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ABSTRACT

Anthropomorphic test dummies (ATDs) have been validated for the analysis of various types of automobile collisions through pendulum, impact, and sled testing. However, analysis of the fidelity of ATDs in rollover collisions has focused primarily on the behavior of the ATD head and neck in axial compression. Only limited work has been performed to evaluate the behavior of different surrogate models for the analysis of occupant motion during rollover. Recently, Moffatt et al. examined head excursions for near- and far-side occupants using a laboratory-based rollover fixture, which rotated the vehicle about a fixed, longitudinal axis. The responses of both Hybrid III ATD and human volunteers were measured. These experimental datasets were used in the present study to evaluate MADYMO ATD and human facet computational models of occupant motion during the airborne phase of rollover. Occupant motion predicted by the Hybrid III ATD computation models provided a good match to the temporal movement patterns and corridors of torso and head excursion measured in the volunteers. Differences in torso and head-neck posture were attributed to active muscle contractions in the volunteers. Simulations performed using the TNO human facet model, in the absence of muscle tone, predicted large head excursions and lateral neck and torso bending. These findings were attributed to the stiffer Hybrid III ATD neck and torso as compared to the spinal model incorporated in the human facet model.

Although it is possible to model active muscle forces using the TNO human facet model, the appropriate control schemes for coordinating muscle activity in the rollover environment have not been established. Without the implementation of appropriate muscular controls, the TNO human model appears to be best suited to high-force environments or low-force environments where the occupant is unconscious or incapacitated.

Our results indicate that among the currently available human computational surrogate models, the Hybrid III ATD provides the best prediction of occupant motion when compared to the available human volunteer data. These results have provided us the impetus to study future human models that incorporate active muscle control.

INTRODUCTION

It is widely accepted that rollover injury potential can be significantly reduced with seatbelt usage because of serious injuries associated with ejections. The increased incidences of vehicle rollover, combined with the improved restraint usage rates, have made restrained occupant rollover injuries a concern. Field data demonstrate that injury risk among restrained rollover occupants is elevated in rollover accidents involving a greater number of quarter revolutions (Hare et al., 2002; Eigen, 2003).

Understanding the nature and extent of head and neck motion with respect to interior vehicle structures has long been an objective of researchers in occupant crash protection and safety (Bahling et al., 1990; Arndt et al., 1995; Herbst et al., 1996; James et al., 1997; Moffatt et al., 1997; Ward et al., 2001). Development of a validated computational rollover model that includes all phases of rollover (trip, airborne, and ground contact) would be instrumental in predicting injury potential. An important step in such development is the identification of appropriate occupant computational surrogates.

To date, the authors are unaware of studies that examine the fidelity of human surrogate models for use in rollover accidents. Human volunteer responses in the rollover environment have been previously documented by Moffatt et al. (2003) using the ground-based Controlled Rollover Impact System (GB-CRIS). However, responses were presented only in terms of gross-head excursion.

In this study, we quantified the time-histories of occupant motions observed in the human volunteer experiments of Moffatt et al. (2003). These results were used to evaluate the biofidelity of two available human surrogate models for the prediction of occupant motion in the rollover environment: the TNO Hybrid III ATD and human facet models.

The Hybrid III 50^{th}-percentile male ATD is probably the most widely utilized surrogate for the evaluation of automotive safety systems in frontal crash testing. It is used in global NCAP testing, and in several safety standards, including FMVSS 208 and ECE R. 94.

The computational 50th male and 5th female used in the current study are multibody ellipsoid models. These models are based entirely on rigid body modeling. The geometry of these models is represented by ellipsoids, with the inertial properties contained in the rigid bodies of the models. Kinematic joints combined with dynamic restraint models are used to model the deformation of flexible components in these models. Contact force characteristics for the ellipsoids are used to represent the deformation of soft materials like the ATD skin and to describe the contact interactions within and between the models and their environment.

The components of the ATD models have been validated using ATD component tests, and the complete ATD models have been validated using full-scale sled tests, drop tests, and airbag deployment interaction (MADYMO Version 6.1 Model Manual, 2003).

MADYMO (Version 6.1) offers two general types of human models, facet models and finite element (FE) models. The former are principally multibody models similar to the ellipsoid models used for ATDs. However, these facet models are more advanced and employ rigid surface FE technology. In these models the outer surfaces are constructed using a mesh of shell-type massless elements used as a contact surface. This outer surface is connected to the rigid and deformable bodies that make up the multibody "skeleton" of the model. This "skeleton" consists of chains of rigid bodies connected by kinematic joints. The ranges of motion of each of the joints are based on published biomechanical data. The human facet model (HFM) is available for the small 5^{th}-percentile female and the 50^{th}-percentile male. The FE human models use both rigid bodies and deformable bodies, with all the important deformable parts modeled using FE. These models are able to capture global deformations and kinematics and can reproduce local deformations of components and flesh or skin.

