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Head and Helmet Biodynamics and Tracking Performance During Exposure to Whole-Body Vibration

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Human Effectiveness Directorate
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Biomechanics Branch
Wright-Patterson AFB OH 45433-7947

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FOR THE DIRECTOR

//SIGNED//

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14. ABSTRACT

Helmet-mounted equipment is being designed to optimize military aircrew effectiveness. The objective of this study was to quantify the effects of head orientation and helmet weight distribution on head, helmet, and helmet slippage rotations, and tracking performance during exposures to fighter aircrew buffeting and multi-axis quasi-random vibration. For both exposures, significant increases in the roll displacements were observed with the SIDE orientation (40ø elevation, 70ø azimuth). Significant increases in the pitch displacements were observed with the UP orientation (40ø elevation, 0 azimuth) during exposure to buffeting, while both the FOR (0ø elevation, 0ø azimuth) and UP orientations showed relatively high pitch motions with the multi-axis exposure. Significantly high performance degradation occurred with the SIDE orientation for two of the three weight distributions during aircraft buffeting, with minimal degradation observed with the multi-axis exposure. The results suggested that the SIDE orientation had the greatest influence on performance degradation, but the effect appeared to depend on the type of exposure.

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HEAD AND HELMET BIODYNAMICS AND TRACKING PERFORMANCE DURING EXPOSURE TO WHOLE-BODY VIBRATION

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Abstract

Helmet-mounted equipment is being designed to optimize military aircrew effectiveness. The objective of this study was to quantify the effects of head orientation and helmet weight distribution on head, helmet, and helmet slippage rotations, and tracking performance during exposures to fighter aircraft buffeting and multi-axis quasi-random vibration. For both exposures, significant increases in the roll displacements were observed with the SIDE orientation (40° elevation, 70° azimuth). Significant increases in the pitch displacements were observed with the UP orientation (40° elevation, 0 azimuth) during exposure to buffeting, while both the FOR (0° elevation, 0° azimuth) and UP orientations showed relatively high pitch motions with the multi-axis exposure. Significantly higher performance degradation occurred with the SIDE orientation for two of the three weight distributions during aircraft buffeting, with minimal degradation observed with the multi-axis exposure. The results suggested that the SIDE orientation had the greatest influence on performance degradation, but the effect appeared to depend on the type of exposure.

1. Introduction

Sophisticated helmet-mounted equipment is becoming integral to military tactical and strategic flight operations. Such equipment includes night vision goggles (NVGs), helmet-mounted displays (HMDs), and helmet-mounted targeting and display (HMT/D) interfaces. There is evidence that the design of helmet-mounted equipment should consider the effects of whole-body vibration encountered during flight operations to insure effective aircrew performance and safety. The effects of helmet-mounted equipment have been and continue to be studied in rotary-wing aircraft, particularly with regards to the effect of weight and weight moments on neck loading and the potential for injury (Butler, 1992; Alem et al., 2000; Barazanji et al., 2000). While low frequency vibration has basically been ignored in the integration of helmet-mounted systems into the cockpit of high-performance jet aircraft, substantial low frequency buffeting has been documented in the F-15 aircraft (Smith, 2002) and blamed for slower-than-desired target lock-on times when using a helmet-mounted targeting system (Kandebo, 2000). More recently, substantial low frequency vibration was documented in the F/A-18C Hornet during catapult launches from Navy aircraft carriers (Smith, 2004) where peak-to-peak helmet pitch was estimated between 9 and 18 degrees at about 3.5 Hz. In a study exposing subjects to vertical-axis vibration while wearing an HMT/D, helmet pitch was found to be the highest with an upward-looking head orientation (40° elevation, 0° azimuth) followed by a combined side and upward orientation (40° elevation, 70° azimuth) (Smith, 2000). These findings coincided with earlier studies showing that looking upwards can increase the seat-to-head transmissibility (Griffin et al., 1979) and head pitching (Cooper, 1986) during exposure to vertical vibration without the use of a helmet.

A preliminary study conducted in this laboratory investigated the effects of helmet weight, weight distribution (center-of-gravity or CG), and head orientation on head and helmet motion and head-slaved tracking performance (Smith et al., 2000). For subjects exposed to the F-15 buffet vibration, significantly higher peak rotations (roll, pitch, and yaw) at 8.5 Hz occurred with the combined side and upward orientation (40° elevation, 70° azimuth) as compared to the forward orientation (0° elevation, 0° azimuth). The helmet showed significant peaks for roll and yaw only. Associated with these results for the combined side and upward orientation (40° elevation, 70° azimuth) were significantly higher degradations in tracking performance. Less dramatic effects were observed for the helmet weights and helmet weight distributions used in the study. The helmet weights ranged from 1.25 to 2.16 kg (medium lightweight HGU-55/P), a difference of less than 1 kg.

