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Development and validation of a computer crash simulation model of an occupied adult manual wheelchair subjected to a frontal impact

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ABSTRACT

Wheelchairs are primarily designed for mobility and are not necessarily intended for use as motor vehicle seats. However, many wheelchairs serve as vehicle seats for individuals unable to transfer to a vehicle seat. Subjecting wheelchairs to sled testing, in part establishes the crashworthiness of wheelchairs used as motor vehicle seats. Computer simulations provide a supplemental approach for sled testing, to assess wheelchair response and loading under crash conditions. In this study a nonlinear, dynamic, computer model was developed and validated to simulate a wheelchair and occupant subjected to a frontal impact test (ANSI/RESNA WC19). This simulation model was developed utilizing data from two frontal impact 20 g/48 km/h sled tests, which consisted of identical, adult manual wheelchairs secured with 4-point tiedowns, occupied with a 50th percentile adult male anthropomorphic test device (ATD), restrained with a 3-point occupant restraint system. Additionally, the model was validated against sled data using visual comparisons of wheelchair and occupant kinematics, along with statistical assessments of outcome measures. All statistical evaluations were found to be within the acceptance criteria, indicating the model's high predictability of the sled tests. This model provides a useful tool for the development of crashworthy wheelchair design guidelines, as well as the development of transit-safe wheelchair technologies.

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1. Background

The Americans with Disabilities Act (ADA) [1] has been instrumental for wheelchair users seeking transportation in motor vehicles. There is an estimated 2.7 million wheelchair users (2002) in the US [2], of which many travel in motor vehicles while seated in wheelchairs that may not be designed for this purpose. As a result, during a motor vehicle crash, these wheelchair-seated individuals are at a higher risk of injury than occupants seated in original equipment manufactured motor vehicle seats.

In response to this problem, a voluntary industry standard was adopted that focused on improving the crashworthiness of wheelchairs used as motor vehicle seats (ANSI/RESNA WC19) [3]. This standard [3] specifies general design and performance requirements along with test procedures for wheelchairs used as seats in motor vehicles. In addition, WC19 requires a 20 g/48 km/h (30 mph) frontal impact sled test to evaluate the dynamic strength and assess the performance of occupied, forward-facing wheelchairs under crash conditions. This sled testing provides insights into the wheelchair and occupant loading and dynamics during a frontal impact that helps assess the wheelchairs crashworthiness. Additionally, the data acquired from such sled tests could facilitate design improvements and development of crashworthy wheelchairs, by studying shortcomings in current designs. However, dynamic testing requires the use of costly sled testing facilities, complex instrumentation and data logging systems in addition to costs associated with the purchasing of test wheelchairs and anthropomorphic test devices (ATD).

Computer simulations, a parallel or supplemental approach to dynamic testing, can offer an economical and versatile method for analyzing wheelchair and occupant crash response. However, caution must be used when employing computer models. A mathematical model is an approximate representation of a real world system and the better the model is at predicting the systems response, the better that model is at predicting results when studying changes to the representative system. However, the model's predictive power is largely dependent upon the robustness of the validation process [24]. Validation is utilized to determine how accurately a model represents a real world system and could be thought of as a similar concept as instrument calibration. Validation consists of an iterative process of comparing model outcomes to experimental outcomes, and then tuning the model so as to reduce discrepancies between the experimental systems and model outcomes.

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Computer simulation has been previously used to study wheelchair/occupant dynamics during frontal impact conditions represented by sled testing [17,19,20,27]. The validity of these wheelchair/occupant computer simulation models were established by visual comparison of kinematics between sled test and computer model along with comparisons of peak values of time history signals recorded during sled testing to those produced by the computer model. Although these models were not rigorously validated, they were valued as a reasonable representation of a wheelchair/occupant in a frontal impact scenario and were utilized for establishing design criteria for wheelchairs intended for use as motor vehicle seats. Additionally, these models were used to conduct parametric sensitivity analyses to determine the influence of various factors on wheelchair loading and occupant injury risk [17–21,25–28]. However, the validation process used in these models could have been more rigorous to assure an increased predictive power.

This study aims to develop a robustly validated frontal impact computer simulation model of a commercially available manual wheelchair, occupied by an adult ATD, which could provide researchers with a versatile, cost effective tool to further the development and design of safe and crashworthy wheelchairs.

