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UNITED STATES ARMY AEROMEDICAL RESEARCH LABORATORY

# Defining Normal Cervical Spine Range of Motion in Rotary-Wing Pilots (Part 1): A Method of Estimating AH-64 Aviator Cervical Spine Range of Motion Using Head Position Data from the Maintenance Data Recorder

S. Tyler Williams, Adrienne M. Madison, & Valeta Carol Chancey

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[1]U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL; [2]Katmai Government Solutions, LLC, Anchorage, AK

**14. ABSTRACT**

Neck pain is an established flight safety issue for military rotary-wing aviators. Military flight surgeons tasked with making determinations regarding an aviator's flight fitness based on cervical spine range of motion (CROM) do not have adequate guidance to make an informed decision as there is currently no regulation defining what range of motion is adequate during flight operations. Describing the real-world CROM during flight would inform flight surgeons and provide a more useful and substantial reference than the normal physiological limits that flight surgeons currently employ. This report describes the process of analyzing head position data from the AH-64 maintenance data recorder (MDR) to estimate CROM requirements of pilots and co-pilots. The data show that pilots and co-pilots generally spent more time in mild and severe postures in night flights than day flights and a showed a lower frequency of neck twisting at night. A statistical analysis of the data revealed a significant difference between estimated neck posture for pilots and co-pilots, as well as between day and night flight operations ($p < 0.05$).

**15. SUBJECT TERMS**

CROM, cervical spine, AH-64, apache, pilot, aviator, head tracking, IBPG

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14. Abstract (continued)

This approach provided a convenient and effective method for analyzing thousands of hours of flight data and resulted in a sufficient amount of measurements to determine pilot and co-pilot neck postures typically seen during flight.

## Summary

Neck pain or injury is a common issue among aviators. However, no U.S. Army regulation currently exists to define what cervical spine range of motion (CROM) is adequate for flight. This lack of regulation leaves flight surgeons responsible for determining the flight fitness of an aviator affected by neck pain or injury without an objective reference. The first attempt towards providing such a reference is to quantify the head motion requirements of these aviators by examining a large amount of flight data. This report describes the process of analyzing head position data from the AH-64 maintenance data recorder (MDR) to estimate the CROM requirements of pilots and co-pilots.

Apache Attack Helicopter Project Management Office provided three-dimensional pilot and co-pilot head position data from the MDR readings from AH-64 missions. Data were filtered down to three-dimensional pilot and co-pilot head position data reported as unit vectors. Missions were classified as a day flight, night flight, or unknown. Each data point was analyzed to determine neck posture. Neck postures were then categorized as neutral, mild, or severe for flexion/extension, lateral bending, and axial twist based on neck postural categories established in previous literature. Severe neck twisting movement rate was also estimated based on these measurements.

The analysis showed that pilots and co-pilots generally spent more time in mild and severe postures in night flights than day flights. Pilots and co-pilots also exhibited a large amount of time in mild and severe twisting postures compared to the other categories. Pilots showed a higher rate of head twisting than co-pilots. Pilots and co-pilots also showed a lower rate of head twisting during night flights. Statistical analysis of the data revealed a significant difference between estimated neck posture for pilots and co-pilots as well as between day and night flight operations.

This method provides the groundwork for future analyses on aviator CROM. The data presented here cannot be related to specific flight maneuvers, environments, or aviator demographics. Hence, future research that can control flight conditions and parameters is recommended to provide a more accurate assessment of operational CROM.

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# Acknowledgements

This research was supported by Defense Health Program (DHP) funds from the Military Operational Medicine Research Program (MOMRP) Joint Program Committee (JPC-5). The authors are greatly appreciative of the contributions of Fred Brozoski, who inspired the initial process for creating the code for neck angle calculation, and Amanda Kelley for providing guidance on the statistical analysis.

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# Introduction

Neck pain is a persistent issue within the military aviator community (Harrison et al., 2015). Pilots are often required to support a significant amount of weight on their head (because of helmet and helmet system wear). This weight, in combination with the head motion necessary for optimal aircraft operation, puts considerable strain on the neck. The consequence of repeated exposure to this environment is neck pain or injury, which can limit cervical spine range of motion (CROM) (Rudolfsson et al., 2012). One study among 113 military aviators revealed that 43% reported neck pain, and 20% reported regular or continuous neck pain (Van den Oord et al., 2010a). A study by Harrison et al. (2010) reported higher peak and cumulative neck loading for flights requiring night vision goggles. Injury risk curves as a function of head-supported mass were developed by the U.S. Army Aeromedical Research Laboratory (USAARL) to reduce the risk of neck injury (McEntire & Shanahan, 1998). The issue of neck pain has become so prevalent that a branch of the U.S. military has proposed personalized health care for its pilots to treat and prevent neck pain and injury (Pawlyk, 2019; Novotny et al., 2021).

Surprisingly, no regulation exists within the U.S. Army that defines the CROM necessary for flight (Department of the Army [DA], 2015). This lack of a regulation puts flight surgeons in the difficult position of determining the flight fitness of pilots with limited CROM due to neck pain or injury with no official guidance to follow (Van den Oord et al., 2010b). Defining the actual CROM requirements of military aviators could lead to the establishment of a set of guidelines for aeromedical waiver authorities to reference when making a flight fitness determination. It could also result in the institution of preventive standards for neck pain and injury, such as an exercise and treatment regimen.

The AH-64 maintenance data recorder (MDR) stores head position values taken during flight operations. Millions of hours of these values are stored in a repository maintained by the Apache Attack Helicopter Project Management Office (PMO). A detailed analysis of these data could characterize the head motion exhibited by pilots and co-pilots during routine flight. This report details an algorithm designed at USAARL to interpolate the head position data in these files to estimate neck posture. The resulting estimated posture analysis was used to gain insight regarding the direction and rate of neck movement required by military aviators during rotary-wing flight. This novel methodology is the first of its kind with aims to establish comprehensive CROM requirements for aviators in the military rotary-wing environment.

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## Methods and Materials

A retrospective study of de-identified three-dimensional pilot and co-pilot head position data was conducted using MDR readings from 127,487 files provided by Apache Attack Helicopter Program Management Office. This study was conducted under an approved non-human subject research protocol; therefore, formal consent was not required.

Figure 1 illustrates the process of analyzing the MDR files. The sections below describe the methodology of each procedure.

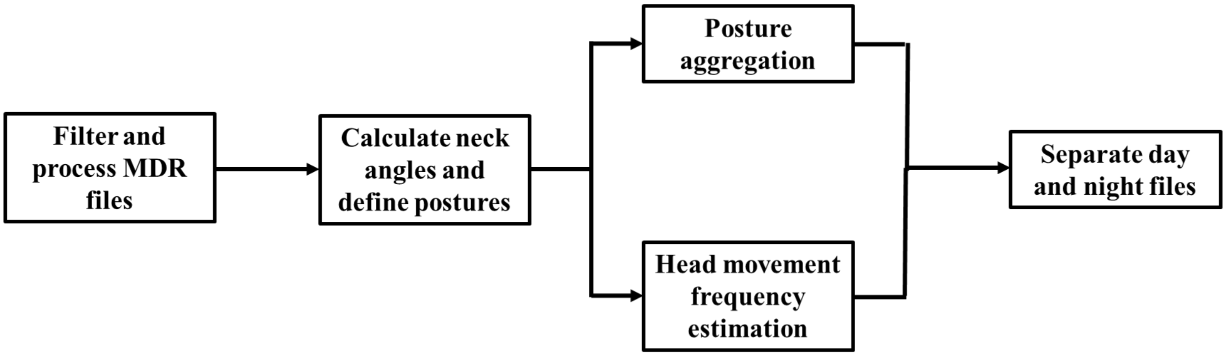
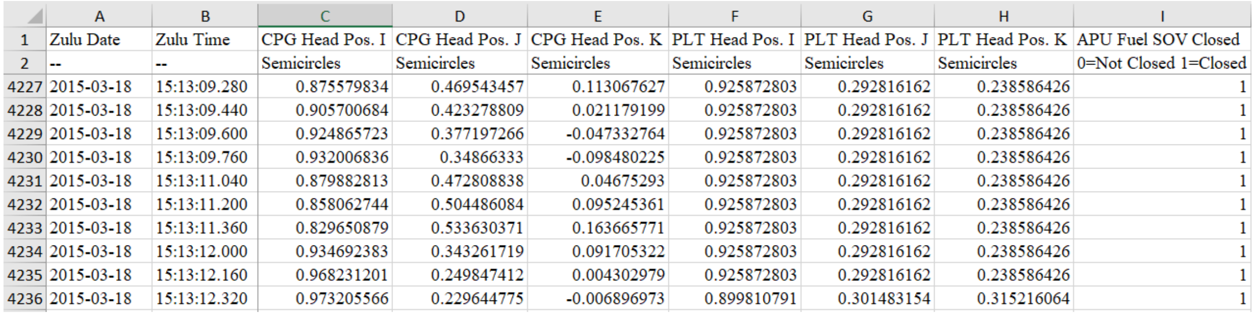


*Figure 1.* Maintenance data recorder (MDR) analysis flow chart.

