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Head and Helmet Biodynamics and Tracking Performance in Vibration Environments

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14. ABSTRACT
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Whole-body vibration, Helmet-mounted systems, Head tracking performance

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Head and Helmet Biodynamics and Tracking Performance in Vibration Environments

SUZANNE D. SMITH AND JEANNE A. SMITH

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Introduction: There are potential effects of vibration on aircrew performance and safety when using helmet-mounted equipment. The objective of this study was to quantify the effects of head orientation and helmet center-of-gravity (CG) on head and helmet biodynamics and tracking performance during exposures to aircraft buffeting and quasi-random vibration. ***Methods:*** Three head orientations, including two off-axis or off-boresight configurations [Side (40° elevation, 70° azimuth) and Up (40° elevation, 0° azimuth)], and three helmet CGs were tested. The overall head, helmet, and helmet slippage displacement rotations, and rms tracking error and percent time-on-target were evaluated. ***Results:*** For both exposures, the two off-axis orientations produced significantly higher head, helmet, and slippage displacements; a relationship was observed between the orientation and the rotation that was affected (roll, pitch, or yaw). The highest slippage observed was in pitch in the forward (For) and Up orientations. Significantly higher performance degradation occurred with the Side orientation for two of the three CGs during aircraft buffeting, with minimal degradation observed with the quasi-random exposure. Higher head pitch and lower pitch slippage were associated with the CG estimated to produce loading behind the human head CG. ***Conclusions:*** The high off-boresight head movements may influence visual performance in operational vibration environments. Helmet instability appeared to be the greatest in pitch, which could have a significant effect on the design size of the exit pupil. The weight distribution or moments-of-inertia of the helmet system may also have a significant influence on both head/helmet biodynamics and tracking performance and should be investigated.

Keywords: whole-body vibration, helmet-mounted systems, head tracking performance.

SOPHISTICATED helmet-mounted equipment is becoming integral to military tactical and strategic flight operations. Such equipment includes night vision goggles, helmet-mounted displays (HMDs), and helmet-mounted targeting and display (HMT/D) interfaces. There are potential effects of low-frequency vibration on head and helmet biodynamics that could affect aircrew performance and safety when using these helmet-mounted systems. The investigation of these effects is paramount since the HMDs are being considered for use as the primary flight reference in certain aircraft. The effects of helmet-mounted equipment have been studied in tactical and rotary-wing aircraft, particularly with regards to the weight and moments on neck loading and the potential for injury (2,3,5). 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 (12) and blamed for slower-than-desired target lock-on times when using a helmet-mounted targeting system (9). Substantial low-frequency vibration has also been documented in the F/A-18C Hornet during catapult launches from Navy aircraft carriers (13).

Factors such as head orientation, helmet center-of-gravity (CG), and helmet weight can affect head and helmet biodynamics during vibration exposure. Studies have shown that looking upwards without a helmet can increase the transmission of vibration to the head (8) and increase head pitching (6) during exposure to sinusoidal vertical vibration. This laboratory found that, when wearing an HMT/D, helmet pitch was the highest with an upward-looking (off-boresight) head orientation (40° elevation, 0° azimuth) followed by a combined side and upward (off-boresight) orientation (40° elevation, 70° azimuth) (10) during exposure to sinusoidal vertical vibration. Initial results from a second study conducted in this laboratory showed significantly higher peak head rotations (roll, pitch, and yaw) at 8.5 Hz with the combined side and upward (off-boresight) orientation (40° elevation, 70° azimuth) as compared with the forward orientation (0° elevation, 0° azimuth) during exposure to F-15 buffet vibration (11). The helmet showed significantly higher peaks at 8.5 Hz for roll and yaw only. Higher degradations in head tracking performance were also observed with the combined side and upward (off-boresight) orientation. Less dramatic effects were observed for the helmet weights and helmet CGs used in the study. The initial study also showed significant degradation in visual performance with the addition of vibration regardless of the head orientation.

Visual performance is a primary concern when using helmet-mounted equipment in jet aircraft. One concern for the HMD is that the projected image moves with the head, reducing the effectiveness of compensatory eye

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TABLE I. HEAD AND HELMET WEIGHT AND CG DATA.

Helmet Weight (kg)		Human Head CG* (cm)		Head/Helmet CG (cm)		Head/Helmet CG Shift from Head CG (cm)		Helmet CG Shift from Head CG (cm)	
		X	Z	X	Z	X	Z	X	Z
Medium (2.33)	CG1	0.83	3.12	0.20	3.50	−0.64	0.38	−1.79	1.08
	CG2	0.83	3.12	1.68	3.89	0.84	0.76	2.37	2.14
	CG3	0.83	3.12	1.02	4.50	0.18	1.37	0.50	3.92
Large (2.38)	CG1	0.83	3.12	0.48	3.02	−0.36	−0.10	−1.02	−0.27
	CG2	0.83	3.12	1.58	3.78	0.74	0.66	2.10	1.85
	CG3	0.83	3.12	0.99	4.27	0.15	1.14	0.47	3.20

*CG = center of gravity; based on human head weight = 4.30 kg (4).
Positive X and positive Z head/helmet CGs are forward and above head anatomical coordinate system, respectively. Data relative to head anatomical coordinate system.

movement associated with the vestibular-ocular reflex during head rotations occurring as high as 20 Hz (7,14). The result is visual blurring. Another concern is the effect of any helmet slippage. Even brief exposures to low-frequency vibration could cause helmet slippage that may exceed the designed exit pupil dimensions of the helmet system, resulting in partial or complete loss of the projected image.

