TEST METHOD FOR DEVELOPING UPDATED NECK BIOFIDELITY CORRIDORS FOR A SMALL FEMALE OCCUPANT

Corina Espelien
John Paul Donlon
Sydney Koerber
Sara Sochor
Kevin Kopp
Brian Overby
Jason Forman
University of Virginia, Center for Applied Biomechanics
USA

Paper Number 23-0197

ABSTRACT

The continued development and improvement of crash evaluation tools for a variety of anthropometries, especially the small female, call for experimental testing to generate anthropometric-specific biofidelity targets. The effect of active musculature on head and neck response in impact loadings cannot be ignored, but data from volunteer testing at impact severities performed in the 1960s and 1970s at the Naval Biodynamics Laboratory (NBDL) is limited to the male response. To generate biofidelity targets for the head and neck response of the small female that include the effect of active musculature, modern testing must rely on combining PMHS data from different anthropometries and retrospective analysis of the original NBDL testing outputs and other volunteer studies. This paper describes the methodology to replicate the original NBDL testing for small female and average male PMHS for the purpose of informing new biofidelity corridors for the 5th percentile female neck.

Publications related to the original testing were reviewed for qualitative and quantitative measures detailing the setup of the NBDL configuration. A custom buck with an upright seat (90° between seatpan and seatback), five-point rigid harness, footpan, and tether head support system was designed and fabricated for use with an acceleration sled. Of critical importance, the head and neck angle in the PMHS tests will be matched to NBDL initial positioning of -0.9° for head and 20.75° for neck. Two input pulse severities for frontal PMHS testing were chosen: a low severity at 3g peak acceleration and a moderate severity at 8g peak acceleration. These curves were chosen to avoid damage or injury to neck structures and to investigate the head and neck response at multiple severities. The boundary conditions on the sled will be measured via load cells and the PMHS kinematics will be measured through bone-mounted instrumentation packages and motion tracking arrays. This methodology will be used in experimental testing of small females and average males in the NBDL frontal impact condition.

INTRODUCTION

Crash evaluation tools, like anthropomorphic test devices (ATDs) or human body models (HBMs), often use tests performed at the Naval Biodynamics Laboratory (NBDL) as part of surrogate neck response validation [1–4]. The NBDL tests exposed volunteers to sled acceleration pulses in frontal and lateral impact loading conditions [5,6]. The resulting dataset is unique because it captured the effect of musculature by testing volunteers, but the severities of the exposures are likely non-repeatable in modern-day volunteer protocols. The NBDL volunteers were mid-size males of military age . Development of the THOR ATDs and introduction of programs to supplement physical crash tests with computational HBMs have highlighted the need for biofidelity targets for anthropometries outside of the average male response [7]. One of the anthropometries of interest is typically the small or 5th percentile female, especially for physical test surrogates (e.g., Test device for Human Occupant Restraint (THOR)-05F).

Translating the head and neck kinematic data from volunteer NBDL tests to the small female anthropometry has typically relied on equal-stress/equal-velocity scaling using ratios of mass and length scales between the original and target anthropometry [8]. The validity of this scaling method cannot be directly assessed, as modern small female volunteer tests at the NBDL severities are likely not possible. Small female post-mortem human surrogate (PMHS) testing replicating the NBDL configuration can potentially fill this gap, providing a translation bridge via mid-sized male PMHS tests performed in the NBDL configuration. Performing average male PMHS testing allows for a direct comparison of volunteer and PMHS male kinematics with matched anthropometry; performing small female PMHS testing allows for a direct comparison of average male PMHS and small female PMHS kinematics and allows for an indirect comparison to average volunteer male kinematics.

This paper will describe an updated methodology to collect small female PMHS data in the NBDL condition for frontal impacts, and to generate biofidelity targets for small female head and neck response. Limitations of the original NBDL dataset, as well as implemented mitigations and remediations for the PMHS test series, are described. This test series will be the first to test small female PMHS in the NBDL test configuration.

METHODS

Accessing and Using the NBDL Data

Information on the NBDL dataset is documented in various conference proceedings, journal articles, and reports. There are several publications describing the original NBDL testing, including original methodology and preliminary results [5,6,9–12], subsequent testing and analyses [13–16], and summaries of the series as a whole [17,18]. It should be noted that similar volunteer testing to investigate the head and neck response was performed at Wayne State University [19–21]. While similar, the Wayne State tests differed from tests performed at the NBDL in terms of the sled system, boundary conditions, and instrumentation, as described by Ewing et al. 1973 [22].

Original NBDL data (e.g., kinematic curves) can be accessed via the National Highway Traffic Safety Administration (NHTSA) Biomechanics Database. For all NBDL tests, the head and upper neck kinematics were tracked with video and surface-mounted instrumentation, as well as the sled acceleration and velocity.

