A NEW NECK FOR MOTORCYCLE CRASH TESTING

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Paper Number 98-S10-W-27

ABSTRACT

A new test dummy neck has been developed specifically for motorcycle crash testing. This new neck is intended to replace the modified Hybrid III neck which is currently used with the Motorcyclist Anthropomorphic Test Device (MATD). The new neck is designed, with the aid of mathematical modeling, to address the unique posture and multi-directional biofidelity requirements of the MATD. It incorporates materials and features that are new to dummy neck design. It may be adjusted for a wide range of inclined torso angles that are typical of the large variety in motorcyclist riding postures. The performance of this neck is presented relative to established biomechanical neck data.

INTRODUCTION

The Motorcyclist Anthropomorphic Test Device (MATD), as the name suggests, is a dummy intended specifically for motorcycle crash testing. Based on the Hybrid III pedestrian dummy, the MATD has undergone several modifications in order to improve biofidelity, to improve injury sensing potential, to include an on-board data acquisition system, and to address the specific needs of the motorcyclist riding position [3, 4, 8].

The pedestrian model Hybrid III differs from the standard seated dummy in the areas of pelvis and lumbar spine. The pelvis soft tissue allows far greater articulation of the hip joints to accommodate a standing posture. The lumbar spine is straight rather than curved, and is less stiff in fore-aft and lateral bending. While these differences alone will allow the dummy to be positioned on a motorcycle, additional changes made to the Hybrid III in transforming it to an MATD include the following:

- Head skin extensions to accommodate a helmet and chinstrap,
- Widened and lightened spine box to house a self-contained data acquisition system,
- Hands that grip the handlebars,
- Crushable abdominal foam insert for penetration detection and measurement,
- String potentiometers for sternal deflection measurement,
- Frangible biofidelic knee assembly with fusible links for injury detection,
- Frangible femur and tibia for detecting leg fracture,
- Increased range of motion at upper and lower neck to accommodate riding posture,
- Addition of torsional module at the upper neck for biofidelic neck twist response.

The last two items are of primary interest here. Attention has been focused extensively on the dummy neck in order to investigate the potential for airbag systems to be used with motorcycles. With the recent widespread introduction of inflatable restraint systems in automobiles, there has become a new class of at-risk occupants called "out-of-position." The potential for airbags to offer motorcyclists protection in crash environments must be weighed against hazards similar to the "out-of-position" occupant in automobiles. Because there is no seat belt or pre-defined seating position for the motorcyclist, it becomes very likely that a rider will be out-of-position when a crash occurs. This, coupled with the added helmet, could put the motorcyclist at additional risk of neck injury.

Efforts to improve the biofidelity and function of the MATD neck have, to date, been based on the standard Hybrid III neck platform [4]. However, it was considered that further improvements to the MATD neck would require a more radical approach, such as the introduction of an all-new neck design. This paper describes the design and performance of such a new MATD prototype neck.

OBJECTIVES AND DESIGN FEATURES

One of the main differences between the motorcyclist riding position and that of the seated automotive driver is the angle of the torso. In an automobile, the torso is *reclined* from vertical, whereas the motorcyclist is *inclined* forwards. In both cases, the driver or rider tends to maintain his head level. Since most automobile seatbacks are set to roughly the same angle, and the driver sits at that angle at all times in the car, the range of neck angle adjustment for an automotive dummy is quite narrow. However, different motorcycles and riding styles dictate a wide range of motorcyclist postures, ranging from upright cruising to racing, requiring a test dummy neck with a wide adjustment range.

Research testing with the MATD has required positioning the dummy with back angles ranging from 15° to 65° forwards. This was confirmed by a brief investigation of volunteer riders on various styles of motorcycles in various riding postures [1]. Here, back angles were found to vary from 16° to 70° forwards. These back angles require that the neck be greatly extended in order to maintain the head level. The previous MATD neck had been modified at the upper and lower ends to allow more extension range, but this only allowed approximately 30°.

Additionally, this investigation of riders in various riding postures revealed that the location of the head relative to the torso changed with increased torso angle, not only the neck angle. Because the human neck curves in extension, it effectively gets shorter, and the position of the head migrates rearwards and downwards towards the torso. Plotting this location of the head relative to the torso, as the neck was progressively extended, revealed that the previous Hybrid III-based MATD neck, which pivoted at both ends, could not be positioned properly at large extension angles. It therefore became one of the primary goals of the new neck design to allow the neck to be set at large extension angles, and in doing so, position the head properly relative to torso[1].

The initial target range of neck positioning angles was chosen to be 15° to 65°. However, there was no biomechanical performance data available for these inclined postures that could be used to evaluate such a neck. The target range was therefore increased to 0° to 65°, allowing for validation at least in the most upright orientation.