The objective of this study was to expand the previous studies (10,11) to further investigate the effects of head orientation and helmet CG on head and helmet biodynamics and head tracking performance during vibration exposure. Given the significant influence of head orientation observed in these previous studies (10,11), all three head orientations, including the forward, upward and side, and up configurations, were included during exposure to the F-15 buffet vibration as well as to multi-axis quasi-random vibration. A third helmet CG was added to reflect the condition where weight would be added to the back of a helmet to offset equipment weight at the front of the helmet. The relative rotational motion between the head and helmet or helmet slippage was also calculated in this study. The off-axis head orientations were expected to produce significantly higher head motion, helmet slippage, and performance degradation. The additional third helmet CG was expected to produce significantly greater head pitch motion and pitch slippage with the upward orientation.

METHODS

The expanded study included the factor of head orientation with three levels [For (0 deg elevation, 0 deg azimuth), Side (40 deg elevation, 70 deg azimuth), and Up (40 deg elevation, 0 deg azimuth)], and the factor of helmet CG with three levels (CG1, CG2, CG3). Details on the CGs are given in **Table I**. The dependent biodynamic variables included head, helmet, and helmet slippage roll, pitch, and yaw displacements. The dependent performance variables included rms tracking error and % time-on-target (%TOT). 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 6° aft of vertical. A lap belt and double shoulder harness were used to loosely restrain the occupant.

Helmet Equipment

Fig. 1A illustrates the modified lightweight HGU-55/P helmet that included a visor, laser pointer, MBU-20/P Combat Edge oxygen mask, metal halo and Velcro for adding weights, an instrumented six-axis bar mounted to a mouthpiece (**Fig. 1B**), and an instrumented six-axis bar mounted to the top of the helmet (Fig. 1B). Six Entran EGA 125-10D accelerometers (Fairfield, NJ) were strategically glued to the six-axis bars used for calculating the head and helmet rotational motions (roll, pitch, and yaw) (Fig. 1B). Each subject was fitted with a custom-molded thermoplastic helmet liner with additional helmet pads positioned to optimize helmet fit and improve comfort. The initial helmet fitting was done by an individual experienced in life support equipment. Only one subject required the use of the large helmet. The oxygen mask (without hose assembly) was modified to allow for clearance of the mouthpiece and six-axis bar by removing a minimal amount of material from the front of the mask. A total of 0.90 kg was added to the basic helmet. For CG1, 0.45 kg was added at each ear. For CG2, 0.225 kg was added at each ear and 0.45 kg was added at the center front of the halo. For CG3, 0.45 kg was added to the back of the helmet and 0.45 kg was added at the center 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. The CGs of the combined human head and helmet were estimated using the mean CG data for the human head (4) and the measured mass properties of the helmet originally determined using a manikin head (1). The weight of the helmet system (medium and large), the CGs of the human head alone (4), and the locations of the combined head and helmet CGs used in the study are given in Table I. The table also includes additional information on CG shifts relative to the combined head and helmet and the helmet alone.

Tracking Performance Equipment

For the head-controlled pursuit-tracking task, a projector (Telex P1000 LCD, Telex Communications, Burnsville, MN) was used to display a 28 × 28 mm target (1.4 mm/pixel) onto a viewing screen using a display video card (Diamond Stealth 3D 3000, Diamond Multimedia,

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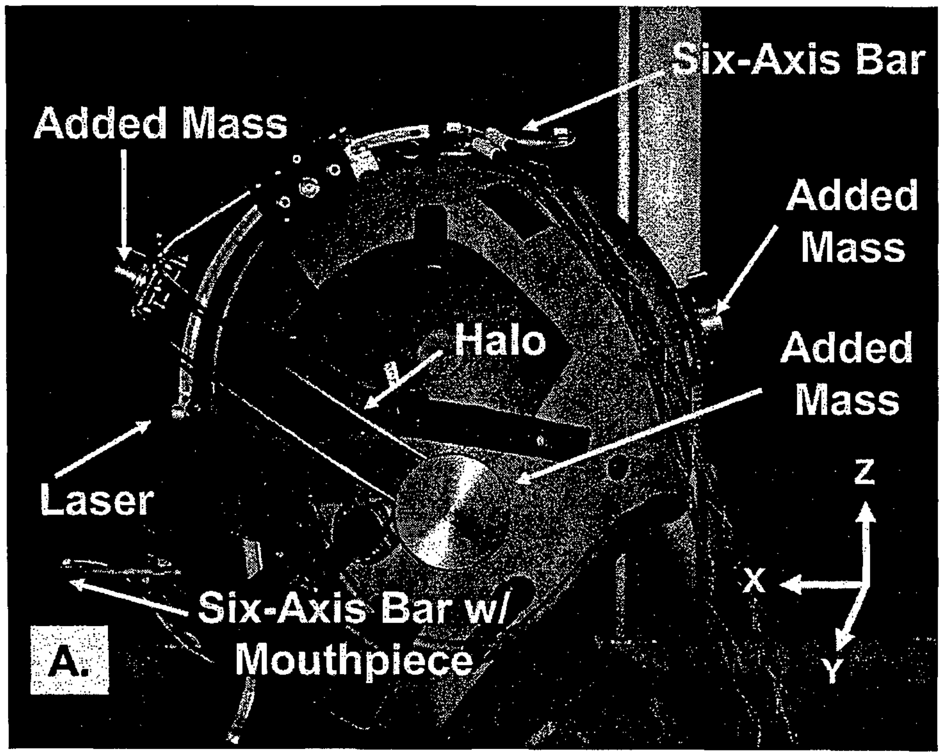

Fig. 1A. Helmet system.

Chatsworth, CA). Three screens were located so that the center position of the target corresponded to the three head/helmet orientations described above. The laser pointer was adjusted to insure correct alignment between the laser and the target with the subject seated upright and looking forward. The distance from the subject's 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° in the horizontal direction and ± 13° 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 (Matrox, Dorval, Quebec, Canada) using a Pulnix TM-6701AN camera (JAI Pulnix, Inc., San Jose, CA).