Reconstructing the NBDL Testing Environment

Acceleration system The NBDL testing was performed on an acceleration sled system, which was a modified version of the Wayne State Wayne Horizontal Acceleration Mechanism (WHAM) II system [10,11] and accelerated by a HYGE® accelerator [11]. Our new tests will be performed on a Seattle Safety Systems 1.2 MN ServoSled ™ acceleration sled system (SESA sled).

On-board physical environment The physical NBDL testing environment is primarily described as an 'upright seat with a rigid harness restraint' [23]. For our new tests, a custom buck was designed and fabricated to replicate the NBDL environment, as shown in Figure 1. The buck includes a footpan (with 6 degrees of freedom (dof) load cell), seatpan (with 6 dof load cell), seatback (with upper and lower 6 dof load cells), shoulder and lap belt anchors, and an overhead tether system for head positioning. The seat was made of aluminum and the seatback consisted of two aluminum plates, separate from each other and separate from the seatpan. This design is intended for tests with small female surrogates (PMHS and THOR-05F) and average male surrogates (PMHS and THOR-50M) in both frontal and lateral impacts. To match positioning targets of the surrogates and restraint system across multiple anthropometries, there is adjustability of the footpan, seatback plates, b-pillars (shoulder belt anchors), and lap belt anchors. The instrumentation and measurement systems on the sled include buck accelerometers, the load cells mentioned above, a drop-release mechanism for the head-support tether system, and two on-board high speed cameras.

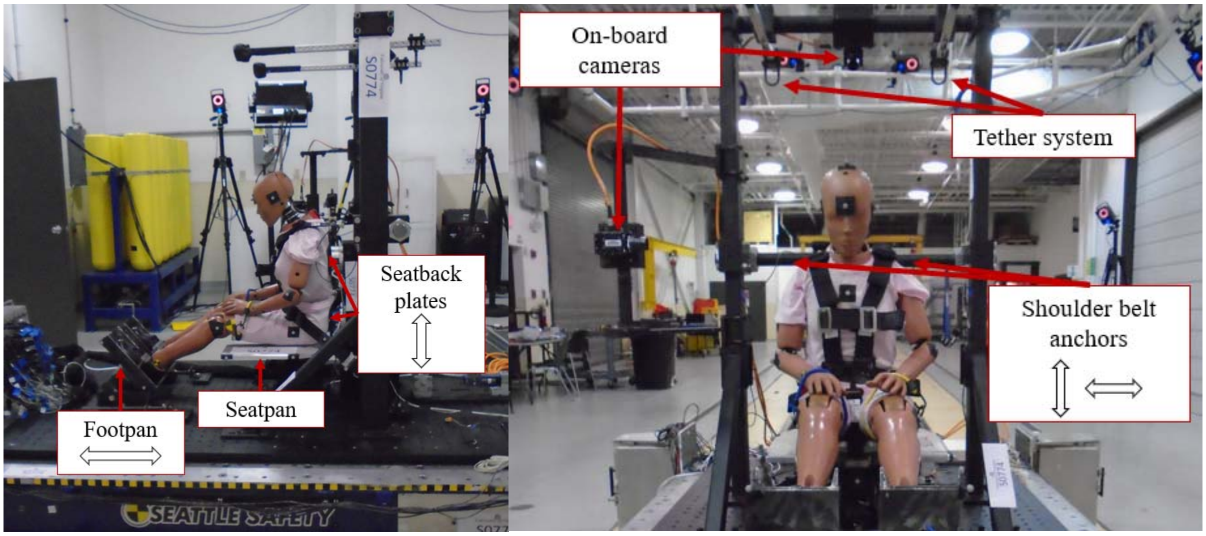

Figure 1. Lateral (left) and anterior (right) views of buck on sled with Hybrid III 5th ATD.

Restraint system A five-point harness (symmetric shoulder and lap belts, with center lap belt, connected through buckle near the umbilicus) was constructed based on that used in the NBDL tests. The harness can be adjusted to fit small females and average males. No pre-tensioning or load-limiting mechanisms were implemented in the restraint system. During positioning, the belts were tightened to a snug fit and the loads were recorded. To accommodate for potential differences with normal automotive seatbelt webbing, belt tension load gauges were tested with this webbing using a material test machine (Figure 2). The offset between the Instron load cell and belt gauge reading is used to correct belt gauge readings from sled tests to ensure accurate belt tension reporting. Lastly, the arms of the subject were restrained to avoid flailing or the arms contacting the head instrumentation packages and minimize obfuscating motion tracking markers.