### Maintenance Data Recorder (MDR) Excel Files

Apache Attack Helicopter PMO provided 127,487 MDR files to USAARL for use in this study. Each file name contains the aircraft tail number, the date of the flight, and the time the flight measurements started. The MDR files contained nine columns: Zulu date, Zulu time, three columns of head position data for the pilot and co-pilot (one column per dimension), and the status of the auxiliary power unit fuel shut-off valve (APU fuel SOV). Figure 2 shows an example of this file format. Note that the MDR reports head positions as components of a unit vector.



|  | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Zulu Date | Zulu Time | CPG Head Pos. I | CPG Head Pos. J | CPG Head Pos. K | PLT Head Pos. I | PLT Head Pos. J | PLT Head Pos. K | APU Fuel SOV Closed |
| 2 | -- | -- | Semicircles | Semicircles | Semicircles | Semicircles | Semicircles | Semicircles | 0=Not Closed 1=Closed |
| 4227 | 2015-03-18 | 15:13:09.280 | 0.875579834 | 0.469543457 | 0.113067627 | 0.925872803 | 0.292816162 | 0.238586426 | 1 |
| 4228 | 2015-03-18 | 15:13:09.440 | 0.905700684 | 0.423278809 | 0.021179199 | 0.925872803 | 0.292816162 | 0.238586426 | 1 |
| 4229 | 2015-03-18 | 15:13:09.600 | 0.924865723 | 0.377197266 | -0.047332764 | 0.925872803 | 0.292816162 | 0.238586426 | 1 |
| 4230 | 2015-03-18 | 15:13:09.760 | 0.932006836 | 0.34866333 | -0.098480225 | 0.925872803 | 0.292816162 | 0.238586426 | 1 |
| 4231 | 2015-03-18 | 15:13:11.040 | 0.879882813 | 0.472808838 | 0.04675293 | 0.925872803 | 0.292816162 | 0.238586426 | 1 |
| 4232 | 2015-03-18 | 15:13:11.200 | 0.858062744 | 0.504486084 | 0.095245361 | 0.925872803 | 0.292816162 | 0.238586426 | 1 |
| 4233 | 2015-03-18 | 15:13:11.360 | 0.829650879 | 0.533630371 | 0.163665771 | 0.925872803 | 0.292816162 | 0.238586426 | 1 |
| 4234 | 2015-03-18 | 15:13:12.000 | 0.934692383 | 0.343261719 | 0.091705322 | 0.925872803 | 0.292816162 | 0.238586426 | 1 |
| 4235 | 2015-03-18 | 15:13:12.160 | 0.968231201 | 0.249847412 | 0.004302979 | 0.925872803 | 0.292816162 | 0.238586426 | 1 |
| 4236 | 2015-03-18 | 15:13:12.320 | 0.973205566 | 0.229644775 | -0.006896973 | 0.899810791 | 0.301483154 | 0.315216064 | 1 |

*Figure 2.* Example of an MDR Excel file. The files contain data for the flight date, flight time, the status of the auxiliary power unit fuel shut-off valve, and three-dimensional head position for the pilot and co-pilot.

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## Batch Processing Script

Flights were analyzed by a batch processing script designed to take each file in a designated directory and convert the information in the file into MATLAB variables. The start time for each flight was defined by the closing of the APU fuel SOV. After filtering the 127,487 files for undesirable data (low or no head position reports with APU Fuel SOV closed for either the pilot or the co-pilot, corrupt data, or other anomalies), 104,556 files remained from which to generate data. The data were separated into structures for the pilot and co-pilot containing the three-dimensional head position data, a time array associated with those data, neck angle estimations, and neck posture classifications. All data for the pilot and co-pilot were then saved as a MATLAB file.

## Neck Angle Calculation and Posture Definition

Each data point during flight was analyzed using an in-house developed MATLAB function to determine neck posture at each data point during flight using the geometric equations shown in Appendix C. Figure 3 illustrates the neck posture definitions and Table 1 shows the classification ranges for the mild and severe postures (Forde et al., 2011). This work will analyze flexion, twisting, and lateral bending postures. Figure 4 shows an example of these posture measurements over one of the selected MDR files.

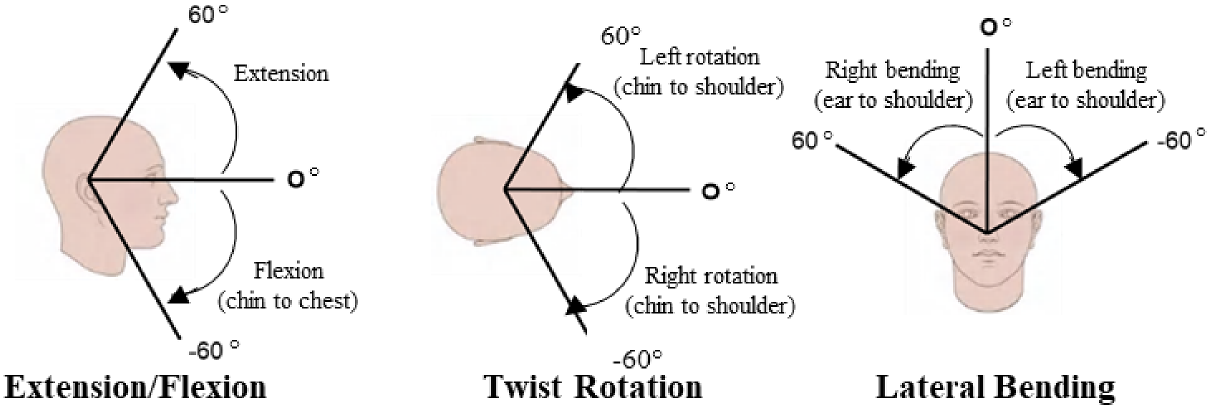

*Figure 3.* Visual diagram of neck postures. The postures are separated into three planes of motion. Extension and flexion correspond to moving the head up and down (chin to chest), respectively. Twist rotation corresponds to turning the head right and left (chin to shoulder). Lateral bending corresponds to bending the head right and left (ear to shoulder).

*Table 1.* Mild and Severe Neck Posture Classification Ranges

| Posture | Mild | Severe |
|---|---|---|
| Flexion | -(10-30°) | <-30° |
| Twist Rotation | ±(15-30°) | >30° or <-30° |
| Lateral Bending | ±(10-40°) | >40° or <-40° |