According to TNO Automotive, the 50^{th}-percentile male HFM has been validated using volunteer tests for low severity loading and cadavers for higher severity loading. These tests include blunt impact tests and sled tests. The 5^{th}-percentile female HFM has been validated using published impactor corridors for SID2 ATDs, and using tests of some small female cadavers. Happee and co-workers have described this model validation in detail (Happee et al., 2000).

MADYMO indicates that the human models are multi-directional and are applicable for frontal, lateral, rearward, and intermediate impact directions, as well as for complicated scenarios like vehicle rollover. It is indicated that they are more biofidelic than dummy models that are developed for a particular loading direction. Specifically, the benefits of using the human body model are summarized as: improved biofidelity; multi-directional; scaleable; allowing the study of injury mechanisms at the material level; ease of incorporating biomechanical data; modeling of post-failure or fracture response; inclusion of muscle activity; and allowing postural analysis (MADYMO Version 6.1 Model Manual, 2003). The human models used in the current study are the 5th female and the 50th male HFM models.

In the present study, we evaluated the suitability of the available MADYMO ATD and human facet computational models for predicting occupant kinematics and head excursion during a rollover event in a ground based fixture.

METHODS

Vehicle roll kinematics and volunteer occupant motion during the CRIS experiments were quantified by digitizing the video. The measured vehicle kinematics were subsequently used as prescribed motion to drive a MADYMO simulation.

GB-CRIS FIXTURE

The GB-CRIS fixture was rotated from rest up to a steady-state roll rate of 220 degrees per second (deg/s) at a rate of approximately 22 deg/s^2. The vehicle was held for a period of approximately 6 seconds at this constant roll rate to facilitate steady-state evaluation of head and torso excursion. The total duration of this procedure was 17 to 20 seconds.

The volunteer testing employed stunt people, two males and two females, approximating the 50^{th}-percentile male and 5^{th}-percentile female, respectively. Frontal plane motion of the volunteers with respect to the occupant compartment was recorded by a digital camera mounted on the hood of the vehicle looking rearward.

VIDEO DATA

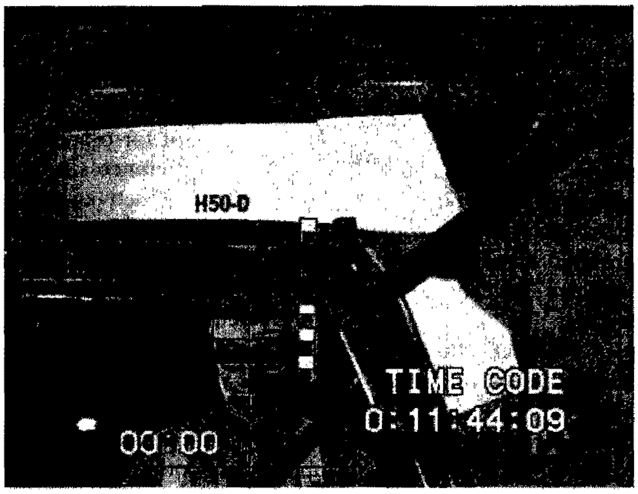

Figure 1 Digitizing template used to track volunteer motion in ground based CRIS fixture overlaid on a sample video frame.

Two-dimensional digital images were recorded at 30 frames per second. Each image was analyzed using ImageExpress MotionPlus Software (SAI, 2002) by utilizing a template to track the following anatomical locations: top of the head, chin, sternum, left and right shoulders. These points were digitized in the Y-Z plane relative to the vehicle's reference frame: +Y outboard and +Z upward. Because head motion was occasionally blocked by the forward margin of the roof rail and A-pillar, template matching of the surrogate's head and head-affixed wand was utilized to identify the position of virtual targets on the surrogate, located on the top of the head and on the chin. A similar approach was used to locate targets on each shoulder and at the top of the sternum. This approach is illustrated in Figure 1. The raw two-dimensional head and torso positional data were smoothed using the generalized, cross-validatory spline (GCVSPL) (Woltring, 1986).

The videos were also analyzed to determine the vehicle roll angle as a function of time. The resulting roll angle time history was then used as input to prescribe the vehicle motion in the MADYMO simulation.

COMPUTATIONAL MODEL

MADYMO version 6.1, published by TNO Automotive, running on a Pentium 4, 3.0 GHz computer with the Microsoft Windows XP operating system was used in the production of the simulations. MADYMO is a mathematical dynamic modeling software package that has been widely used in automotive crash engineering applications.

Using a MADYMO vehicle and interior model of the GB-CRIS fixture which was developed in Newberry et al., 2005, simulations were performed using measured vehicle roll kinematics and the following computational occupant models: 50th-percentile male Hybrid III and human facet model, and the 5th-percentile female Hybrid III and human facet surface model.