Vibration Exposure Signals

The 10-s buffet acceleration signal (Buffet), collected during F-15 aircraft tactical maneuvers (12), and the 10-s quasi-random flat constant bandwidth acceleration spectrum (Hiflat) were regenerated on the SIXMODE at 1024 samples $\cdot$ s^{-1} using a male subject weighing approximately 76 kg (12). The buffeting was characterized by a distinct and prominent acceleration peak around 8.5 Hz in the vertical (Z) direction of the aircraft, a relatively smaller peak around 7 Hz in the lateral (Y) direction of the aircraft, and very low vibration in the fore-and-aft (X) or longitudinal direction of the aircraft. The percent rms error between the overall acceleration level of the original F-15 signal and the regenerated signal was 6% or less in all three axes. Examples of F-15

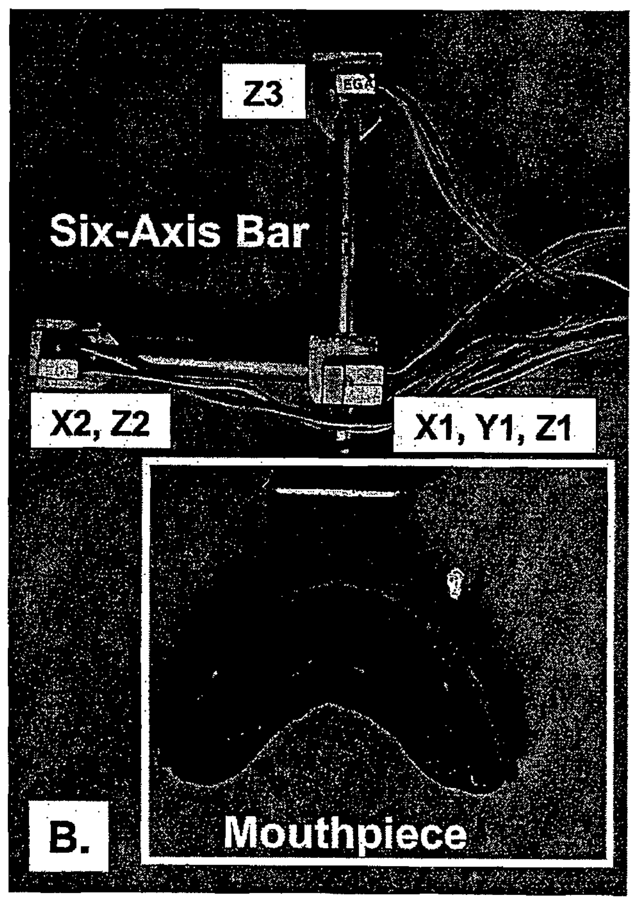

Fig. 1B. Six-axis bar and mouthpiece.

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buffeting time histories are provided in Smith (12). The multi-axis flat spectrum 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 $\cdot$ s^{-1} and an overall acceleration level of 2.0 ms^{-2} rms in the fore-and-aft (X), lateral (Y), and vertical (Z) directions. A flat spectrum is ideally characterized by frequency components that are generated at the same acceleration level. Further details on the input spectra are given in the Results.

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 $\cdot$ s^{-1}. All head and helmet rotations were calculated with respect to the head regardless of head orientation. With reference to Fig. 1B, roll was calculated as the difference between the Z1 and Z2 vertical accelerations divided by the moment arm (distance between sensors), pitch was calculated as the difference between the Z1 and Z3 vertical accelerations divided by the moment arm, and yaw was calculated as the difference between the fore-and-aft X1 and X2 accelerations divided by the moment arm. The head and helmet rotation displacement time histories (degrees) were estimated from the rotation acceleration data (12,13). 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 (16; Matlab® Signal Processing Toolbox, The Mathworks, Natick, MA). The rms acceleration and displacement at each frequency were calculated from the square root of PSD $\times$ Δf where Δf was the frequency increment of 0.5 Hz. The overall head, helmet, and slippage displacements (degrees) were calculated as

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

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 s, which included a 10-s warm-up for both vibration exposures. The target and laser images were captured every 10 ms (100 samples $\cdot$ s^{-1}). The images were concurrently scanned to locate the centers of the target and laser based on pixel intensity and the known dimensions of the target. The tracking error (TrErr) was calculated as

$$\text{TrErr}_i = \sqrt{\text{XErr}_i^2 + \text{YErr}_i^2} \qquad \text{Eq. 2}$$

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

$$\text{RmsTrErr} = \frac{\sqrt{\sum_{i=1}^{n}(\text{XErr}_i^2 + \text{YErr}_i^2)}}{n} \qquad \text{Eq. 3}$$

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 s.

Subjects

This study was reviewed and approved by the Wright Site Institutional Review Board at Wright-Patterson AFB, OH, and the U.S. Air Force Surgeon General's Research Oversight Committee. Subjects were military members of the Impact Acceleration Panel at Wright-Patterson AFB, OH, and provided written informed consent before participating. Six subjects (two women and four men) weighing between 50.4 and 82.4 kg (mean 67.4 $\pm$ 8.5 kg) participated.

Test Procedures and Data Analysis

For each type of exposure, there were nine combinations of head orientation and helmet CG. The acceleration data were collected just prior to initiating the tracking task with the subject pointing the laser at the stationary target located at the center position defined for the respective head orientation. The exposures with nine combinations were repeated three times on separate days. The means of the three sets of data (both biodynamic and performance) were used in the statistical analysis. Repeated measures analysis of variance and the Bonferroni comparison test were used to statistically evaluate the significance of the main effects and interactions of head orientation and CG. For these two factors, the statistical analysis was applied to the natural log of the overall head, helmet, and helmet slippage displacement data, respectively, for each of the three rotational directions (roll, pitch, and yaw) and each of the two types of vibration exposure (Buffet and Hiflat). The statistical analysis was also applied to the rms tracking error and %TOT, respectively, for each of the exposures.