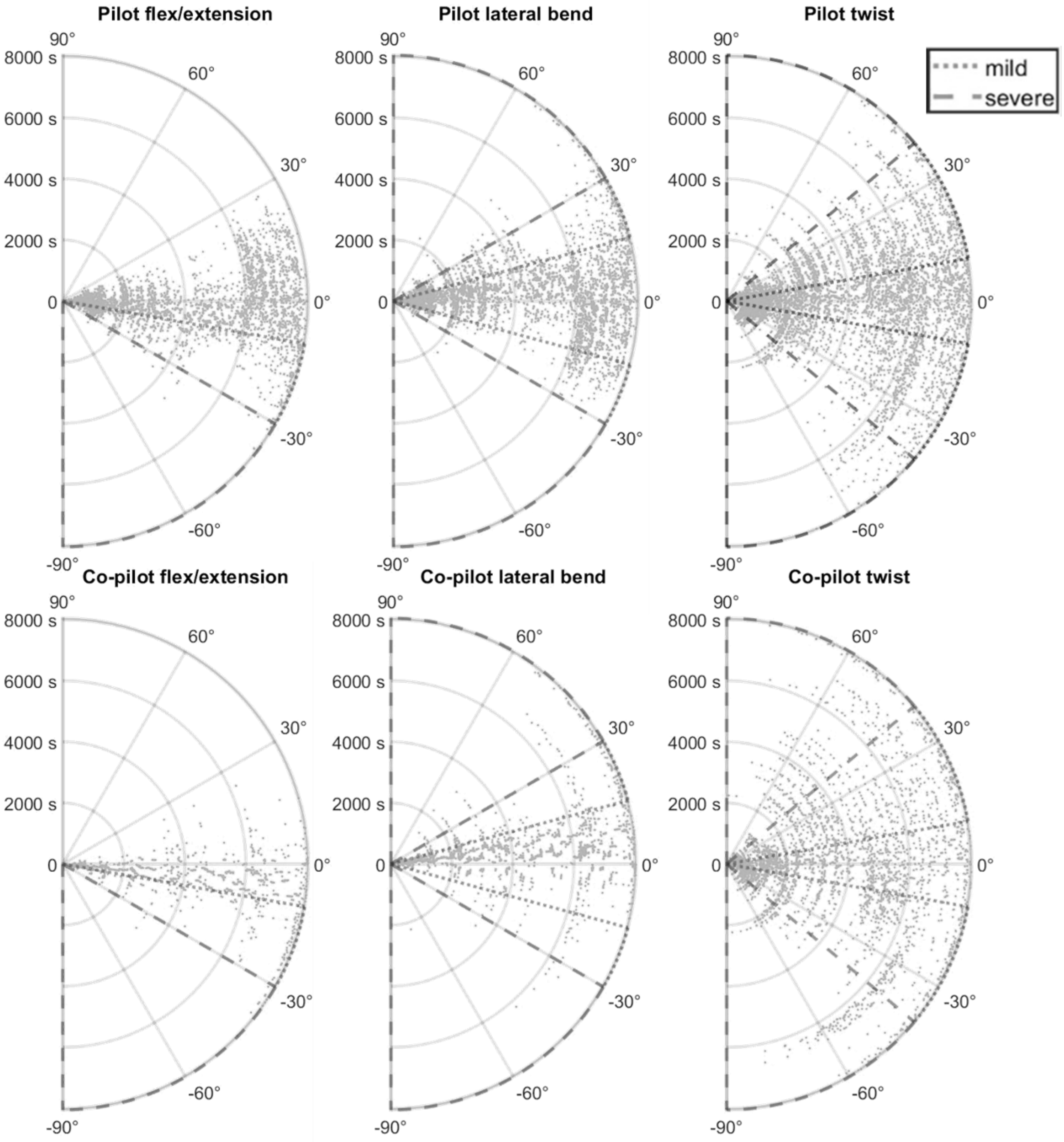

*Figure 4.* Polar plots of aviator crew head movement over a selected day flight. The plots are separated based on the posture definitions. The radial axis represents time and the angular axis represents the position of the head.

## Posture Aggregation

The saved pilot and co-pilot posture data were referenced to perform an aggregate analysis of all flights to determine the amount of time aviators are typically spending in the three posture bins. Information from all flights was combined; the total time in each posture bin was compared to the total flight time to calculate the percentage of flight time within those posture bins. Appendix D shows the code used to aggregate the posture information.

### Neck Movement Rate Estimation

The method for estimating neck movement rate involves calculating the number of instances a neck twist rotation occurs from a neutral position to a magnitude of greater than 30 degrees (the minimum angle for a severe neck twist classification). The pilot and co-pilot neck angle calculations for twisting are used as an input to a function that finds local peaks within a data set. Figure 5 shows an example of the output of the peak-finding function based on head position data. The length of that output is used to determine the number of times a neck twist rotation has been performed, and the rate is calculated by dividing the mission length by the number of twist rotations. The twist rates were aggregated for pilots and co-pilots, and time of day to calculate mean twist rate and the percent difference.

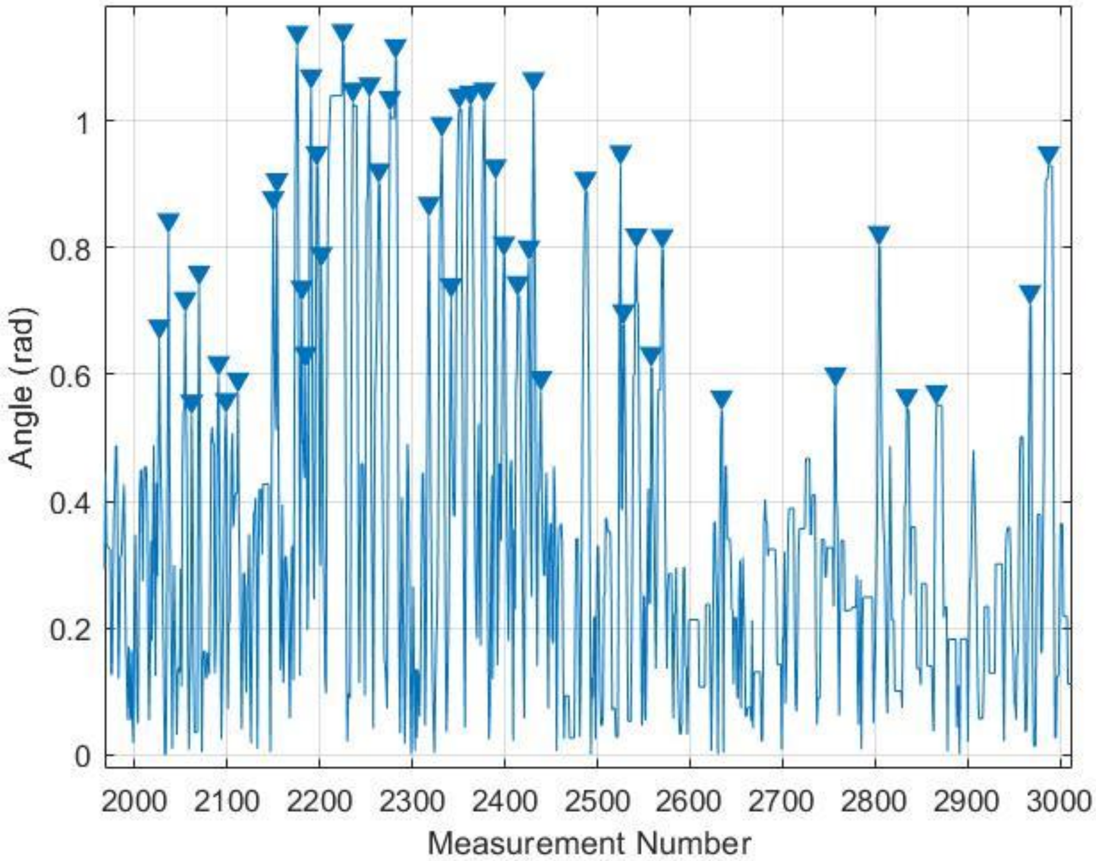

*Figure 5.* Example of the output of the peak finding function. Data shown are neck twist angles calculated from one MDR output. Peaks found by the algorithm are marked with blue triangles.

### Separation of Day and Night Flights

One of the objectives of this research effort was to investigate the difference in cervical spine activity between day and night flights. The provided MDR files were continental U.S. (CONUS) flights, but no other geographic information was provided within the files. Since there was no way to know where the flights took place, the only way to classify the flights as day or night with a high degree of confidence was to define the times where the continental 48 states are in complete sunlight and complete darkness. This can only be an estimate as the sunrise and sunset times depend on the date at which the flights took place. To ensure the reliability of the classification, three-hour windows of time (1600-1900 Zulu for day; 0400-0700 Zulu for night) for the beginning of the flight were used to categorize the day and night flights. Of the 104,556 filtered flight files, 29,916 were classified as a day flight and 12,924 as a night flight. All others had no classification.

## Statistical Analysis

Statistical analysis was performed to determine the significance of the results between pilots and co-pilots and day and night flights. First, a paired t-test was implemented to analyze the results between the pilot and co-pilot data independent of day and night classification. A two-way analysis of variance (ANOVA) for pilot and co-pilot data using a day or night classification was performed.

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## Results

### Findings from Analysis of All Files

All provided MDR files (127,487 files) were analyzed for this study. The following data are from the 104,556 files filtered as discussed in the previous section. From those files, neck posture percentages were calculated for each flight. The average flight length for those files was 16.7 minutes. These percentages were then aggregated to determine an average for pilots and co-pilots for each flight (Figures 6 and 7). The data show that pilots spent slightly more time in mild flexion and bending than co-pilots, but slightly less time in severe flexion and bending. The data also show that co-pilots spent nearly 10% more time in mild twisting, but nearly the same amount of time in severe twisting compared to pilots.

The percentages from all flights were also used to perform a t-test to determine statistical significance (Table 2). The results of the t-test showed statistical significance for all postures with the exception of severe twist ($p < 0.001$).