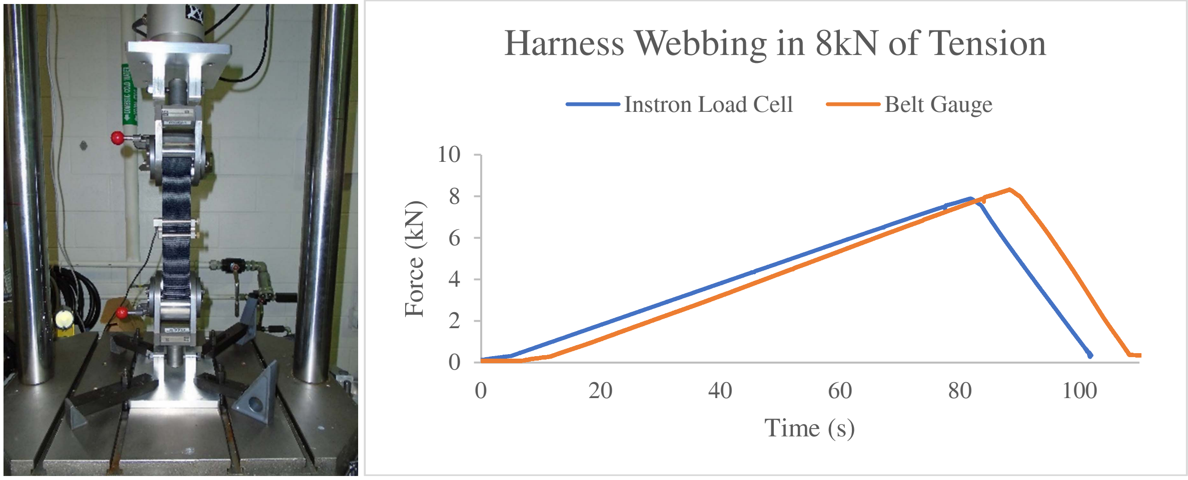

Figure 2. Harness webbing tensile test setup (left) and force time-history of Instron ® uniaxial tensile tester load cell and supplemental belt gauge (right).

Initial positioning There is little quantified or measured detail on the initial positioning for individual NBDL runs, other than the initial positions recorded in the photos and videos. Preliminary qualitative comparisons were made to the original photos to ensure that the initial position is generally similar (Figure 3).

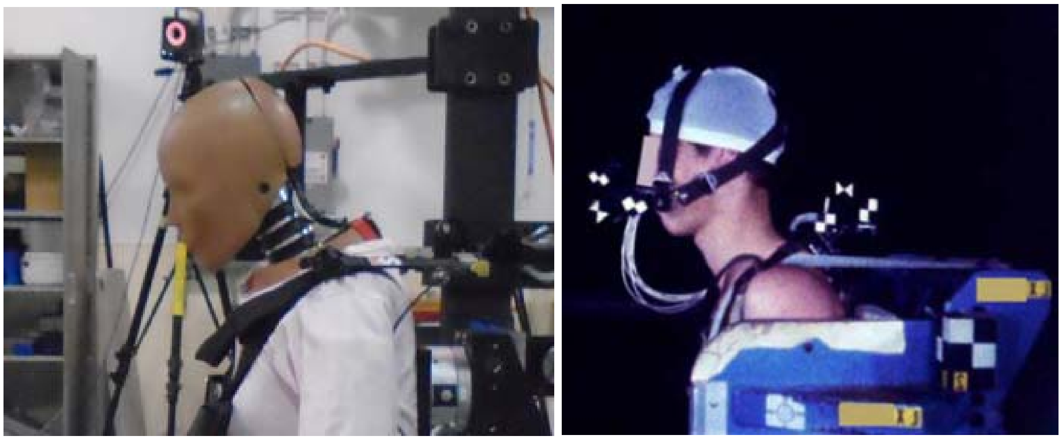

Figure 3. Qualitative comparison of upright postures of the Hybrid III 5th ATD (left) and NBDL volunteers (right; original image flipped for comparison) [16]. Note that although the head angle of the Hybrid III is different than the volunteer (due to the limited adjustability of the occipital condyles), the neck angle is relatively similar.

While no initial positioning was reported for the subjects and runs used to generate the sled pulses described in Table 3 of this paper's results, NBDL did perform a sensitivity study regarding head and neck position on earlier subjects and test runs under 6g and 10g pulses [11]. The four categories of initial position were "neck up, chin up" ("NUCU"), "neck up, chin down" ("NUCD"), "neck forward, chin up" ("NFCU"), and "neck forward, chin down" ("NFCD") (Figure 4). The photo targets of the surface-mounted instrumentation were transformed to anatomical origins of the head and T1, from which the head and neck angles relative to the global (lab) coordinate system were defined (Figure 5). The mean head and neck angles for thirteen subjects for two severities considered by Ewing et al. 1975 are listed in Table 1. The planned PMHS tests will be performed to match the "NUCU" condition; this position was used in later test runs, including the runs used to refine the target sled input pulses. Specifically, the mean of the head and neck angles from the 6g and 10g tests will be targeted (-0.9° for head, 20.75° for neck).

