

Further Validation of Age-Dependent FE Models of a Mid-Sized Male Thorax

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ABSTRACT

The objective of this study was to further validate three previously-developed, age-dependent finite element models representing 35, 55, and 75 year old mid-sized males. The validation was based on comparisons with the following published tests involving post mortem human subjects: oblique thoracic and abdominal pendulum impact (4-10 m/s), oblique and lateral thoracic pendulum impact (2.5 m/s), and lateral thoracic pendulum impact (4.3 and 6.7 m/s). The responses of the models were compared to cadaveric response corridors and responses from specific cadavers similar in size and age. When compared to the cadaveric response corridors, the model responses were generally within those corridors. When compared to the responses of specific cadavers, the results were mixed. In some of the cases the model responses predicted the age-dependency of the cadaveric responses. In other cases, the model responses had the opposite trend of those of the cadavers. The comparisons of the model-predicted impact force, normalized chest compression, and viscous criterion to those of the cadavers were deemed acceptable. The model-predicted peak rib stress and strain for the different simulations were also reported and were compared to the injury outcome of the tests.

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INTRODUCTION

The number of people in the world who are 65 years old (YO) or older is projected to exceed 1.5 billion by the year 2050 (U. S. Census Bureau 2011). In the United States, people who are 65 years old or older are projected to constitute 35% of the total population in the year 2050 (He et al., 2005). Choi et al. (2009) defined a "super-aged" society as one in which at least 20% of its total population is 65 years old or older. By this definition, Italy, Japan, and Germany are already "super-aged" societies (Choi et al. 2009). Mertz and Dalmotas (2007) analyzed 1998-2005 NASS data and concluded that the "older" occupants (50+ YO) were more than twice as likely to experience serious-to-fatal chest injuries compared to "younger" occupants. Thus, the design of restraint systems in vehicles has been a research topic for a number of years (Zhou, Rouhana, and Melvin, 1996; Rouhana et al., 2003) to account for the increasing number of older-age people.

The geometry and properties of the different parts of the human body change with age. Biomechanical research relies on tests of post mortem human subjects (PMHS) to understand these changes. However, there are limiting factors associated with using PMHS data. Two of these limiting factors are availability (low sample count) and age bias

(skewed toward old age). Finite element (FE) modeling can help address these limitations. Numerical models of humans can represent any size, gender, or age. These models, if properly validated, can quantify tissue-level injuries to different body parts under various loading conditions.

During the last two decades, a number of whole-body FE models have been developed. In recent years, some researchers tried to study age and its effects using FE modeling. For example, the effects of age on the properties of different body parts have been investigated. Researchers varied the properties and geometry of some parts in the human body FE models to account for age. The studies of Tamura, Watanabe, and Miki (2005), Kent et al. (2005a), Dokko et al. (2009a), Dokko et al. (2009b), and Ito et al. (2009) are examples of that effort.

El-Jawahri et al. (2010) estimated that the Ford human body FE model represents an age of 53-59 years old mid-sized male. It was accordingly termed a "55 YO." This age estimation was based on the ribcage geometry and properties of the ribs and long bones. Subsequently, the geometry and properties of the ribs, long bones, intercostal muscles, flesh, and skin in that model were varied to reflect two additional ages: 35 and 75 YO mid-sized males. The resulting three age-dependent models were validated against PMHS tests. The

validation focused on the thorax because it was the region with the most age-related changes. In the previous study, only frontal thoracic and abdominal impacts and frontal sled impact tests were considered.

The objective of the current study was to further validate the thorax and abdomen of the age-dependent models by considering more test conditions. They included oblique thoracic impacts, lateral thoracic impacts, and oblique abdominal impacts. These tests were performed at different levels of severity.

METHODS

In the current study, no changes were made to the age-dependent models. The studies used for validating the age-dependent models were organized by impact category: oblique thoracic, lateral thoracic, and oblique abdominal. Details of the aforementioned test data used are discussed next.