Visual performance is the primary concern when using helmet-mounted equipment in jet aircraft. In addition to the orientation effects on visual performance mentioned above, significant degradation of visual performance was noted with the addition of vibration regardless of the head orientation. Helmet slippage caused by even brief exposures to low frequency vibration could further degrade tracking performance using an HMT/D, causing partial or complete loss of the projected image (vignetting) in the HMD or the visual field in an NVG. Another concern for the HMD is that the projected image moves with the head, reducing the effectiveness of compensatory eye movement associated with the vestibular-occular reflex (VOR) during head rotations occurring as high as 20 Hz (Furness and Lewis, 1978; Stott, 1984). The result is visual blurring that could be exacerbated by any helmet slippage.

Design guidelines and criteria are needed for developing effective helmet-mounted equipment for use in high-performance jet aircraft. The current study is an expansion of the preliminary study (Smith et al., 2000) to include additional head/helmet orientations and helmet weight distributions of operational interest. The objective was to investigate the effects of head/helmet orientation and helmet weight distribution on head/helmet motion and head-slaved tracking performance. Emphasis was placed on estimating the relative motion between the head and helmet or helmet slippage. This paper describes the results for exposures to a representative F-15 buffet signal and to quasi-random vibration at 2.0 m/s^2 rms.

2. Methods

The expanded study included the independent and dependent variables listed in Table 1. The Six Degree-of-Freedom Motion Simulator (SIXMODE) was used to generate the vibration. The rigid seating system included a flat seat pan with the seat back oriented at six degrees aft of vertical. A lapbelt and double shoulder harness were used to loosely restrain the occupant.

2.1 Helmet Configurations

TABLE 1. INDEPENDENT AND DEPENDENT VARIABLES

INDEPENDENT	DESCRIPTION
Exposure (EXP)	BUFFET (F-15 Signal) HIFLAT (Flat Acceleration Spectrum @2.0 m/s^2 rms)
Head Orientation (OR)	FOR (0 Deg Elevation, 0 Deg Azimuth (0, 0)) SIDE (40 Deg Elevation, 70 Deg Azimuth (+40, +70)) UP (40 Deg Elevation, 0 Deg Azimuth (+40,0))
Helmet Weight Distribution (CG)	CG1 (weight distributed at ears) CG2 (weight at ears and front of halo) CG3 (weight at helmet back and halo)
DEPENDENT	DESCRIPTION
Head/Helmet Biodynamics	Head Roll, Pitch, Yaw Displacements Helmet Roll, Pitch, Yaw Displacements Helmet Roll, Pitch, Yaw Slippage Displacements
Tracking Performance	Rms Tracking Error %Time-On-Target (%TOT)

Figure 1 illustrates the helmet assembly. A medium and a large lightweight HGU-55/P helmet were modified to allow for variable weight and weight distribution. Each subject was fitted with a custom-molded thermoplastic helmet liner with additional helmet pads positioned to optimize helmet fit and improve comfort. An MBU-20/P Combat Edge oxygen mask (without hose assembly) was modified to accommodate a six-axis bitebar (described below) by removing material from the front of the mask, assuming a minimal effect on any helmet stabilization provided by the oxygen mask. A clear visor was also included in the helmet assembly. A laser-pointing device was mounted onto the helmet for performing the tracking task. A total of 0.90 kg was added to the basic helmet by screwing weights onto the halo structure shown in Figure 1, or by attaching weight to the back of the helmet with Velcro (along the mid-sagittal plane). For the first weight distribution (CG1), the added weight was equally distributed at the ears. For the second weight distribution (CG2), one-half of the weight (0.45 kg) was equally distributed at each ear and one-half was located at the center front of the halo. For the third weight distribution (CG3), one-half of the weight (0.45 kg) was added to the back of the helmet and one-half was located on the front of the halo. The goal was to offset the added weight to produce shifts in the CGs that were lower and higher than measured in current HMT/Ds.

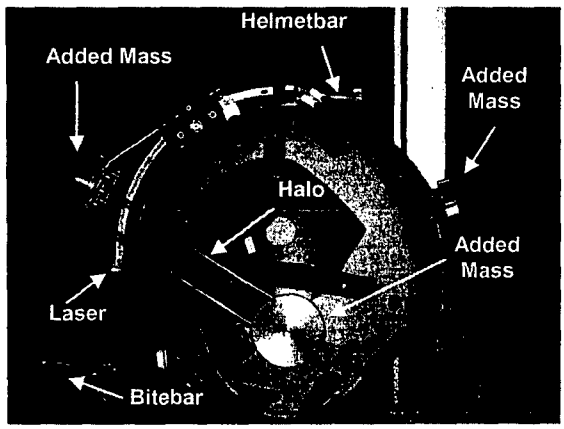

Figure 1. Helmet System

The CGs for the Hybrid II manikin head (First Technology Safety Systems) and the combined head/helmet were measured in three orthogonal directions (Albery et al., 1997). The CGs for the helmet system alone were calculated from these data by assuming that the moment of the total weight of the combined head and helmet was equal to the sum of the moments of the weights of the head and helmet components in each of the three axes of rotation. The origin was defined by the anatomical coordinate system of the head, i.e., by the external auditory meatus (EAM), Frankfort Plane, and mid-sagittal plane. The CGs of the combined human head and helmet were then estimated using the mean CG data for the human head (Beier et al., 1980). The shifts in the CGs of the combined human head/helmet and helmet

alone relative to the CGs of the human head alone were calculated for each weight distribution. These data and details on the helmet configurations are given in Table 2.