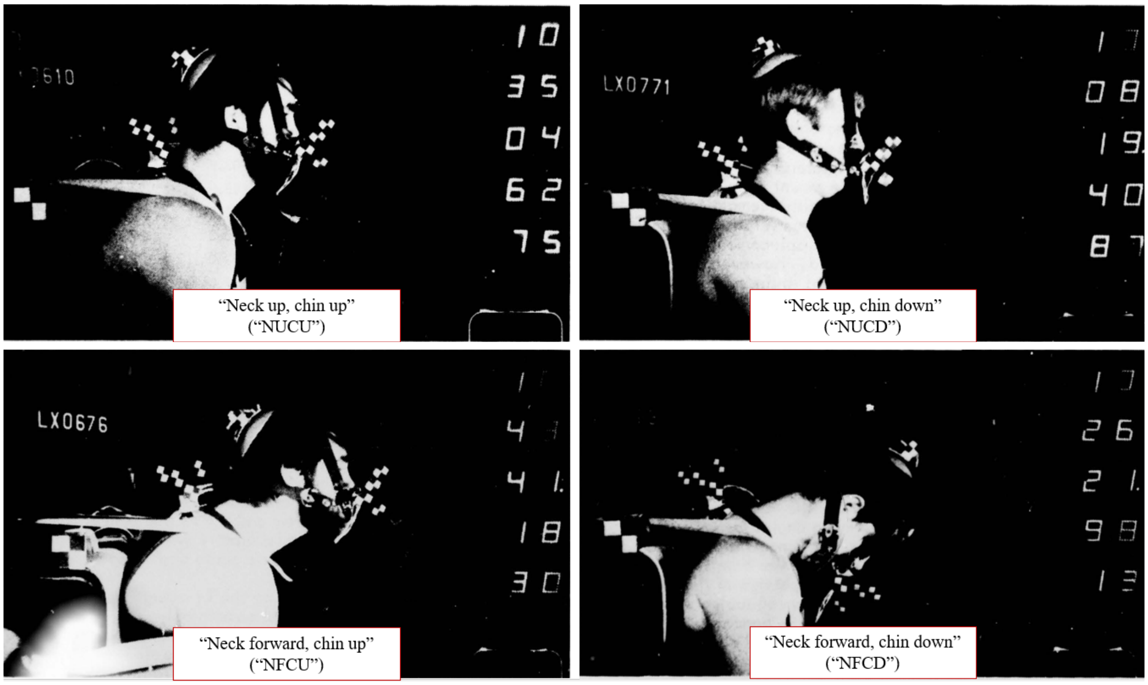

Figure 4. Initial positions considered in NBDL investigation [11].

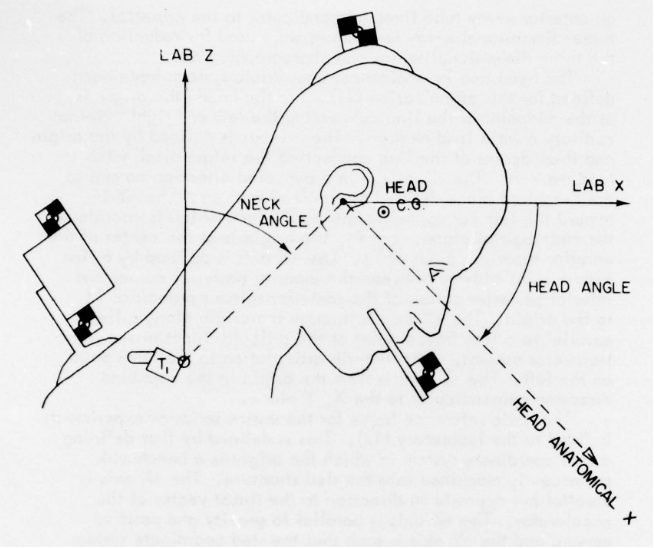

Figure 5. Definitions of head and neck angles for initial positions [11].

Table 1.
The mean (standard deviation) head and neck angles (degrees) for two severities of tests in different initial positions from n = 13 subjects.

