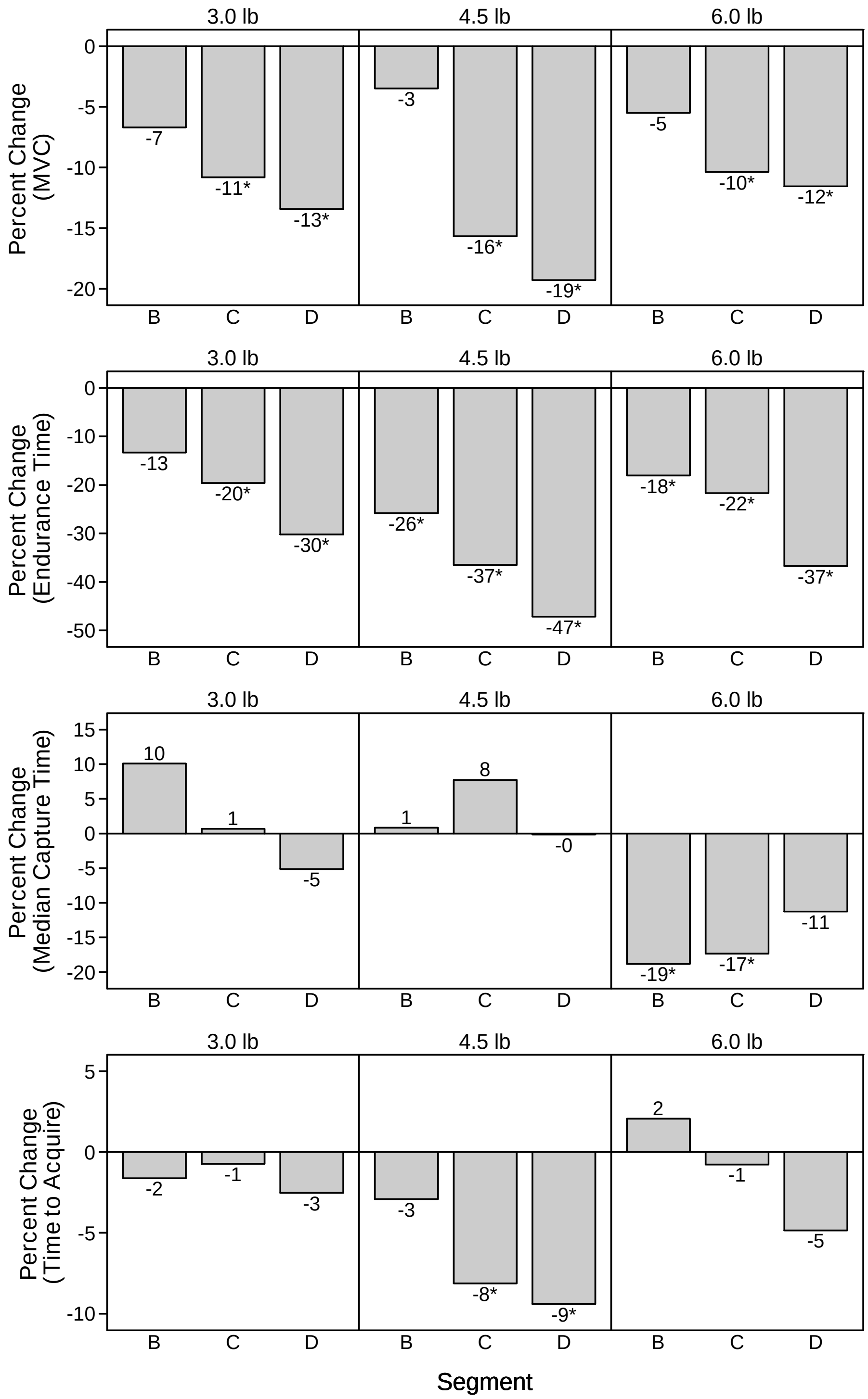


Figure 9. Mean percent change from segment A (n = 11).
* percent change significantly different from 0 ($p \leq 0.05$).