OBLIQUE THORACIC IMPACT

Two studies were used to validate the responses of the age-dependent models in oblique impacts. In the first study, [Shaw et al. \(2006\)](#) performed oblique impacts to the thoraces of seven male cadavers whose average age was 74 ± 12 years. The impactor was a 23.4 kg, 152 mm diameter rigid cylinder. The impact speed was 2.5 m/s for all tests. The impact was delivered 30 degrees anterior of lateral at the level of 4th intercostal space. The responses were normalized to those of a mid-sized male. Force-time and force-deflection cadaveric response corridors were developed. External chest deflections were obtained from a chest-band placed on the thorax at the level of impact. Similar to the tests, the model-based magnitudes of the vectors connecting five pairs of diametrically-opposed nodes on the exterior surface and at the level of impact were monitored. One pair was along the line of impact and two pairs on each side of that line. The pair of nodes that yielded the maximum chest deflection was used for the chest deflection calculation. The model responses were compared to the corridors and to the non-normalized responses from specific cadavers.

In the second study, [Viano \(1989\)](#) conducted oblique thoracic impacts on 14 cadavers whose average age was 54 ± 14 years. The impactor was a 23.4 kg, 152 mm diameter rigid cylinder. Similar to Shaw et al.'s tests, the impacts were delivered 30 degrees anterior of lateral. However, the impacts were at the xiphoid level, about 75 mm below mid-sternum. The impact speed range was 3.6-10.2 m/s. The responses were normalized to those of a mid-sized male. The external chest deflections were determined from film analysis. Force-time and force-deflection response corridors were developed for three speeds: 4.4, 6.5, and 9.5 m/s. The F_{max} , C_{max} , and VC_{max} values were also reported.

The age-dependent models were used to simulate the tests for the aforementioned three speeds. As in the PMHS tests, the impactor was positioned 30 degrees anterior of lateral and

was 75 mm below the 4th intercostal space of the models. The chest deflection was obtained from the impactor displacement minus the displacement of a node diametrically along the line of impact on the exterior of the non-impacted side. The model responses were compared to the corresponding cadaveric response corridors and to the aforementioned peak values. In addition, the age-dependent model responses were compared to the non-normalized responses from specific cadavers that matched the size, gender, and age of the models. For that, the age-dependent models were used to simulate some of the tests at specific test speeds.

LATERAL THORACIC IMPACT

[Shaw et al. \(2006\)](#) performed lateral impacts to the thoraces of the same cadavers used in their oblique impact tests (average PMHS age 74 ± 12 years). The impact speed was 2.5 m/s for the lateral tests. The cadavers were impacted laterally at the level of 4th intercostal space level. The PMHS responses were normalized to the mid-sized male. Force-time and force-deflection cadaveric response corridors were developed. The chest deflections of the age-dependent models were calculated using the method previously described for the oblique impacts. The model responses were compared to the corresponding tests (corridors, peak values, and time histories).

The ISO TC22/SC12/WG5 developed test protocols and impact response requirements for assessing the side impact biofidelity of the head, neck, shoulder, thorax, abdomen and pelvis of test dummies, subcomponent test devices, and math models that are used to represent a 50th percentile adult male. The response requirements were the results of thorough evaluation of data selected from tests agreed to by experts as being the best and most up-to-date information available. Among those requirements, the ISO group developed force-time cadaveric response corridors for lateral thoracic pendulum impacts at 4.3 and 6.7 m/s (ISO, 1999). The 4.3 m/s impact speed corridor was based upon the results of three lateral impact tests from [Eppinger, Augustyn, and Robbins \(1978\)](#), and five oblique impact tests from [Viano \(1989\)](#). The 6.7 m/s impact speed corridor was developed from three lateral impact tests (ISO, 1999) and five oblique impact tests from Viano's study. The responses were normalized to those of a mid-sized male. The impactor used in all these tests was a 23.4 kg, 152 mm diameter rigid cylinder. The age-dependent models were used to simulate the tests for both speeds. The model responses were compared to the corridors.

