



Head Flail Corridors for use in Occupant-Centric Vehicle Design: Summary and Recommendations

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Human subject data from legacy studies conducted at the Naval Biodynamics Laboratory (NBDL) were used in this report. The participation of the human subjects (1974 - 1995) was in accordance with procedures specified in the Secretary of the Navy Instruction 3900.39 series and the Bureau of Medicine and Surgery Instruction 3900.6 series. These instructions are based upon free and informed voluntary consent, and met or exceeded the provisions of national and international guidelines at the time of research.

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14. ABSTRACT In aircraft crashes, injuries to the head and upper torso are frequently reported, with head injury reported most frequently of all body regions. Head strikes due to flail are of particular importance because loss of awareness or consciousness can prevent evacuation post-crash. Because preventing flail of the head and body is of utmost importance for occupant survival, the Aircraft Crash Survival Design Guide (ACSDG), which was published in 1989 to guide crashworthy aircraft design, defines occupant flail envelopes. The current ACSDG occupant flail envelopes, which are based on a single frontal impact test with an anthropometric test device (ATD), are inadequate for modern Army aviation. This report quantifies the head flail response for a well-restrained occupant using a collection of legacy human research volunteer exposure data that includes frontal, axial, lateral, oblique, and off-axis impacts. Final recommended flail corridors for anteroposterior, lateral, and vertical head position of the occupant are provided.					
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This work was only possible because of legacy data due to the vision, dedication, and scientific efforts of the research staff and military sponsors along with the contributions of the human volunteers at the Naval Biodynamics Laboratory (NBDL). Their contributions to occupant protection for Service Members and civilians will continue for generations.

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Background

Head and upper torso injuries that have been attributed to flail (Alem et al., 1998; Greth et al., 1993; Shanahan & Shanahan, 1989) still occur in helicopters built to crashworthy standards (Barth & Balcena, 2007; Labun, 2014; Mapes, 2008), so the current design guidance for occupant flail should be reevaluated for next generation vehicles and the modern Soldier. Head strikes due to flail are of particular importance because loss of awareness or consciousness can prevent evacuation post-crash (DeWeese, 2017). Because preventing flail of the head and body is of utmost importance for occupant survival, the Aircraft Crash Survival Design Guide (ACSDG), which was published in 1989 (most recent version) to guide crashworthy aircraft design (Desjardins et al., 1989), defined occupant flail envelopes. The ACSDG was also used in the development of the Military Standard MIL-STD-1290A (AV), which currently defines the criteria for light fixed and rotary-wing aircraft crash resistance. The flail envelopes from the ACSDG define the space that the occupant and their extremities might occupy during a crash.

The current ACSDG flail envelopes for a torso-restrained occupant are based on a single test with an anthropomorphic test device (ATD) subjected to a frontal acceleration of 30 G, and the flail envelope in the lateral direction is extrapolated from this single test. However, while ATDs are useful test surrogates and validated for some types of impacts (Mertz & Irwin, 2015), ATDs have not yet been validated to exhibit a human-like response for all impact directions that might be experienced during aircraft crash (Labun et al., 2014). Rather than relying only on human surrogates (e.g., ATDs), using human response data, from exposures with impact vectors representative of those observed in aircraft crashes, would improve flail envelopes.

This report quantifies the head flail response for a well-restrained occupant using a collection of legacy human research volunteer (HRV) exposure data that includes frontal (-X), axial (+Z), lateral (+Y), oblique (-X+Y), and off-axis (+Z-X10 and +Z-X30) impacts (Schmidt et al., 2009). Response data were obtained from the collection of HRV exposures within the Biodynamics Data Resource (BDR) at the U.S. Army Aeromedical Research Laboratory (USAARL). Over 714 HRV tests were identified and included in the analysis. For each impact direction, tests were grouped according to matched exposure characteristics – including peak sled acceleration (PSA), rate of onset, peak sled velocity, and duration – that were calculated from sled accelerometer data, resulting in 42 groups with PSAs of up to 15 G.

To obtain head position, sled-mounted and subject-mounted phototarget positions were tracked and used to calculate the location of points defining the area of the head. Head position data were translated to the seat origin, defined as the midpoint of the seat pan along the edge where the seat back and the seat pan meet (i.e., seat reference point). To account for variation in anthropometry of the test subjects, initial head position for each test was aligned using sitting height and head length to represent a 50th percentile male Army aviator (Gordon et al., 2016). For each group of matched exposures, head flail corridors were developed for relevant points defining the head area (e.g., top of head). The flail corridor means were evaluated for maximum anteroposterior (AP), maximum lateral, and minimum vertical positions, and the groups with the most extreme positions were developed into final recommendations. The final recommendations were compared to the ACSDG flail envelopes and used to calculate a predicted head flail response for a frontal impact at 24 G. For additional details, see Olszko et al. (n.d.), “Head flail corridors for use in occupant-centric vehicle design: Comprehensive technical analysis”.

Recommendations

Recommended flail corridors for the well-restrained occupant at non-injurious exposure levels as well as an example of these corridors with equipment standoff are provided. The recommended corridors provide data for AP (AP vs. vertical) and lateral (lateral vs. vertical) position with respect to the seat origin. The AP and lateral position data represent the maximum AP, maximum lateral, and minimum vertical position expected for frontal, lateral, axial, oblique, and off-axis impacts. The AP and lateral position data of the recommended corridors were compared to the published ACSDG strike envelope curves. To demonstrate how the flail response might change at higher exposure levels, the predicted position of the top of the head for a 24 G frontal impact is provided and compared to the recommended flail corridor.

The recommended flail corridors for AP position (Figure 1) were developed using 15 G frontal impact tests. The maximum AP and minimum vertical positions of the mean response for this group of tests were 40.2 centimeters (cm) and 43.8 cm, respectively (Figure A1). The time-based corridor values for the maximum AP and minimum vertical position of the head were 48.3 and 39.0 cm, and the position-based corridor values for the maximum AP and minimum vertical position were 46.6 and 39.6 cm, respectively (Figures A1 - A3).

The recommended flail corridors for lateral position (Figure 2) were developed using 7 G lateral impact tests. The maximum lateral and minimum vertical positions of the mean response for this group of tests were 36.7 cm and 53.7 cm, respectively (Figure A2). The time-based corridor values for the maximum lateral and minimum vertical position of the head were 46.3 and 44.8 cm, and the position-based corridor values for the maximum lateral and minimum vertical position were 47.8 and 45.0 cm, respectively (Figures A4 - A6).

The AP ACSDG curve was exceeded by neither the mean nor corridor values (Figure B1) and can be considered adequate for a well-restrained occupant at a non-injurious exposure level, but, at higher exposure levels or with a modified restraint, the AP ACSDG curve may be exceeded. Likely, a typical five-point harness used in aviation would allow for greater AP displacement than the restraint systems used by the Naval Biodynamics Laboratory (NBDL) for the tests in this analysis.

Conversely, the lateral ACSDG curve was exceeded by both the mean and corridor values (Figure B2), which suggests that the current lateral curve is not adequate. Given that these data represent impacts to well-restrained occupants at non-injurious exposure levels, less than what is expected in an aircraft crash, the lateral limit could be even further exceeded in an aircraft crash. Furthermore, the lateral displacement of the subjects in this analysis was restricted using side panels attached to the seat. In an aircraft without any comparable restrictions to lateral displacement, the ACSDG lateral limit would likely be inadequate.

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Finally, though the vertical limits of the ACSDG curves were never exceeded, the relationship of the vertical limit to sitting height should be considered. The vertical ACSDG limit (102.0 cm) is nearly equivalent to the sitting height of a 99th percentile male Army aviator, 101.5 cm (Gordon et al., 2016), and flight school entrance standards allow sitting heights up to 102.0 cm (U.S. Army Aeromedical Activity [USAAMA], 2021). Thus, considering appropriate standoff distances from additional equipment that the occupant might don is critical because the vertical limit (as well as the AP and lateral limits) will need to be adjusted accordingly.