Table 5. Main effect paired comparison of helmet.

Dependent Variable	Helmet Means 3.0	4.5	6.0	MSD	*p*
MVC	-10.3	-12.8	-9.1	12.3	0.7298
Endurance Time	-21.1	-36.5	-25.5	22.9	0.2167
Median Capture Time	1.9	2.8	-15.8	18.1	0.0228
Time to Acquire	-1.6	-6.8	-1.2	7.1	0.0964

Table 6. Main effect paired comparison of segment.

Dependent Variable	Segment Means B	C	D	MSD	*p*
MVC	-5.2	-12.3	-14.8	4.9	0.0002
Endurance Time	-19.1	-25.9	-38.0	10.6	0.0006
Median Capture Time	-2.6	-3.0	-5.5	11.9	0.7904
Time to Acquire	-0.8	-3.2	-5.6	2.9	0.0014

The target recognition task consisted of 50 trials. Approximately half of these trials had a target present and half didn't. The subject was to decide within 5 seconds whether there was a red circle present among a field of red squares and blue circles. The primary dependent variable was how long it took the subject to find the target when it was present (capture time). Since there was a 5 second time-out period, if the subject did time-out it is not known how long after the 5 seconds it would have taken the subject to find the target. Due to this, median capture time was used instead of mean capture time. Median capture time is a reasonable measure of central tendency as long as most of the trials do not time-out (always the case) since the median is the middle value.

As stated earlier, the primary dependent variable for the target recognition task was how long it took the subject to find the red circle among a field of red and blue distractors when the target was present. There were three possible selections with a target present and three possible selections with a target absent.

Choices with Target Present:
(1) Hit = find target (primary dependent variable)
(2) Miss = incorrectly decide target is not present
(3) Time-out = no response

Choices with Target Absent:
(1) Correct rejection = decide target is absent
(2) False alarm = decide target is present
(3) Time-out = no response