2. Methods

2.1. Methods – sled testing

The performance of two identical, manual, adult wheelchairs (Invacare, Compass Allegro – mass 21 kg – fixed seating system) was previously evaluated by Leary [20] in accordance with the frontal impact testing procedures set forth in Vol. 1, Annex A of Section 19 ANSI/RESNA. In each test, the wheelchair was secured to the sled platform using a surrogate 4-point, strap type tiedown, while the wheelchair occupant, represented by a 50th percentile adult, male Hybrid III (76 kg) ATD was restrained by a surrogate, vehicle-anchored, 3-point occupant restraint system [33]. Instrumentation consisted of load cells fitted to the wheelchair tiedowns and occupant restraint system (WTORS) along with accelerometers located at the wheelchair center of gravity (CG), ATD head CG, chest and pelvis; all filtered as per SAE J211 [32]. Additionally, three high-speed (1000-fps) digital video cameras were used to record these tests. This sled testing provided impact response characteristics and kinematic data for the wheelchair and ATD, as well as WTORS loading; all utilized in computer model validation.

2.2. Methods – model development

A model consisting of the sled platform, wheelchair and ATD, was developed in MADYMO™ [31] to represent the above mentioned sled test configuration. MADYMO™ was selected over other simulation software as it is capable of analyzing a combination of multi-body and finite element (FE) segments allowing for an enhanced, realistic representation of the occupant restraints and wheelchair components. Also, MADYMO™ has successfully been used previously to develop models of manual, powered, surrogate [30] and pediatric wheelchairs [22]. The wheelchair and sled platform were represented in MADYMO™ by a combination of ellipsoids and planes with relevant dimensions, mass and inertial properties. The entire wheelchair was represented by 32 ellipsoids joined together using a combination of revolute, slip, and fixed joints. Belt segments were used to model the 4-point strap type tiedowns used to secure the wheelchair to the sled platform.

The Hybrid III 50th percentile male ATD available within MADYMO™ represented the wheelchair-seated occupant in the model [34]. The ATD was restrained by a 3-point vehicle-anchored belt system (lap and shoulder belt) modeled using FE belts. The FE belts provide an enhanced belt fit and realistic simulation, by allowing sliding between belts and contacting surfaces. This developed model (Fig. 1) was subjected to a 20 g/48 km/h (30 mph) frontal impact crash pulse using data recorded from sled testing (Fig. 2).

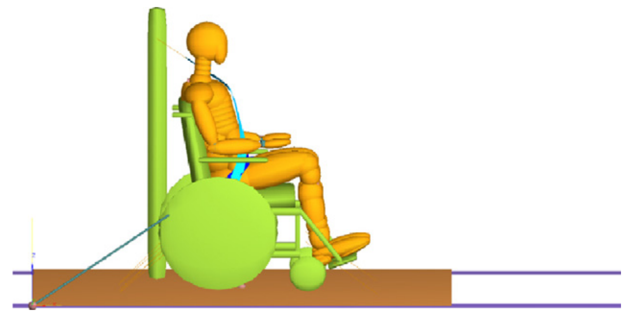

Fig. 1. MADYMO™ model of secured wheelchair and restrained occupant on sled platform.

2.3. Methods – model validation

Following a similar trend established by previous studies to test the validation of computer simulation models, visual comparisons of kinematics and outcome measures from sled testing and the computer model were employed in this study [4–17,20–22].

The first step in the model validation consisted of visual comparisons of the gross motion of wheelchair and ATD from the sled tests vs. those predicted by the computer model. Next, the model's predicted time histories of force and acceleration data were superimposed over respective sled test time history min–max corridors for visual comparison. These min–max corridors were established from the time history data recorded from the two sled tests. Adjustments and tuning of model parameters including, but not limited to, changes in the stress–strain, stiffness and damping characteristics of the occupant belt, tiedowns, seat, seatback and tires were performed until time history plots shared similar trends across sled tests and model.

The rigor of statistical analysis has not typically been conducted to prove computer model validation within the wheelchair transportation field, with the exception of a few studies [19]. However, statistical analysis can quantify the association between outcome measures of the sled test and computer model, and hence was utilized in this study. Statistical assessments (Table 1) were employed in comparing sled test data (mean value of the two sled tests) to computer model outcome measures (Table 1) for time histories of nine outcome measures, including the acceleration time histories of the wheelchair CG, ATD head CG, chest and pelvis, and force time history signals of the occupant lap belt, shoulder belt and wheelchair rear tiedowns (front tiedowns were not evaluated since front tiedown loading is negligible in frontal impacts). Additionally, the statistical tests were used to compare the two sled test time histories against each other, to evaluate the variation between the two sled tests. The statistical tests used, their definitions and the range of possible test outcome values are shown in Table 1 [35]. The statistical tests ('r', 'r^2', Peak Value and Time Occurrence, MAPE and Standard Deviation of Absolute Percentage Error) were calculated by performing a point-by-point analysis over the entire time history curve.

3. Results

A side-by-side comparison of time sequenced images (20 ms apart) from the high-speed videos of the sled tests and the com-