OBLIQUE ABDOMINAL IMPACT

In addition to the thoracic impact tests, [Viano \(1989\)](#) performed oblique abdominal impact tests on the same cadavers (average age 54 ± 14 years). The impacts were delivered 30 degrees anterior to lateral and 150 mm below the mid-sternum level. The impact speed range was 3.8 - 9.9 m/s. The responses were normalized to those of a mid-sized male. The impact force was determined from the impactor

acceleration and mass. The external abdominal deflection was determined from film analysis. Force-time and force-deflection corridors were developed for three speeds: 4.8, 6.8, and 9.4 m/s. The $F_{\max}$, $C_{\max}$, and $(VC)_{\max}$ values were reported. The abdominal tests were simulated with the age-dependent models for the three speeds. The impactor was positioned 30 degrees anterior of lateral and 150 mm below the 4th intercostal space. The deflection was measured from the impactor displacement minus that of a node diametrically along the line of impact on the exterior of the non-impacted side. The responses of the models were compared to the corresponding cadaveric response corridors and to the aforementioned peak values. In addition, the model responses were compared to those of specific cadavers that matched the size, gender, and age of the models.

El-Jawahri et al. (2010) studied the effect of modeling rib fracture on strain. The same test conditions were simulated with and without fracture modeling. In that study, it was reported that the model-predicted peak strain values in both simulations (with and without modeling fracture) were slightly different. However, at the time when the first element was eliminated in the fracture model, the element with the highest strain in the no-fracture model was the same as the eliminated element. Accordingly, rib fracture modeling was not used in any of the simulations in the current study. This will be further addressed in the discussion.

RESULTS

Two methods were used to measure the deflection in the thoracic pendulum impact tests cited in the current study. In the studies from Viano and ISO the displacement of the pendulum was measured relative to a diametrically-opposed point along the line of impact on the exterior of the non-impacted side. In the study from Shaw et al. (2006), the maximum difference between the magnitudes of the original and deformed vectors connecting pairs of diametrically-opposed points along or around the line of impact was measured and referred to as the “chest deflection.” In all the studies considered for validation, the term “chest deflection” was used to represent the external thoracic deformation regardless of the way it was measured. This term will be used in the current study, while acknowledging the implicit contextual differences.

Moreover, for brevity in the present paper, the responses from the human body models will always be reported in order of increasing age. For example, if the peak forces were 1, 2, and 3 kN for the 35 YO, 55 YO, and 75 YO models, respectively, they would be presented as follows: “the age-ordered peak forces were 1, 2, and 3 kN.”

OBLIQUE THORACIC IMPACT

The force-time and force-deflection responses of the age-dependent models were compared to the cadaveric response corridors for the oblique thoracic impact (2.5 m/s) developed by Shaw et al. (2006) in Figure 1. The figure shows that the

35 YO response exceeded the force-time corridor except for the time period between 32 and 48 ms. However, the force-time curves of the 55 and 75 YO models were within the corridor. The onset of the response of the 55 YO model was at the upper limit of the force-time corridor. The figure also shows that the 35 YO model response was initially within the force-deflection corridor up to 9 mm of chest deflection; after that, the response exceeded the corridor. The entire response from the 55 YO model was within the force-deflection corridor. The response from the 75 YO model entered the force-deflection corridor at 10 mm of chest deflection. The response remained within the corridor even at the peak deflection.

Figure 2 shows the force-deflection curves of the age-dependent models compared to the non-normalized responses from specific cadavers (Shaw et al., 2006). In that study, each cadaver was subjected to two tests: oblique and lateral. The cadaveric responses shown in Figure 2 were from the cadavers tested first in oblique impact. The cadavers were 77, 79, and 87 YO, had masses of 66, 67, and 66 kg, and were 178, 180, and 175 cm tall. As seen from the figure, the thoracic stiffnesses of the 79 and 87 YO were similar, but both were higher than that of the 77 YO cadaver. The figure also shows that the response of the 75 YO model, which was closer in age to the cadavers, was similar to the responses of the 79 and 87 YO cadavers. The peak chest deflections were 67, 56, and 49 mm for the 77, 79, and 87 YO cadavers, respectively, compared to 47 mm for the 75 YO model. The peak impact forces were 0.8, 1.3, and 1.2 kN for the cadavers compared to 1.1 kN for the 75 YO model.