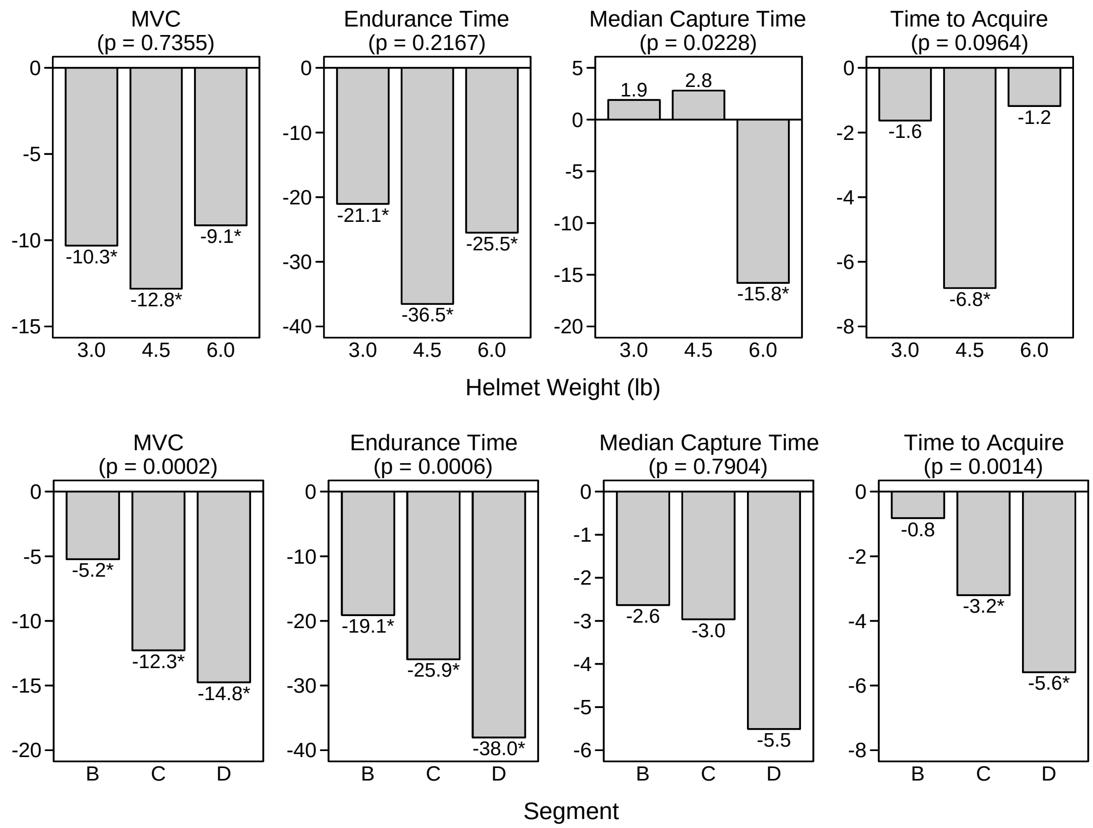


Figure 10. Mean percent change from segment A. Above each panel is the F-test p-value comparing the three helmets. * percent change significantly different from 0 (*p* ≤ 0.05).

Analysis of the primary dependent variable led to the results shown below (**Table 7** and **Table 8**). Descriptive statistics from all 6600 trials are detailed for 11 subjects * 3 days * 4 segments * 50 trials. They are separated by both helmet and segment.

Across all trials:

Target present: 86% hit, 10% miss, 4% no response
Target absent: 70% correct rejection, 1% false alarm, 29% no response

By Helmet:

Table 7. Percents for each possible selection.

Helmet Weight (lb)	Target Present			Target Absent		
	Hit	Miss	No Response	Correct Rejection	False Alarm	No Response
3.0	86	9	5	66	1	33
4.5	84	11	5	69	1	30
6.0	89	9	2	74	1	25

By Segment:

Table 8. Percents for each possible selection.

	Target Present			Target Absent		
Segment	Hit	Miss	No Response	Correct Rejection	False Alarm	No Response
A	85	10	5	66	1	33
B	85	10	5	69	1	30
C	87	9	4	71	1	28
D	88	10	2	74	1	25

A question of interest is whether smaller subjects wearing a heavy helmet would have more difficulty maintaining task performance over an extended period of time. To examine this, the worse case scenario was used. For each subject, the percent change from segment A to segment D for the 6.0 lb helmet was determined. Two analysis techniques were used.

The first analysis correlated the percent change from segment A to segment D with height and weight separately. No significant correlations were found for any of the four tasks ($p \geq 0.2668$).

The second analysis used the percent change from segment A to segment D as the dependent variable in simple linear regression with height and weight as independent variables. No significant effects were found for MVC, median capture time, or time to acquire ($p \geq 0.1709$). For endurance time at 70% of segment A MVC, both height ($p = 0.0227$, slope estimate = 6.3) and weight ($p = 0.0401$, slope estimate = -0.8) were significant. There are two interesting findings: (1) for subjects of the same weight, taller subjects had greater endurance, (2) for subjects of the same height, lighter subjects had greater endurance. **Figure 11** is a bubble plot. The size of the bubble is the relative magnitude of percent change (smaller bubble indicates a greater percent decrease or less endurance). This figure indicates the significant findings of the linear regression are largely driven by subject 6 (ht = 65 in, weight = 165 lb) who had the greatest percent change (-85%).