	NUCU	NUCD	NFCU	NFCD
6g – head angle	-1.29 (7.15)	6.15 (11.02)	-3.74 (10.10)	66.04 (10.65)
6g – neck angle	20.22 (3.35)	12.19 (9.67)	43.29 (6.55)	79.13 (13.69)
10g – head angle	-0.48 (10.68)	6.87 (10.43)	4.32 (10.96)	64.18 (13.10)
10g – neck angle	21.28 (8.27)	12.90 (10.32)	45.07 (10.06)	74.08 (15.59)

To assist future validation work of ATDs and HBMs, detailed positioning measurements of the PMHS and restraint system will be documented. This includes head and neck positioning based on instrumentation mounts that are rigidly attached to the skull and T1 vertebra. Additionally, a pre-test static x-ray of the head and neck will be performed after final positioning to document the initial positions of the skull and vertebrae.

Reconstructing the NBDL Pulses

Pulse selection A variety of input pulses were considered representing multiple past volunteer tests, ranging from 3g to 15g peak accelerations present in the NBDL tests [17]. The original tests show that the neck response may be sensitive to input pulse severity [17]. Therefore, testing PMHS at multiple severities may be warranted. In addition to lower severities, impact severities should also be selected based on pulses that will generate maximal neck flexion (e.g., generate the most head and neck motion) to bound the extreme response. This desire for an extreme bound must also be balanced with the injury tolerance of the neck, ensuring that the tests do not damage structures related to neck flexion in a way that would adversely affect the biofidelity corridor (i.e. even the high-severity tests should ideally be non-injurious). To identify the potential threshold for injurious loading, previous sled tests with matched small female and average male PMHS performed at UVA were reviewed for neck injuries. Table 2 describes the examined tests and resulting injuries. In addition to these observations, PMHS tests in the NBDL configuration performed at the University of Heidelberg noted neck injuries in 9 of the 13 runs performed across 11g to 15g peak sled acceleration [15]. From this data, the possibility of neck injuries in small females restrained in a three-point load-limited automotive belt appears to increase around a peak sled input acceleration of 9g. For a small female restrained by a rigid five-point harness, the likelihood of injury could be similar, if not greater (due to the increased restraint of the torso). Therefore, to stay below an injurious threshold, the maximum input sled peak acceleration selected for our small female PMHS tests was 8g. To investigate the sensitivity of the head and neck response to input sled severity, an additional input sled pulse with a peak acceleration of 3g was also selected.

Table 2.
Noted neck injuries from previous PMHS testing with an automotive three-point belt.

Sample	Sled peak accel.	Sled Δ velocity	Restraint details	UVA Run ID: Reported neck injuries
n = 2 females	4g	10 km/h	3-pt belt No load-limiter	470: anterior longitudinal lig. disruption (likely due to prep)
n = 3 females	6g	20 km/h	3-pt belt 1.3 kN load-limiter	None
n = 10 female	9g	30 km/h	3-pt belt 2 kN load-limiter	210: right C5/C6 facet capsule tear 211: left C5/C6 facet capsule tear 213: right C3/C4 facet joint disruption/instability 374: bilat. C7/T1 facet capsule tear, inter/supra-spinous lig. disruption
n = 3 male	9g	30 km/h	3-pt belt 3 kN load-limiter	302: bilat. C7/T1 facet dislocation, ligament disruptions 303: right C7/T1 facet disruption, C7 body fx (flexion), ligament disruptions

For each PMHS, the 3g pulse will be run prior to the 8g run. To check for injuries between sled runs performed on the same PMHS, post-run x-rays and physical examinations will be performed. To check for injuries after the 8g run, CT and autopsy will be performed.

Limitations of Original NBDL Data and Implemented Changes

Subject anthropometry Test subjects in the NBDL series were male volunteers from the U.S. military. As mentioned previously, this study aims to supplement the existing knowledge of male volunteer response with average male and small female PMHS in the NBDL configuration.

Instrumentation uncertainties There are instrumentation uncertainties in the NBDL data regarding attachment, tracking, and timing. The head and neck kinematics have been corrected by video analysis previously in literature by Thunnissen et al. [16], used subsequently for development of THOR-50M neck biofidelity targets [1]. For this study, PMHS kinematic data of the head and T1 will be captured by accelerometers and angular rate sensors at 10,000 Hz and motion capture data at 1,000 Hz. Motion capture data will be acquired with an optoelectronic motion capture system consisting of 20 cameras (Vicon MXTM, VICON, Centennial, CO, USA) and four-marker arrays rigidly attached to the skull and T1. Acquired kinematic data will be transformed using rigid body mechanics and coordinate transformations at each time step to track the corresponding skeletal landmarks. This method has been used in previous PMHS sled test studies [12]. While the restraint system ideally couples the surrogate to the seat with minimal displacement of the pelvis and torso, there may be some forward excursion. A right and left string potentiometer attached to the seatback assembly will be attached to the pelvis to measure any forward pelvis excursion.