TABLE 2. HELMET CONFIGURATIONS

HELMET WEIGHT (kg)	WEIGHT DISTRIBUTION (CG)	HEAD/ HELMET CG (cm)		HEAD/ HELMET CG SHIFT FROM HEAD CG (cm)		HELMET CG SHIFT FROM HEAD CG (cm)	
		X	Z		Z	X	Z
Medium 2.33	CG1	0.20	3.50	-0.64	0.38	-1.79	1.08
	CG2	1.68	3.89	0.84	0.76	2.37	2.14
	CG3	1.02	4.50	0.18	1.37	0.50	3.92
Large 2.38	CG1	0.48	3.02	-0.36	-0.10	-1.02	-0.27
	CG2	1.58	3.78	0.74	0.66	2.10	1.85
	CG3	0.99	4.27	0.15	1.14	0.47	3.20

Based on human head weight = 4.30 kg (from Beier, et al., 1980)
Positive X and positive Z Head/Helmet CGs are forward and above head anatomical coordinate system, respectively. Data relative to head anatomical coordinate system.

2.2 Biodynamic Instrumentation

A bitebar and a helmetbar were used to measure head and helmet accelerations (Figure 1). Six Entran EGA 125-10D accelerometers were strategically glued to the bitebar and helmetbar for calculating the head and helmet rotational motions (roll, pitch, and yaw). Three Entran EGA 125-10D accelerometers were also attached to the base of the rigid seat for measuring the triaxial input motions.

2.3 Tracking Performance Equipment

For the head-slaved pursuit-tracking task, a projector (Telex P1000 LCD) was used to display the 28 x 28 mm target onto a viewing screen using a display video card (Diamond Stealth 3D 3000). Three screens were located so that the center position of the target corresponded to the three head/helmet orientations listed in Table 1. The laser pointer was positioned at the subject's eye level, centered between the eyes, and adjusted to insure correct alignment between the laser and the target with the subject seated upright and looking forward. The distance from the subject eyes to the screens was approximately 126 cm. Dual-axis target motion was computer-generated using sum-of-sines algorithms with a viewing field of about +/- 15 degrees in the horizontal direction and +/- 13 degrees in the vertical direction (relative to the head/helmet orthogonal system). During tracking, the images of the target and laser were captured onto a Matrox Millennium G200 video capture card using a Pulnix TM-6701AN camera.

2.4 Vibration Exposure Signals

The 10-s buffet signal (BUFFET) was selected from an actual acceleration time history collected during tactical maneuvers aboard the F-15 and regenerated on the SIXMODE at 1024 samples/s (Smith, 2000). A male subject weighing approximately 86 kg was used for this procedure. The quasi-random vibration was a relatively flat constant bandwidth acceleration spectrum that was digitally created using the sum-of-sines of frequencies in the range of 2 to 40 Hz at a sampling rate of 1024 samples/s, overall acceleration level of 2.0 m/s^2 rms, and duration of 10 s. The flat acceleration spectrum signal was generated in all

three axes (fore-and-aft or X, lateral or Y, and vertical or Z) with a one-second delay between axes to produce inputs that were not fully correlated.

2.5 Data Collection and Processing

During exposure, all acceleration data were simultaneously collected for 10 s, low-pass filtered at 100 Hz, and digitized at 1024 samples/s. The calculations of head and helmet roll, pitch, and yaw rotation accelerations have been previously described (Smith et al., 2000). All head and helmet rotations were calculated with respect to the head orthogonal axes regardless of head orientation. The head and helmet rotation displacement time histories were estimated from the rotation acceleration data (Smith, 2002; Smith, 2004). Helmet slippage rotation displacement was defined as the difference between the helmet and head rotation displacements in the time domain in each respective axis. The acceleration and displacement power spectral densities (PSD) for the head and helmet rotations, helmet slippage, and the seat base translations were calculated using Welch's Method (Welch, 1967; Matlab® Signal Processing Toolbox, The Mathworks, Natick, MA). The rms acceleration or displacement at each frequency was calculated from the square root of the (*PSD x* Δf) where Δf was the frequency increment of 0.5 Hz. The overall head, helmet, and slippage displacements were calculated as

$$Displacement = \sqrt{\Sigma(d_i^2)} \qquad 1$$

where d_i is the rms displacement at frequency i, with i = 1 to 50 Hz in 0.5 Hz increments.