Figure 3 shows the force-time and force-deflection cadaveric response corridors and the corresponding responses of the age-dependent models of the oblique thoracic impact tests (Viano, 1989) for the 4.4 m/s impact speed. The 35 YO model response was within the force-time corridor, whereas the force-deflection response from the 35 YO model exceeded the corridor up to a chest deflection of 34 mm. The response remained within the corridor after that. The 55 YO responses were within both corridors. The force-time response of the 75 YO model was within the respective corridor; however the force-deflection response of the 75 YO model were within the corridor except for the first 10 mm of chest deflection.

Figure 4 shows the force-time and force-deflection cadaveric response corridors and the corresponding responses of the age-dependent models of the oblique thoracic impact tests (Viano) for the 6.5 m/s impact speed. The responses of the 35 YO model exceeded both corridors between 8-27 ms and 28-95 mm for the force-time and force-deflection response corridors, respectively. However the responses of the 55 and 75 YO models were within both corridors.

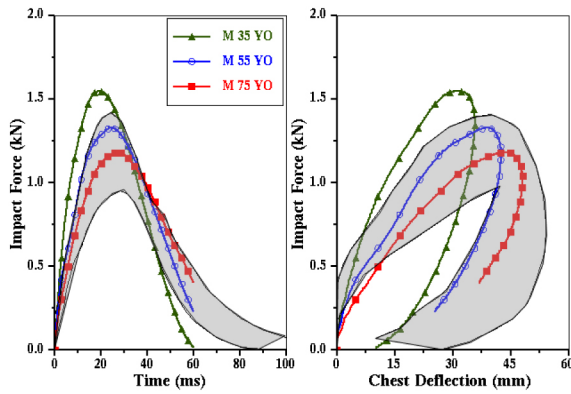


Figure 1. Force-time (left) force-deflection (right): Corridors vs. models (Shaw et al., 2006, oblique thoracic impact 2.5 m/s).

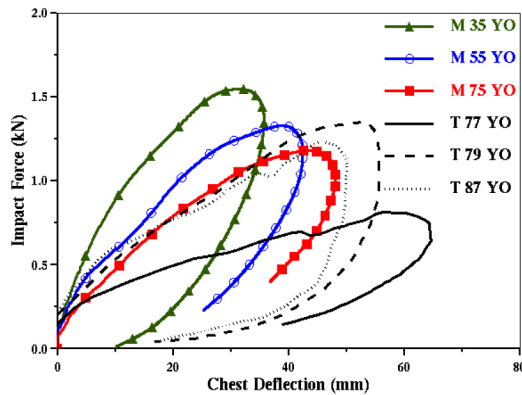


Figure 2. Force-deflection: Tests vs. models (Shaw et al., 2006, oblique thoracic impact 2.5 m/s).

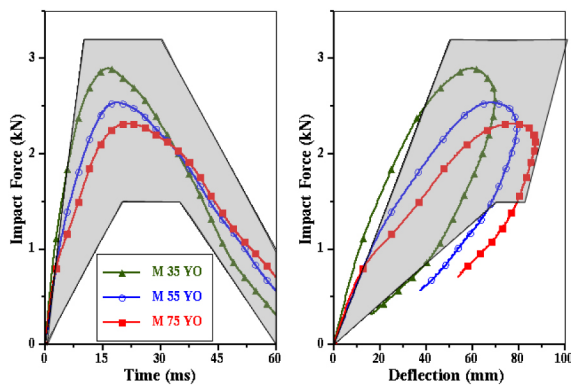


Figure 3. Force-time (left) force-deflection (right): Corridors vs. models (Viano, 1989, oblique thoracic impact 4.4 m/s).