RESULTS

Displacement Frequency Spectra

Fig. 2 illustrates the input displacement spectra and head rotation displacement spectra for the six subjects for the two exposures. The input displacement for Buffet showed peaks at the same frequencies as described previously for the input acceleration spectra. In addition, a prominent displacement peak was also observed around 2.5 Hz (Fig. 2A). The frequency location of this low-frequency vibration may have been influenced by the acceleration-to-displacement conversion process (displacement = acceleration/angular frequency^2), but a small peak was observed between 2 and 3 Hz in the input acceleration data that could result in a relatively large displacement. The highest displacement associated with the Hiflat exposure occurred around 2.5 Hz, as expected given the relationship between displacement and acceleration described above (Fig. 2A). The

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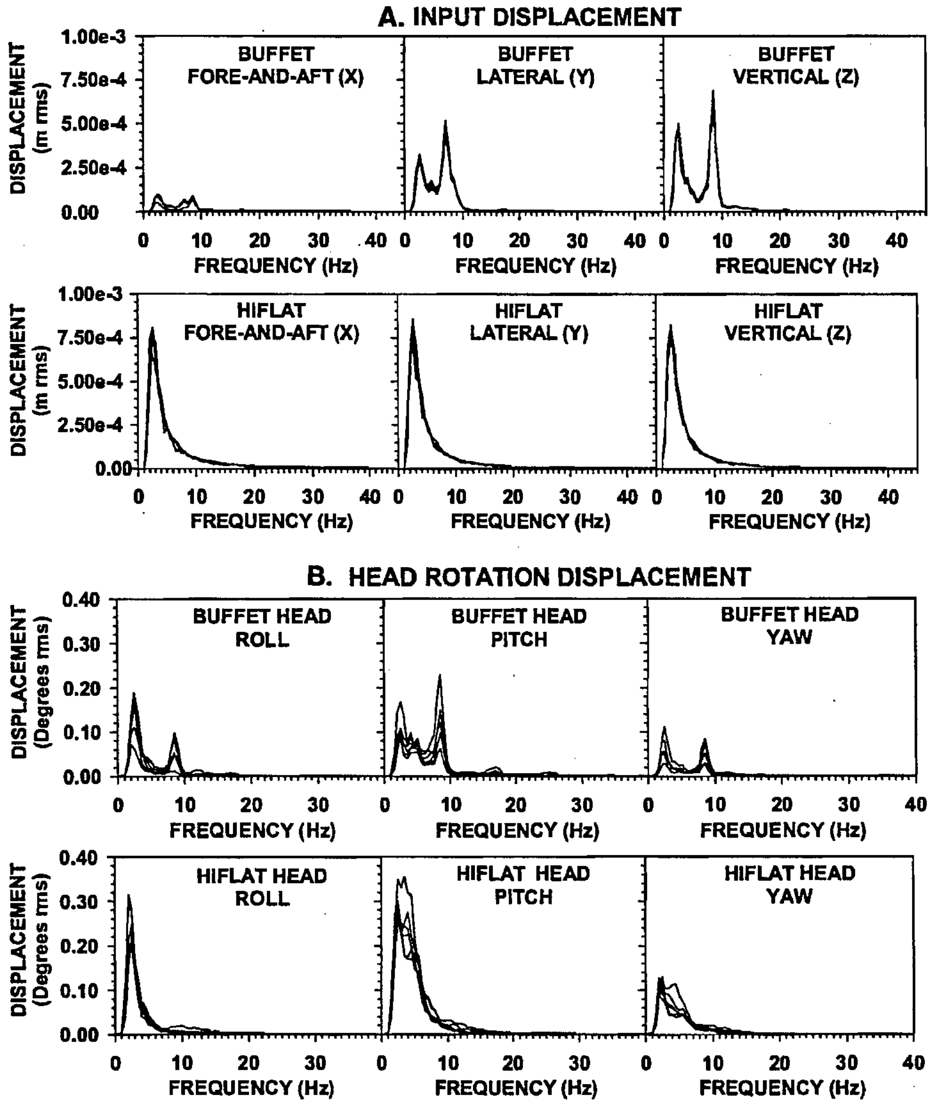

Fig. 2. A) Input displacement and B) head rotation displacement for the Buffet and Hiflat exposures for the six subjects.

head rotation displacement frequency spectra are shown with the head forward orientation (For) and CG2 (Fig. 2B). The figure illustrates the variability in the peak magnitude 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 displacement (~2.5 Hz and 8.5 Hz) (Fig. 2A). For the Hiflat exposure, the peak head and helmet rotation displacements occurred across a wider frequency band between 2 and 6 Hz (Fig. 2B), particularly for pitch, as compared with the distinct input peak observed around 2.5 Hz (Fig. 2A). The broad peaks appeared to have been influenced by the primary whole-body resonance known to occur below 10 Hz during vertical vibration exposure (12). The frequency location of the peaks for the remaining combinations of head orientation and CG showed similar effects, while the peak displacement magnitudes varied with the measurement site (head or helmet), head orientation, and CG.

Fig. 3 illustrates a one-second time history sequence of the head, helmet, and helmet slippage pitch displacement for the Buffet and Hiflat exposures. The highest peak-to-peak pitch displacement with Buffet was observed in a male subject weighting approximately 70.8 kg in the Up orientation with CG1. The helmet pitch reached as high as 7° peak-to-peak, while the helmet slippage reached about 4° peak-to-peak (Fig. 3A). The distinct motions at 8.5 Hz are seen in the figure with some suggestion of the 2.5 Hz contribution. The figure also shows a phase lag between the head and helmet displacements. The highest peak-to-peak pitch displacement with Hiflat was observed for a male subject weighing approximately 77.1 kg in the For orientation with CG1. Again, the helmet pitch approached 7° peak-to-peak and the helmet slippage reached 4° peak-to-peak (Fig. 3B). For this 1-s time history sequence, the predominant frequency appeared to be about 5 Hz. As mentioned above and illustrated in Fig. 2B for the Hiflat exposure, the head pitch response occurred over a broader frequency band between 2 and 6 Hz.