The other primary goal was to achieve multi-directional biofidelity. Because the motorcycle dummy is not well coupled to its vehicle, the principal impact direction cannot be well predicted. For this reason, it is important that the dummy neck be biofidilic in several directions. The primary modes of biofidelity targeted for this neck design were in frontal flexion and extension, lateral flexion and torsion. While axial tension and compression were not identified as performance targets at this time, it was recognized that there should be the potential for at least some compliance in tension, precluding such features as a central neck cable.

The previous MATD neck incorporated an additional module at the upper end to increase the torsional compliance of the Hybrid III neck. It was intended that the new neck would not require such an additional module, and that torsional compliance would be built into the neck structure itself.

PERFORMANCE TARGETS

Described in the following are the biomechanical data that were the performance targets of the neck design. Graphical illustrations of this data are shown later under "Performance," in relation to the prototype neck response, in order to minimize repetition.

Frontal Flexion

Two criteria were chosen to measure neck performance in frontal flexion. The first was the kinematic data by Thunnissen et al [9] which describes the positions in time of the head centre of gravity and occipital condyles, based on upright seated volunteers with 0° back angles. This data illustrates the "head lag" phenomenon, based on the analog of the neck acting as a straight link between the first thoracic vertebra and the occipital condyles. A rearward acceleration to the base of the neck causes the head to translate forwards with little rotation, yet causing the neck to begin rotation, followed by coincident head and neck rotation.

The second criterion was the Mertz and Patrick [7] neck torque-angle relationship at the occipital condyles. However, this corridor was modified to account for the 0° initial position of the prototype neck, compared to the typically reclined seating position of the automotive occupant, upon which the corridor was based. It was modified by shifting the entire corridor by the approximate difference between the automotive seated back angle and the fully upright motorcycle rider. This was taken to be nominally fifteen degrees. The rationale was that if a seated automotive occupant's neck is already flexed more than a motorcyclist's, then the motorcyclist has more degrees of flexion available from their base position, and fewer degrees of extension. The corridor is simply shifted to account for this. However, it is recognized that this modification may be appropriate only within a modest range from the original Mertz corridor.

Extension

There is very little relevant kinematic data available for neck extension, so only dynamic criteria were chosen. The dynamic response target was the Mertz and Patrick [7] torque-angle relationship, again modified to account for the zero degree test posture.

Lateral Flexion

The ISO has developed response requirements for test dummies used in side impact [6]. Of these response requirements, peak lateral displacement of the head centre of gravity and the peak lateral head angle, based on volunteer experiments by Ewing et al [2], and analyzed by Wismans et al [10] were chosen as design targets.

Torsion

The same ISO requirements as above include a peak head twist angle, which occurs during lateral flexion, based on the above Ewing et al volunteer experiments. Additional

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[1] This must accomplished with good stability, to resist neck sag and creep, especially with the added weight of a helmet.

requirements on neck twist are described in the ISO requirements for certification of a motorcycle impact dummy neck [5].

DESIGN

Mathematical Modeling and Design Concept

A MADYMO model of a test dummy neck was created to assist in defining the component characteristics required of a new neck. The overall shape and length of the model were based on volunteer measurements mentioned earlier. The model joints were chosen with consideration for the eventual physical neck construction, which consists of elastomeric materials separated by thin aluminum disks, similar in concept to the Hybrid III. By iterating the stiffness functions of each elastomeric disk, the shape of each disk was designed for frontal and lateral directions.

The base of the neck attaches to the standard Hybrid III lower neck bracket, which is to be set permanently to its 7° extension mark. At the upper neck, a slider mechanism is used to allow an amount of fore-aft compliance, specifically in a forward flexion situation. The slider plate is attached to the standard Hybrid III upper neck load cell by a standard condyle pin. Front and rear nodding blocks are included to control head pivot at the occipital condyles.

Midway along the neck length, a locking adjustment is provided to set the head angle level for a given riding posture. This also changes the shape of the neck, and position of the head centre of gravity.

The neck and slider joint assembly total 1.63 kg. This compares favourably with the General Motors specification of 1.55 kg (GM drawing 78051-338) for the same assembly of the Hybrid III. However, it is anticipated that some parts of the slider mechanism in future prototypes could be made with aluminum, rather than steel, for weight reduction.

Deformable Disks

Four disks were chosen to represent bending of the human neck. Each disk is approximately 20 mm in thickness, and each has a unique cross-section. The shape of each disk was designed based on the required frontal versus lateral stiffness determined from the mathematical modeling. Laboratory material tests determined the basic bending responses of common geometric shapes, which were found to vary closely with the area moment of inertia of that particular shape. By scaling the desired response to the laboratory response, the desired moments of inertia for each disk in the frontal and lateral directions were obtained. Shapes were then designed to achieve these moments of inertia.

The result was a stack of disks that became progressively smaller from bottom to top, following the stiffness functions determined from the modeling. Additionally, the upper disks were made to be "egg-shaped" in cross-section, with the rear being wider than the front. The aim here was to encourage head twist with lateral bending.