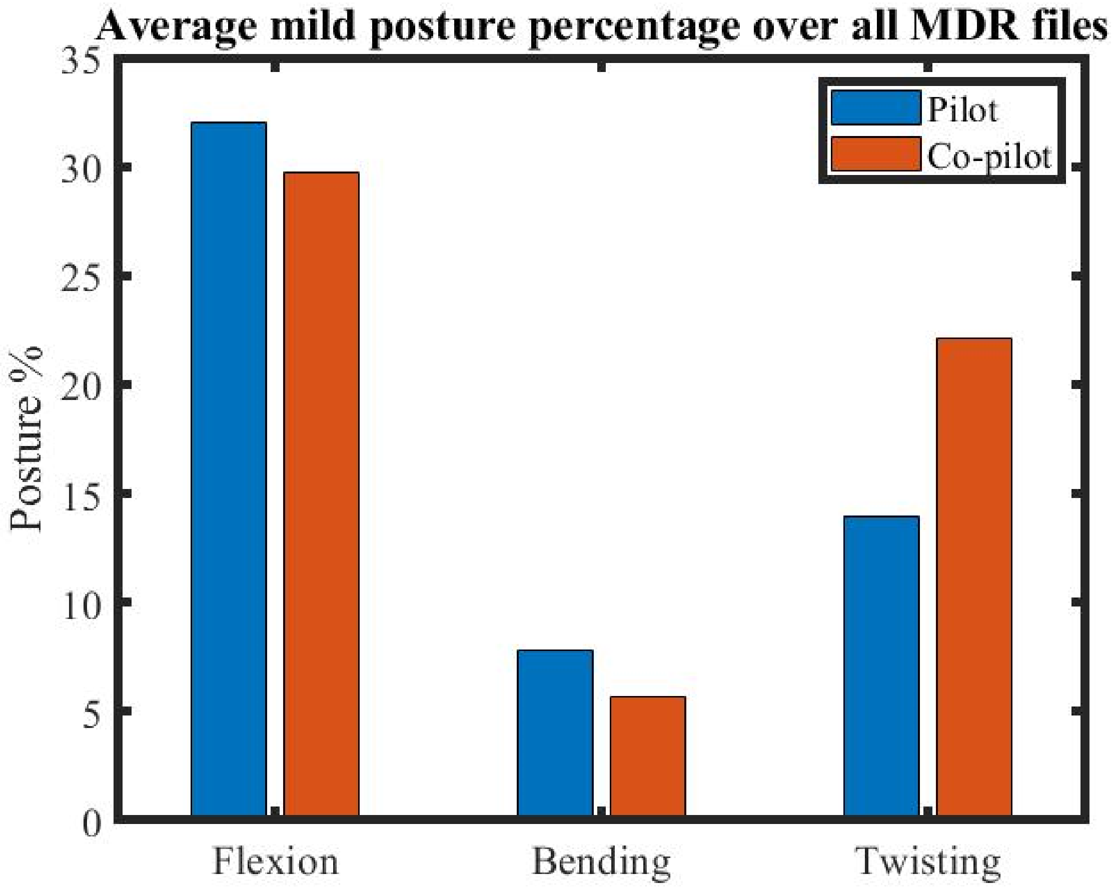

*Figure 6.* Average mild posture percentages over all MDR files. The data show that pilots spent slightly more time in mild flexion and bending than co-pilots, but less time in mild twisting.

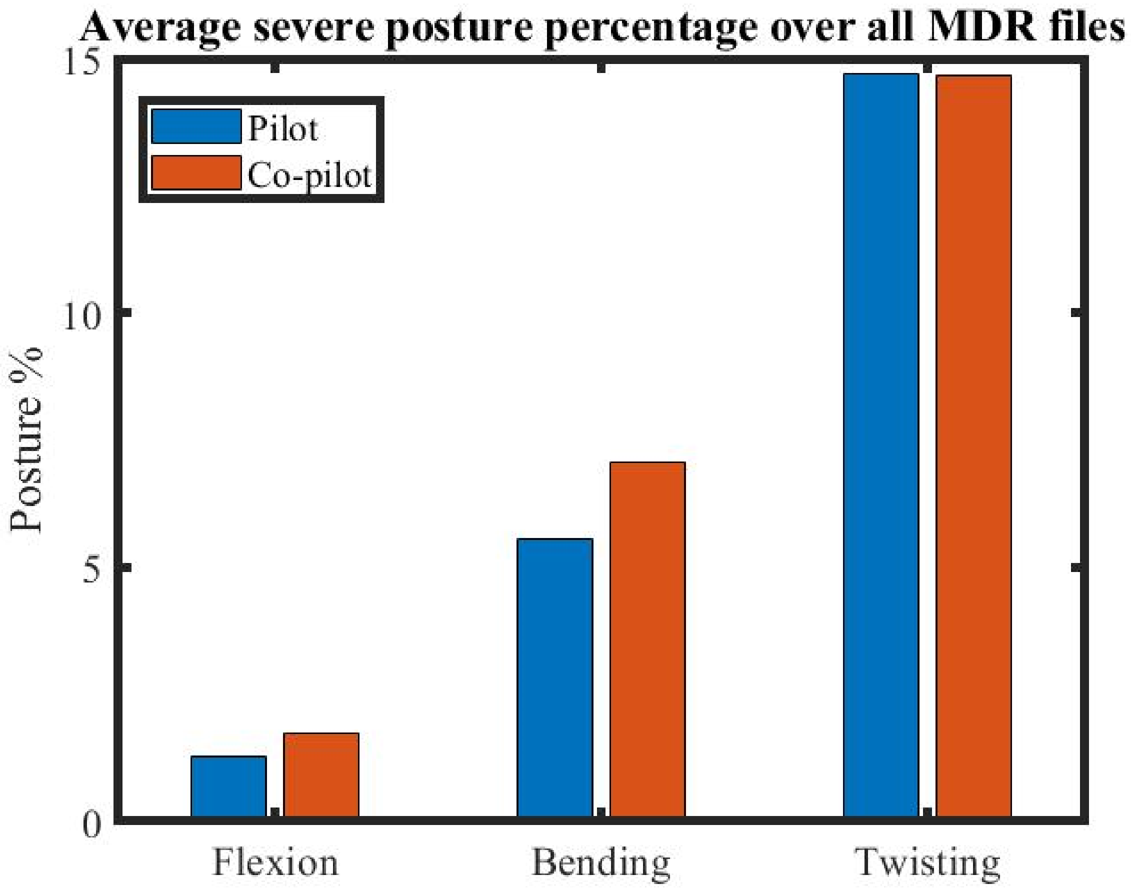

*Figure 7.* Average severe posture percentages over all MDR files. The data show that co-pilots spent slightly more time in severe flexion and bending than pilots, but nearly the same time in twisting.

*Table 2.* Results from Paired T-Test for Pilot and Co-Pilot Postures over all MDR Files

| **Posture** | **P-Value** |
|---|---|
| Mild Flexion | **< 0.001** |
| Severe Flexion | **< 0.001** |
| Mild Bending | **< 0.001** |
| Severe Bending | **< 0.001** |
| Mild Twisting | **< 0.001** |
| Severe Twisting | > 0.05 |

*Note.* The bold values denote $p < 0.001$. The results are all significant with the exception of severe twist.

### Analysis of Day and Night Flights

The 104,556 MDR files were subsequently filtered into 29,916 day and 12,924 night flights to investigate trends in pilot and co-pilot head motion based on time of day. The following data reflect analysis of 1000 of the longest day flights and 1000 of the longest night flights. These data correspond to approximately 760 day and 900 night flight hours (APU fuel SOV closed to shutdown). The average length of the flights was 50 minutes. Figures 8 and 9 show the percentage of flight time spent in mild and severe neck postures for the pilot and co-pilot. Pilots and co-pilots generally spent more time in mild and severe postures in night flights than day flights. Pilots and co-pilots also spent a large amount of time in mild and severe twisting postures compared to the other categories. Pilots showed 4.54% greater time spent in a severe twisting posture at night than during the day, while co-pilots showed 5.32% greater time in a severe twisting posture during the night than during the day. The data also show that co-pilots spent more time in nearly all posture categories than pilots, except day and night severe twisting and mild flexion during the day.

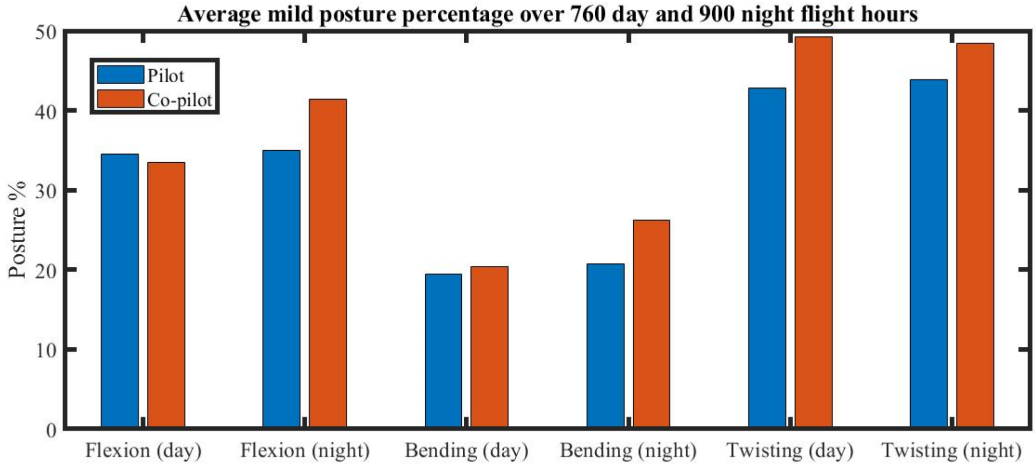

*Figure 8.* Average mild posture percentages over 760 day and 900 night flight hours. Co-pilots spent more time in all posture categories except for flexion during the day.