The tracking task was presented for 50 seconds, which included a 10-second warm-up for both the no vibration and vibration exposures. The target and laser positional data were collected and digitized at 100 samples per second. The distance between the centers of the target and laser in two orthogonal directions were calculated from the digitized data. The tracking error (*TrErr*) was calculated as

$$TrErr_i = \sqrt{XErr_i^2 + YErr_i^2} \qquad 2$$

where $XErr_i$ and $YErr_i$ are the distances between the centers of the target and the laser in the horizontal and vertical directions, respectively, at the ith data point. The rms tracking error (*RmsTrErr)* was calculated as

$$RmsTrErr = \frac{\sqrt{\sum_{i=1}^{n}(XErr_i^2 + YErr_i^2)}}{n} \qquad 3$$

where n is the number of data points. Any $TrErr_i$ of 25 mm or less was considered 'on target'. The number of data points associated with being 'on target' was accumulated during the tracking task to give the resultant time-on-target (TOT). The percent time-on-target (%TOT) was calculated by dividing the TOT by the total tracking task time of 40 seconds.

2.6 Test Procedures and Data Analysis

Six subjects (two females and four males) weighing between 50.4 and 81.6 kg (mean 67.4 ± 8.5) participated as subjects. Only one subject required the use of the large helmet. For each exposure (BUFFET and HIFLAT), there were nine combinations of head/helmet orientation and weight distribution. Head and helmet acceleration data were collected during vibration exposure just prior to initiating the tracking task. All six subjects were exposed to each vibration signal and all nine combinations. These conditions were repeated three times on separate days. For each subject, the three sets of data were averaged for each dependent variable listed in Table 1. These data were used in the statistical analysis. The Repeated Measures Analysis of Variance and the Bonferroni Comparison Test were applied to the natural log of the overall displacement rotations (degrees) to evaluate the main effects and interactions of head orientation and weight distribution on the head, helmet, and helmet slippage data for each of the three rotational directions. For the tracking performance data, the statistical analysis was performed on the rms tracking error and %TOT for the two factors of head orientation and helmet weight distribution.

3. Results

3.1 Head and Helmet Frequency Response Characteristics

Figure 2 illustrates a representative displacement input profile for the BUFFET and HIFLAT exposures, respectively, in each of the three orthogonal directions for the six subjects. Each of the

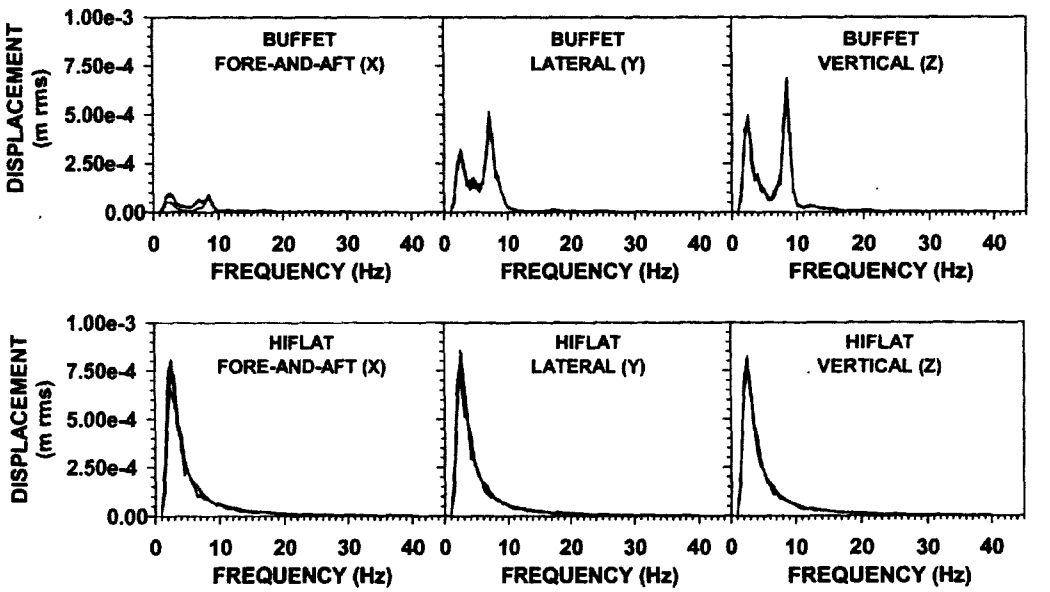

Figure 2. Representative Input RMS Displacements for Six Subjects

BUFFET and HIFLAT displacement inputs was similar among the subjects as reflected in the frequency spectra. The BUFFET profile was characterized by a distinct and prominent acceleration peak around 8.5 Hz in the vertical (Z) direction, a relatively smaller peak around 7 Hz in the lateral (Y) direction, and

very low vibration in the fore-and-aft (X) direction. The BUFFET input displacement frequency spectra showed similar peaks as described for the acceleration spectra, but also included significant displacement around 2.5 Hz (Fig. 2). The frequency location of this low frequency vibration may have been influenced by the conversion process, but a small acceleration peak was observed at this frequency. The highest displacement associated with the HIFLAT exposure occurred around 2.5 Hz as expected given the relationship between displacement and acceleration. Figure 3 depicts the head rotation displacement frequency spectra for the BUFFET and HIFLAT exposures with the head forward orientation (FOR) and CG2 weight distribution. The figure illustrates the variability in the peak magnitude