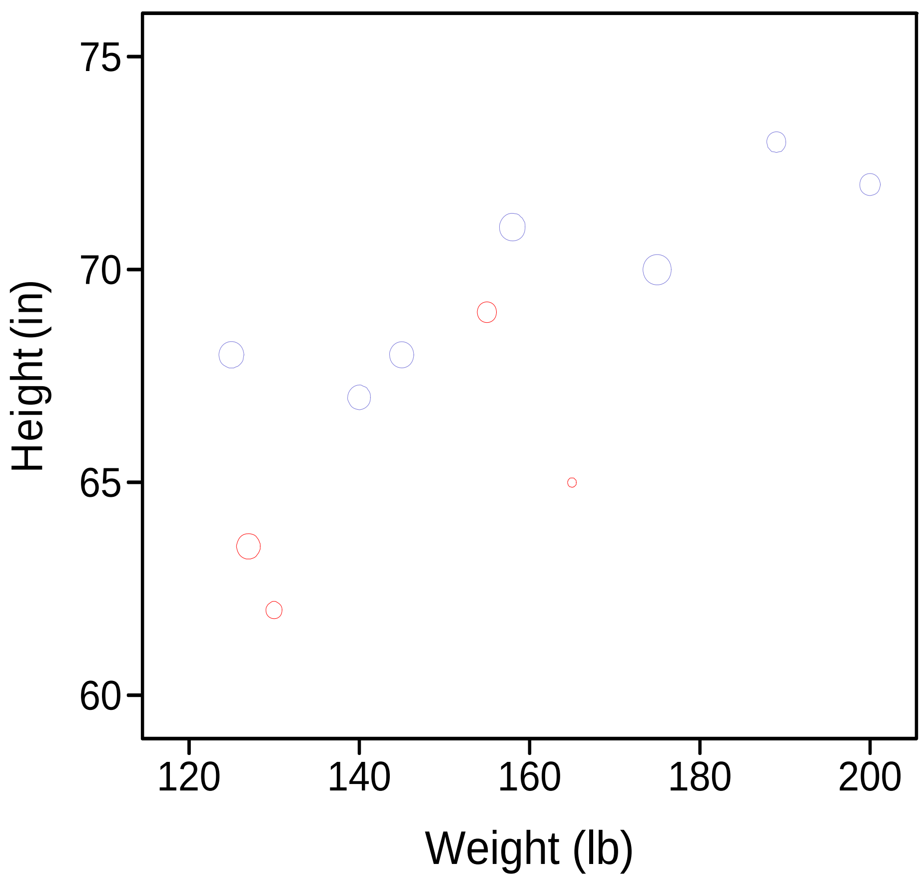
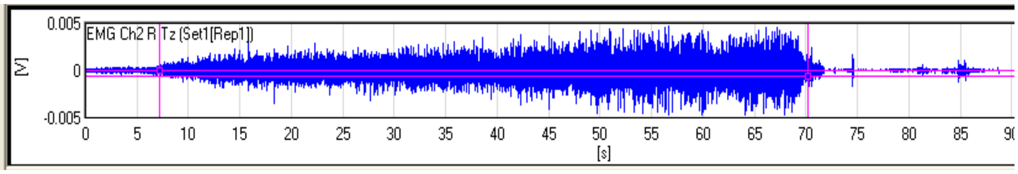


Figure 11. Relative magnitude of percent change from segment A to segment D for endurance time. *A smaller bubble indicates less endurance. Red = female, blue = male.

After analysis of the strength data, the next step was to examine the data from electromyography (EMG). This EMG data can be used to describe the activity of the neck muscles during the neck strength testing. The results are shown in **Figure 12** as presented at the Aerospace Medical Association meetings in May 2008. The sample shows changes in the EMG trace over an endurance test period. It is clear that amplitude increases over that time.