The deformable disks were made from hot-cast Adiprene® urethane, by Uniroyal. An extensive review of candidate materials was conducted, which identified highly resilient materials with minimal damping as being desirable [1]. Such materials would likely result in a neck structure with good repeatability and reproducibility, due to the minimal viscoelastic characteristics in comparison to other elastomers. While human tissue tends to exhibit high damping and hysteresis, these qualities in a test device tend to introduce poor repeatability and rate sensitivity.

Slider Mechanism

The mathematical modeling demonstrated the impossibility for a stacked elastomeric neck to achieve the desired "head-lag" phenomenon in frontal flexion (see Figure 4). A stack of elastomeric disks, regardless of stiffness, tended to bend simply as a beam, causing the upper neck to travel in a circular arc, unless a rear control element pulled down on the rear of the skull. However, the presence of external control elements, such as cables or elastic bands, was undesirable due to the large extension set angles required for motorcyclist testing, and the presence of a helmet.

It was found that a relatively simple way to mimic the initial head translation in frontal flexion was by introducing a unidirectional sliding joint at the upper neck. The stiffness of this slider was determined by modeling to be relatively low compared to the neck structure, such that sliding of the head on the neck would occur before neck bending began. In this fashion, the head-lag would be observed without external control elements. The slider is controlled by a return spring made of the same material as the neck, and which acts as a bumper stop. A schematic of the slider is shown in Figure 1.

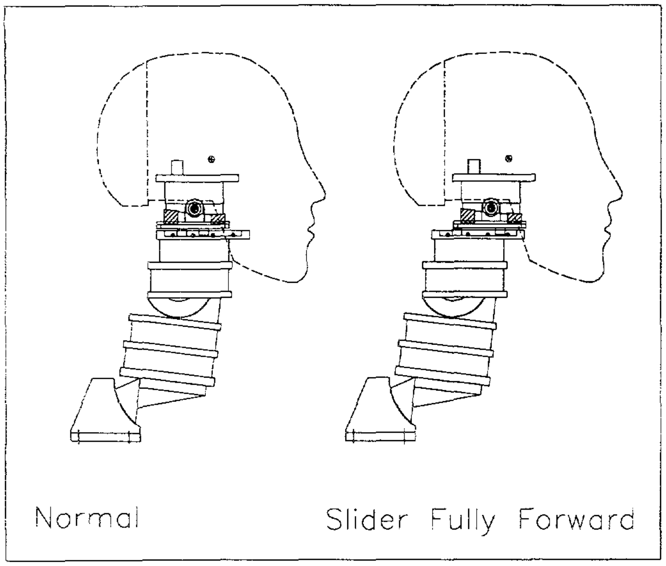

Figure 1: Slider mechanism.

Head Angle Adjustment

Head angle adjustment is provided by a spline-toothed interface and locking bolt. The splines form a circular arc, the centre of which is the virtual pivot location of the upper and lower neck that positions the head centre of gravity in the correct location for any head angle. Each spline tooth adjusts the head angle by 2.5°, from a 0° upright angle to a 65° inclined riding posture. Although infinite adjustment is not possible, the most that the head angle would be out of level would be half of the 2.5°, or 1.25°. A schematic of the head angle adjustment, together with the thoracic spine box, is shown in Figure 2.

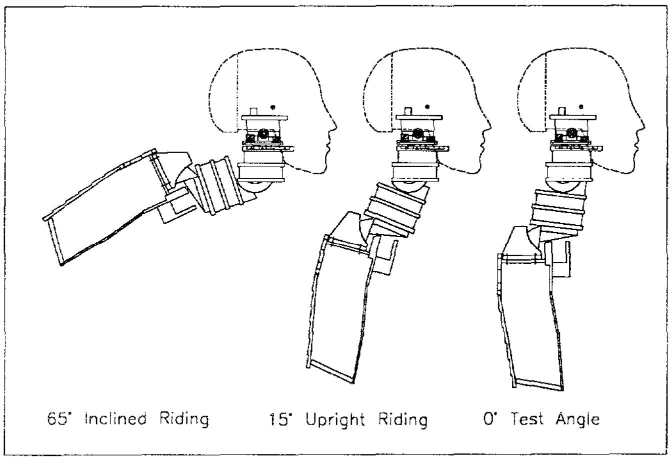

Figure 2: Head angle adjustment.

Nodding Blocks

Nodding blocks were incorporated into this design mainly due to compatibility with the existing Hybrid III upper neck load cell. The front nodding block is much stiffer than the rear, to assist with the "head lag" phenomenon. Both nodding blocks are made with the same urethane as the neck disks. Although the material properties of this urethane did not weigh heavily in this specification, it was felt that it would be better for manufacturing economics if the same urethane recipe could be used for all parts.

The rear nodding block was softened by making it triangular rather than rectangular, and by boring a hole through it. The nodding blocks sit in recessed pockets on the upper slider plate.