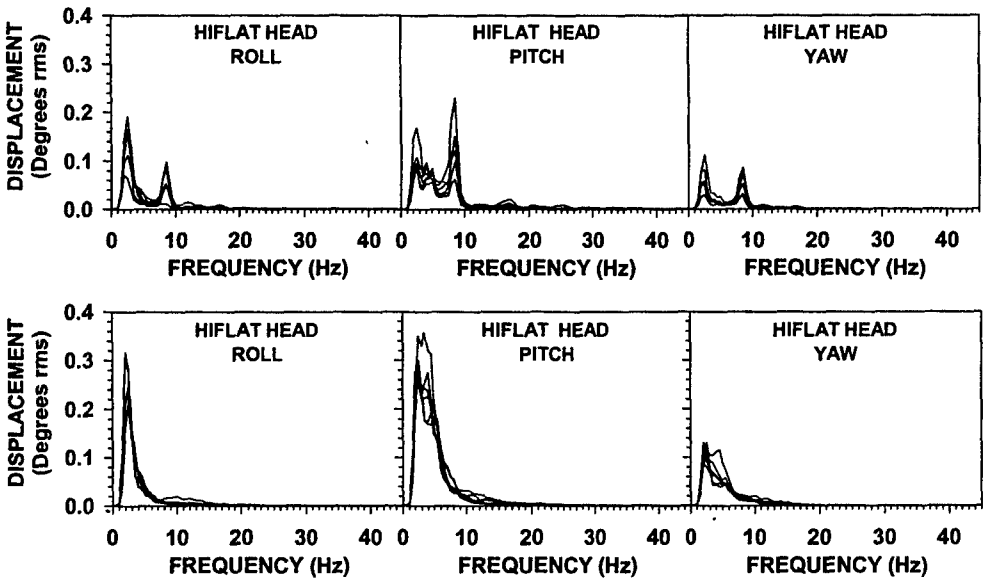

Figure 3. Subjects' Head Rotation Displacements With Head Forward Orientation

responses among the subjects. For the BUFFET exposure, the peak head and helmet rotation displacements occurred at the same frequencies as described for the vertical input (Fig. 2). For the HIFLAT exposure, the peak head and helmet rotation displacements occurred across a wider frequency band between 2 and 6 Hz, particularly for pitch, as compared to the peak input at 2.5 Hz. These peaks appeared to have been influenced by the primary whole-body resonance in the vicinity of 4 to 5 Hz. The frequency location of the peaks for the remaining combinations of head orientation and weight distribution showed similar effects, while the peak displacement magnitudes varied with the measurement site (head or helmet), head orientation, and weight distribution.

3.2 Biodynamic Effects

Significant main effects and interactions were observed for head orientation and weight distribution. Figures 4 and 5 illustrate the mean overall head and helmet rotation displacements and helmet slippage rotation displacements for all head orientations and weight distributions for the BUFFET and HIFLAT exposures, respectively. All overall head and helmet rotations showed a significant main

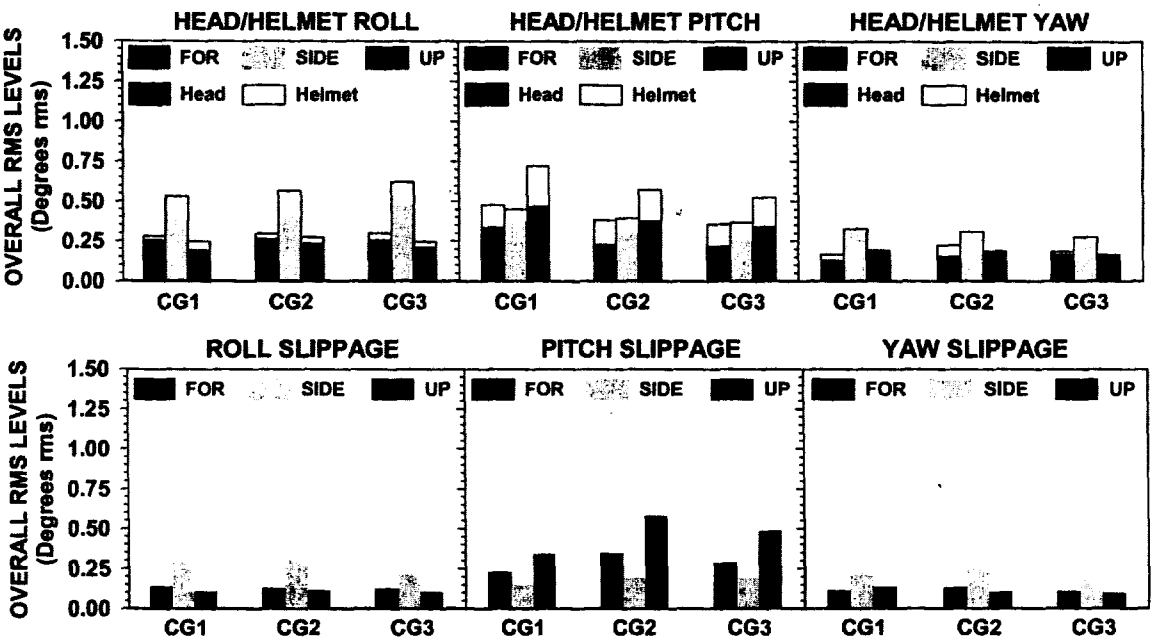

Figure 4. Mean Overall Head and Helmet Rotation Displacements and Helmet Rotation Slippages with the BUFFET Exposure