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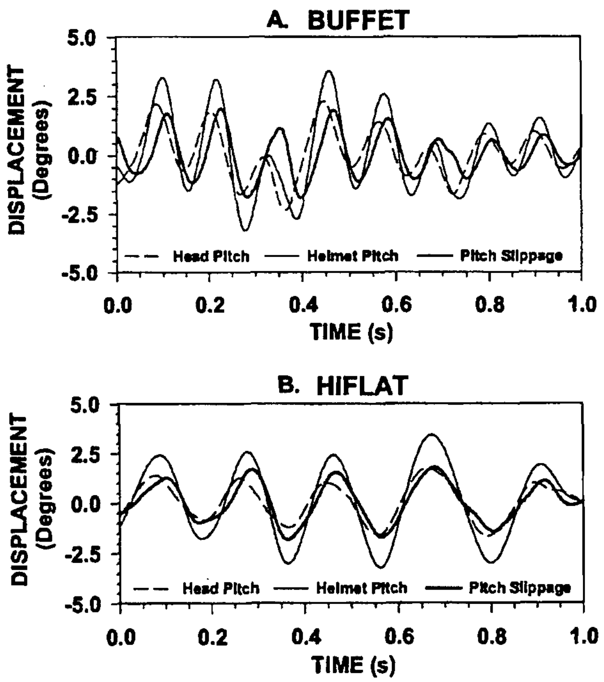

Fig. 3. One-second time history sequence of the head, helmet, and helmet slippage pitch displacement for A) Buffet and B) Hiflat.

Biodynamic Effects of Head Orientation and CG

The mean overall head and helmet rotation displacements and helmet slippage rotation displacement for all head orientations and CGs for the Buffet and Hiflat exposures are shown in **Fig. 4A and B**, respectively (note differences in ordinate axis range). The factor of head orientation showed a more substantial effect on the head, helmet, and slippage motions as compared with the factor of CG. The plots in Fig. 4A and B are drawn to emphasize the effects of head orientation. In the figures, the shaded areas indicate displacements that showed no significant differences ($p < 0.05$) for the compared orientations. The rectangles indicate mixed results. For example, in Fig. 4B for helmet yaw, the overall displacement with the Side orientation was similar to the displacement with the Up orientation, and the displacement with the Up orientation was similar to the displacement with the For orientation, but the displacement with the Side orientation was significantly higher than the displacement with the For orientation.

In Fig. 4A for Buffet, the CG was found to significantly influence the orientation effect (interaction) for head roll and head yaw (noted with CG1 where displacements associated with the three orientations were significantly different from one another). In Fig. 4B for Hiflat, the CG influenced the orientation effect (interaction) for head pitch, head yaw, roll slippage, and pitch slippage. Fig. 4A and B show that all roll displacements, including the roll slippage, were significantly higher with the Side orientation for both the Buffet and Hiflat exposures with one exception. For the Hiflat exposure, the overall roll slippage was significantly higher with the Side orientation for CG1 and CG2, with mixed results for CG3. Significantly higher yaw displacements, including yaw slippage, were observed with the Side orientation for the Buffet exposure with the one exception shown in Fig. 4A for yaw slippage with CG1. For yaw motion, large variations were observed among the subjects, contributing to the difficulty in visualizing the significant effects and interactions for head yaw in Fig. 4A. The Side orientation did not have the same effect on the yaw motions with the Hiflat exposure as compared with the Buffet exposure. As shown in Fig. 4B, the only significant effect occurred for head yaw (with CG1) and helmet yaw, where the Side orientation showed greater motions as compared with the For orientation with no significant effect on slippage.

In contrast to the effects of the Side orientation on roll and yaw motions, the Up orientation resulted in significantly higher pitch displacements, including pitch slippages during the Buffet exposure (Fig. 4A). Fig. 4A also shows that the Side orientation produced a significantly lower pitch slippage displacement with all three CGs during Buffet. For the Hiflat exposure, the Up orientation produced significantly higher head pitch with CG2 and CG3 only. Otherwise, the most notable result was the significantly lower helmet and slippage displacements occurring with the Side orientation (Fig. 4B), similar to the effect observed for pitch slippage during the Buffet exposure (Fig. 4A).

While the factor of CG did not show the dramatic and consistent effects on the head, helmet, and slippage motions as observed with head orientation, a notable effect of CG was observed in the overall pitch displacements. The effect is best illustrated for Buffet. With reference to the pitch motions plotted in Fig. 4A, the head and helmet pitch displacements were significantly higher for CG1 as compared with CG2 and CG3. However, the pitch slippage tended to be the lowest with CG1 regardless of the head orientation. The effect was significant when compared with CG2; the pitch slippages were similar between CG1 and CG3. Similar tendencies were also observed with Hiflat, although CG1 showed significantly higher head pitch only as compared with CG3. Helmet slippage during Hiflat showed the same results as observed for Buffet for the For and Up orientations. No significant effects were observed in the pitch slippage for the Side orientation.