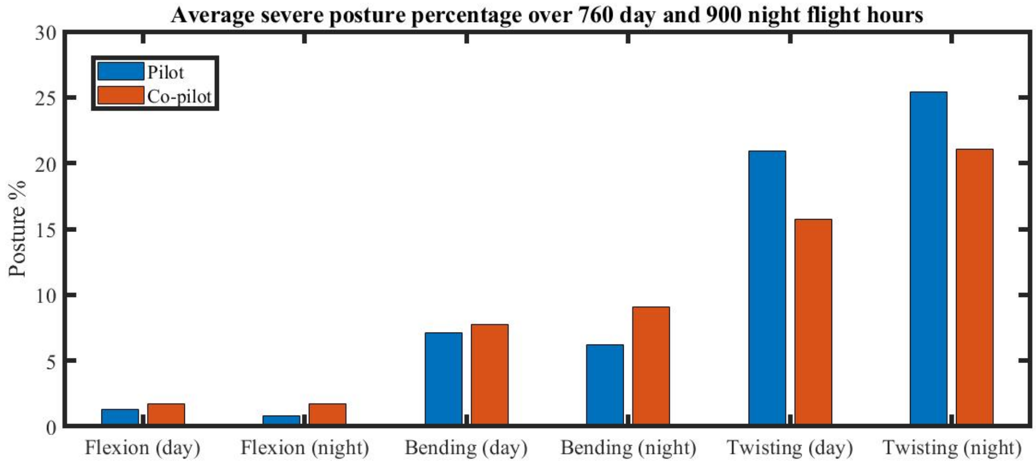

*Figure 9.* Average severe posture percentages over 760 day and 900 night flight hours. Pilots spent more time in severe twisting postures in day and night, but co-pilots spent more time in flexion and bending categories in day and night.

*Table 3.* Neck Twist Movement Rate Estimations over 760 Day and 900 Night Flight Hours

| Neck Twist Movement Rate | | |
|---|---|---|
| **Operator** | **Day Rate (s)** | **Night Rate (s)** |
| Pilot | 1.762 ± 0.683 | 18.250 ± 4.795 |
| Co-pilot | 2.714 ± 1.325 | 27.009 ± 9.598 |

*Note.* Each number represents the average number of seconds between a neck movement from a near-neutral twisting position to a severe twisting position (greater than 30 degrees)

As was the case for the analysis of all files, a t-test was performed involving only the files classified as day and night. The t-test reported $p < 0.001$ for all postures, which implies a difference between pilots and co-pilots with respect to the amount of time spent in each posture (Table 4). The results from the two-way ANOVA (Table 5) show statistical significance at $p \leq 0.001$ for all postures and variables with three exceptions (day/night for severe bend, day/night for mild twist, and interaction of variables for severe twist). Furthermore, a two-way ANOVA for twist movement rate (Table 6) shows statistical significance ($p < 0.001$) for the day/night and pilot/co-pilot variables and their interaction.

*Table 4.* Results from Paired T-Test For Pilot and Co-Pilot Postures over 760 Day and 900 Night Flight Hours

| **Posture** | **P-Value** |
|---|---|
| Mild Flexion | **< 0.001** |
| Severe Flexion | **< 0.001** |
| Mild Bending | **< 0.001** |
| Severe Bending | **< 0.001** |
| Mild Twisting | **< 0.001** |
| Severe Twisting | **< 0.001** |

*Note.* The bold values denote p < 0.001. The results are all significant, suggesting that there is a difference in the amount of time spent in the postures between pilots and co-pilots.

*Table 5.* Results from the Two-Way ANOVA over 760 Day and 900 Night Flight Hours Showing the Independent Variables (Day/Night and Pilot/Co-Pilot) and Their Interaction

| **Posture** | **Pilot/Co-pilot** | **Day/Night** | **Interaction** |
|---|---|---|---|
| Mild Flexion | **< 0.001** | **< 0.001** | **< 0.001** |
| Severe Flexion | **< 0.001** | **< 0.001** | **< 0.001** |
| Mild Bending | **< 0.001** | **< 0.001** | **< 0.001** |
| Severe Bending | **< 0.001** | > 0.05 | **< 0.001** |
| Mild Twisting | **< 0.001** | > 0.05 | **< 0.001** |
| Severe Twisting | **< 0.001** | **< 0.001** | > 0.05 |

*Note.* The bold values denote $p < 0.001$.

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*Table 6.* Results from the Two-Way ANOVA over 760 Day and 900 Night Flight Hours Showing the Independent Variables (Day/Night and Pilot/Co-Pilot) and Their Interaction for Twist Movement Rate

| **Posture Measurement** | **Pilot/Co-pilot** | **Day/Night** | **Interaction** |
|---|---|---|---|
| Twist Rate | **< 0.001** | **< 0.001** | **< 0.001** |

*Note.* The bold values denote $p < 0.001$.

A check for normality was performed on the pilot and co-pilot data (Figures 10 and 11). The histograms revealed non-normality for non-twisting postures. The skewness and kurtosis values are shown in Table 7. A non-parametric Mann-Whitney U-Test was performed on the merged aviator crew day and night data to address this non-normality. Table 8 shows the results of the test.

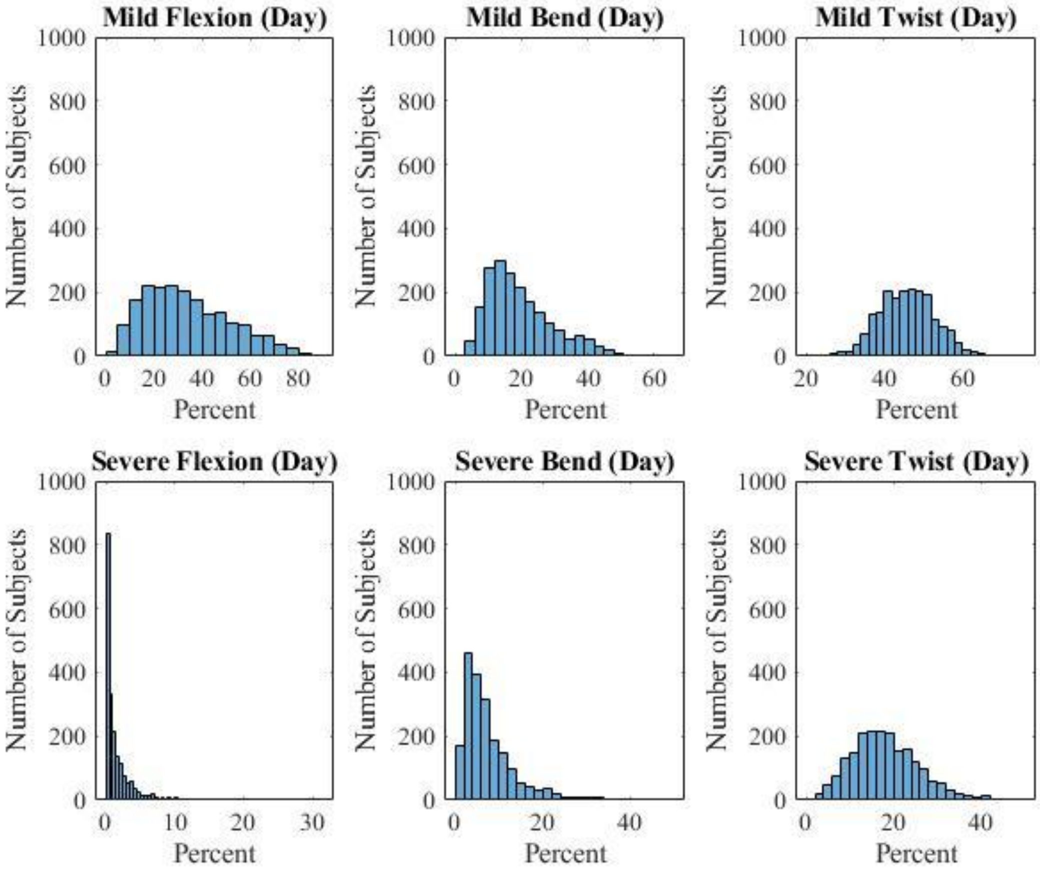

*Figure 10.* Histograms for mild (top row) and severe postures (bottom row) for merged aviator crew day flights.