- Overall snapshot – EMG traces reviewed for quality
  - Evidence of muscle fatigue during tests?
  - Supports concept of increased EMG amplitude (MAV), decreased frequency (MDF) with fatigue
  - Characteristics of Muscle Fatigue
    - Increased Amplitude, 74.7% muscles
    - Decreased Frequency, 85.9% muscles

Figure 12. Representative muscular activity shown by EMG

Discussion

While we cannot disprove the hypothesis of this research, we can pass on useful information for use in night vision goggle development. That hypothesis was that prolonged exposure to heavier helmet systems will lead to neck muscle fatigue. This fatigue can be identified by changes in neck muscle force in extension. Analysis of electromyography will show evidence to support fatigue through changes in signal amplitude and frequency. It is also expected that subject feedback might support the idea that pilots' performance is affected by muscle fatigue.

Experimental results did show evidence of muscle fatigue, both from neck muscle strength testing and electromyography. Both maximal efforts and the ability to sustain those efforts at a 70% of maximum level were affected. Force generated was reduced over the course of the test day as subjects were exposed to high G acceleration representing an operational mission. Total time pulling at 70% of MVC was also reduced.

Compared to baseline (Segment A), MVC and Endurance values were reduced over the day from earliest to latest. The same pattern of reduction was apparent for each helmet configuration. It should not be surprising that the volunteer subjects fatigued after each exposure to high G acceleration and that the fatigue might be cumulative. The question

of whether there is sufficient time to recover between Segments C and D might appear to be negative. Subject performance results continued to be in a declining mode.
An important aspect of addressing this hypothesis is determining if human performance is affected differently by the heavier helmets than the controls or the 4.5 pound helmet currently in service. That might provide insight into the risk of increasing helmet weight. Statistical analyses used to evaluate helmet*segment interaction were performed in attempting to differentiate among the helmets. Performance with each helmet was affected similarly in that declining performance was found after baseline measurements, from B to C to D. Main effect paired comparisons were made for helmet means and for segment means. In examining **Table 5** containing helmet means, one can tell that it takes a minimum significant difference (MSD) of 12.3 to obtain significance among helmets for MVC. The means are tightly grouped and no significance can be found. Similarly, for Endurance time, a MSD of 22.9 is necessary. Means for all three helmets are closer than that. Thus, measurements of neck muscle strength could not be used to differentiate performance changes based on helmet configuration.

EMG analyses were another option to differentiate between helmets. Muscle fatigue can be shown by increased amplitude and decreased frequency. This was shown in this research with 75% increases for amplitude and 80% for freq. Analysis of slope was begun to learn if amplitude and/frequency might change more or less quickly for any of the helmets evaluated. Mean absolute value (MAV) for amplitude is plotted in **Figure 13**. Slopes associated with muscle activity while using helmet 2 may change more after centrifuge exposures than for the other helmets. Median frequency has not been completed at publication time. This review of slope data is proposed as a way to possibly learn more about muscle activity with each helmet although first look seems to indicate differences are small and may not be indicative of any practical difference.

The wearing of any of these helmets during exposure to a representative high G mission profile, under the controlled conditions of this experimental protocol, resulted in a similar pattern of performance decline. Application of the neck muscle to tasks may be needed to tease out any differences in the way a person might adapt to the changes to perform those tasks. No tasks were conducted during exposure in the DES, therefore it cannot be determined how fatigued neck muscles might fail or succeed. Since previous testing indicated that females used 80% of their muscle capability to complete a tracking task (2) questions arise regarding their ability to do similar tracking with fatigued muscle. A reduction in functional capability might be expected.