Neck Shroud

In order to meet the kinematic requirements for lateral flexion, the neck design calls for the neck to be rather slender in width. For this reason, it is felt that a shroud similar to that used with the current MATD neck shall be necessary for testing that might involve airbag interaction with the neck. The aim is to keep the airbag out from beneath the dummy's chin. The different profile of this new prototype, along with the articulation at the mid-length will not be compatible with current Hybrid III neck shrouds. It is intended that the shroud be designed only when all design iterations are finalized.

PERFORMANCE

Sled Testing

All acceleration-based testing was performed at the Defence and Civil Institute of Environmental Medicine (DCIEM) Impact Studies Facility, North York, Ont., Canada. Testing was conducted in forward flexion, lateral flexion and rearward extension. Note that DCIEM coded their tests in sequence. For this test series, test numbers ranged from 2960 to 2967

HyGe Sled Pin

The required acceleration pulse at the base of the neck for frontal and lateral flexion was based on the NBDL volunteer T1 acceleration measurements [9]. However, these pulses are very different than those normally achieved by a HyGe sled. This is because the T1 pulse is a function of the belt webbing and torso compliance of the volunteers. Therefore, it was necessary to have a custom sled pulse created.

This was accomplished by constructing a custom HyGe piston pin for the DCIEM facility. Although the frontal and lateral pulses are different, the characteristic shapes are similar, with a rapidly rising peak followed by a plateau of approximately half the peak (see Figure 3 and Figure 9). For economic reasons, it was felt that one pin could simulate both pulses by configuring the piston pressures accordingly. The following sections describe the actual sled pulses compared to the ideal T1 pulses. Note that the ideal T1 pulses [9] were used in the MADYMO modeling.

Instrumentation and Data Collection

The instrumentation and visual recording for this head/neck testing included the following:

- 3-axis head acceleration,
- 3-axis upper neck bending moments,
- 3-axis upper neck forces,
- 1 high-speed video camera (viewing lateral to sled travel),
- 2 high-speed film cameras (top and longitudinal views),

Data was collected at 8 kHz for 400 ms, following the protocol of SAE J211. Video was captured at exactly 500 fps, and film at nominally 500 fps. Targets were installed at the head centre of gravity, occipital condyles, and on the neck and lower neck bracket. For lateral flexion, where some head twist was expected, two outboard targets were mounted such that the head centre of gravity was exactly between them.

High Speed Video Analysis

All kinematic analysis was conducted by tracking targets with high-speed video. Software was used to track the targets on the dummy head and neck. This software provided the horizontal and vertical positions of each target relative to a chosen target on the sled. This data was then processed to compare the head-neck kinematics to the performance corridors.

Frontal Flexion (TESTS 2962, 2963)

Tests for frontal flexion were conducted at the zero degree (no extension) position of the neck adjustment. The Hybrid III lower neck bracket was set to 7° of extension, which is the permanent setting for this neck design.

Frontal Flexion Sled Pulse - The sled pulse for frontal flexion is shown below in Figure 3. The dashed line indicates the ideal volunteer average pulse of the NBDL volunteers. The custom pin reproduces this pulse quite closely, with notable differences being the slight plateau on the initial rise, the initial peak being slightly too low and narrow, and the third peak being higher and later. To prevent this third peak from being too high, the peak target sled acceleration was made 25 G with a velocity change of 17.0 m/s.

The sled pulse repeatablility is shown to be excellent (both pulses lie practically on top of each other).

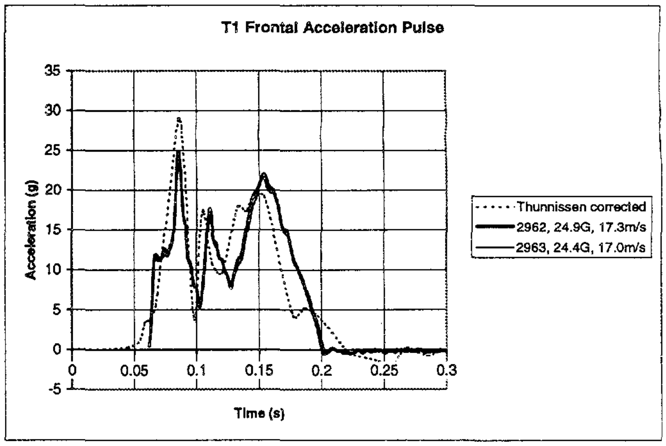

Figure 3: Frontal sled pulse.

Frontal Performance - The positions of the head centre of gravity and the occipital condyles are shown in Figure 4. The slider was tested both in the normal sliding and "locked" configurations, in order to investigate the effects of the slider joint. To lock the slider, the spring cavity was filled with a urethane block, limiting its sliding motion to no more than a few millimetres from its initial position.

The results for the sliding configuration show that the OC and CG follow the corridors very well until near full head excursion, where both demonstrate excessive forward travel. The locked configuration follows a similar path, except that it departs the corridor with excessive forward travel earlier, having less vertical travel.