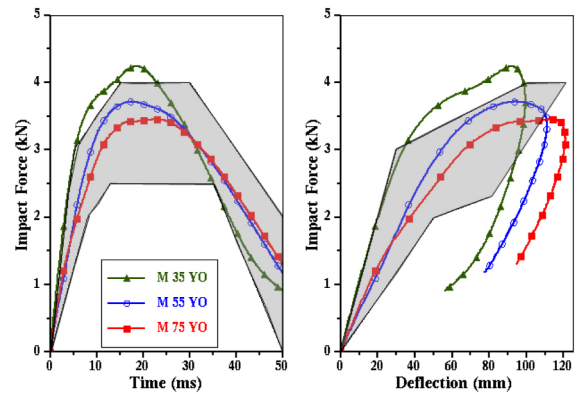


Figure 4. Force-time (left), force-deflection (right): Corridors vs. models (Viano, 1989, oblique thoracic impact 6.5 m/s).

Figure 5 shows the force-time and force-deflection curves of the age-dependent models and the corresponding cadaveric response corridors of the oblique thoracic impact for the 9.5 m/s impact speed. The force-time histories of the age-dependent models were within the corridor. The force-deflection traces of the models were also within the corresponding corridor. The onsets of the 35 YO responses were at the upper limits of both corridors.

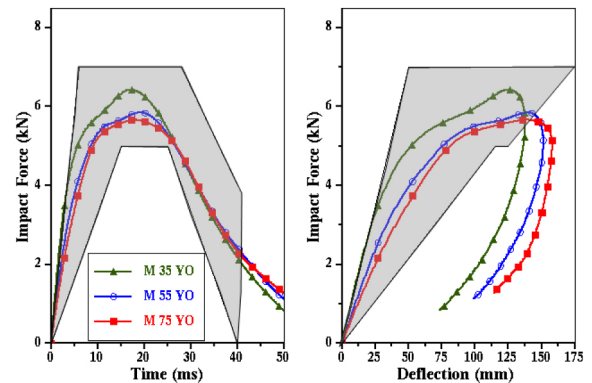


Figure 5. Force-time (left), force-deflection (right): Corridors vs. models (Viano, 1989, oblique thoracic impact 9.5 m/s).

Figure 6 shows the force-deflection traces of the age-dependent models compared to the non-normalized responses of two male cadavers. The cadavers were 37 and 64 YO, had masses of 68 and 76 kg, and were both 186 cm tall. The age-ordered masses were 79, 78, and 78 kg. The stature for the three models was 182 cm. The impact speeds of the tests were 4 and 3.8 m/s. The average speed (3.9 m/s) was used in the simulation. The figure shows that the initial thoracic stiffnesses of the age-dependent models were higher than those of the cadavers up to 18 mm of chest deflection. From 19 to 55 mm of chest deflection, the response of the 37 YO cadaver was between those of the 35 and 55 YO models. The thoracic stiffness of the older 64 YO cadaver was

significantly lower than that of the younger 37 YO cadaver. It was also more compliant than the 75 YO model. The peak chest deflections of the 37 and 64 YO cadavers were 63 mm and 94 mm, respectively, compared to the age-ordered deflections of 63, 72, and 80 mm for the models. The peak forces were 2.4 and 2.0 kN for the 37 and 64 YO cadavers, respectively, compared to the age-ordered model-predicted values of 2.6, 2.3, and 2.1 kN.

Similarly, Figure 7 compares the force-deflection curves of the age-dependent models and the non-normalized responses of two male cadavers for the 6.5 m/s impact speed. The cadavers were 63 and 64 YO, they had masses of 70 and 62 kg, and they were 174 and 171 cm tall. Although the cadavers were of similar age, their responses were different. The initial thoracic stiffness of the 63 YO cadaver was higher than those of the models, even that of the 35 YO model. However, the initial thoracic stiffness of the 64 YO was comparable to the 55 and 75 YO models and less than the 35 YO model. The peak chest deflections were 113 and 126 mm for the 63 and 64 YO cadavers, respectively, compared to 123 mm for the 75 YO model. The peak impact forces were 2.3 and 3.5 kN for the cadavers, compared to 3.7 kN for the 75 YO model.