The seatbelt was modeled using the MADYMO recommended combination of linear and belt segments attached to a finite element belt system.

All the simulations started with the human surrogate model in a nominal seated position with no initial velocity or acceleration. The motion of the occupant is solely due to gravity and the prescribed roll rate of the vehicle about a revolute joint. No additional joint restraints were used to define the internal joint properties of the ATD and the HFM.

The same anatomical positions were tracked in the MADYMO simulations with respect to the vehicle reference frame as were digitized in the videos. The performance of the computational models was assessed by comparing motion time histories, and by the root mean squared (rms) error between an average of the two volunteers versus the results of the ATD or HFM simulation.

RESULTS

VOLUNTEER DATA

A qualitative review of the videos showed that the 5th-percentile females (subjects 2 and 4) appeared to rock inboard and outboard more than the 50th-percentile males (subjects 1 and 3). This appears to be related to the relative geometry of the occupants and the vehicle interior. It may also be influenced by the relative strength of the occupants. With the exception of subject 3, the occupants biased their heads and torsos inboard in an apparent effort to resist the centrifugal forces from the roll motion.

It appears that volunteers exhibited two distinct strategies in response to the forces produced by the rotating vehicle. Subjects either: (i) attempted to avoid outboard interior contacts by leaning inboard, or (ii) adopted a stiffness strategy and passively rocked back and forth under the influence of the gravity vector, but limited neck lateral bending through apparent neck muscle contraction.

Examples of these two strategies are shown in Figures 2 and 3. Figure 2 is a comparison of the neck angle with respect to the vehicle vertical as measured in the 50th-percentile males (subjects 1 and 3), while Figure 3 presents the torso angle with respect to the vehicle vertical for the 5th-percentile females (subjects 2 and 4). Positive angles are outboard and negative angles are inboard. Although there is a significant centrifugal acceleration of 0.5 g associated with the vehicle's rotation, the volunteers were able to compensate at this roll rate of 220 degrees per second. Subjects 1 and 2 employed an avoidance strategy by biasing their bodies inboard in an attempt to avoid interior contacts. Subjects 3 and 4 on the other hand were more affected by the centrifugal forces. Table 1 presents the time average of torso and neck angles for the volunteers. Subjects 1, 2, and 4 all exhibited a tendency to posture their necks in opposition to the centrifugal forces indicating active muscle resistance.

Table 1 Time average during steady state vehicle roll of the torso and neck angles, head and torso horizontal displacement of all volunteers.

Subject	Torso Angle deg	Neck Angle deg	Head Horiz cm	Torso Horiz cm
1 50th%tile male	-0.45	-10.01	0.55	5.10
2 5th%tile female	-2.90	-8.71	2.96	5.86
3 50th%tile male	2.89	0.32	7.37	8.49
4 5th%tile female	1.34	-5.71	6.83	8.00

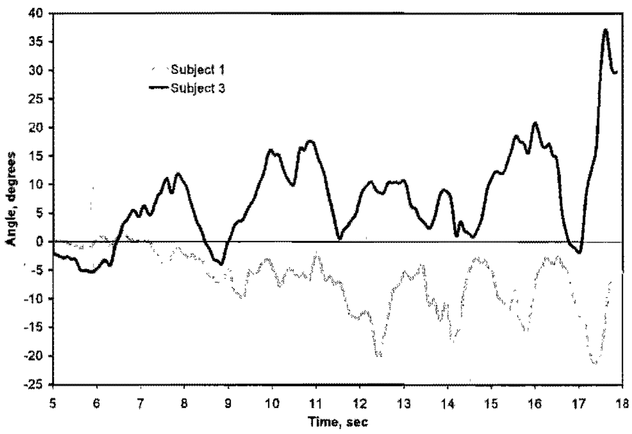

Figure 2 Comparison of 50th-percentile male volunteer stiffness strategies: Neck angle plotted as a function of time. Subject 1 exhibited an inboard bias and avoidance strategy with a peak inboard angle of approximately 20 degrees.

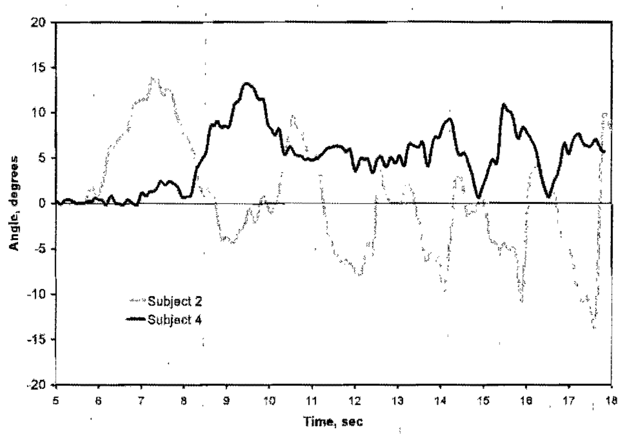

Figure 3 Comparison of 5th-percentile female volunteer stiffness strategies: torso angle plotted as a function of time. Subject 2 exhibited an inboard bias and avoidance strategy. Subject 4's torso was projected outboard in keeping with the centrifugal forces and exhibited a lack of oscillation indicating a stiffness strategy. However, she was able to maintain an inboard neck posture like subject 2 (see Figure 15).