For ATD neck evaluation, the time-histories of the head resultant acceleration, head x- and z-axis motion, head angle, and neck angle as well as ‘head lag’ (head vs. neck angle) and ‘moment-angle’ (moment about the occipital condyles vs. head-neck angle), will be assessed. For the calculation of the moment about the occipital condyles (M_{OC_y}), the free body diagram in Figure 6 and Equation 1 are used, including terms for the mass and moment of inertia of the head (m_H and I_{yy}), the distance between the head center of gravity and the occipital condyles ($x_{OC} - x_{CG}$ and $z_{OC} - z_{CG}$), and the kinematics of the head (a_x, a_z, and α_y). If and when the chin contacts the chest, another force is introduced and the calculation in Equation 1 is no longer valid. Therefore, the time of chin-to-chest contact will be recorded (via contact switch) to define the cutoff of moment-angle curves used for neck biofidelity assessments.

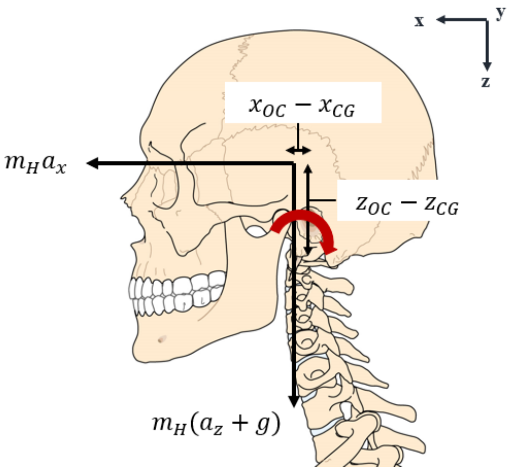

Figure 6. Free body diagram for calculation of the moment about the occipital condyles with forces and moment arms.

$$M_{OC_y} = I_{yy}\alpha_y - m_H a_x (z_{OC} - z_{CG}) - m_H(a_z + g)(x_{OC} - x_{CG}) \qquad \textit{Equation (1)}$$

RESULTS

Reconstructing NBDL Pulses

Two characteristic pulses were reconstructed at nominal peak accelerations of 3g and 8g by averaging the runs in Table 3. These nominal severities have a high sample size of runs in the original NBDL tests consisting of individual volunteers tested at all severities in similar initial positions, namely the "neck up chin up" (NUCU) position [17]. The resulting curves are shown in Figure 7. These curves were modified for input into our SESA sled software by left-shifting by 35 ms (to eliminate the initial zero acceleration portion of the curve), inverting, and extrapolating the curves, as needed to return to zero acceleration.

Table 3.
The run numbers from the original NBDL series used to generate the characteristic input pulses for our PMHS tests. The NBDL subject IDs, as well as the original NBDL run numbers ('Ref #' in NHTSA biomechanics database) are listed, with the NHTSA biomechanics database test number in parentheses.

Subject ID	Nominal 3g run(s)	Nominal 8g run(s)
H00118	LX3796 (1547)	LX3886 (1590)
H00120	LX3793 (1545)	LX3882 (1587)
H00127	LX3794 (1546)	LX3883 (1588)
H00131	LX3804 (1552) LX3840 (1570)	LX3894 (1594)
H00132	LX3805 (1553)	LX3997 (1649)
H00133	LX3798 (1549) LX3841 (1571)	LX3895 (1595)
H00134	LX3807 (1554) LX3842 (1572)	LX3890 (1593)
H00135	LX3808 (1555)	LX3898 (1596)
H00136	LX3809 (1559)	LX3901 (1597)