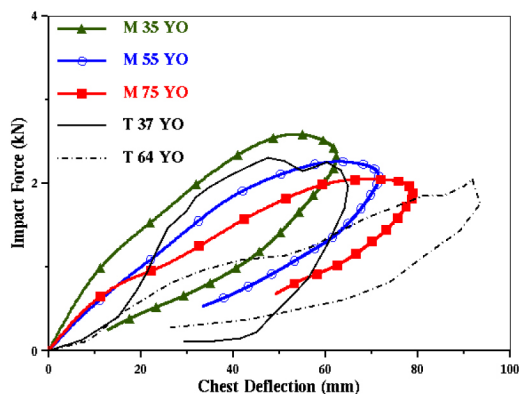


Figure 6. Force-deflection: Tests vs. models (Viano, 1989, oblique thoracic impact 3.9 m/s).

Figure 8 shows a comparison of the force-deflection responses of the age-dependent models and those from two male cadavers. The cadavers were 29 and 37 YO, had masses of 70 and 68 kg, and were 173 and 186 cm tall. The initial thoracic stiffnesses, up to 20 mm chest deflection, of both cadavers were similar to that of the 35 YO model, which is closer in age to both cadavers. The response from the 37 YO cadaver was closer to the 35 YO model than that of the 29 YO cadaver. The peak chest deflections were 142 and 132 mm for the 29 and 37 YO cadavers, respectively, compared to 137 mm for the 35 YO model. The peak impact forces were 6.3 and 7.8 kN for the cadavers, compared to 6.3 kN for the 35 YO model.

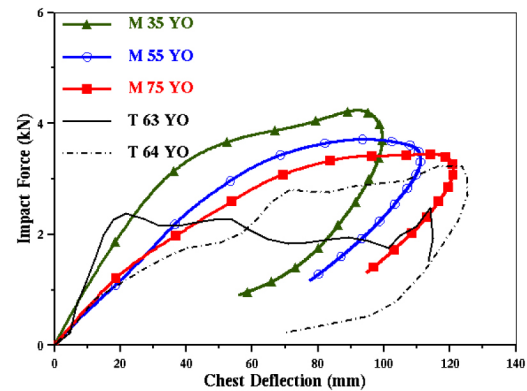


Figure 7. Force-deflection: Tests vs. models (Viano, 1989, oblique thoracic impact, 6.5 m/s).

LATERAL THORACIC IMPACT

Figure 9 shows the force-time and force-deflection traces of the age-dependent models and the corresponding cadaveric response corridors for the lateral thoracic impact (2.5 m/s) developed by Shaw et al. (2006). The 35 YO response exceeded the force-time corridor between 8-25 ms, which included the time of peak impact force. The force-time responses of the 55 and 75 YO models were within the corridor. The onset of the 35 and 55 YO force-time traces were close to the upper limit of the corridor. The figure also shows that the responses of the 35, 55, and 75 YO models were initially outside the force-deflection corridor but entered the corridor at 9, 18, and 23 mm of chest deflection, respectively. The response of the 35 YO model slightly exceeded the corridor at the peak deflection. After entering the corridor, the responses of the 55 and 75 YO models then remained within the corridor, even at their peak chest deflections.

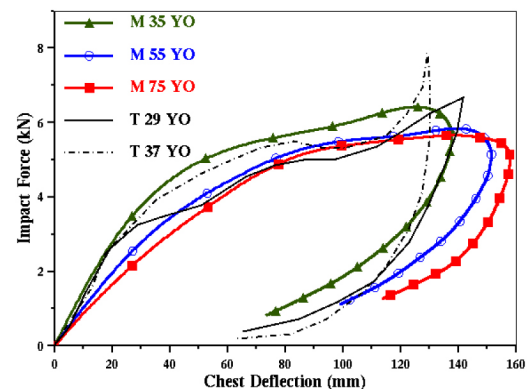


Figure 8. Force-deflection: Tests vs. models (Viano, 1989, oblique thoracic impact 9.5 m/s).