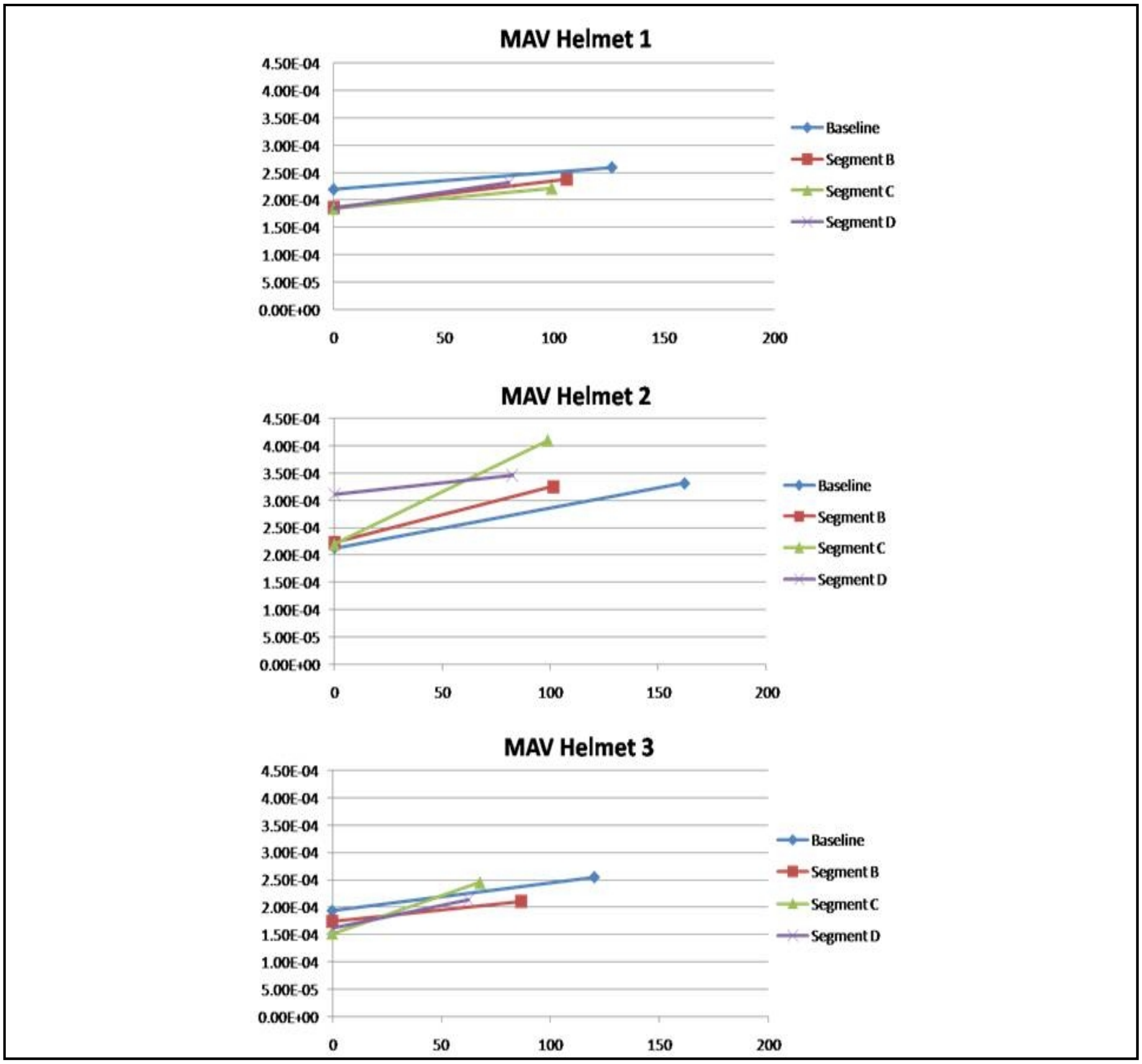


Figure 13. Slopes indicating change in amplitude of muscle activity

The remaining tasks measured as part of the test battery were included in the protocol in order to learn about additional performance. Specifically, the computer-based target recognition task was included to evaluate the ability to recognize a target and the time necessary to accomplish identification of a series of targets. It involved minimal muscle activity so might reasonably be minimally affected by muscle fatigue. The median capture time from this test was found to be different with a p value of 0.0228. The importance of this finding is questionable. The difference between means for the 4.5 and 6.0 pound helmets are separated by a value greater than the MSD of 18.1. In this case, it might be due to decisions made to test the 6.0 pound helmet last for every subject. During protocol development, concerns that exposure to the heaviest helmet immediately might lead to loss of subjects before obtaining data for the remaining helmets led to randomly assigning each person to either the 3.0 or 4.5 pound helmets first. The heaviest was always last. A training effect may be responsible for the improved performance and apparent ability to capture the target better at the end of the subject experience.