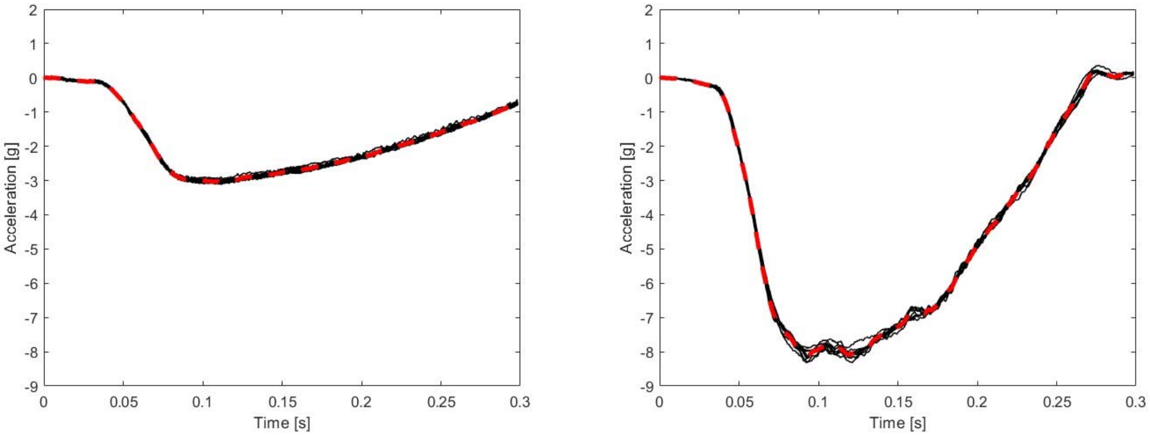

Figure 7. The original NBDL input sled pulses (black) and the averaged curves for PMHS tests (red) for the 3g (left) and 8g (right) severities.

Subject Anthropometry for Planned PMHS Tests

Table 4 describes the anthropometries of the planned PMHS tests to evaluate frontal neck flexion, which includes multiple small female PMHS and average male PMHS. The target mass and stature ranges for the small female subjects were 39-54 kg and 147-162 cm, respectively. Four of the subjects listed were over the mass target (of which one was within the target stature, two were on the border of the target stature, and one was over the target stature). The target mass and stature ranges for the mid-size males were 67-84 kg and 169-182 cm, respectively, to match reported anthropometry for NBDL volunteers [10,12,23]. All PMHS have been obtained and treated in accordance with the ethical guidelines established by the National Highway Traffic Safety Administration in Order 700-5, and all testing and handling procedures were reviewed and approved by the Institutional Review Board for Human Subjects Use established for the University of Virginia Center for Applied Biomechanics (Charlottesville, VA, USA).

Table 4.
Planned PMHS IDs and anthropometries.

UVA Subject ID	Sex	Age	Mass (kg)	Stature (cm)
982*	Female	78	63.0	170.2
1018	Female	77	61.2	162.6
1042	Female	75	49.9	160.0
1046	Female	69	58.0	162.6
1048	Female	71	42.6	165.1
TBD (pending)	Female	69	56.2	152.4
TBD (pending)	Female	84	45.4	165.1
1031	Male	76	76.6	172.7
1032	Male	72	74.4	177.8
1038	Male	62	67.6	177.8

*May be used as alternate if six small females cannot be acquired.

DISCUSSION

A critical review of the existing literature regarding the NBDL test series was performed. The limitations of the original testing motivated the current study and were addressed in the methodology proposed for PMHS tests. These improvements pertain primarily to an inclusive subject anthropometry, more robust instrumentation and data acquisition, and more thorough documentation of the methodology for reproducibility. Extensive consideration was given to replicating the original boundary conditions of the NBDL test series to allow for comparison between the historical volunteer testing and the planned PMHS testing of small females and average males, especially regarding initial positioning of the head and neck.

In the NBDL test series, lateral and oblique impact loadings were also investigated. This paper only reviewed the frontal impact volunteer tests and discussed the planned methodology for the corresponding PMHS tests. The buck and test equipment described for the PMHS tests were designed explicitly for adjustment to lateral and oblique impact directions. Therefore, the same review, analysis, and matched PMHS testing can be performed to establish response corridors for the head and neck for other impact loading directions.

Understanding how to relate the outputs of the original NBDL tests series and the current PMHS test series is not trivial. There are several innate differences in the studies, especially regarding the surrogates used. To generate biofidelity corridors that include the effect of active musculature for a variety of anthropometries (e.g., small females), functional data analysis is being considered to explicitly examine the explanatory variables, such as surrogate type (volunteer vs. PMHS), anthropometry (e.g., sex, stature, mass), and pulse severity. By doing so, the effect of active musculature may be isolated and used to supplement the biofidelity targets from the PMHS tests.

CONCLUSIONS

A methodology was developed to test multiple anthropometries of PMHS in a replicated NBDL configuration, with a focus on generating head and neck biofidelity corridors for the small female that include the effect of active musculature. The modern test series will introduce improvements to the NBDL methodology to mitigate data and knowledge gaps from the original test series. By addressing the data gaps described, we aim to develop small female neck biofidelity corridors that are applicable in multiple scenarios, accounting for a range of severities and muscle activation levels, which can be used in the development of ATDs and HBMs.

ACKNOWLEDGEMENT

US Department of Transportation National Highway Traffic Safety Administration provided both technical and financial support via Contract No. 693JJ921F000180. The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Department of Transportation or the National Highway Traffic Safety Administration. The United States Government assumes no liability for its contents or use thereof.