COMPARISON OF MODELS TO VOLUNTEERS

Head and Torso Displacement

Figures 4 through 11 compare the head and torso displacement time histories for the volunteers, ATD, and HFM. The displacements are plotted relative to initial positions. Positive horizontal displacements are outboard and negative horizontal displacements are inboard, while positive vertical displacements are upward and negative vertical displacements are downward. The motion of the two male or two female volunteers are bounded by the shaded gray areas in the plots. The rms values are presented in the figure captions.

It is clear that for the male head displacements (Figures 4 and 5), the ATD (thick line) matches the volunteer data better than the HFM (thin line). When the final roll rate is achieved (, centrifugal forces are more significant and the extreme displacements exhibit by the HFM, as compared to the volunteers and ATD, are reduced.

The behavior of both the HFM and ATD computational models matched the temporal patterns of torso excursion observed in the volunteers; however, maximum inboard and outboard excursion differed (Figure 6 and 7). This finding is attributed to differences in torso stiffness in the models. The ATD produced realistic inboard torso excursions approximating the apparent muscular resistance of the volunteers. However, outboard excursion in the ATD was limited by contact between the stiff shoulder assembly and the door panel. In contrast, the compliance of the HFM produced realistic outboard excursions, but allowed far too much inboard movement. Both models provided reasonable predictions of torso vertical excursions, within average errors of approximately 3 cm.

Figures 8 through 11 show that the female models exhibit the same general trends. For head displacement, the ATD shows better agreement than the HFM. For torso displacement, both ATD and HFM models have similar rms values. The female HFM appears to have less oscillations compared to the male HFM as reflected by the lower rms values.

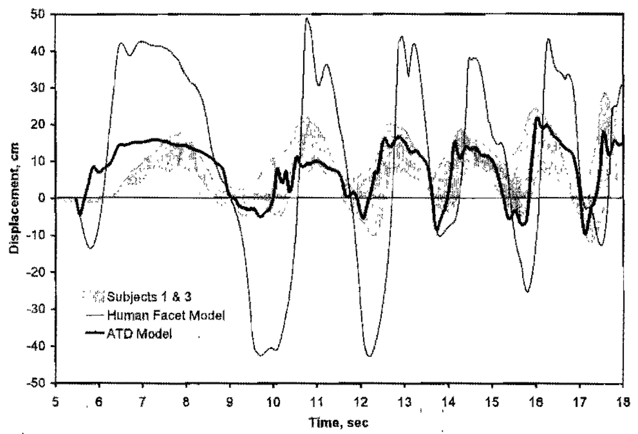

Figure 4 50th-percentile male head horizontal displacement time history. Root mean squared error versus volunteers: mATD rms = 6.21, mHFM rms = 23.95.

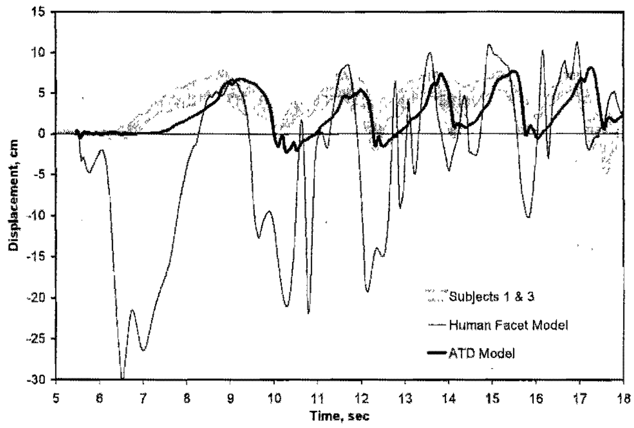

Figure 5 50th-percentile male head vertical displacement time history. Root mean squared error versus volunteers: mATD rms = 2.46, mHFM rms = 11.13.