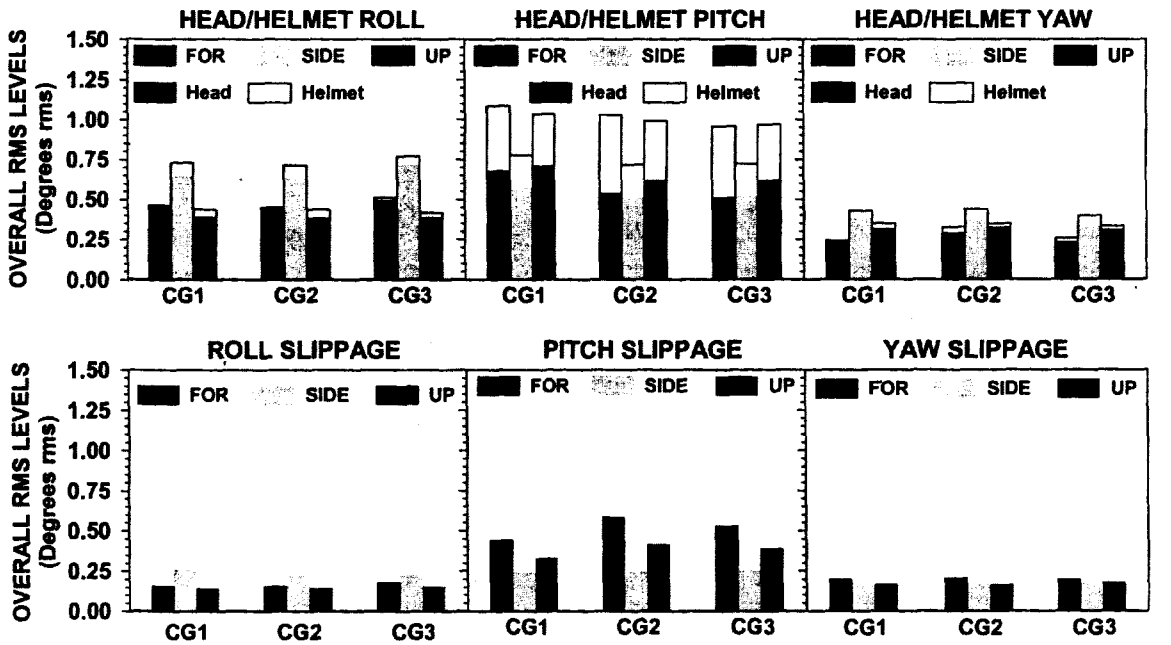

Figure 5. Mean Overall Head and Helmet Rotation Displacements and Helmet Rotation Slippages with the HIFLAT Exposure

effect for orientation. For all overall helmet rotations, there were no interactions between orientation and weight distribution. For roll motions, both the overall head and helmet roll displacements were significantly higher with the SIDE orientation as compared to the FOR and UP orientations for all weight distributions and for both types of exposure. The overall head and helmet roll displacements were similar

with the FOR and UP orientations except for the head roll during the BUFFET exposure with CG1 (Fig. 4). In this case, head roll with the UP orientation was the lowest. The overall helmet roll displacements were higher as compared to the overall head roll displacements, particularly for the SIDE orientation, regardless of the exposure. Overall roll slippage also tended to be the highest for the SIDE orientation. These results were significant for the BUFFET exposure with the slippage being similar for the FOR and UP orientations (Fig. 4). For the HIFLAT exposure, the overall roll slippage was significantly higher with the SIDE orientation for CG1 and CG2, but similar for the FOR and SIDE orientations for CG3 (Fig. 5). The significance of the interactions is difficult to identify in Figure 5.

For pitch motions, significantly higher head and helmet displacements occurred with the UP orientation for the BUFFET exposure with no interactions (Fig. 4). There were interactions for the head displacements during the HIFLAT exposure. The highest head pitch displacements occurred in the UP orientation for CG1 and CG3 with mixed results for CG2 (Fig. 5). For the overall helmet pitch during the HIFLAT exposure, the displacements were similar with the FOR and UP orientations, with both being significantly higher than the overall pitch response for the SIDE orientation (Fig. 5). The overall helmet pitch displacements were higher as compared to the overall head pitch displacements, regardless of the exposure. The highest helmet slippage occurred in pitch. For the BUFFET exposure, the UP orientation produced the highest, while the SIDE orientation produced the lowest overall pitch slippage (Fig. 4). For the HIFLAT exposure, mixed results occurred due to interactions. As suggested in Figure 5, the overall pitch slippage with the FOR orientation tended to be equal to or higher than the overall slippage occurring with the UP orientation but did depend on the weight distribution.