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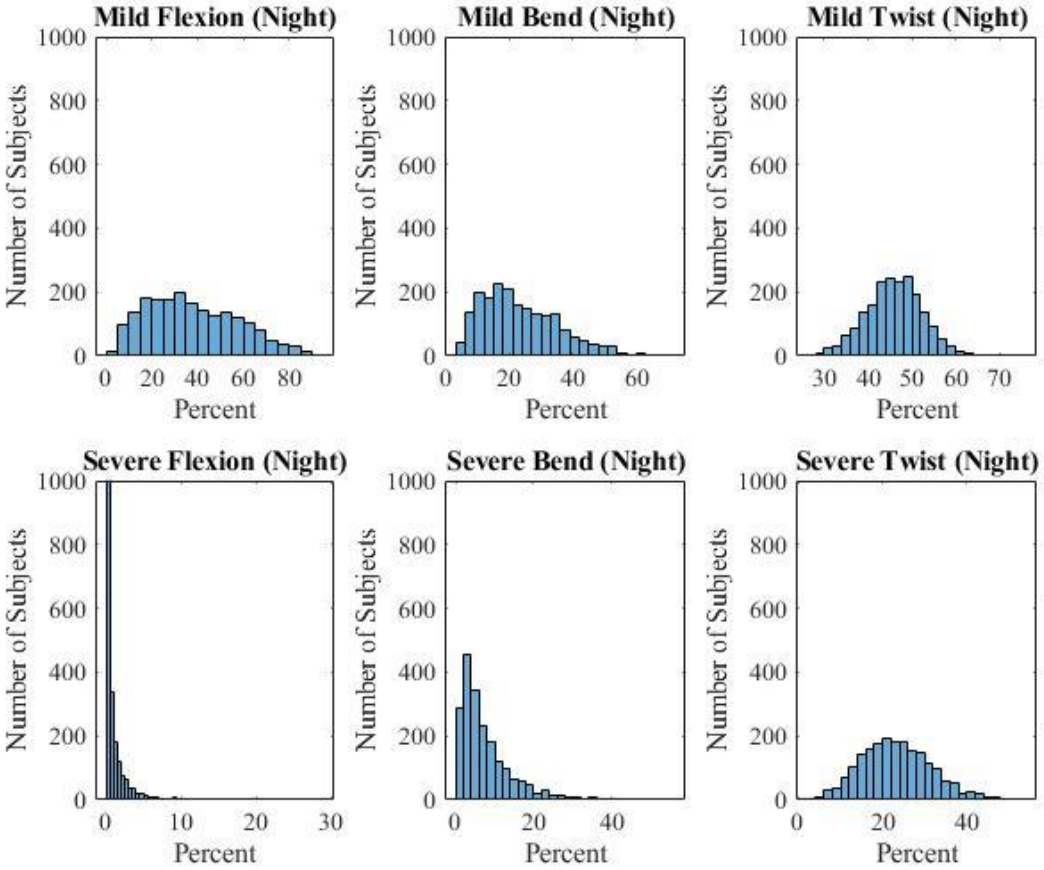

*Figure 11.* Histograms for mild and severe postures for merged aviator crew night flights.

*Table 7.* Skewness and Kurtosis Values for Aviator Crew Day and Night Flights

| **Skewness** | **Mild Flex** | **Severe Flex** | **Mild Bend** | **Severe Bend** | **Mild Twist** | **Severe Twist** | **Twist Rate** |
|---|---|---|---|---|---|---|---|
| **Pilot (day)** | 0.5349 | 1.0798 | 0.121 | 2.9127 | 1.6755 | 0.4825 | 4.6867 |
| **Co-pilot (day)** | 0.6563 | 1.0633 | -0.1192 | 3.4087 | 1.9107 | 0.2466 | 2.7101 |
| **Pilot (night)** | 0.6315 | 1.0055 | -0.14 | 4.3754 | 2.1233 | 0.8712 | 2.379 |
| **Co-pilot (night)** | 0.18 | 0.469 | 0.1151 | 4.098 | 1.7995 | 0.2699 | 4.3963 |

| **Kurtosis** | **Mild Flex** | **Severe Flex** | **Mild Bend** | **Severe Bend** | **Mild Twist** | **Severe Twist** | **Twist Rate** |
|---|---|---|---|---|---|---|---|
| **Pilot (day)** | 2.6178 | 4.1992 | 2.9014 | 13.5327 | 7.0252 | 3.3797 | 50.2522 |
| **Co-pilot (day)** | 2.6857 | 3.9141 | 2.6988 | 19.7818 | 7.3811 | 2.8181 | 20.7862 |
| **Pilot (night)** | 2.6112 | 3.5962 | 3.9618 | 34.4915 | 9.1653 | 4.4048 | 12.1456 |
| **Co-pilot (night)** | 2.2271 | 2.8309 | 3.2033 | 26.1497 | 7.5456 | 2.802 | 49.5849 |

*Table 8.* Results from the non-parametric Mann-Whitney U-Test for Aviator Crew Merged Day and Night Flights

| **Posture** | **P-Value** |
|---|---|
| Mild Flexion | **< 0.001** |
| Severe Flexion | **< 0.001** |
| Mild Bending | **< 0.001** |
| Severe Bending | **< 0.001** |
| Mild Twisting | **< 0.001** |
| Severe Twisting | **< 0.001** |
| Twist Rate | **< 0.001** |

*Note.* The highlighted rows denote $p < 0.001$.

## Discussion

The results of the analysis for all flights (with no classification of day or night) suggest that there is a significant difference between pilots and co-pilots with respect to the amount of time spent in all posture categories (Table 2). Co-pilots spent statistically significantly more time in mild twisting postures than pilots, but significantly less time in flexing and bending postures (Figure 6). Pilots and co-pilots spent similar amounts of time in severe twisting postures (Figure 7). Extension measurements were not included in this analysis for two reasons: publications that defined mild and severe neck postures did not define a range for extension, and extension measurements for pilots and co-pilots were infrequently above 30 degrees (Figure 4). The reported statistical outcomes for severe twist were expected since the average percentage of time in a severe twisting posture for pilots and co-pilots was so close.

The MDR files were filtered into day and night flights to investigate trends in pilot and co-pilot head motion based on time of day. The longest day and night flight files (1000 of each) were selected from the available 29,916 day and 12,924 night flight files to avoid takeoff and landing dominating the total flight duration. Classifying the flights based on time of day was conducted to test the hypothesis that there would be differences in severe twisting exhibited by pilots and co-pilots between day and night flights (unlike what was seen in the analysis where the time of day was not taken into account). The analysis of day and night flights also provides insight into the effects night vision goggles may have on head and neck motion in pilots and co-pilots.

The analysis of flights classified as day and night revealed statistical significance ($p < 0.001$) for nearly every variable and posture. Only severe bending and mild twisting between day and night and severe twisting interaction showed no statistical significance (Table 5). Co-pilots also spent statistically significantly more time in severe flexion and bending postures than pilots. The difference between day and night flights is most evident in the neck twist movement rate estimations (Table 3). Pilots and co-pilots performed more than ten times the amount of twisting movements during the day than at night. The twist movement rate data show a statistically significantly higher rate of neck twisting for pilots than co-pilots, but co-pilots also were in a severe neck twist posture every 2.71 seconds during the day on average. When looking at the percent difference of twisting movements between the aviators, pilots executed 42.5% more twisting movements during the day and 38.7% more at night compared to co-pilots. Such a high rate of movement that requires neck muscle activation should emphasize the importance of cervical spine range of motion wellness for AH-64 aviators.

The amount of time spent in mild flexion and twist rotation suggest that cumulative loading on the neck resulting from helmets and helmet system wear in combination with vibration exposure in rotary-wing aviation operational environments, could be a factor for Army aviators. Previous studies in occupational health have indicated that smaller loading with high duration should be considered in these analyses (Sakzewski & Naser-ud-Din, 2014). The frequent neck twisting exhibited in the daytime flights could affect muscular endurance, as the repeated activation of various neck muscles could result in fatigue or injury. Curiously, there was about ten times less frequent neck twisting movement during night flights, yet a higher amount of time was spent in severe neck twisting postures at night. The latter finding is supported by other published data that suggested higher peak and cumulative neck loading for flights requiring night vision goggles (Harrison et al., 2010).