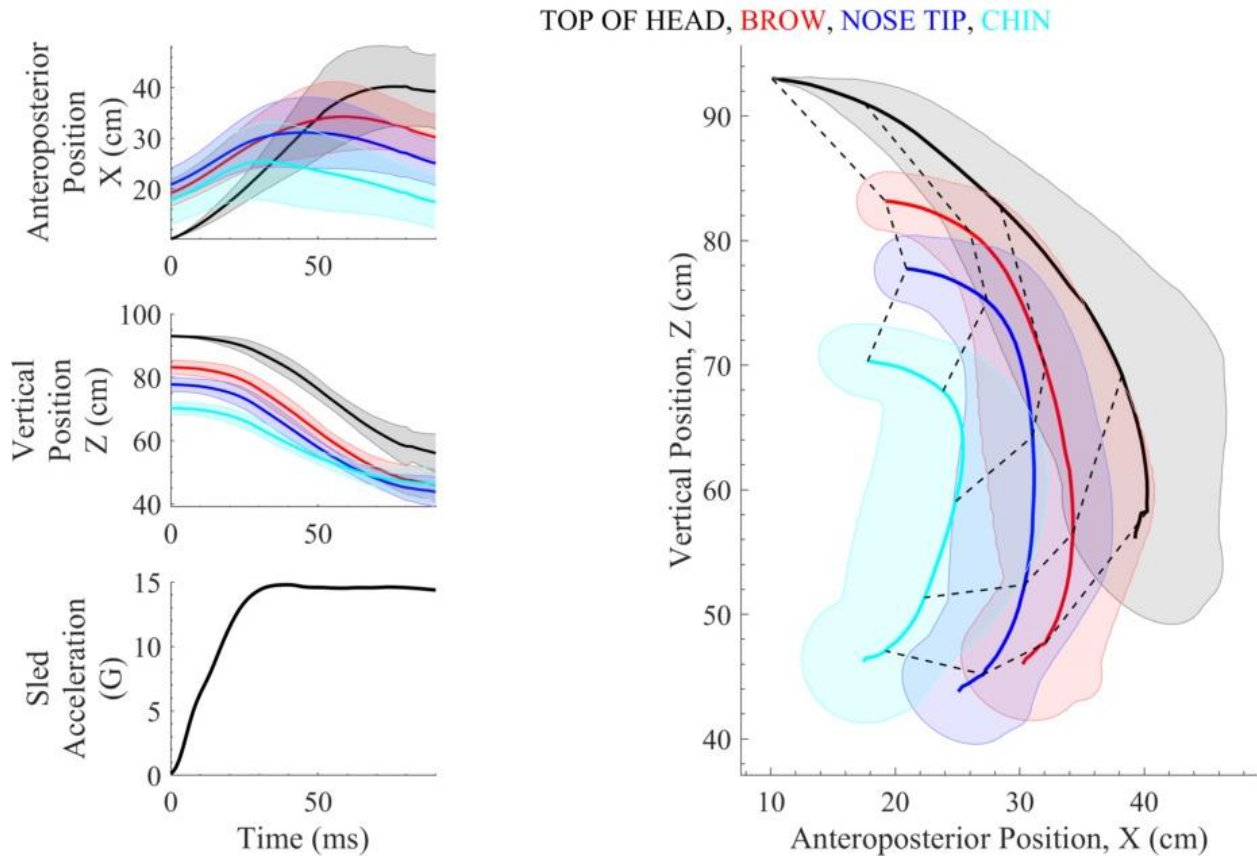


Figure 1. Recommended flail corridors for anteroposterior (AP) and vertical position. The flail corridors represent the maximum AP and minimum vertical position measured from frontal, axial, oblique, and off-axis impacts. The mean response for each head point (top of head, brow, nose tip, and chin) is represented by the solid lines. The standard deviation is represented by the envelope around each line. All position data are with respect to the seat origin. For the position-based corridor (right), timing is provided by the dashed lines connecting the mean values at the corresponding time for each point on the head. The dashed lines begin at time zero and continue every 20 milliseconds (ms). The corresponding sled acceleration, calculated as the mean of the sled acceleration for all tests within the matched group, is provided in the bottom left.

With dimensions added to the flail corridors to approximate helmet and NVG standoffs, the maximum AP, maximum lateral, and minimum vertical values corresponding to the mean flail response were exceeded (Figure 3). With an added 2-inch dimension representing helmet standoff and an added 3-inch dimension representing night vision goggles (NVGs), the

maximum AP and minimum vertical position of the head was 45.3 cm and 39.6 cm, respectively. With an added 2-inch dimension representing helmet standoff, the maximum lateral position of the head was 41.7 cm, while the minimum vertical position of the head did not change.

Based on the predicted flail response, the maximum AP position for a frontal impact will increase with higher exposure levels, and the duration of the response will decrease. The maximum AP position predicted (47.9 cm) for the frontal impact at 24 G (Figure C1) was similar to the standard deviational maximum AP position (48.3 cm) of the recommended flail corridors. When compared to the recommended corridors, the predicted minimum vertical response for the top of the head (53.1 cm) exceeded the minimum vertical response of the top-of-head mean (44.2 cm) but did not exceed the overall top-of-head corridor vertical minimum (43.8 cm). The duration of the predicted response was less than the duration of the recommended flail corridors. Though the duration of the predicted response was less, the ATD response for a matched exposure was still shorter in duration than the predicted human response (Figure C2).

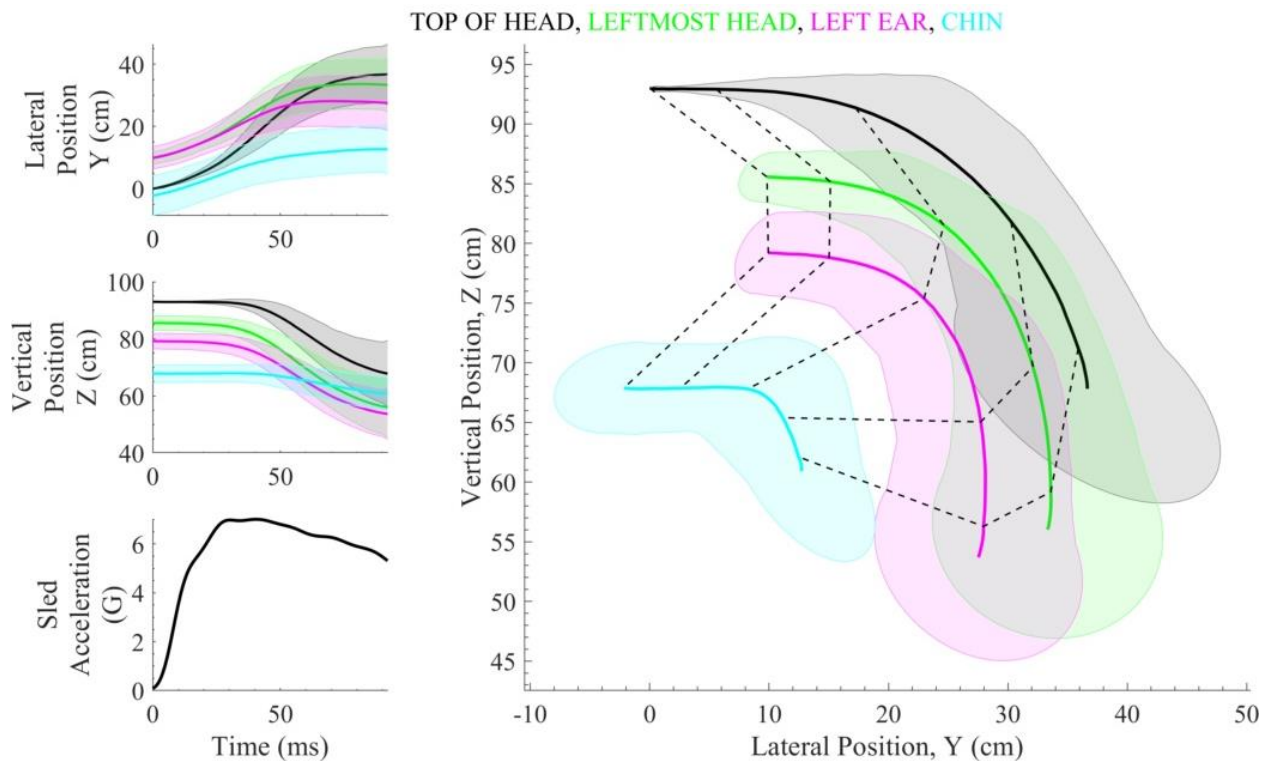


Figure 2. Recommended flail corridors for lateral and vertical position. The flail corridors represent the maximum lateral and minimum vertical position measured from lateral and oblique impacts. The mean response for each head point (top of head, leftmost head, left ear, and chin) is represented by the solid lines. The standard deviation is represented by the envelope around each line. All position data are with respect to the seat origin. For the position-based corridor (right), timing is provided by the dashed lines connecting the mean values at the corresponding time for each point on the head. The dashed lines begin at time zero and continue every 20 ms. The corresponding sled acceleration, calculated as the mean of the sled acceleration for all tests within the matched group, is provided in the bottom left.