From the high-speed video, the last acceleration peak is noticeably responsible for this excessive forward excursion late in the trajectory. The entire neck is seen to shear forwards as the head is pulled by this last peak. It is expected that if the acceleration profile had been more similar to the volunteer's pulse, where the predominance of the high acceleration was earlier in the event than later, the trajectory would not have shown such high forward travel.

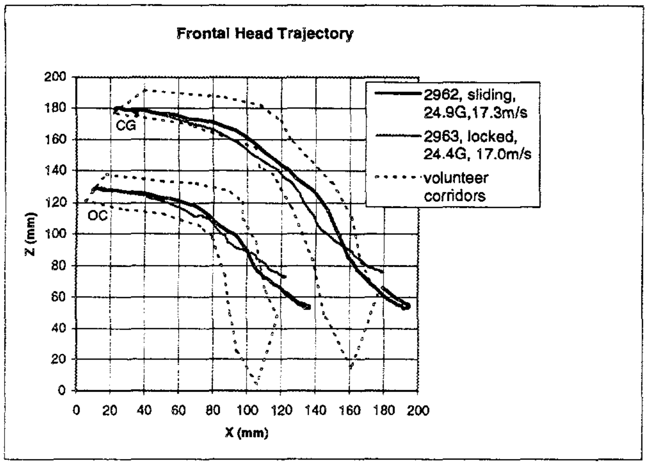

Figure 4: Frontal head and OC trajectories.

The difference between the locked and sliding configurations is illustrated better by Figure 5 where the head lag is more apparent. The slider mechanism allows the head to move forwards without rotating. Geometrically, this appears as the neck link pivoting through approximately twenty degrees, compared to the locked configuration where the neck link only pivots through approximately ten degrees before head rotation begins.

After the head begins rotating, the shape of both curves is nearly identical, and follows the shape of the corridor very well. It is anticipated that approximately 10 mm more sliding travel would situate the response inside the corridor.

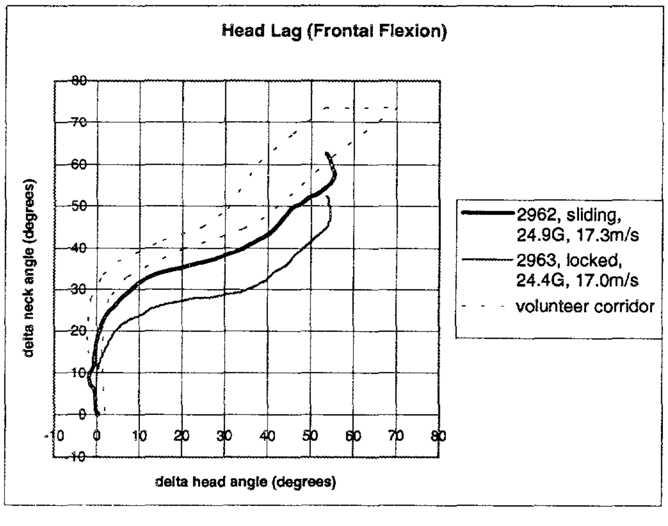

Figure 5: Frontal head lag.

The upper neck torque versus head angle response is shown below in Figure 6 compared to the Mertz modified bending response corridors. The reader will recall that the zero degree axis was shifted to account for the initial angle of the automotive seated occupant compared to a motorcycle rider. The results show that both the locked and sliding configurations satisfy this performance criterion. This corridor is for the loading condition only. Since the loading portion finishes at peak torque and head angle, the prototype neck is shown to fall completely within the corridor.

It should also be noted that the upper right portion of the corridor represents a person's chin contacting their chest. Since this prototype neck was mounted at the end of a cantilever, simulated chest contact was not possible, and therefore the latter half of the corridor is not relevant in the current testing.

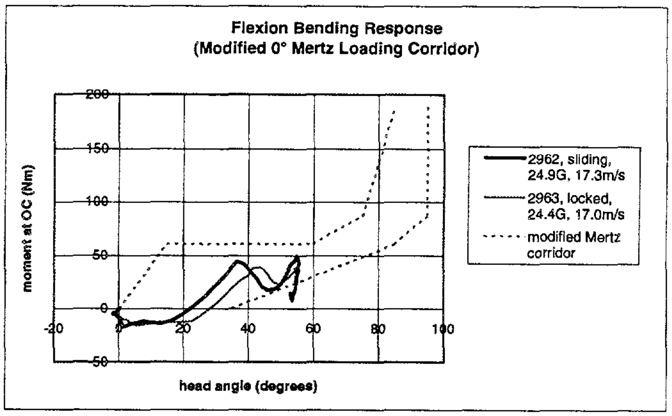

Figure 6: Flexion bending response.

Extension (TESTS 2966, 2967)

Tests for rearward extension were conducted at the zero degree (no extension) position of the neck adjustment.

<u>Extension Sled Pulse</u> - The extension sled pulse was intended to represent the Mertz and Patrick volunteer experiments, with a peak acceleration of 6G and velocity change of 4.4 m/s. While the exact shape of this pulse was unknown, the peak acceleration and velocity change were recreated well by the HyGe sled.