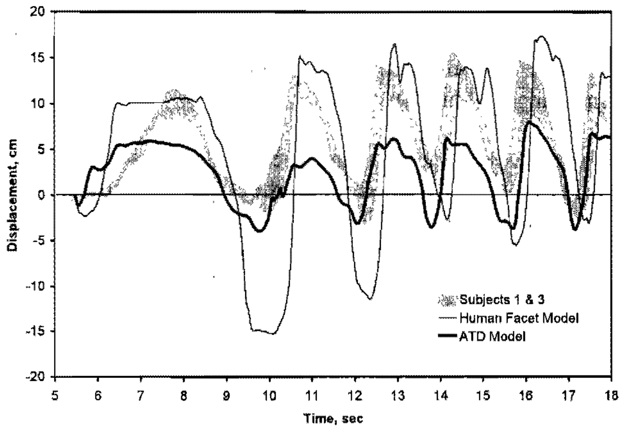

Figure 6 50th-percentile male torso horizontal displacement time history. Root mean squared error versus volunteers: mATD rms = 4.19, mHFM rms = 7.60.

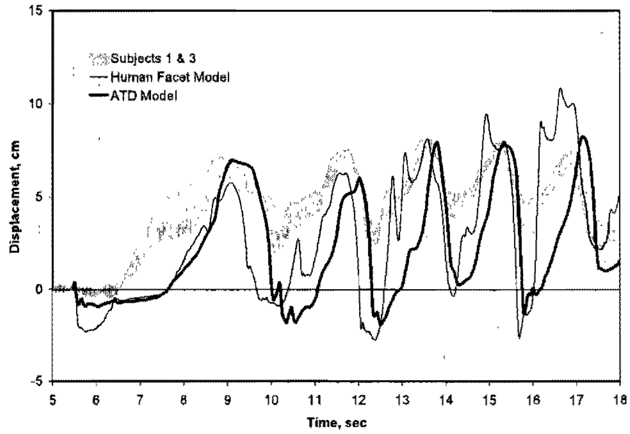

Figure 7 50th-percentile male torso vertical displacement time history. Root mean squared error versus volunteers: mATD rms = 3.20, mHFM rms = 2.96.

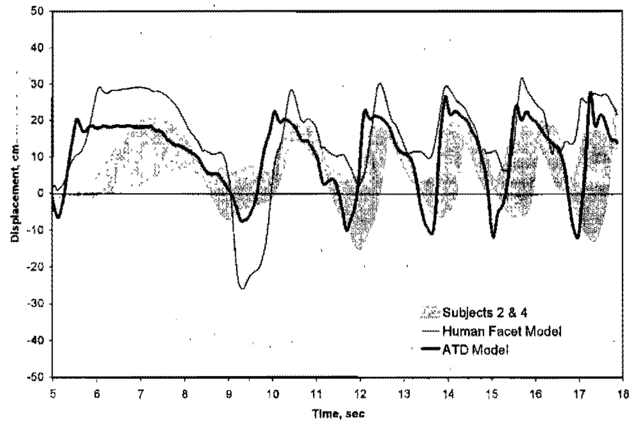

Figure 8 5th-percentile female head horizontal displacement time history. Root mean squared error versus volunteers: fATD rms = 10.98, fHFM rms = 14.97.

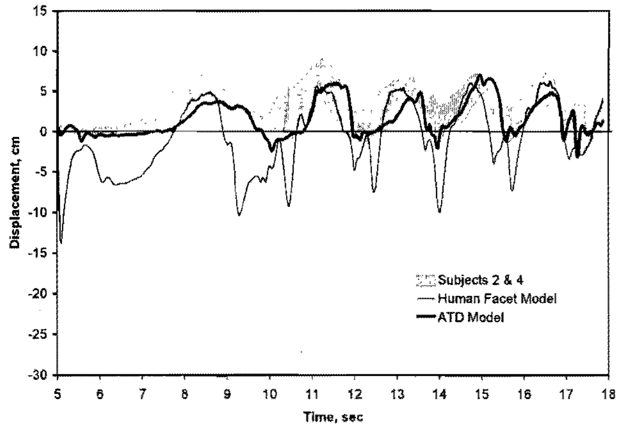

Figure 9 5th-percentile female head vertical displacement time history. Root mean squared error versus volunteers: fATD rms = 1.54, fHFM rms = 4.62.

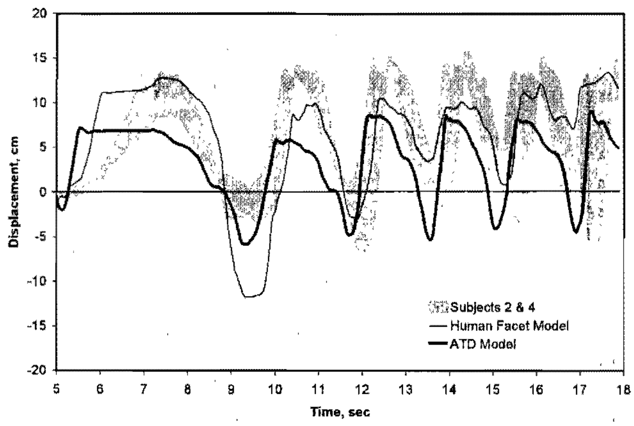

Figure 10 5th-percentile female torso horizontal displacement time history. Root mean squared error versus volunteers: fATD rms = 4.80, fHFM rms = 4.48.