The recommended flail corridors provide a useful baseline for representing the well-restrained occupant response at lower, non-injurious exposure levels and across multiple impact directions. While the flail corridors selected were based on only frontal and lateral impact, they included the maximum excursions of the head from its initial position for tests spanning frontal, axial, lateral, oblique, and off-axis impact directions. The standoff dimensions representing additional equipment donned by occupants, like a helmet and NVGs, can be added to the recommended flail corridors for specific design needs. The recommended flail response corridors can be used to inform vehicle, personal protective equipment, and occupant restraint designs that reduce the potential for injury within the projected flail strike zone in both enduring and future platforms. Future work will evaluate the relationships within the data to expand and revise the recommended flail corridors to address additional variations in exposure conditions (e.g., peak sled acceleration, rate of onset, peak sled velocity, and duration).

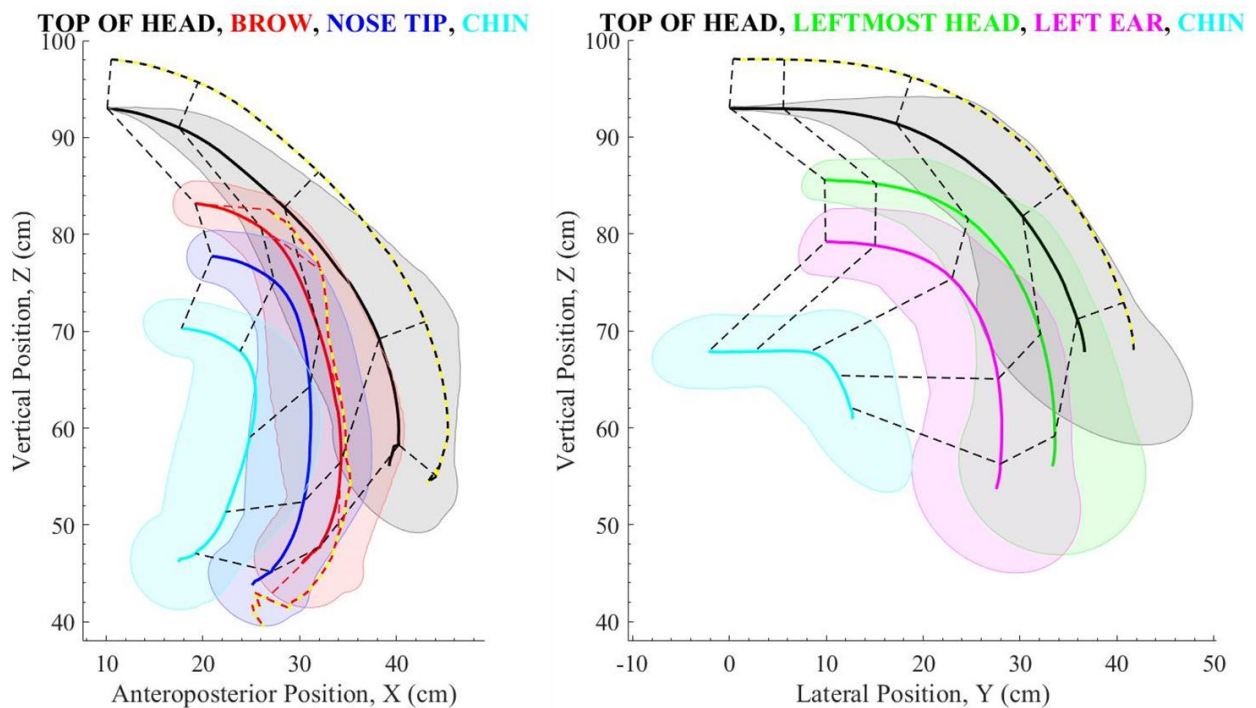


Figure 3. Recommended flail corridors with helmet and night vision goggles standoffs applied. The mean position of the most distal point on the helmet (approximated with a 2-inch standoff) is represented by the black-and-yellow dashed line. The mean position of the most distal point on the NVGs (approximated as a 3-inch standoff) is represented by the red-and-yellow dashed line. Standard deviations of the helmet and NVGs positions are not included but are expected to exceed the maximum AP, maximum lateral, and minimum vertical positions represented by the mean. Timing is provided by the dashed lines connecting the mean values at the corresponding time for each point on the head. The dashed lines begin at time zero and continue every 0.02 seconds. Additional black dashed lines connect the top-of-head and helmet curves at corresponding points in time. Red dashed lines connect the brow and NVGs curves at corresponding points in time.

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Appendix A. Recommended Flail Corridors

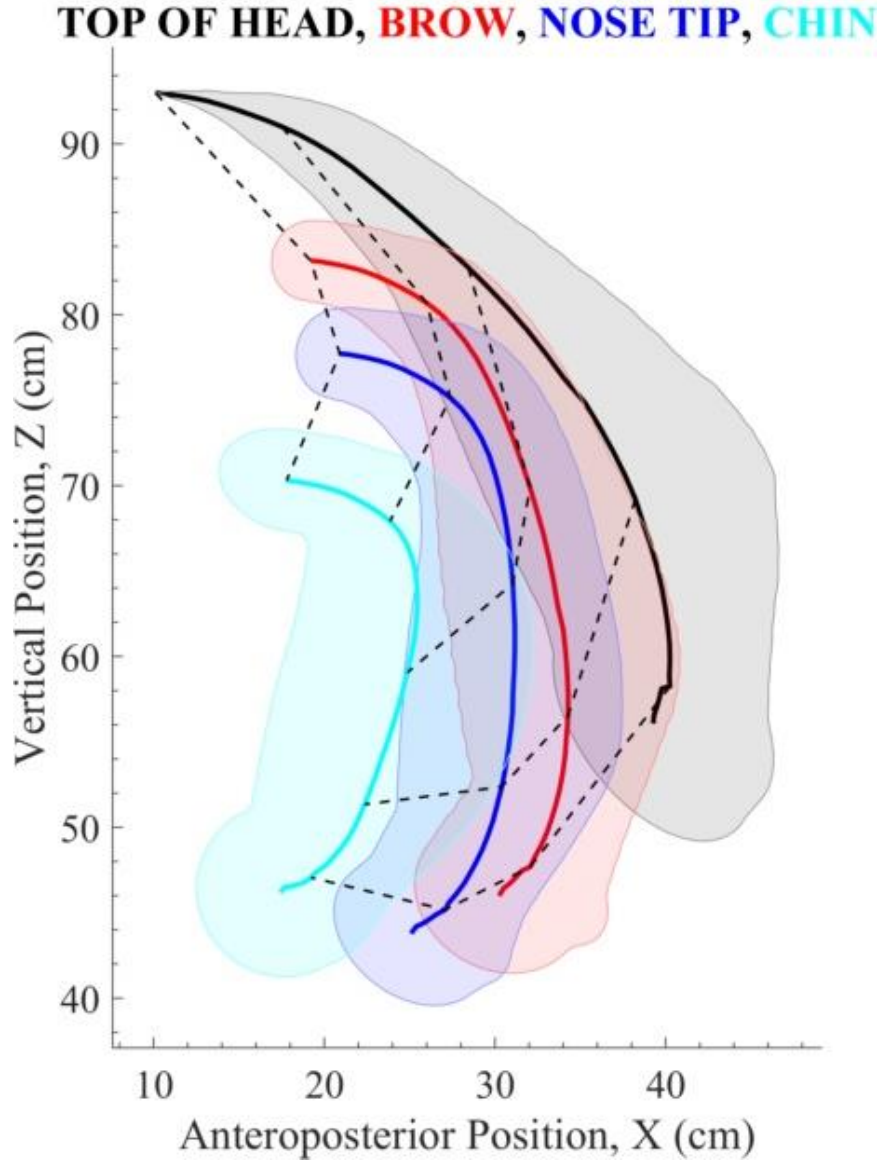


Figure A1. Head flail corridor for anteroposterior vs. vertical position. The flail corridors represent the maximum anteroposterior (AP) and minimum vertical head position expected for a torso-restrained occupant in a non-injurious frontal, axial, oblique, or off-axis impact. The mean response for each head point (top of head, brow, nose tip, and chin) is represented by the solid lines. The standard deviation is represented by the envelope around each line. All position data are with respect to the seat origin. Timing is provided by the dashed lines connecting the mean values at the corresponding time for each point on the head. The dashed lines begin at time zero and continue every 20 ms. The mean and standard deviational maximum AP position for all head points is 40.2 cm and 46.6 cm, respectively. The mean and standard deviational minimum vertical position for all head points is 43.8 cm and 39.6 cm, respectively.