The standard HyGe "trapezoidal" pulse pin was installed for extension tests, as shown in Figure 7.

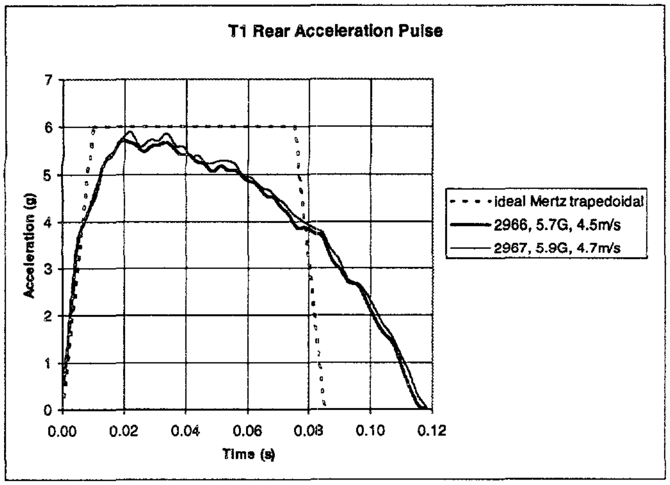

Figure 7: Extension sled pulse.

Extension Performance - The only criteria specified for rearward performance was the Mertz upper neck torque versus head angle relationship. The response of the prototype neck relative to this corridor, which is modified to adjust for the zero degree back angle of the upright motorcyclist, is shown in Figure 8.

Because the slider mechanism does not affect rearward response, there was no comparison made for a locked slider. The neck is shown to fall completely within the corridor, and to be repeatable in these two tests.

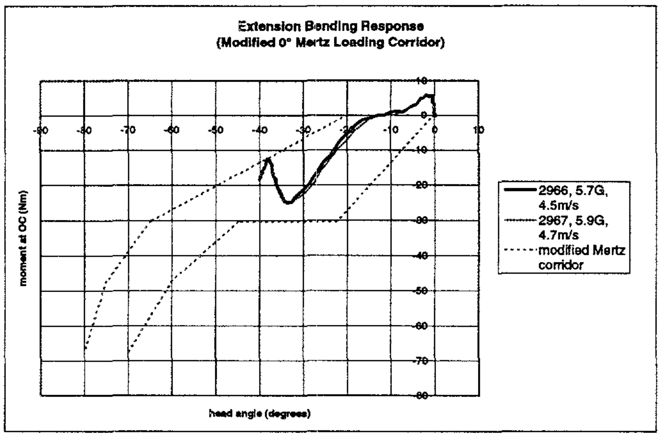

Figure 8: Extension bending response.

Lateral Flexion (TESTS 2960, 2961)

Tests for lateral flexion were conducted at the zero degree (no extension) position of the neck adjustment.

For forward flexion and rearward extension tests, it can be assumed that all motion will be in the mid-saggital plane, since the neck is symmetric about this plane, and the centre of gravity lies within it. But, for lateral flexion, where the head centre of gravity is not in line with the neck, and the neck is asymmetric, there is expected to be some out of plane motion, as well as torsion. For this reason, it becomes very difficult to resolve the position of the head centre of gravity from targets on the surface of the skull.

To remedy this, a thin rod was inserted through the skull's centre of gravity marking holes, and bent into "lollipops" on each side to mount targets. In this fashion, the video camera could see both targets, even if the head twisted. Having position data for the two targets throughout the event, the centre of gravity, which was exactly between the targets, could be tracked.

Lateral Flexion Sled Pulse - The lateral performance requirements, which comprise a series of peak measurements, do not necessitate as precise a test pulse as the frontal requirements. In fact, only a peak acceleration is dictated in the ISO lateral neck performance specifications [6]. However, the general characteristics of the frontal T1 pulse are also seen in the lateral pulse, where there is a sharp initial rise, followed by a series of lower peaks of relatively equal magnitude. Therefore, the HyGe pin that was designed for the frontal pulse was also used for the lateral pulse. The proper peak acceleration and velocity change set pressures for the sled were set after a few trial runs.

The resulting pulse is shown in Figure 9 relative to the NBDL volunteer pulse, corrected by Thunnissen et al. [9] to account for a non-rotating T1. The objective was to achieve a 14 G pulse with a velocity change of 7 m/s. In test 2960, the set pressure was too low, and the final velocity was too low. However, in the next test, the velocity change was very good. Peak accelerations were very good in both tests.

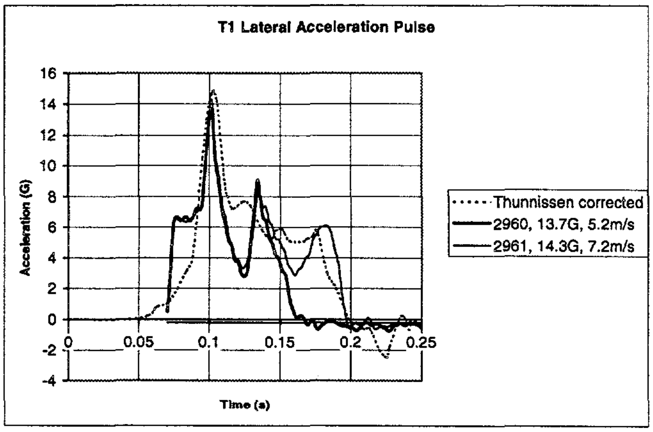

Figure 9: Lateral sled pulse.