REFERENCES

1. Parent, D., Craig, M. & Moorhouse, K. Biofidelity Evaluation of the THOR and Hybrid III 50th Percentile Male Frontal Impact Anthropomorphic Test Devices. *Stapp Car Crash Journal* **61**, 227–276 (2017).
2. Wang, Z. J. Biofidelity Report of the THOR 5th Percentile Anthropomorphic Test Device. 165.
3. Elemance, LLC. *GHBMC M50-O Version 6.0 Users' Manual*. (2021).
4. Elemance, LLC. *GHBMC F05-O Version 5.1 Users' Manual*. (2020).
5. Ewing, C. L., Thomas, D. J., Beeler, G. W., Patrick, L. M. & Gillis, D. B. *Dynamic Response of the Head and Neck of the Living Human to —G_x Impact Acceleration*. https://www.sae.org/publications/technical-papers/content/680792/ (1968) doi:10.4271/680792.
6. Ewing, C. L. *et al.* Dynamic Response of the Human Head and Neck to +Gy Impact Acceleration. in 770928 (1977). doi:10.4271/770928.
7. United States. Department of Transportation. National Highway Traffic Safety Administration. Office of Advanced Vehicle Safety Research. *Interim Report to Congress — Crash Test Dummies*. https://rosap.ntl.bts.gov/view/dot/64706 (2022).
8. Lee, E. L. *et al. Biomechanical Response Manual: THOR 5th Percentile Female NHTSA Advanced Frontal Dummy, Revision 2*. https://rosap.ntl.bts.gov/view/dot/43641 (2020).
9. Ewing, C. L., Smith, M. J., Beeler (Jr), G. W., Patrick, L. M. & Laboratory (U.S.)), D. J. T. (Of the N. A. M. R. *Living Human Dynamic Response to -Gx Impact Acceleration: Accelerations Measured on the Head and Neck. II*. (Naval Aerospace Medical Research Laboratory, Naval Aerospace Medical Institute, Naval Aerospace and Regional Medical Center, 1970).
10. Ewing, C. L. & Thomas, D. J. *Human Head and Neck Response to Impact Acceleration.* https://apps.dtic.mil/sti/citations/AD0747988 (1972).
11. Ewing, C. L. *et al. The Effect of the Initial Position of the Head and Neck on the Dynamic Response of the Human Head and Neck to -Gx Impact Acceleration,*. https://apps.dtic.mil/sti/citations/ADA043031 (1975).

12. Ewing, L. *et al.* Effect of Initial Position on the Human Head and Neck Response to +Y Impact Acceleration. *SAE Transactions* **87**, 3151–3165 (1978).
13. Wismans, J. & Spenny, C. H. Head-Neck Response in Frontal Flexion. *SAE Transactions* **93**, 916–926 (1984).
14. Wismans, J., Philippens, M., van Oorschot, E., Kallieris, D. & Mattern, R. Comparison of Human Volunteer and Cadaver Head-Neck Response in Frontal Flexion. *SAE Transactions* **96**, 1323–1335 (1987).
15. Kallieris, D., Mattern, R., Wismans, J. S. H. M., & United States. National Highway Traffic Safety Administration. *Comparison of human volunteer and cadaver head-neck response in frontal flexion*. https://rosap.ntl.bts.gov/view/dot/29928 (1988).
16. Thunnissen, J. G. M., Wismans, J. S. H. M., Ewing, C. L. & Thomas, D. J. Human Volunteer Head-Neck Response in Frontal Flexion: A New Analysis. *SAE Transactions* **104**, 3065–3086 (1995).
17. Spenny, C. H. & John A. Volpe National Transportation Systems Center (U.S.). *Analysis of Head Response to Torso Acceleration. Vol. I - Development of Performance Requirements*. https://rosap.ntl.bts.gov/view/dot/11956 (1987).
18. Rife, J. P. *Impact acceleration and the human response: a history of the Naval Biodynamics Laboratory*. (U.S. Army Aeromedical Research Laboratory USAARL, 2018).
19. Mertz, H. J. & Patrick, L. M. Strength and Response of the Human Neck. in *Stapp Car Crash Conference Proceedings* vol. 15 207–255 (1971).
20. King, W. & Mertz, H. J. Human Impact Response: Measurement and Simulation. in (General Motors Research Laboratories, 1972).
21. Patrick, L. M. & Chou, C. C. *RESPONSE OF THE HUMAN NECK IN FLEXION, EXTENSION AND LATERAL FLEXION*. https://trid.trb.org/view/61565 (1976).
22. Ewing, C. l. & Thomas, D. J. Torque versus angular displacement response of human head to -Gdx impact acceleration. *Proceedings: Stapp Car Crash Conference* **17**, (1973).
23. Ewing, C. L. *et al.* The Effect of Duration, Rate of Onset, and Peak Sled Acceleration on the Dynamic Response of the Human Head and Neck. in 760800 (1976). doi:10.4271/760800.