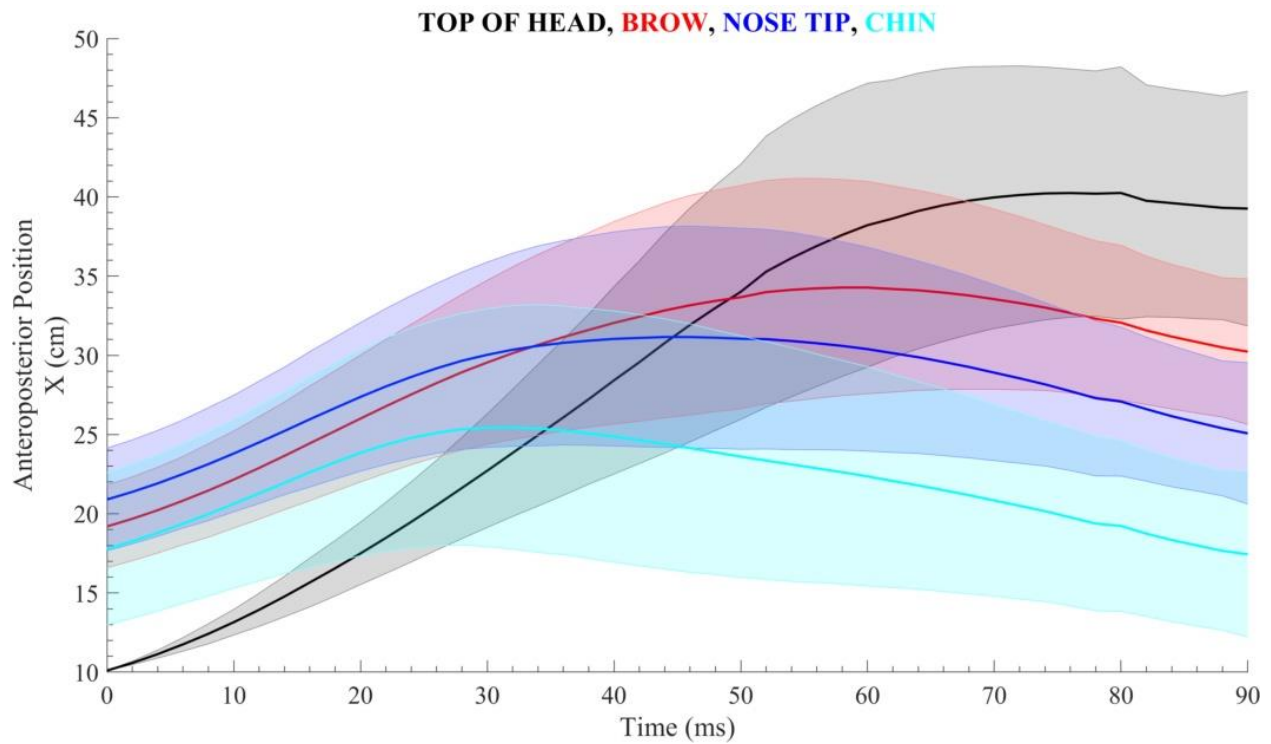


Figure A2. Head flail corridor for anteroposterior position over time. The flail corridors represent the maximum anteroposterior (AP) head position expected for a torso-restrained occupant in a non-injurious frontal, axial, oblique, or off-axis impact. The mean response for each head point (top of head, brow, nose tip, and chin) is represented by the solid lines. The standard deviation is represented by the envelope around each line. All position data are with respect to the seat origin. The mean and standard deviational maximum AP position for all head points is 40.2 cm at 80 ms and 48.3 cm at 72 ms, respectively.

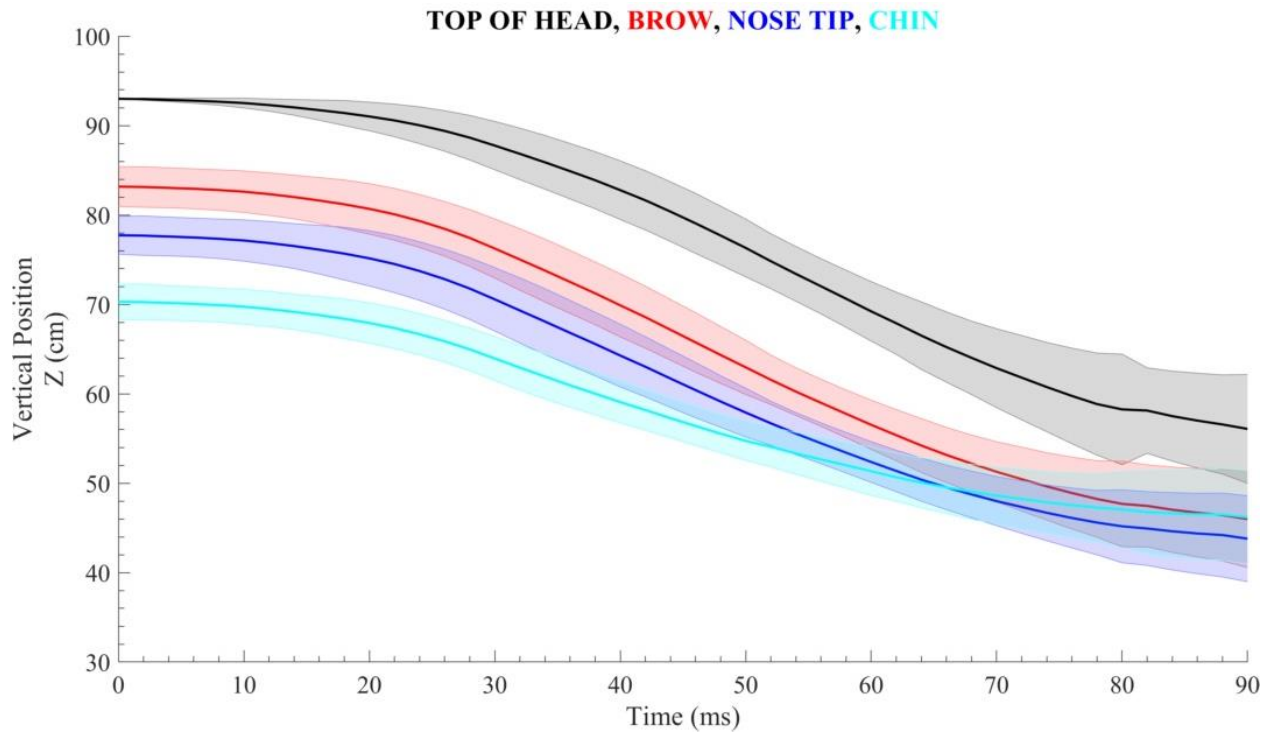


Figure A3. Head flail corridor for vertical position over time. The flail corridors represent the minimum vertical head position expected for a torso-restrained occupant in a non-injurious frontal, axial, oblique, or off-axis impact. The mean response for each head point (top of head, brow, nose tip, and chin) is represented by the solid lines. The standard deviation is represented by the envelope around each line. All position data are with respect to the seat origin. The mean and standard deviational minimum vertical position for all head points is 43.8 cm at 90 ms and 39.0 at 90 ms, respectively.