Tracking Performance Effects

Fig. 5 shows the mean rms tracking error and %TOT for all head orientations and CGs for the Buffet (Fig. 5A) and Hiflat (Fig. 5B) exposures. Fig. 5A shows that the tracking error was significantly higher with the Side orientation for CG1 and CG2 during the Buffet exposure, indicating an influence of CG on the orientation effects. Likewise, the %TOT was significantly lower with the Side orientation for CG1 and CG2. In contrast, Fig. 5B shows that there was no significant effect of orientation on tracking error for the Hiflat exposure. There were mixed results for the %TOT as shown in Fig. 5B.

There were some effects of the factor CG on tracking performance during the Buffet exposure, but the results were affected by interactions. In Fig. 5A, the interactions can be seen by comparing the effect of CG among

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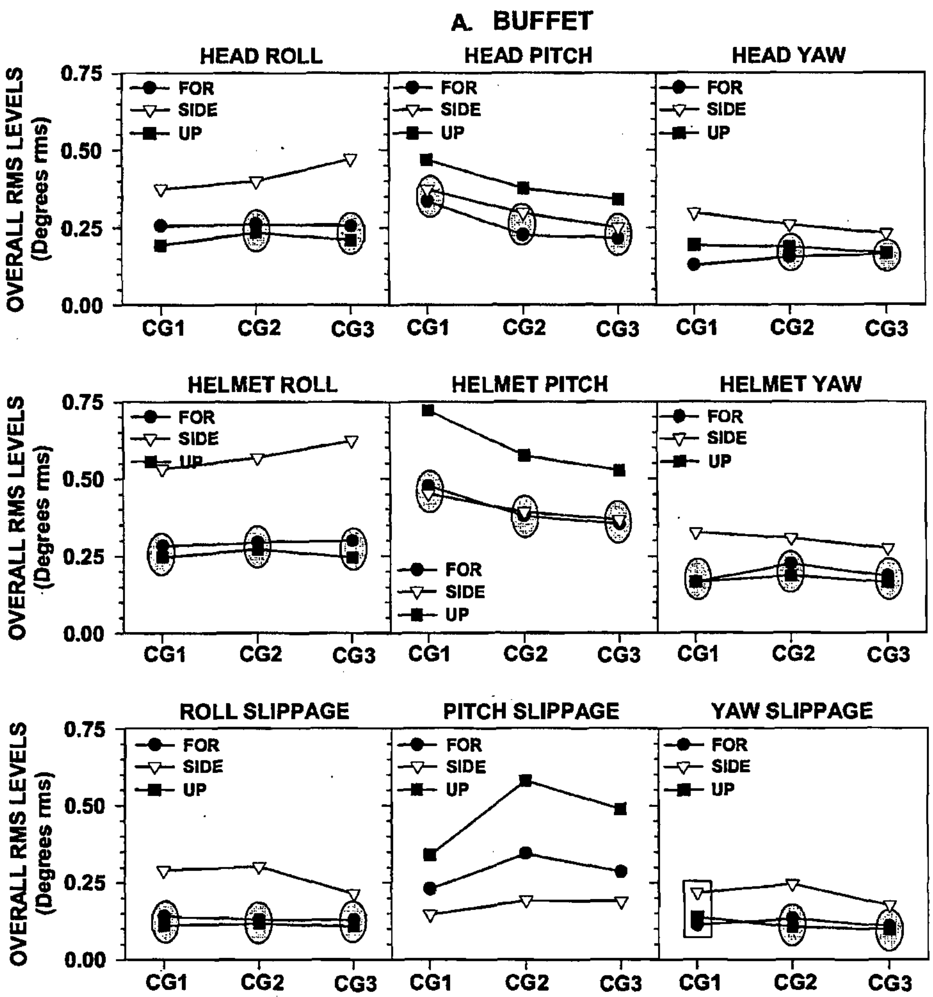

Fig. 4A. Mean overall head and helmet rotation displacements and helmet rotation slippages for Buffet (shaded area = no significant difference, white rectangle = mixed results).

the head orientations. For example, CG3 shows the highest rms tracking error and lowest %TOT for the Up orientation, while CG1 shows the highest rms tracking error and lowest %TOT with the Side orientation. There were no significant effects of CG on either the rms tracking error or %TOT for the Hiflat exposure.

DISCUSSION

This study investigated the effects of two factors, head orientation and helmet CG, on head and helmet biodynamics and head tracking performance. The biodynamic analysis included the evaluation of the difference between the head and helmet rotations or helmet slippage for roll, pitch, and yaw. For the biodynamic analysis, the overall rms rotational displacement (degrees) was used to evaluate significant effects. In the previous study (11), the peak head and helmet rotational acceleration spectral densities were used to evaluate the effects of head orientation and CG. In general, both assessment methods showed similar results for the F-15 buffet exposure (Buffet).

During the Buffet exposure, the subjects' helmet pitch rotations did reach levels that were estimated for the F-15 aircraft pilots [7° peak-to-peak in the time histories (12)], 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 in pitch, occur below 10 Hz in the vicinity of the greatest human body vibration sensitivity.

The off-axis head orientations did produce higher head and helmet motions, higher helmet slippage, and higher degradations in tracking performance. The characteristics of the head/helmet and slippage motions and the performance degradation depended on the specific off-axis orientation. In general, the significant effects of these orientations were similar among the CG configurations for both the head/helmet motion and the associated helmet slippage, particularly for the Buffet exposure. All three CG configurations showed significantly higher head and helmet roll, and roll slippage with the Side orientation. All three CG configurations showed significantly higher head and helmet pitch, and pitch slippage with the Up orientation.