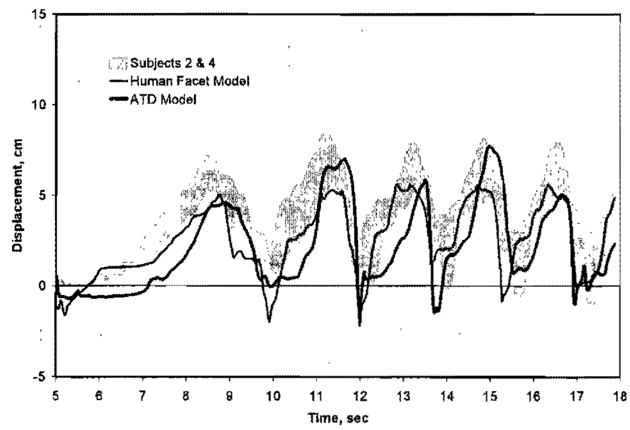

Figure 11 5th-percentile female torso vertical displacement time history. Root mean squared error versus volunteers: fATD rms = 1.98, fHFM rms = 1.39.

Torso and Neck Angle

Figures 12 through 15 compare the neck and torso angle time histories for the volunteers, ATD, and HFM. The angles are plotted relative to initial position. Positive angles are outboard and negative angles are inboard.

The male volunteer torso angles were slightly outboard and ranged approximately between –10 and +10 degrees. On the other hand, the ATD torso angle remained predominately outboard during the simulation while the HFM moved inboard and outboard continuously. Again, as in the head displacement data, the ATD better matches the volunteer data.

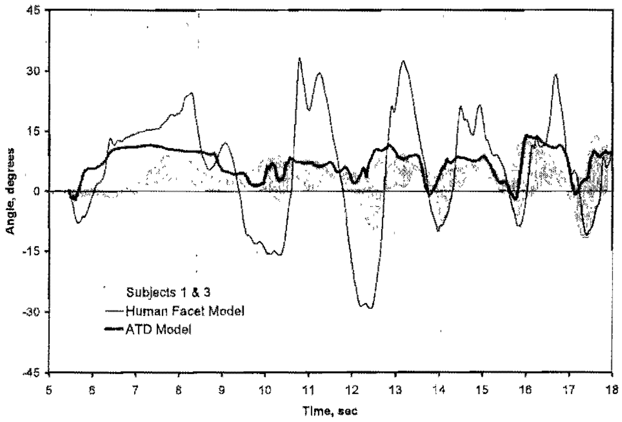

Figure 12 50^{th}-percentile Male torso angle time history. Root mean squared error versus volunteers: mATD rms = 6.54, mHFM rms = 13.45.

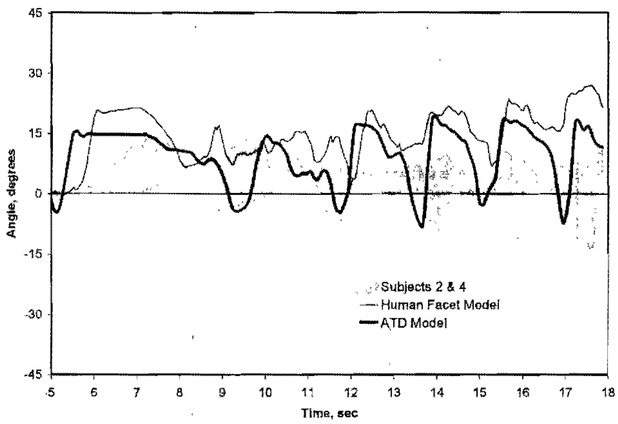

Figure 14 5^{th}-percentile female torso angle time history. Root mean squared error versus volunteers: fATD rms = 10.77, fHFM rms = 14.90.

The male volunteer and ATD neck angles were closer to vertical than the HFM, with the ATD biased outboard. The HFM neck was oscillating back and forth between both extreme ranges of motion.

The female volunteer torso and neck angles (Figures 14 and 15) again are more aligned along the vehicle's vertical than either the ATD or HFM. The ATD has a slightly smaller rms than the HFM and appears to have less erratic motion.