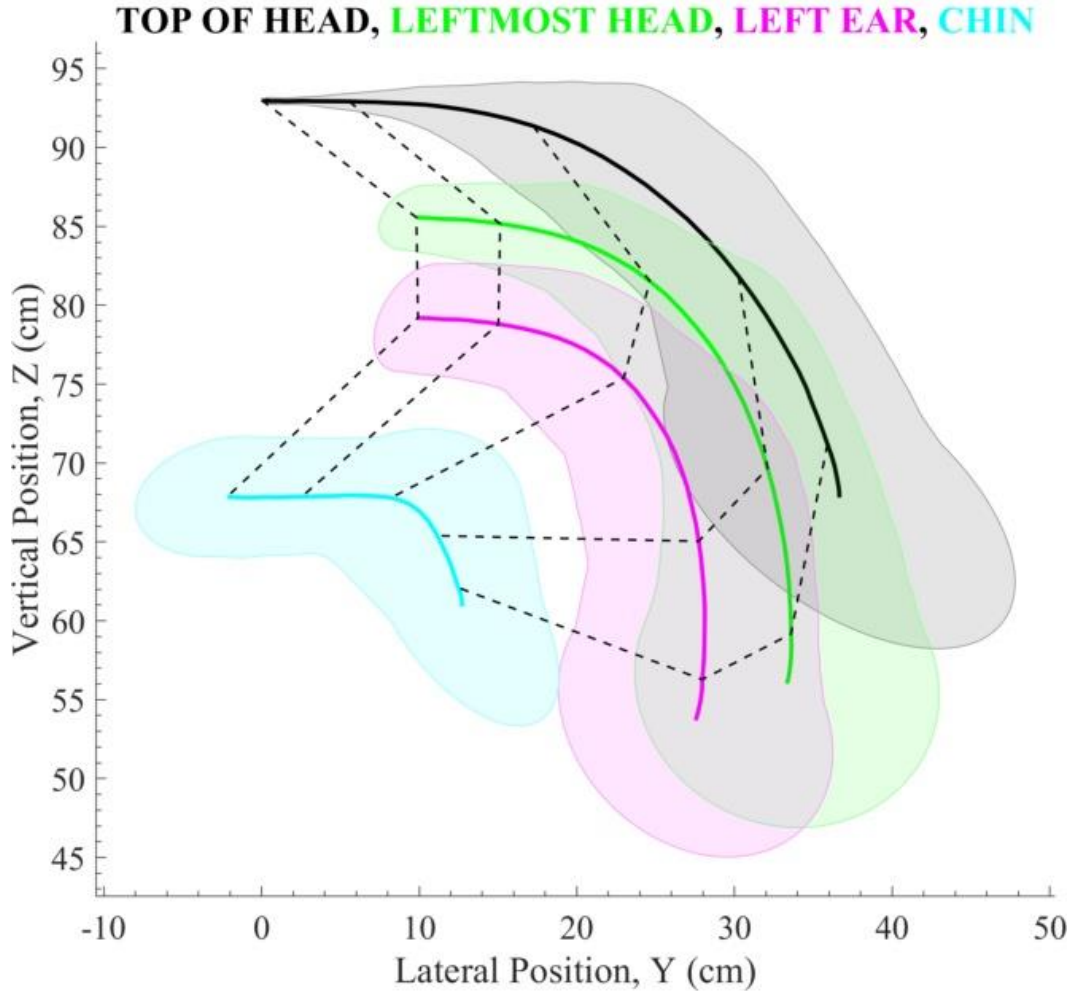


Figure A4. Head flail corridor for lateral vs. vertical position. The flail corridors represent the maximum lateral and minimum vertical head position expected for a torso-restrained occupant in a non-injurious lateral or oblique impact. The mean response for each head point (top of head, leftmost head, left ear, and chin) is represented by the solid lines. The standard deviation is represented by the envelope around each line. All position data are with respect to the seat origin. Timing is provided by the dashed lines connecting the mean values at the corresponding time for each point on the head. The dashed lines begin at time zero and continue every 20 ms. The mean and standard deviational maximum lateral position for all head points is 36.7 cm and 47.8 cm, respectively. The mean and standard deviational minimum vertical position for all head points is 53.7 cm and 45.0 cm, respectively.

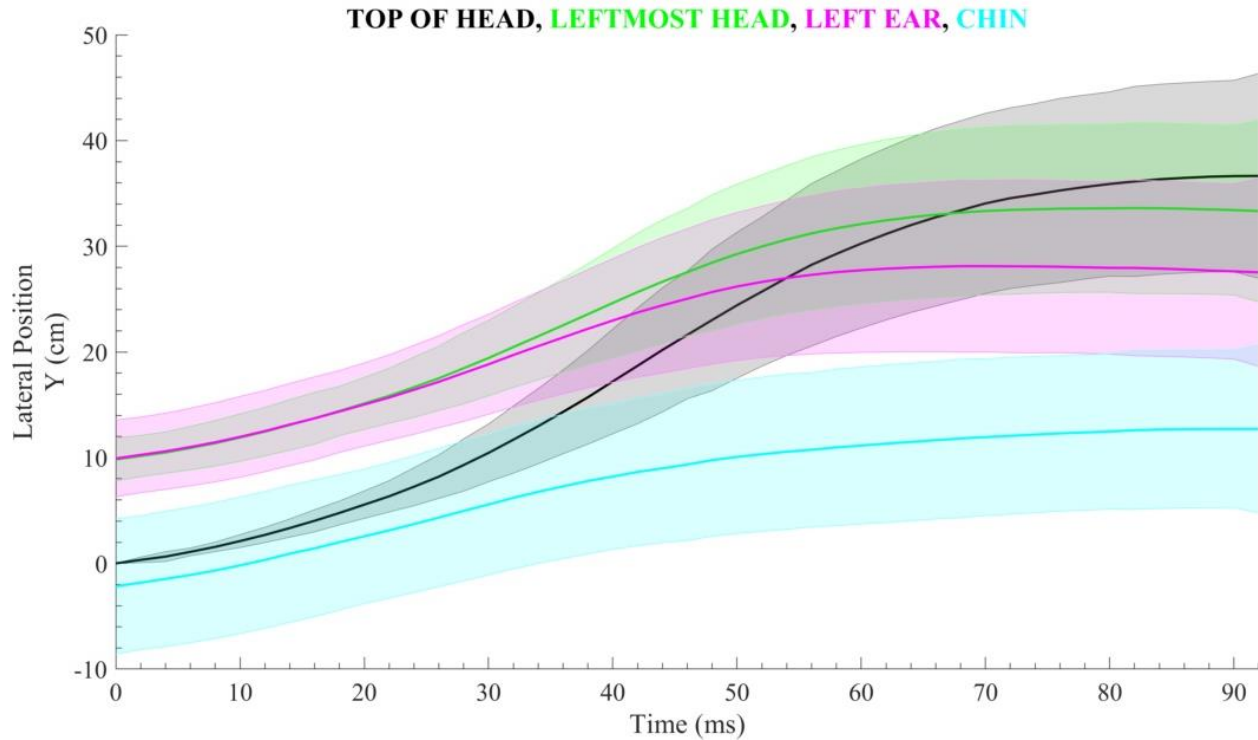


Figure A5. Head flail corridor for lateral position over time. The flail corridors represent the maximum lateral head position expected for a torso-restrained occupant in a non-injurious lateral or oblique impact. The mean response for each head point (top of head, leftmost head, left ear, and chin) is represented by the solid lines. The standard deviation is represented by the envelope around each line. All position data are with respect to the seat origin. The mean and standard deviational maximum lateral position for all head points is 36.7 cm at 92 ms and 46.3 cm at 92 ms, respectively.

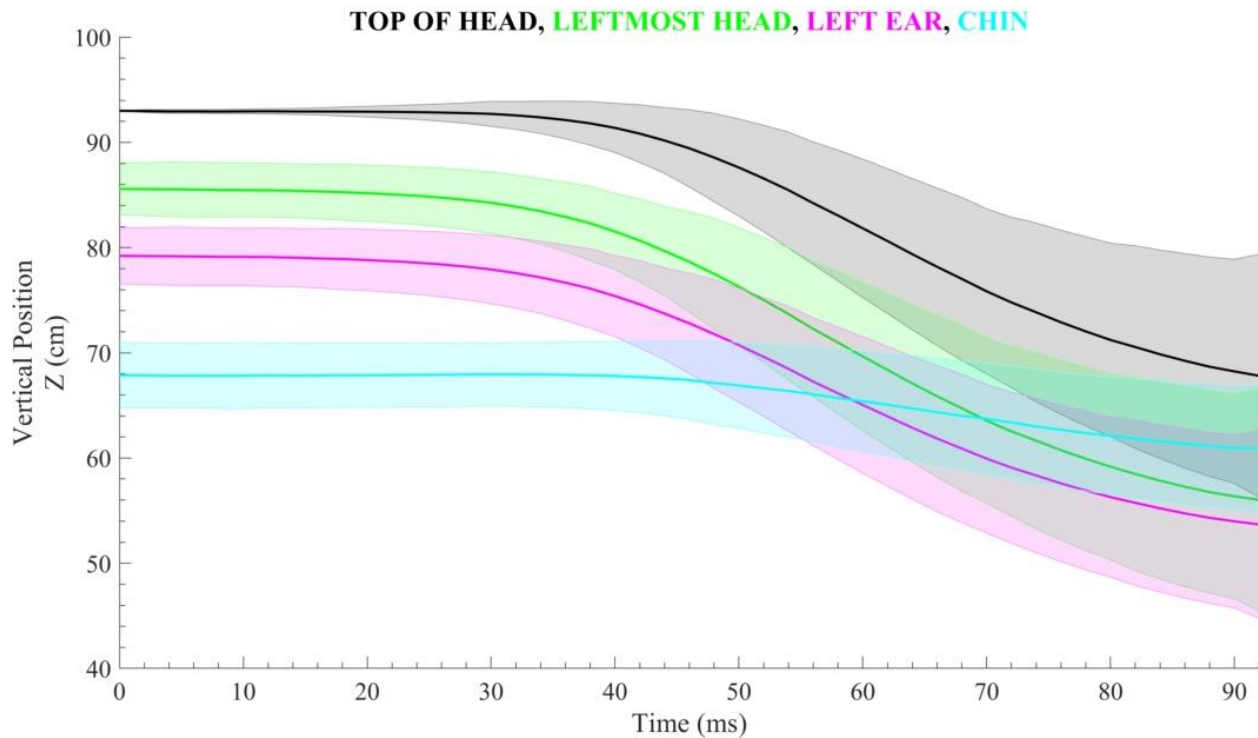


Figure A6. Head flail corridor for vertical position over time. The flail corridors represent the minimum vertical head position expected for a torso-restrained occupant in a non-injurious lateral or oblique impact. The mean response for each head point (top of head, leftmost head, left ear, and chin) is represented by the solid lines. The standard deviation is represented by the envelope around each line. All position data are with respect to the seat origin. The mean and standard deviational minimum vertical position for all head points is 53.7 cm at 92 ms and 44.8 cm at 92 ms, respectively.