With regard to CG, the higher head motions expected for CG3 during the Up orientation were not seen and

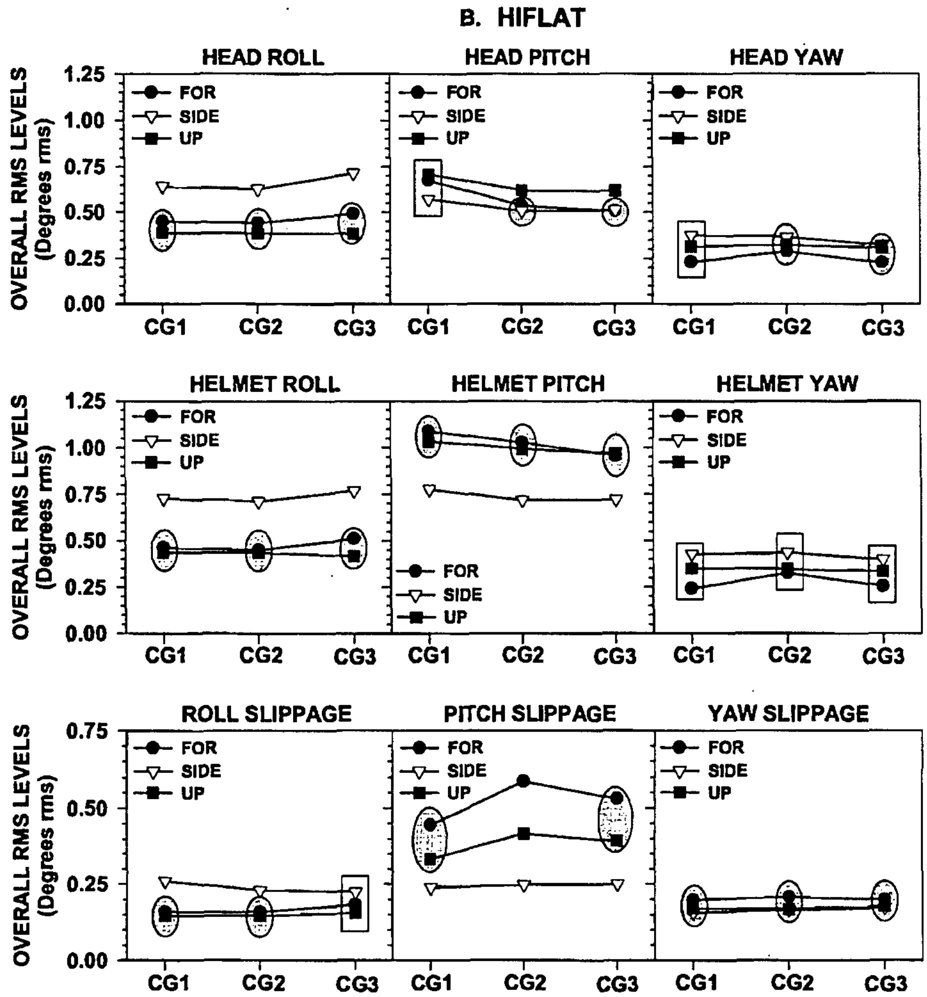

Fig. 4B. Mean overall head and helmet rotation displacements and helmet rotation slippages for Hiflat (shaded area = no significant difference, white rectangle = mixed results).

the helmet slippage associated with CG3 was similar to that observed with CG1 and CG2. However, the significantly higher head and helmet pitch motions observed with CG1 were of interest. CG1 caused the head loading to occur behind the head CG [based on human head estimates (4), Table I]. The Army studies (2,3) described previously also showed a tendency for higher pitch accelerations with head loadings behind the head CG; the results were significant for female aviators. The investigators theorized that the results may be related to musculoskeletal differences. Interestingly, CG1 tended to cause the least amount of helmet pitch slippage, i.e., higher head and helmet motions did not necessarily coincide with higher slippage when comparing CG configurations, the results for pitch being the most pronounced and consistent. The lower pitch slippage associated with CG1 was only significant when compared with CG2. Interestingly, CG2 showed a higher fore-and-aft (X) as well as vertical (Z) shift in the helmet CG relative to the head CG when compared with CG1 (Table I), suggesting that a higher helmet pitch moment would occur with CG2. Factors affecting this tendency for an inverse relationship between head/helmet pitch and pitch slippage are discussed below.

Tracking performance was most degraded with the Side orientation. While head/helmet biodynamics and tracking performance were evaluated separately, 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 for CG1 and CG2 during Buffet was noteworthy. Tracking performance did not appear to be affected by the relatively high levels of pitch slippage, raising the general question about the contribution of helmet slippage to tracking performance. The placement of the weights for CG1 and CG2 would produce higher moments-of-inertia about the X and Z axes of the head that could influence both the head/helmet biodynamics and tracking performance with the off-axis Side orientation.

Tracking performance with CG3 followed the trends observed for head and helmet pitch, although the tendency for greater performance degradation during the Up orientation with CG3 was not significant. As noted in Table I, CG3 showed the highest helmet CG shift