There are two factors to consider when interpreting these data. For one, the co-pilot sits behind and above the pilot in an AH-64 (a tandem cockpit). Secondly, pilots and co-pilots are typically tasked with different responsibilities during the flight (DA, 2005), especially with co-pilots serving as the gunner. The results of this analysis are very likely to be influenced by these factors.

The primary limitation of this analysis is that it does not take into account the ability of aviators to enhance their CROM capabilities with minor torso or lumbar spine movement; hence, we must recognize that the neck postures calculated from the MDR head position data are estimates of CROM. Furthermore, the CROM calculations presented here are specific to the AH-64; other aircraft may necessitate different CROM requirements for pilots and co-pilots. For instance, an aircraft with a side-by-side cockpit may produce different results than the tandem cockpit of the AH-64. Other limitations include the lack of knowledge of the types of maneuvers performed during flight, the flight conditions, and the absence of demographic and anthropometric information regarding the aviators.

Follow-up work will be performed on rated UH-60 volunteer aviators to address these limitations. The aviators will follow a prescribed flight plan involving a one-hour flight on a UH-60 research aircraft and flight simulator. Subjects will have an optical-based inertial tracker attached to their helmet to record head position data. Cameras will be installed in the cockpit for observation of contributions of the cervical and lumbar spine to head position. This will allow calculation of “true” CROM rather than “estimated” CROM, as was presented here. Investigating biomechanical equivalence in simulated flight could result in an accessible method for flight surgeons to perform flight fitness observations in an operational environment.

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## Recommendations

The results of this analysis strongly support the concern for neck pain and injury in Army rotary-wing aviators. Future research is recommended to cover the knowledge gaps in the analysis of the AH-64 MDR files, specifically:

1. A human subject research study must be conducted in order to evaluate aviator CROM in controlled real and simulated flight environments. The objective should be to characterize typical head/neck motion of helicopter pilot CROM during normal flight operations by quantifying head and neck motion.
2. The recruited, screened, and enrolled subjects for the study should be representative of a broad military rotary-wing aviator population.
3. Demographic, anthropometric, and flight history information should be collected from all participants.
4. The human subject study should include head/neck motion tracking during a predetermined flight profile such that neck postures can be associated with specific flight maneuvers under repeatable and controllable conditions.
5. The human subject study should also include video recordings of the pilots during flight in order to observe possible contributions of the lumbar spine and torso to head motion.
6. Data analyses, assessments, and comparisons should lead to findings or outcomes that will provide a more ideal, and specific reference on what CROM is required for aviators.
7. USAARL should continue to provide subject matter expert consultation and assessment support to aeromedical authorities regarding guidelines and policy recommendations for neck-related flight fitness evaluations and determinations by conducting research in order to improve aviator operational readiness and efficiency, improve flight safety and performance, and increase aviator retention.

## Conclusions

The presented method of using head position data from the AH-64 MDR proved to be both a novel and effective approach to estimate the CROM of pilots and co-pilots that are typically exhibited in flight. This approach was convenient because it provided the ability to leverage thousands of hours of preexisting data while concurrently eliminating the need for human subject research requiring large population recruitment and consent. Furthermore, it required no instrumentation. The data were also easy to process since it was provided in a simple and consistent format. Nevertheless, the limitations mentioned earlier necessitate the implementation of a human subject research study to bridge the gaps inherent with the AH-64 MDR head position data.

A future study at USAARL will involve pilots following a prescribed flight plan on a UH-60 aircraft and wearing an optical-based inertial tracker to calculate head position while being recorded by video to observe possible contributions of the lumbar spine and torso. The expectation is that this and future investigations will result in the development of a set of CROM standards for aviator flight fitness, which could lead to higher aviator retention rates.

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# Appendix A. Day/Night Classification Code

```
function apacheDayNight(filepath)
% Define Apache MDR flights in filepath as day or night assuming CONUS.
% DAY: 1600-1900 Zulu
% NIGHT: 0400-0700 Zulu
% DAY/NIGHT: All others

% Find the files in the specified filepath.
x = dir(filepath);

% Indicies 16 and 17 in x note the hour of the beginning of flight record.
nightpath = 'Z:\_DATA\Data_Field\CROM_Cervical Spine Range of Motion\Night Files\';
daypath = 'Z:\_DATA\Data_Field\CROM_Cervical Spine Range of Motion\Day Files\';
for i = 1:length(x)
   % Check to make sure the length of file name is 26.
   if length(x(i).name) == 26
      % Night flight
      if strcmp(x(i).name(16:17),'04') || strcmp(x(i).name(16:17),'05') || ...
        strcmp(x(i).name(16:17),'06') || strcmp(x(i).name(16:17),'07')
         copyfile(fullfile(filepath,x(i).name),fullfile(nightpath,x(i).name));
      end
      % Day flight
      if strcmp(x(i).name(16:17),'16') || strcmp(x(i).name(16:17),'17') || ...
        strcmp(x(i).name(16:17),'18') || strcmp(x(i).name(16:17),'19')
         copyfile(fullfile(filepath,x(i).name),fullfile(daypath,x(i).name));
      end
   end
end
```

## Appendix B. Batch Processing Code

```
function [p,cp] = apacheCROM(file)
%APACHECROM  Calculate CROM from Apache MDR head position values.
%   [p,cp] = apacheCROM(file) returns the data contained in 'file' in
%   structures p (pilot) and cp (co-pilot) with the following fields:
%
%   x - head position x-coordinate (unitless)
%   y - head position y-coordinate (unitless)
%   z - head position z-coordinate (unitless)
%   time - time array associated with flight data (seconds)
%   flex - neck flexion (radians)
%   bend - neck bend (radians)
%   twist - neck twist (radians)
%   flexmild - # measurements defined as mild or severe flexion
%   flexsevere - # measurements defined as severe flexion
%   bendmild - # measurements defined as mild or severe bend
%   bendsevere - # measurements defined as severe bend
%   twistmild - # measurements defined as mild or severe twist
%   twistsevere - # measurements defined as severe twist

% Mission begins when "APU Fuel SOV Closed" reads "Closed".
[data,zuludatetime,~] = xlsread(file);

% Check that data is in expected format. If not, return empty values.
if size(data,2)==7
    fuel = data(:,7)';
    % Mission is active when "APU Fuel SOV Closed" reads "Closed".
    % Determine mission begin and end time.
    % NOTE: Sometimes the fuel sov reads closed again at the end of the table.
    % To circumvent this, we disregard the last two measurements.
    x1 = find(fuel==1,1,'first');
    x2 = find(fuel==1,3,'last');
    % If there is an insufficient amount of data, return empty info.
    if length(x2) < 3 || length(zuludatetime{x1,1}) < 10
        p  = [];
        cp = [];
        return
    end
    x2 = x2(1);

    % Filter active pilot and co-pilot data. Co-pilot is columns 1, 2, and 3.
    % Pilot is columns 4, 5, and 6.
    cp.x = data(x1:x2,1)'; cp.y = data(x1:x2,2)'; cp.z = data(x1:x2,3)';
     p.x = data(x1:x2,4)';  p.y = data(x1:x2,5)';  p.z = data(x1:x2,6)';

    % Create time array using MDR report frequency (12.5 Hz).
    time = (1:length(p.x))*(1/12.5);
```

```
    cp.time = time; p.time = time;

    % Calculate flex/extension, lateral bending, and twisting.
     p.flex  = -asin(p.z);
     p.bend  = atan(p.z./p.x);
     p.twist = atan(p.y./p.x);
    cp.flex  = -asin(cp.z);
    cp.bend  = atan(cp.z./cp.x);
    cp.twist = atan(cp.y./cp.x);

    % Define posture as mild or severe and report length.
     p.flexmild    = length(p.flex(p.flex*180/pi<=-10)); % negative is flexion
     p.flexsevere  = length(p.flex(p.flex*180/pi<=-35)); % negative is flexion
     p.bendmild    = length(p.bend(abs(p.bend*180/pi)>=15));
     p.bendsevere  = length(p.bend(abs(p.bend*180/pi)>=30));
     p.twistmild   = length(p.twist(abs(p.twist*180/pi)>=10));
     p.twistsevere = length(p.twist(abs(p.twist*180/pi)>=40));
    cp.flexmild    = length(cp.flex(cp.flex*180/pi<=-10));
    cp.flexsevere  = length(cp.flex(cp.flex*180/pi<=-35));
    cp.bendmild    = length(cp.bend(abs(cp.bend*180/pi)>=15));
    cp.bendsevere  = length(cp.bend(abs(cp.bend*180/pi)>=30));
    cp.twistmild   = length(cp.twist(abs(cp.twist*180/pi)>=10));
    cp.twistsevere = length(cp.twist(abs(cp.twist*180/pi)>=40));
else
     p = [];
    cp = [];
end
```