Table A1. Mean Anteroposterior and Vertical Position Data for the Head during Flail

TIME (ms)	TOP OF HEAD X (cm)	TOP OF HEAD Y (cm)	BROW X (cm)	BROW Y (cm)	NOSE TIP X (cm)	NOSE TIP Y (cm)	CHIN X (cm)	CHIN Y (cm)
0	10.1	93.0	19.2	83.2	20.9	77.7	17.8	70.3
2	10.6	93.0	19.7	83.1	21.4	77.7	18.3	70.3
4	11.1	92.9	20.2	83.0	21.9	77.6	18.8	70.2
6	11.8	92.8	20.8	82.9	22.5	77.5	19.4	70.1
8	12.4	92.7	21.5	82.8	23.1	77.3	20.0	69.9
10	13.2	92.5	22.2	82.6	23.8	77.1	20.6	69.7
12	13.9	92.3	22.9	82.3	24.5	76.9	21.3	69.5
14	14.8	92.0	23.7	82.0	25.2	76.5	21.9	69.2
16	15.7	91.7	24.4	81.6	26.0	76.1	22.6	68.8
18	16.6	91.4	25.2	81.2	26.7	75.7	23.2	68.4
20	17.5	91.0	26.0	80.7	27.4	75.2	23.8	67.9
22	18.5	90.6	26.8	80.1	28.0	74.5	24.4	67.4
24	19.5	90.0	27.5	79.3	28.6	73.7	24.8	66.7
26	20.5	89.4	28.2	78.5	29.2	72.8	25.1	65.9
28	21.6	88.7	28.9	77.4	29.7	71.8	25.3	65.0
30	22.7	87.8	29.5	76.2	30.0	70.6	25.4	64.0
32	23.8	86.8	30.1	75.0	30.4	69.3	25.4	62.9
34	25.0	85.9	30.7	73.8	30.6	68.1	25.4	61.9
36	26.1	84.9	31.1	72.5	30.8	66.8	25.3	60.9
38	27.2	83.9	31.6	71.2	30.9	65.6	25.1	60.0
40	28.4	82.8	32.0	69.9	31.0	64.3	24.9	59.1
42	29.6	81.6	32.4	68.6	31.1	63.0	24.6	58.2
44	30.8	80.4	32.8	67.2	31.2	61.7	24.4	57.3

TIME (ms)	TOP OF HEAD X (cm)	TOP OF HEAD Y (cm)	BROW X (cm)	BROW Y (cm)	NOSE TIP X (cm)	NOSE TIP Y (cm)	CHIN X (cm)	CHIN Y (cm)
46	31.9	79.1	33.2	65.8	31.2	60.4	24.1	56.4
48	33.0	77.7	33.4	64.3	31.1	59.1	23.9	55.5
50	34.0	76.3	33.7	63.0	31.0	57.9	23.6	54.7
52	35.3	74.8	34.0	61.6	31.0	56.7	23.4	54.1
54	36.1	73.4	34.1	60.2	30.9	55.5	23.1	53.3
56	36.9	72.0	34.2	59.0	30.8	54.5	22.9	52.7
58	37.6	70.6	34.3	57.8	30.6	53.4	22.6	52.0
60	38.2	69.2	34.3	56.5	30.4	52.4	22.4	51.3
62	38.6	67.9	34.2	55.4	30.1	51.4	22.1	50.7
64	39.1	66.5	34.1	54.2	29.9	50.4	21.8	50.1
66	39.5	65.2	34.0	53.2	29.6	49.5	21.5	49.5
68	39.8	64.0	33.8	52.2	29.3	48.7	21.2	49.1
70	40.0	62.9	33.5	51.3	28.9	48.0	20.8	48.6
72	40.1	61.8	33.3	50.5	28.5	47.3	20.5	48.2
74	40.2	60.8	33.0	49.6	28.2	46.7	20.2	47.9
76	40.2	59.8	32.7	48.9	27.7	46.1	19.8	47.5
78	40.2	58.9	32.3	48.2	27.3	45.6	19.4	47.3
80	40.2	58.3	32.1	47.7	27.1	45.2	19.2	47.1
82	39.8	58.1	31.6	47.5	26.6	44.9	18.7	46.8
84	39.6	57.5	31.2	47.0	26.2	44.6	18.3	46.6
86	39.5	57.0	30.8	46.7	25.8	44.4	18.0	46.5
88	39.3	56.6	30.5	46.4	25.4	44.2	17.7	46.5
90	39.3	56.1	30.2	46.0	25.1	43.8	17.4	46.2

Note. The x-coordinate (X) corresponds to the anteroposterior (AP) displacement from the seat origin, and the y-coordinate (Y) corresponds to the vertical displacement from the seat origin.

Table A2. Mean Lateral and Vertical Position Data for the Head during Flail

TIME (ms)	TOP OF HEAD X (cm)	TOP OF HEAD Y (cm)	LEFTMOST HEAD X (cm)	LEFTMOST HEAD Y (cm)	LEFT EAR X (cm)	LEFT EAR Y (cm)	CHIN X (cm)	CHIN Y (cm)
0	0.0	93.0	9.8	85.6	9.9	79.2	-2.2	67.9
2	0.3	93.0	10.2	85.6	10.3	79.2	-1.8	67.9
4	0.6	92.9	10.5	85.5	10.6	79.2	-1.5	67.8
6	1.1	92.9	10.9	85.5	11.0	79.2	-1.1	67.8
8	1.6	92.9	11.4	85.5	11.5	79.1	-0.7	67.8
10	2.1	92.9	11.9	85.5	12.0	79.1	-0.2	67.8
12	2.7	93.0	12.5	85.4	12.5	79.1	0.3	67.8
14	3.3	92.9	13.1	85.4	13.1	79.0	0.9	67.8
16	4.0	92.9	13.7	85.3	13.7	79.0	1.4	67.8
18	4.8	92.9	14.4	85.3	14.4	78.9	2.0	67.9
20	5.6	92.9	15.1	85.2	15.0	78.8	2.6	67.9
22	6.3	92.9	15.9	85.1	15.7	78.7	3.1	67.9
24	7.3	92.9	16.7	84.9	16.4	78.6	3.7	67.9
26	8.2	92.8	17.5	84.7	17.2	78.4	4.3	67.9
28	9.3	92.8	18.5	84.5	18.0	78.2	5.0	67.9
30	10.5	92.7	19.4	84.3	18.8	77.9	5.6	68.0
32	11.7	92.6	20.5	83.9	19.7	77.6	6.2	67.9
34	13.0	92.4	21.5	83.5	20.6	77.2	6.8	67.9
36	14.3	92.1	22.5	82.9	21.4	76.7	7.3	67.9
38	15.7	91.8	23.6	82.3	22.2	76.1	7.8	67.9
40	17.2	91.4	24.6	81.5	23.0	75.4	8.2	67.8
42	18.7	90.8	25.7	80.7	23.7	74.6	8.7	67.7
44	20.2	90.2	26.6	79.7	24.4	73.7	9.0	67.6
46	21.6	89.4	27.6	78.6	25.0	72.8	9.4	67.4