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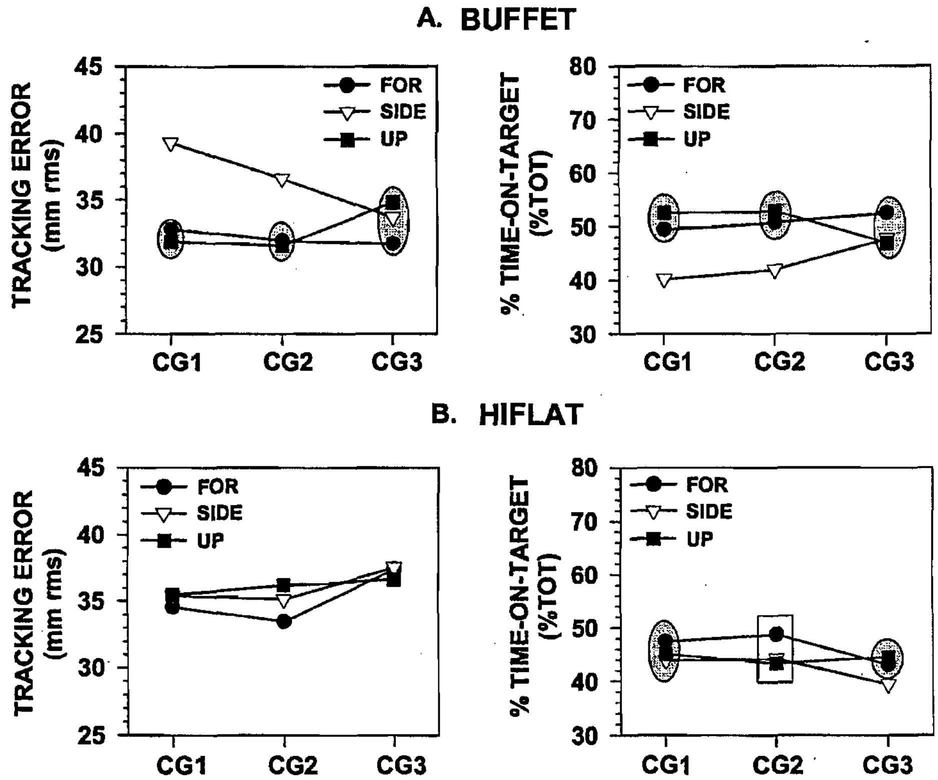

Fig. 5. Mean rms tracking error and %time-on-target (%TOT) for A) Buffet and B) Hiflat (shaded area = no significant difference, white rectangle = mixed results).

along the head Z-axis, but showed the lowest helmet CG shift along the head X-axis among the tested 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. These characteristics could affect the voluntary control of head excursion during tracking, particularly since CG3 produced the highest tracking degradation with the Up orientation (Fig. 5), but not the highest head and helmet motion or helmet slippage (Fig. 4). These results did indicate that the effects of CG are complex and that the moment-of-inertia may be another critical factor affecting head/helmet biodynamics and tracking performance. It is speculated that the lack of association between the relatively higher roll motions with the Side orientation and tracking performance degradation during the Hiflat exposure may be related to the differences in the multi-axis frequency spectra that defined the two types of exposures, emphasizing the need to understand the relationship between the frequency content and associated acceleration levels that affect head and helmet motions.

The highest helmet slippages were observed in pitch, regardless of the type of exposure. This strongly suggested that the helmet was most unstable in pitch regardless of any significant effect of orientation on other directions of motion. This observation has particular significance when considering the optimum size of the exit pupil of a helmet-mounted display. The exit pupil should be designed to include the lateral eye translation, the eye pupil projection for the desired field-of-view, and helmet slippage to minimize image vignetting (15). The exit pupil would have to be large enough to accommodate the effects of multi-axis helmet slippage on the projected displacement based on the eye relief of the particular helmet system. The results of this study strongly suggested that the pitch slippage would have the greatest influence on this projected displacement, particularly when looking forward or up. Since the center-of-rotation of the helmet on the head was not known in this study, the helmet slippage data cannot be used to calculate projected displacements. Several factors could influence helmet pitch stability. A helmet system that has good fit, defined in this context as a helmet that is closely coupled to the individual's head and maintains high friction between the head and helmet, could reduce slippage. However, other factors could compromise these effects. Although the previous study conducted in this laboratory (11) found no substantial effect of helmet weight on head or helmet motion and helmet slippage, the helmet systems were relatively light (1.25 to 2.16 kg). The Army (2,3) found significant increases in head pitch acceleration with increased helmet weight in female aviators exposed to vertical vibration, but the helmet weights ranged from 2.23 to 4.17 kg. It is obvious from these studies that a lighter helmet system is desirable to minimize both head and helmet motion and reduce undesirable musculoskeletal loading, even with a good fit. If the combined head and helmet CG were placed close to the head CG, this could certainly aid in minimizing head and helmet moments. However, the moments-of-inertia

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associated with the weight distribution may have a substantial effect on head motion, helmet slippage, and tracking performance regardless of fit or CG and is being investigated in this laboratory.

With low frequency vibration of the head, the potential exists for visual blurring of the displayed image in a HMD with regard to compensatory eye movement. The higher head motions observed during off-axis head orientations in this study are expected to occur during high off-boresight targeting in the operational environment, increasing the risk of visual effects during critical flight activity. The selection of the display symbology and the use of image stabilization techniques are important design considerations affecting visual performance. Finally, low frequency vibration transmitted to the head/helmet system could compromise the effectiveness of a pilot to lock onto a target, as demonstrated in the F-15. It is very important to characterize any vibration associated with the tactical operation of an aircraft in order to design effective targeting systems.

CONCLUSIONS

1. Off-axis head orientations significantly increased head rotation and helmet slippage, as well as significantly degraded tracking performance during operational exposure to low frequency vibration. These high off-boresight head movements may increase the potential for visual impairment during critical tactical maneuvers in military aircraft.

2. The helmet was the most unstable in the pitch direction, as noted in the pitch slippages observed with the For and Side orientations. While not necessarily affecting the tracking performance, the pitch slippage could have a major influence on image vignetting and significantly impact the effective size of a helmet system's exit pupil.

3. During vibration, tracking performance was the most sensitive to the Side orientation. The role of helmet slippage in degrading performance was not clear, given the ineffectiveness of the relatively high pitch slippages to affect performance in the For and Up orientations. The weight distributions associated with the tested CGs did suggest that the associated moments-of-inertia may play a role in affecting head/helmet motion and the subject's ability to voluntarily control head movement during tracking.

4. It is understood that helmet systems should be designed to minimize helmet slippage by being lightweight, well fitted to the head, with head/helmet CGs that are close to the head CG. However, it is imperative that other factors be considered, including the weight distribution (moment-of-inertia), display symbology, and image stabilization techniques for minimizing head and helmet motion and optimizing the performance and safety of the aircrew.

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