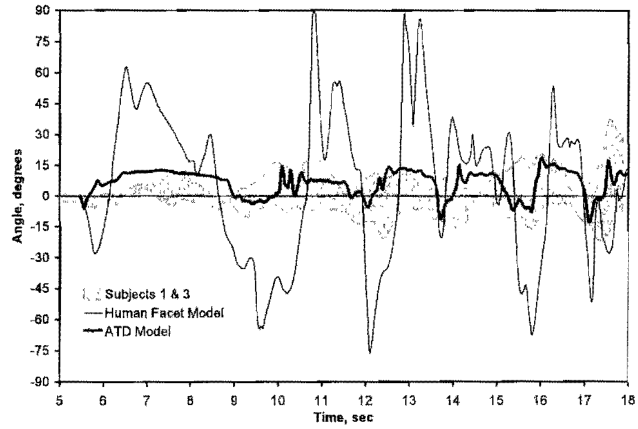

Figure 13 50^{th}-percentile Male neck angle time history. Root mean squared error versus volunteers: mATD rms = 11.01, mHFM rms = 37.00.

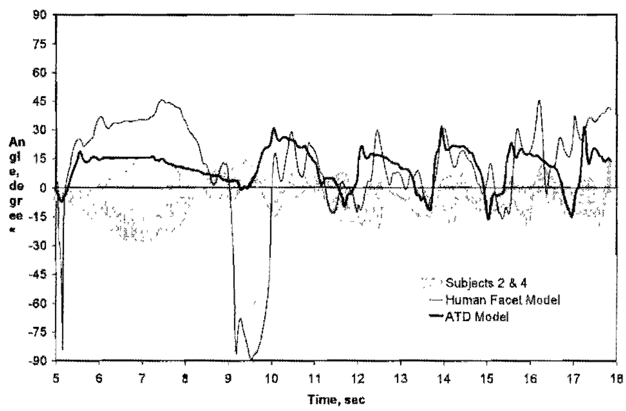

Figure 15 5^{th}-percentile female neck angle time history. Root mean squared error versus volunteers: fATD rms = 10.77, fHFM rms = 14.90.

The data presented above were replotted in the form of area charts to illustrate the head and torso occupant motion corridors for the volunteers and computational models (Figures 16 and 17). As shown in these summary figures, the ATD (in light gray) offers a much better prediction of the volunteer data response corridor than the HFM.

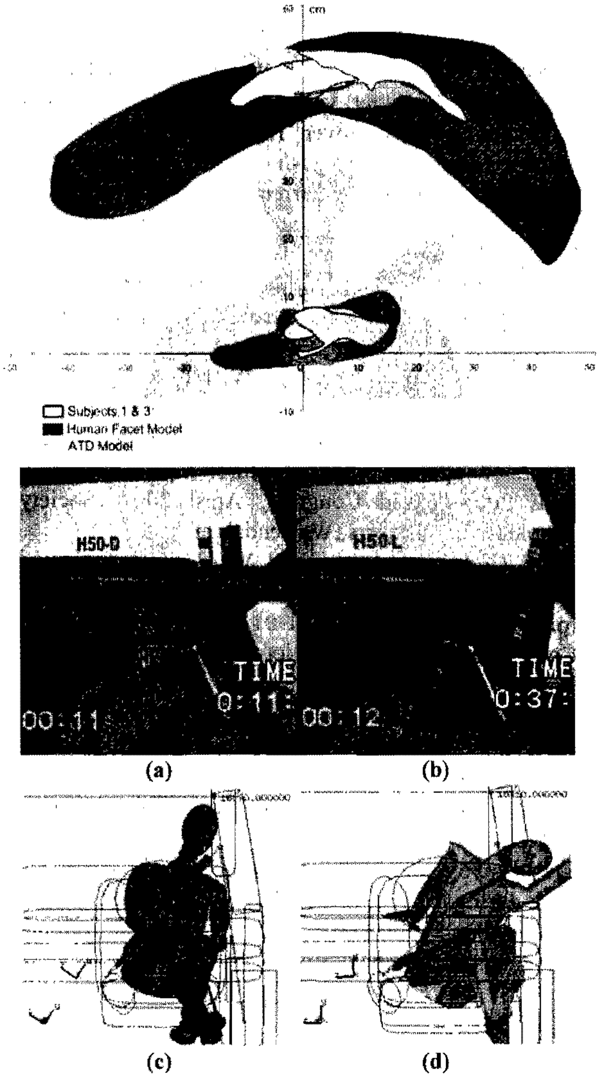

Figure 16 50^{th}-percentile male head and torso trace (above). Snapshots taken at an extreme outboard displacement for (a) Subject 1, (b) Subject 3, (c) Hybrid III ATD, and (d) human facet model.