Lateral Flexion Performance - The centre of gravity trajectory of the head is shown below in Figure 10. Run 2960 is shown to make it just to the volunteer window, but the velocity change of this pulse was too low. In run 2961, the centre of gravity trajectory fell within the window.

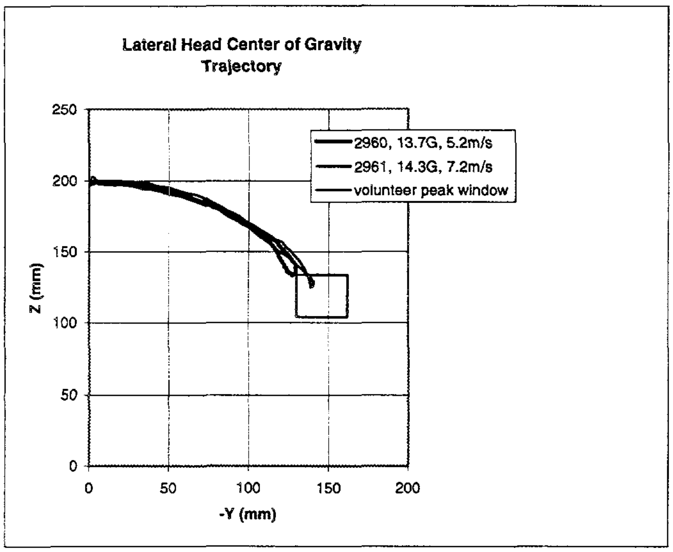

Figure 10: Lateral flexion head CG tragjectory.

The peak lateral flexion head angle achieved is shown in Figure 11. In both tests, the peak head angle exceeded the maximum allowable 59°, with 65° in test 2960 and 70° in test 2961.

The combination of the head CG being on the low side of the window and the peak head angle being over the limit suggests that the neck link should have rotated more, relative to the head link. In turn, this implies that the lower neck needs to be less stiff laterally, and the upper neck stiffer.

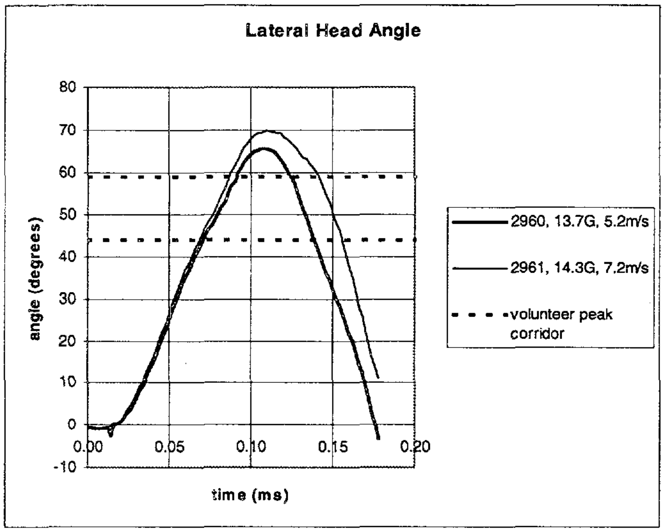

Figure 11: Lateral flexion head angle.

Torsion

Neck twist is specified in the ISO requirements as being from 32° to 45°, when tested in lateral flexion. However, film interpretation showed the neck twist, around the Z axis, to be only about 15°. This is supported by testing conducted in pure neck twist, similar to the certification tests for the MATD neck, specified by the ISO. Several tests were conducted at different torsion rates, and the resulting torque versus angle responses were very similar.

The response of the prototype in torsion is shown below in Figure 12. The two tests shown were done at a rapid twist rate (approximately 150°/second) shown in Test 1, and at a slower twist rate (approximately 60°/second) in Test 2. The results show that the neck is approximately 50% too stiff in torsion, compared to the target corridors. This excessive stiffness is supported by the lateral flexion test results, where the head needed to twist an additional 150% to fall within the established boundaries.

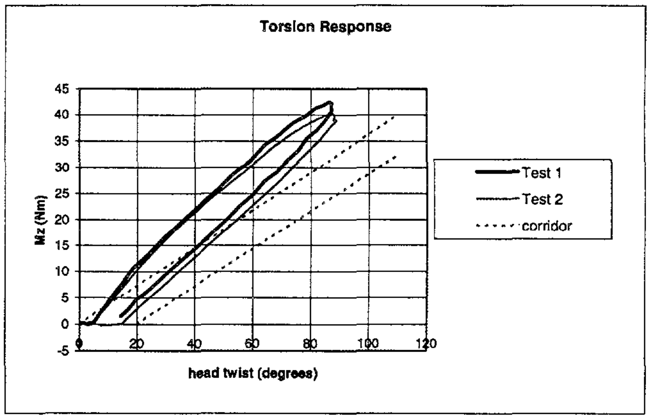

Figure 12: Torsion response.