For yaw motions, head orientation had a significant effect on the overall head and helmet rotations and slippage for the BUFFET exposure, with most overall levels being significantly higher for the SIDE orientation (Fig. 4). However, the overall yaw slippage was similar with the SIDE and UP orientations for CG1. The interactions are difficult to visualize in Figure 4, although large variations among the subjects were observed with the SIDE orientation. For the HIFLAT exposure, the most significant effect of head orientation on the yaw displacements occurred at the helmet. Higher helmet yaw displacements tended to occur with the SIDE orientation. This effect was significant for CG2 and CG3. In contrast, there was no significant effect of orientation on the overall head yaw displacements with CG2 and CG3. For both the head and helmet yaw displacements at CG1, the SIDE orientation produced significantly higher motions as compared to the FOR orientation, but showed similar motions when compared to the UP orientation. There was no significant effect of head orientation on the overall yaw slippage for the HIFLAT exposure (Fig. 5).

The most noticeable effect of the helmet weight distribution occurred for the overall head and helmet pitch during the BUFFET exposure, with both sites showing significantly higher pitch with CG1 regardless of the head orientation (noted particularly at CG1 with the UP orientation in Fig. 4). This effect was also significant for the head with the FOR and UP orientations during the HIFLAT exposure (Fig. 5). At the

helmet, higher overall pitch displacements occurred with CG1 as compared to CG3 regardless of the orientation during the HIFLAT exposure. In contrast to the results observed for the overall head and helmet pitch, the overall pitch slippage tended to be the lowest with CG1 and significantly lower at CG1 as compared to CG2 for all orientations during BUFFET (Fig. 4), and for the FOR and UP orientations during the HIFLAT exposure (Fig. 5).

3.3 Tracking Performance Effects

Figure 6 illustrates the mean rms tracking error and %TOT for the BUFFET and HIFLAT exposures. Head orientation had a significant effect on the rms tracking error and %TOT but there were interactions

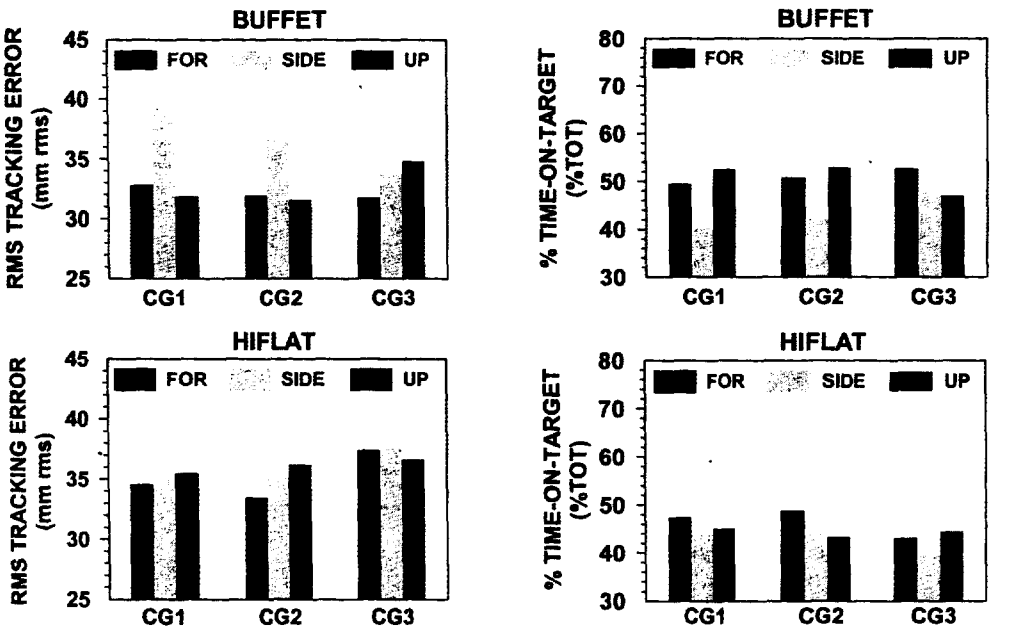

Figure 6. Rms Tracking Error and %Time-on-Target (%TOT) for the BUFFET and HIFLAT Exposures

between orientation and weight distribution. As depicted in Figure 6 for the BUFFET exposure, significantly higher rms tracking error and lower %TOT occurred with the SIDE orientation for CG1 and CG2, with no differences observed among the orientations with CG3. While showing no significant effect of orientation on the rms tracking error, the HIFLAT exposure did show significantly lower %TOT effects with the UP orientation as compared to the FOR orientation with CG2, while significantly lower %TOT was observed for the SIDE orientation with CG3. No significant effects of orientation on the %TOT were observed for the HIFLAT exposure with CG1.

The effects of weight distribution on tracking performance were less consistent as compared to the effects of head orientation. During the BUFFET exposure with the UP orientation, significantly higher rms tracking error and lower %TOT was observed with CG3. However, the mean magnitude of this rms tracking error appeared to be lower as compared to the rms tracking error occurring with CG1 and CG2

with the SIDE orientation. Likewise, the %TOT for the UP orientation with CG3 appeared to be higher as compared to the results for CG1 and CG2 with the SIDE orientation. These findings can be observed in Figure 6. There were no significant effects of weight distribution on either the rms tracking error or %TOT for the HIFLAT exposure.