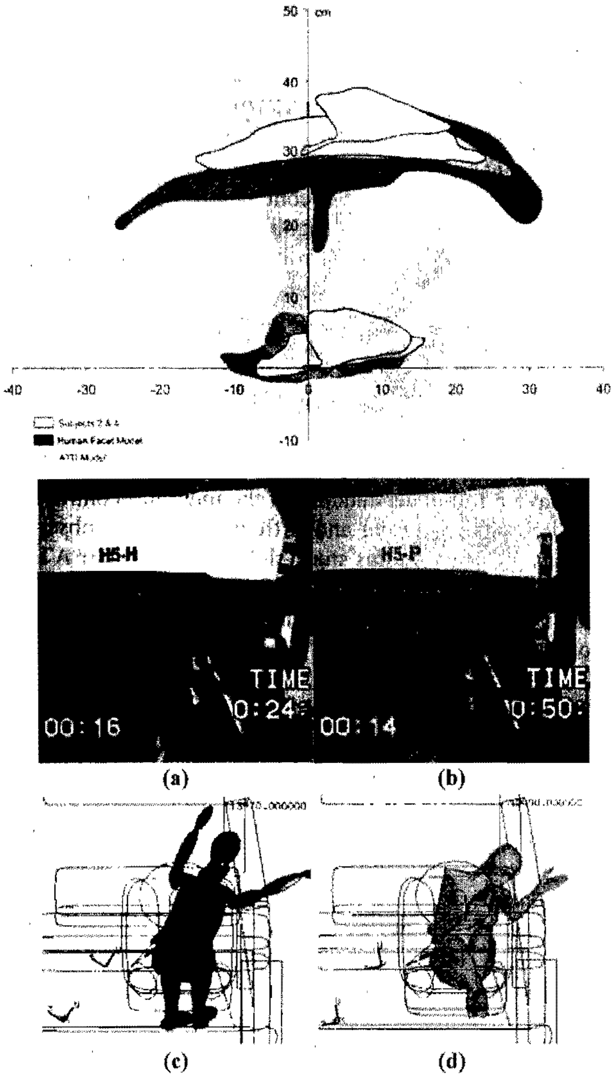

Figure 17 5^{th}-percentile female head and torso trace (above). Snapshots taken at an extreme outboard displacement for (a) Subject 2, (b) Subject 4, (c) Hybrid III ATD, and (d) human facet model.

DISCUSSION

Although the gravitational vector does not affect occupant motion during the airborne phase (Newberry et al., 2005), we chose to model the GB-CRIS fixture given the paucity of volunteer data, especially under dynamic conditions. It is important to note that the volunteers were stuntmen and were possibly resisting the centrifugal forces more strongly than most of the population. In order to better characterize the "typical" muscular response during rollover, additional volunteer studies may be necessary. Another limitation of the volunteer data is the relatively low roll rate of 220 degrees per second, a constraint imposed by the human subject testing review committee (Moffatt et al., 2003). In a related study, we have investigated occupant motion at roll rates up to 720 degrees per second by simulating the ATD in the GB-CRIS fixture (Newberry et al., 2005).

Our results demonstrate that active muscle contractions play an important role. In a recent human volunteer study involving fishhook steering maneuvers leading to vehicular tip-up (Yamaguchi et al., 2005), restrained volunteers were observed to actively posture their necks and lean their heads in opposition to the centrifugal forces and decelerations associated with the tip-up event. The role of active muscle contractions in shaping these kinematic responses was confirmed by analysis of electromyographic activity, which demonstrated consistent temporal patterns of activity in the sternocleidomastoid and trapezius, bilaterally.

Without muscle tone, the passive and pliable HFM moves too much. Albeit passive, the ATD lateral stiffness better approximates the muscle activity observed in the volunteer testing. At present, without a validated or empirical quantification of appropriate muscle controls for the HFM, the ATD is clearly the better choice for modeling occupant motion during the airborne phase. However, if an occupant were unconscious the unmodified HFM with its lack of muscle tone may be appropriate.

CONCLUSION

Most occupant kinematic models are for very short accident sequences for which muscle contraction and resistance is negligible considering the magnitude and duration of the accelerations involved. With rollover sequences involving airborne phase accelerations on the order of a few g's or less and lasting on the order of seconds instead of milliseconds, muscle control plays a larger role.

As demonstrated in the comparison of the computational results with the volunteer responses, occupant kinematics are strongly influenced by muscle activity. Although at present we do not have a full understanding of the muscular contractions that underlie the posturing and stiffening strategies observed, the results presented in this study show that the stiffer ATD is the better computational model for rollover until muscle contractions in the HFM model can be quantified and modeled appropriately.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

mATD, fATD: Hybrid III anthropomorphic test dummy, 50^{th}-percentile male and 5^{th}-percentile female respectively.

mHFM, fHFM: Hybrid male human facet model, 50^{th}-percentile male and 5^{th}-percentile female respectively.

Neck Angle: the angle with respect to vehicle vertical formed by the top of the head and the chin. + outboard, - inboard.

Torso Angle: the angle with respect to vehicle vertical formed by the midline perpendicular to the shoulders. + outboard, - inboard.