TIME (ms)	TOP OF HEAD X (cm)	TOP OF HEAD Y (cm)	LEFTMOST HEAD X (cm)	LEFTMOST HEAD Y (cm)	LEFT EAR X (cm)	LEFT EAR Y (cm)	CHIN X (cm)	CHIN Y (cm)
48	23.0	88.6	28.5	77.5	25.7	71.8	9.8	67.1
50	24.4	87.6	29.3	76.3	26.2	70.7	10.1	66.9
52	25.7	86.6	30.0	75.0	26.6	69.6	10.3	66.6
54	27.0	85.5	30.6	73.7	27.0	68.5	10.6	66.4
56	28.2	84.2	31.2	72.3	27.3	67.3	10.7	66.1
58	29.3	83.0	31.7	71.0	27.6	66.2	11.0	65.7
60	30.3	81.8	32.1	69.7	27.7	65.0	11.1	65.4
62	31.2	80.6	32.4	68.4	27.9	64.0	11.3	65.1
64	32.0	79.4	32.7	67.1	28.0	62.9	11.5	64.7
66	32.7	78.2	33.0	65.9	28.1	61.9	11.7	64.4
68	33.4	77.0	33.2	64.7	28.1	60.9	11.8	64.0
70	34.1	75.8	33.3	63.6	28.1	59.9	11.9	63.7
72	34.5	74.8	33.4	62.5	28.1	59.1	12.1	63.4
74	34.9	73.8	33.5	61.6	28.1	58.3	12.2	63.0
76	35.3	72.9	33.6	60.7	28.1	57.6	12.3	62.7
78	35.6	72.0	33.6	59.9	28.0	56.9	12.4	62.4
80	35.9	71.2	33.6	59.2	28.0	56.3	12.5	62.1
82	36.1	70.5	33.6	58.5	28.0	55.7	12.6	61.8
84	36.3	69.9	33.6	57.8	27.9	55.2	12.7	61.6
86	36.5	69.2	33.6	57.3	27.8	54.7	12.7	61.3
88	36.6	68.7	33.5	56.8	27.7	54.3	12.7	61.1
90	36.6	68.2	33.4	56.4	27.6	54.0	12.7	61.0
92	36.7	67.8	33.3	56.0	27.5	53.7	12.7	60.9

Note. The x-coordinate (X) corresponds to the lateral displacement from the seat origin, and the y-coordinate (Y) corresponds to the vertical displacement from the seat origin.

Appendix B. Comparison of Recommended Flail Corridors to the ACSDG

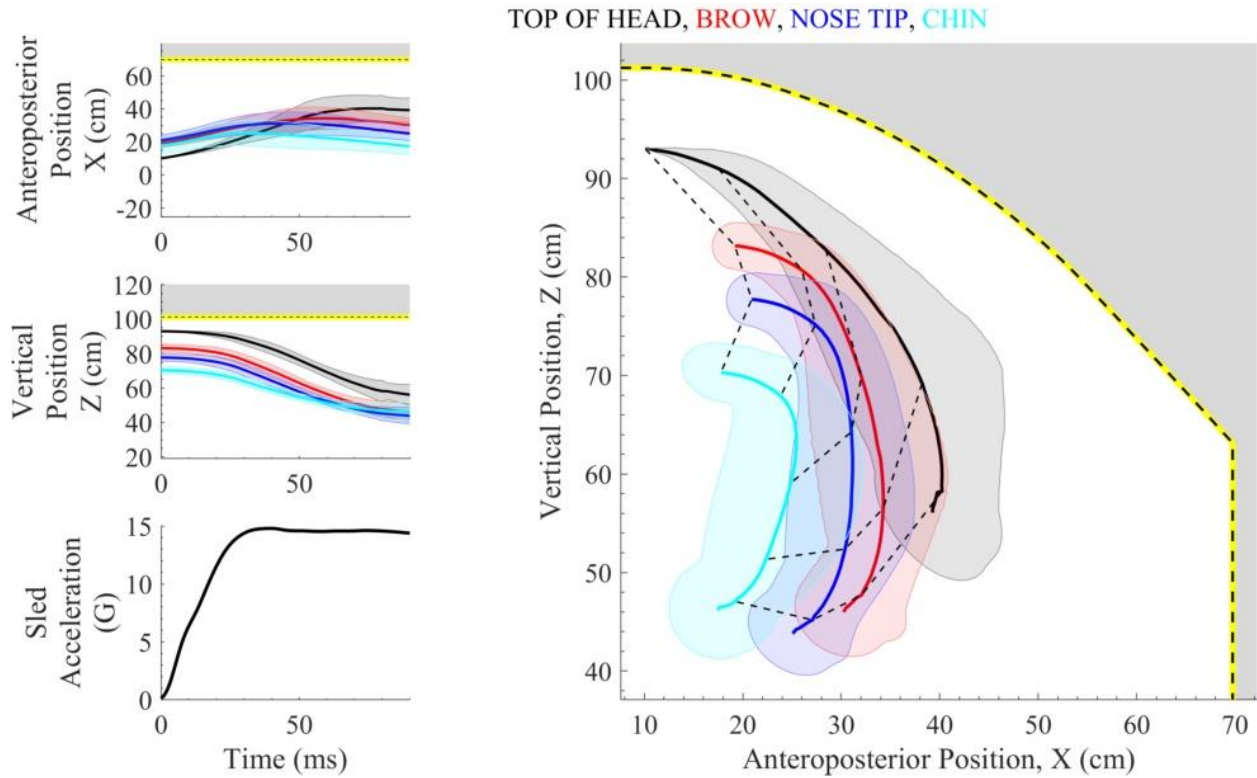


Figure B1. Comparison of the Aircraft Crash Survival Design Guide flail envelopes with the recommended flail corridors for anteroposterior and vertical position. For each plot, the Aircraft Crash Survival Design Guide (ACSDG) flail envelopes are represented by the black-and-yellow dashed lines. The gray area is beyond the ACSDG flail envelope (exceeds the flail envelope). The time-based plots only include the maximum anteroposterior (69.8 cm) and vertical limits (102.0 cm) of the flail envelope because the ACSDG flail envelopes do not include a time component.

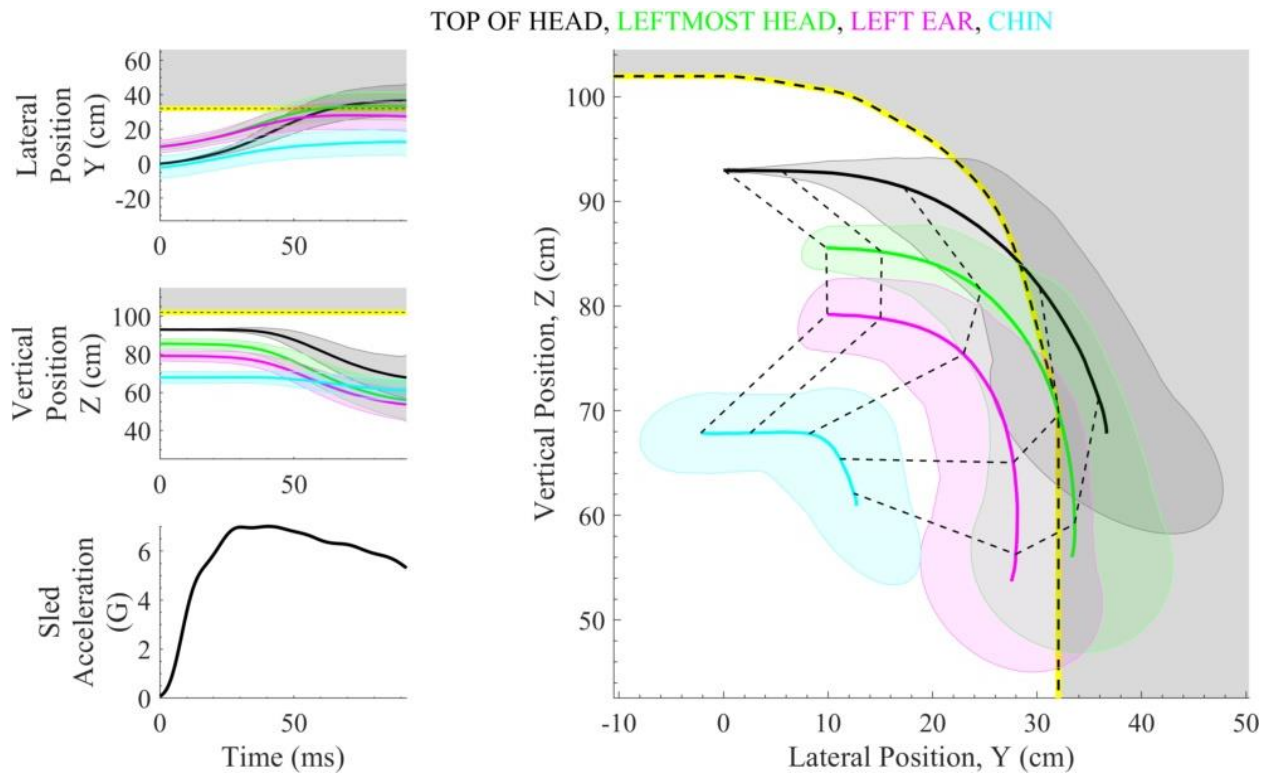


Figure B2. Comparison of Aircraft Crash Survival Design Guide flail envelopes with the recommended flail corridors for lateral and vertical position. For each plot, the Aircraft Crash Survival Design Guide (ACSDG) flail envelopes are represented by the black-and-yellow dashed lines. The gray area is beyond the ACSDG flail envelope (exceeds the flail envelope). The time-based plots only include the maximum lateral (32.1 cm) and vertical limits (102.0 cm) of the flail envelope because the ACSDG flail envelopes do not include a time component.