4. Discussion

This study investigated the effects of head orientation and helmet weight distribution on head and helmet roll, pitch, and yaw displacements and helmet roll, pitch, and yaw slippages during exposure to two types of vibration. A method was established for estimating helmet slippage. In this study, the overall rms rotational displacement (in degrees) was used to evaluate significance effects. In the previous study (Smith, et al., 2000), the peak head and helmet rotational acceleration spectral densities were used to evaluate the effects of head orientation and weight distribution. In general, both assessment methods showed similar results for the F-15 buffet exposure. The overall rms head and helmet rotational displacements calculated in this study showed the increases in the roll and yaw responses identified in the previous acceleration responses with the SIDE orientation.

During the BUFFET exposure, the subjects' helmet pitch rotations did reach levels that were estimated in the F-15 aircraft pilots (seven degrees peak-to-peak (Smith, 2002)), although the head orientations in the F-15 pilots were unknown. The responses to the flat acceleration spectrum confirmed that the highest head and helmet displacement rotations, particularly pitch, occur below 10 Hz in the vicinity of the greatest human body vibration sensitivity. While both types of exposures showed similarities in the effects of head orientation and helmet weight distribution, there were differences that emphasized the importance of multi-axis vibration. The fore-and-aft (X) vibration present in the HIFLAT exposure (Fig. 2) most likely influenced the similarity in the head and helmet pitch observed with the FOR and UP orientations. Very low levels of fore-and-aft (X) vibration were present in the BUFFET exposure (Fig. 2) where the highest pitch motions were restricted to the UP orientation.

Head/helmet orientation has a dramatic effect on the biodynamic responses of the head and helmet and on head-slaved pursuit tracking performance. In general, the effects of orientation on helmet slippage were similar to those observed for the head and helmet motions; in most cases, higher slippage coincided with higher head and helmet rotations. The coincidence of higher head and helmet roll and yaw displacements, higher helmet roll and yaw slippage, and greater degradation in tracking performance with the SIDE orientation during the BUFFET exposure was noteworthy. However, for CG3, the degradation in tracking performance tended to follow the trends observed for head and helmet pitch, although differences in the degradation were not significant. This is discussed below. The minimal association between head and helmet motion and tracking performance for the HIFLAT exposure may have been influenced by the similarity among the overall helmet yaw slippage displacements. Significant differences were observed for the BUFFET exposure that may have contributed to the significant performance effects

with the SIDE orientation. Regardless, the magnitudes of the degradations with the HIFLAT exposure approached the higher levels observed with the BUFFET exposure.

The helmet weight distribution did not have the pronounced effect on the head and helmet rotations that was observed for head orientation, but also did not vary to the degree used in the Army studies mentioned previously. Of interest were the higher head and helmet pitch motions observed with the CG1 weight distribution. CG1 caused the head loading to occur behind the head CG. The Army studies also showed a tendency for higher pitch accelerations with head loadings behind the head CG; the results were significant for female aviators. The investigators summarized that the results may be related to musculoskeletal differences.

Helmet weight distribution may have also affected the ability of the subject to perform the tracking task, as suggested by the difference observed with CG3 as compared to CG1 and CG2. CG3 did show the highest helmet CG shift along the head Z-axis and lowest helmet CG shift along the head X-axis from the respective head CGs. CG3 also showed the highest moment-of-inertia estimated about the Y-axis due to placing the weights at the extreme front and back of the helmet. It is not clear how these characteristics may have specifically affected the tracking performance in a dynamic environment. Unfortunately, the effects of the moments-of-inertia on the dependent variables were not statistically evaluated. Any associations between the helmet CGs and moments-of-inertia, and the head/helmet biodynamics and tracking performance appear to be quite complex, requiring greater restrictions on the selection and values of the independent variables.

This study confirms that, with off-axis head orientations (relative to the directions of the vibration entering the seated upright occupant), increases in head and helmet rotations and helmet slippage can occur during exposure to low frequency vibration. This is a particular concern during military operations since these off-axis head orientations are expected during tactical and strategic flight maneuvers where low frequency vibration may occur. The consequences of these motions on visual performance were described in the **Introduction**. Factors to consider that may have an effect on the extent of visual performance degradation include pilot or crewmember posture, musculoskeletal development, and helmet fit. The seat back angle would certainly influence the pilot's postural behavior. As suggested in the Army studies, the head/neck musculoskeletal system may play a critical role in head stabilization.

The operational vibrations that have so far been documented in high-performance jet aircraft have occurred at relatively discrete frequencies below 10 Hz and primarily in the vertical direction, including the large helmet pitch observed around 3.5 Hz during the F/A-18C catapult launch (Smith, 2002, 2004). At this time, the levels of head and helmet displacements or accelerations necessary for visual blurring or image vignetting at those frequencies characteristic of the operational environments are not known. In addition, the effects of multi-axis vibration suggested by this study strongly indicate the need for

documenting the human vibration exposures and helmet motions that occur during various military operations where helmet-mounted equipment is expected to be used.

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