Since the frontal, rearward and lateral responses of the neck are all reasonably good, there is the risk of upsetting these responses by changing the shape of the neck disks. Instead, it is felt that the torsional stiffness might be reduced by cutting selected disks through the midsaggital and/or coronal planes. In this manner, the torsional moment of inertia will be reduced, but the bending moments of inertia will remain unchanged. Some further experimentation shall be required to finalize the number and position of these cuts. There is a reluctance simply to add a torsional module, due to the combined complexity of a torsional/sliding joint.

SUMMARY

The following summarises the work completed, and provides recommendations for future work:

- A new prototype MATD neck has been designed, built and tested. This neck is intended to recognize a motorcyclist posture, as well as provide biofidelity in forward, rearward, and lateral bending, and in torsion.
- New features of this design include an adjustment for torso angles of 0° through 65°, as well as a slider mechanism to simulate the "head-lag" phenomenon
- The materials used in this design are hot-cast urethane for the deformable disks, aluminum for between these disks and for the adjustment mechanism, and steel for the slider mechanism.
- MADYMO modeling was used in designing the bending stiffness of the neck along its length.
- A customized HyGe sled pin was built to provide a reasonable representation of volunteers' T1 acceleration pulse.
- Testing was conducted in forward, rearward and lateral bending. Photographic and instrumentation data were collected.
- In forward flexion, the neck and slider mechanism showed good performance relative to the target corridors. A slight departure from the trajectory corridor is possibly due to deviation from the ideal acceleration pulse. Head-lag was introduced, although some increased sliding travel would be beneficial. Torque at the occipital condyles was within the corridors.
- In rearward extension, the torque at the occipital condyles was within the corridors. Kinematic performance data would be useful in complementing these requirements, but are not available at this time.
- In lateral flexion, the head centre of gravity traveled the correct distance, but head rotation was slightly excessive. This indicates that further optimization of the neck is required in lateral bending.
- Torsional response, both in lateral flexion as well as pure twist, showed the neck to be too stiff. It is anticipated that the torsional response might be softened by cuts in the urethane disks.
- A neck shroud similar to that currently used with the MATD shall be required for this neck to be used in airbag testing.

ACKNOWLEDGEMENTS

The author would like very much to thank Dynamic Research Inc., Torrance, California, for their support in the development of this dummy neck.

REFERENCES

1. Biokinetics Report R97-01, "Preliminary Design of the Next Generation MATD Neck," January, 1997.
2. Ewing, C. L., Thomas, D. J., Lustick, L., Becker, E., Willems, G., Muzzy III, W.H., "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," Proceedings of the 19th Stapp Car Crash Conference, 1975.
3. Gibson, T., Newman, J., Zellner, J., Wiley, K. "An Improved Anthropometric Test Device," Advisory Group for Aerospace Research and Development (AGARD), France, 1992.
4. Gibson, T., Shewchenko, N., Withnall, C.,/ "Biofidelity Improvements to the Hybrid III Neck," 14th International Technical Conference on Enhanced Safety of Vehicles (ESV), Paper 94-S1-O-13, Germany, 1994.
5. ISO/DIS 13232-3, "Draft Standard for Motorcycles – Test and Analysis Procedures for Research Evaluation of Rider Crash Protective Devices Fitted to Motorcycles; Part 3: Requirements for a Motorcycle Anthropometric Impact Dummy." August, 1995.
6. ISO/TC22/SC12 Document N455 – Revision 4 "Road Vehicles – Anthropomorphic Side Impact Dummy – Lateral Impact Response Requirements to Assess the Biofidelity of the Dummy," May, 1997.
7. Mertz. H., J., Patrick, L., M., "Strength and Response of the Human Neck." Proceedings of the 15th Stapp Car Crash Conference, SAE Paper No. 710995, SAE, Warrendale, PA, 1971.
8. St-Laurent, A., Szabo, T., Shewchenko, N., and Newman, J. A., "Design of a Motorcyclist Anthropometric Test Device," 12th International Conference on Experimental Safety Vehicle, Götberg, Sweden, 1989.
9. Thunnissen, J., Wismans, J., Ewing, C. L., Thomas, D. J., "Human Volunteer Head-Neck Response in Frontal Flexion: A New Analysis", Proceedings from the 39th Stapp Car Crash Conference, 1995. SAE paper no. 952721.
10. Wismans, J., Spenny, C.H., "Performance Requirements for Mechanical Necks in Lateral Flexion", Proceedings from the 27th Stapp Car Crash Conference, SAE Paper No. 831613, 1983.