Appendix C. Predicted Head Flail Response

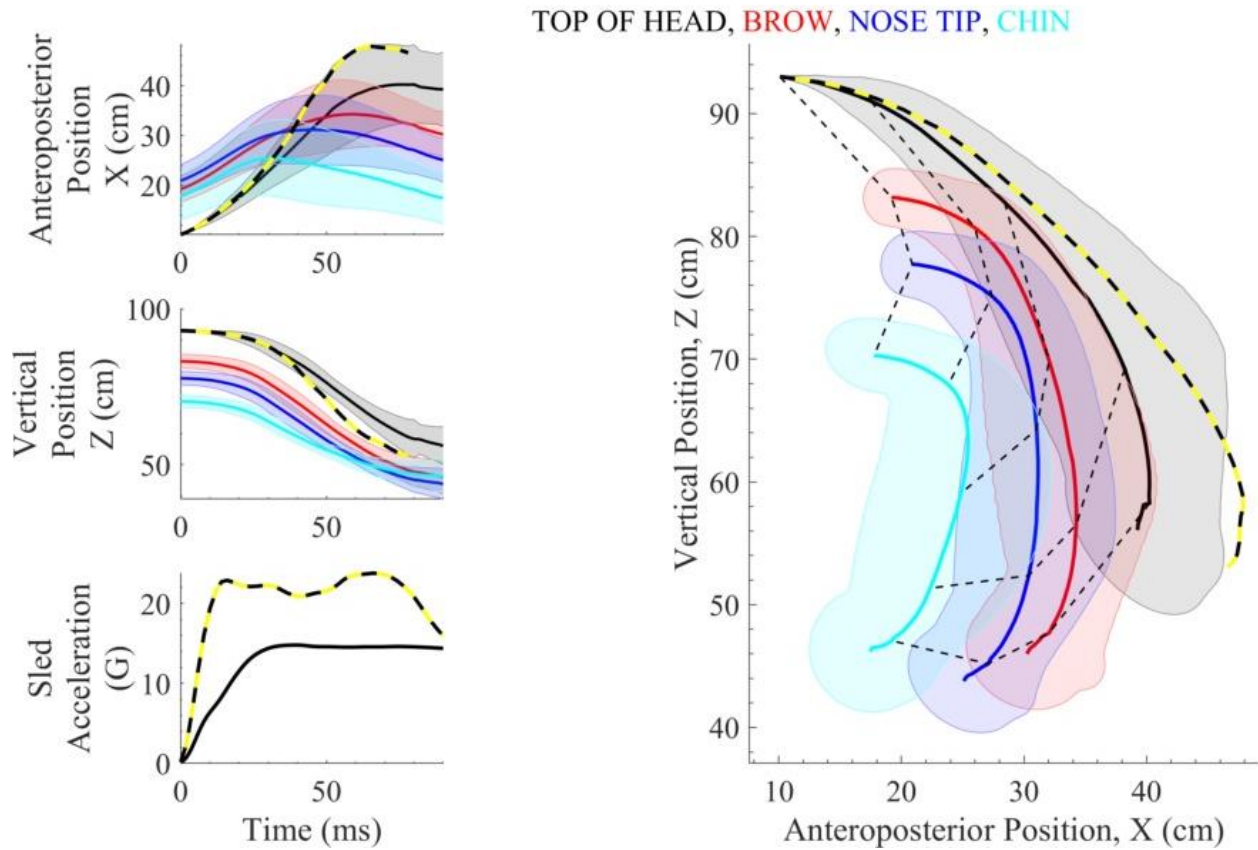


Figure C1. Predicted mean top-of-head response for frontal impact with peak sled acceleration of 24 G. For each plot, the position data corresponding to the predicted mean response for the top of the head are represented by the black-and-yellow dashed line. Standard deviation of the predicted mean response is not included but is expected to exceed the maximum AP and minimum vertical positions represented by the predicted mean. The sled acceleration exposure corresponding to the predicted response (bottom left) was collected during an actual ATD test. The remaining data used for comparison correspond to the frontal impact match group at 15 G peak sled acceleration that was selected for the recommended flail corridors. The predicted mean top-of-head response exceeds the maximum AP and minimum vertical positions of the top-of-head flail corridor mean, which shows that the maximum AP and minimum vertical positions of the recommended flail corridors will likely be exceeded for exposures with a PSA higher than 15 G.

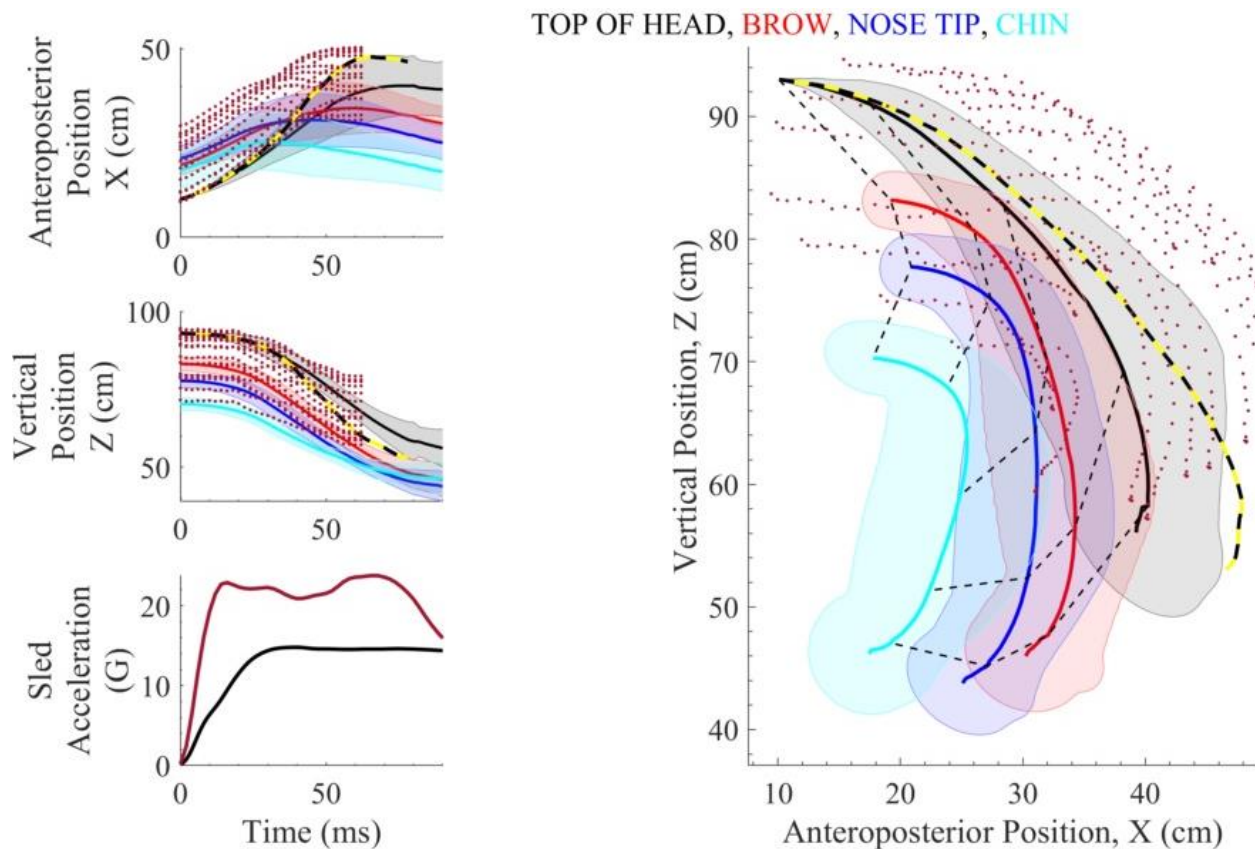


Figure C2. Anthropomorphic test device response data compared to the predicted human mean top-of-head response for frontal impact with peak sled acceleration of 24 G. For each plot, the position data corresponding to the predicted mean response for the top of the head are represented by the black-and-yellow dashed line. The anthropomorphic test device (ATD) response data are represented by the dotted red lines. The sled acceleration exposure corresponding to the ATD test and predicted response (red, bottom left) was collected during an actual ATD test. The remaining corridor data used for comparison correspond to the frontal impact match group of human volunteers at 15 G peak sled acceleration that was selected for the recommended flail corridors. The ATD response data exceed the maximum AP position but not the minimum vertical position of the predicted human mean response, and the ATD response has a shorter duration than the predicted human mean response.

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