The simulator-based target acquisition task did require head movement while wearing helmets. Performance in this task might therefore be affected by neck muscles fatigued by high G missions. Neck muscle involvement might reasonably be expected to be important in stabilizing the head and neck as targeting crosshairs were lined up on target. Acquiring the target required movement of the head, following a visual prompt, and holding steady while the crosshairs are "locked on" the target. Failure to hold this locked position required reacquisition and holding the required minimal time. Interestingly, there were no significant statistical differences of means. Review of literature and theoretical discussion of moment affects of helmet CG during the targeting the process prompted lively debate. Would the configuration of any particular helmet contribute to greater "overshoot" requiring the subject to adjust and settle in on the target? It is uncertain how fatigued muscles might affect performance.

Subject responses to survey questions tell us that they were most fatigued during the highest G loads and immediately after the centrifuge runs concluded. Similarly, Gallagher et al (5) reported that, in their static research program, subjects were able to complete the five, 8-hour test sessions regardless of helmet configuration. Males had significantly stronger MVCs and longer endurance times than females. Helmets with a forward CG were significantly more uncomfortable on the subjects' neck and back than the helmets with a nominal CG shift. Significant increases in upper neck and upper and lower back discomfort were reported as early as the second hour and continued throughout the session. The 4.5 lb. helmet with forward CG was significantly more uncomfortable on the subjects' neck and back than the 6.0 lb. helmet with the nominal CG shift. Again, significant increases in upper neck discomfort were reported as early as hour 2 and continued throughout the session. In general, no significant gender differences were found for comfort. Surface EMG amplitude analyses indicated higher levels of fatigue for the final hours as compared to the beginning hours of each session regardless of helmet. For complete analysis, a heavier 6 pound helmet should be tested with a CG more representative of night vision systems with an extended center of gravity.

Further clues for human performance were discovered from evaluation of PNVG variants during developmental testing in actual aircraft flights. There was insufficient data for statistical significance but a case study of one individual pilot provided interesting results (3). Measures of neck muscle strength and endurance declined over nearly consecutive days of flying with HMDs but, after non-flying days, values returned to a normal range. One might develop a hypothesis that, much as performance declined "additively" over consecutive days of flight; muscle fatigue might accumulate if missions are at high operational tempo.

Loss of centrifuge resources prevented completion of testing with a full group of female test subjects. It is unknown how this reduction and resulting imbalance might affect the overall results.

Conclusions

The research plan developed an effective method for fatiguing neck muscles of the volunteer test subjects. Performance was affected by long duration exposure to high G acceleration regardless of the simulated helmet system the subjects wore. All indicators from post testing were affected over the course of a test day. The effects were not significantly different so we cannot say the heaviest helmet influenced performance more than the lighter, 4.5 pound version. Comments made by the subjects involved indicated they disliked the heaviest but were able to tolerate it. Still, questions remain unanswered. Test dates were several days apart. Earlier observations indicate that capability might decline with daily or near daily exposure. These observations indicated that the capability returned after rest. Different results might be seen in research with a different test schedule reflecting increased operational tempo.

Although statistical results describing volunteer subject performance with the two simulated helmet systems were similar, caution in development should still be recommended. Previous research showed dramatic differences in subject reaction with relatively small changes in CG. It is unknown how a CG shift with otherwise similar helmets might affect performance. This is especially important since performance during high G exposure was not measured or evaluated. If mission requirements could include head movement with added weight while experiencing high G loading, there might be cause for concern. This might be critical with females who have been shown to utilize most of their maximum muscular capability to perform tracking tasks under G.

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