# Appendix C. Neck Angle Calculation Derivation

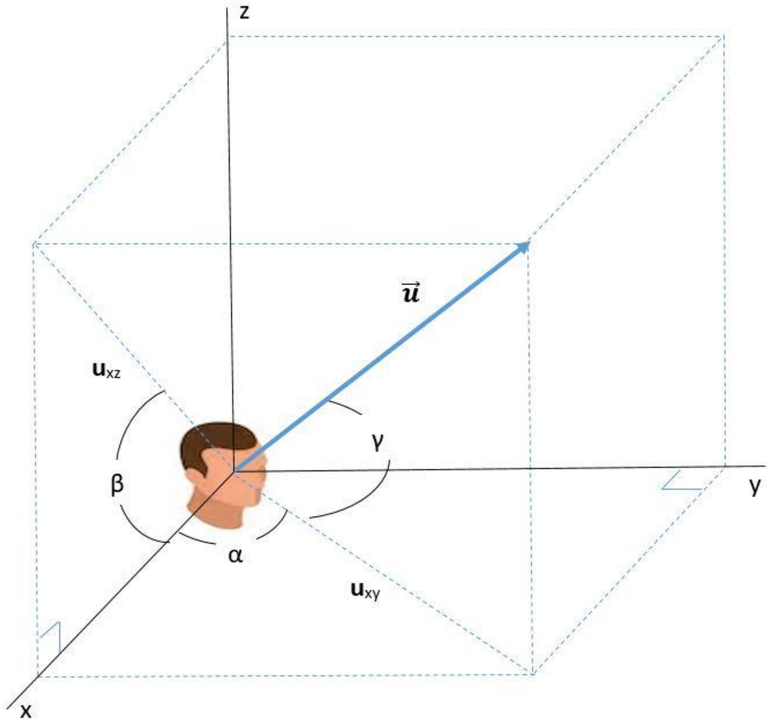

*Figure C1.* Cartesian coordinate system used by the AH-64 MDR. The unit vector **u** defines the head position of the pilot or co-pilot in three-dimensional space. Angles α, β, and γ are angles of the head from the origin in each plane of motion.

The AH-64 MDR uses a right-handed Cartesian coordinate system as shown in Figure C1. At the origin, the x-axis extends out of the ear, the y-axis originates from the subject line-of-sight, and the z-axis is perpendicular to the top of the head. The head position data reported by the AH-64 MDR is a three-dimensional unit vector. That is,

$$\vec{u} = \sqrt{{u_x}^2 + \ {u_y}^2 + {u_z}^2} = 1$$

Figure C2 presents a two-dimensional view of each neck angle based on its respective neck posture category. Angle α is the angle for twist rotation and is the angle between the x component of the unit vector **u** ($u_x$) and the projection of that unit vector onto the x-y plane ($u_{xy}$). Angle β is the angle for lateral bending and is the angle between the x component of the unit vector **u** ($u_x$) and the projection of that unit vector onto the x-z plane ($u_{xz}$). Angle γ is the angle for flexion and extension and is the angle between the unit vector **u** and the projection of that unit vector onto the x-y plane ($u_{xy}$).

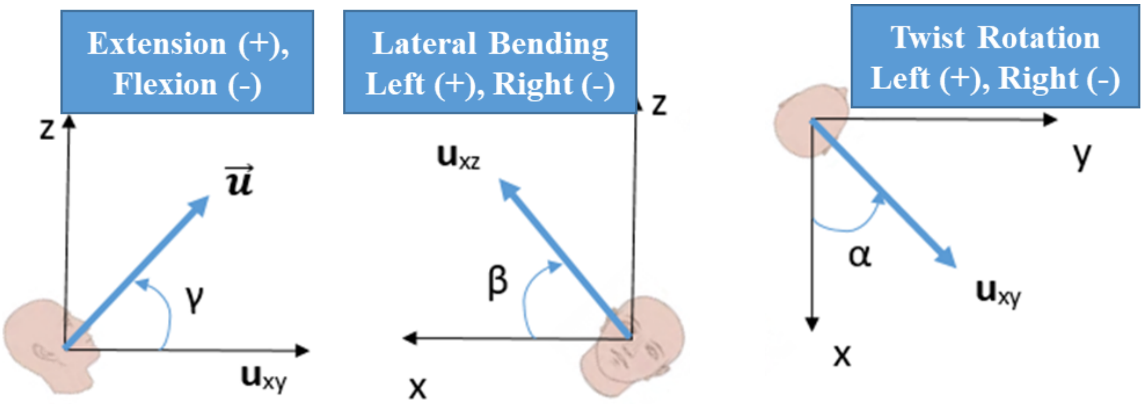

*Figure C2.* A two-dimensional view of each neck angle with respect to its posture category. The postures are separated into three planes of motion. Extension and flexion correspond to moving the head up and down (chin to chest) and are associated with the angle γ. Twist rotation corresponds to turning the head right and left (chin to shoulder) and is associated with the angle α. Lateral bending corresponds to bending the head right and left (ear to shoulder) and is associated with the angle β.

These angles are defined as a function of the components of the unit vector by using trigonometric functions.

$$\alpha = \tan^{-1}\frac{u_y}{u_x}$$

$$\beta = \tan^{-1}\frac{u_z}{u_x}$$

$$\gamma = \sin^{-1}\frac{u_z}{\vec{u}} = \sin^{-1}u_z$$

## Appendix D. Posture Aggregation Code

```matlab
function [pilot,copilot] = postureMDR(filepath)
%POSTUREMDR Combine posture information from a collection of MDR MAT files.
% [pilot,copilot] = postureMDR(filepath) reads a collection of MDR MAT
% files located in "filepath" and aggregates that information into
% structures output as pilot and co-pilot information. This output is
% intended to be used to perform analyses over a large number of flights.

% Find the files in the specified filepath.
x = dir(filepath);

% Allocate the filenames in a cell.
n = length(x);
for i = 1:n
    filename{i} = x(i).name;  %#ok<AGROW>
end

% Initialize variables
pilot = struct('L',0,...
               'flexmild',0,...
               'flexsevere',0,...
               'bendmild',0,...
               'bendsevere',0,...
               'twistmild',0,...
               'twistsevere',0);
copilot = pilot;

% Evaluate the files.
for i = 1:n
    if isempty(strfind(filename{i},'.mat'))
        continue
    end
    file = fullfile(filepath,filename{i});
    load(file,'p','cp')
    if isempty(p) || isempty(cp)
        continue
    end
    pilot.L             = pilot.L + length(p.x);
    pilot.flexmild      = pilot.flexmild + p.flexmild;
    pilot.flexsevere    = pilot.flexsevere + p.flexsevere;
    pilot.bendmild      = pilot.bendmild + p.bendmild;
    pilot.bendsevere    = pilot.bendsevere + p.bendsevere;
    pilot.twistmild     = pilot.twistmild + p.twistmild;
    pilot.twistsevere   = pilot.twistsevere + p.twistsevere;
    copilot.L           = copilot.L + length(cp.x);
    copilot.flexmild    = copilot.flexmild + cp.flexmild;
    copilot.flexsevere  = copilot.flexsevere + cp.flexsevere;
```

```
    copilot.bendmild    = copilot.bendmild + cp.bendmild;
    copilot.bendsevere  = copilot.bendsevere + cp.bendsevere;
    copilot.twistmild   = copilot.twistmild + cp.twistmild;
    copilot.twistsevere = copilot.twistsevere + cp.twistsevere;
    clear p cp
end
```

# Appendix E. Head Movement Rate Estimation Code

```
function [pF,cpF] = frequencyCROM(file)
%FREQUENCYCROM Calculate rate of neck movement from MDR MAT file.
%   [pF,cpF] = frequencyCROM(file) calculates the number of times a neck
%   twist rotation is performed from a near-neutral position to at least 30
%   degrees for pilot and co-pilot head position data contained within the
%   MDR MAT file in the path "file".
%
% OUTPUTS:
% pF  = rate of pilot neck twist rotation (seconds/occurence)
% cpF = rate of co-pilot neck twist rotation (seconds/occurence)

% Load the variables from the MAT file.
load(file,'p','cp');

% Define the mission length.
time = p.time(end);

% Calculate instances of neck movement from origin to > 30 degrees.
pF = time/length(findpeaks(abs(p.twist),'MinPeakHeight',30*pi/180));
cpF = time/length(findpeaks(abs(cp.twist),'MinPeakHeight',30*pi/180));
```

# U.S. Army Aeromedical Research Laboratory
# Fort Rucker, Alabama

**Army Futures Command**
**U.S. Army Medical Research and Development Command**