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Development and validation of rear impact computer simulation model of an adult manual transit wheelchair with a seated occupant

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ABSTRACT

It has been shown that ANSI WC19 transit wheelchairs that are crashworthy in frontal impact exhibit catastrophic failures in rear impact and may not be able to provide stable seating support and thus occupant protection for the wheelchair occupant. Thus far only limited sled test and computer simulation data have been available to study rear impact wheelchair safety. Computer modeling can be used as an economic and comprehensive tool to gain critical knowledge regarding wheelchair integrity and occupant safety. This study describes the development and validation of a computer model simulating an adult wheelchair-seated occupant subjected to a rear impact event. The model was developed in MADYMO™ and validated rigorously using the results of three similar sled tests conducted to specifications provided in the draft ISO/TC 173 standard. Outcomes from the model can provide critical wheelchair loading information to wheelchair and tiedown manufacturers, resulting in safer wheelchair designs for rear impact conditions.

1. Background

The Americans with Disabilities Act (ADA) [1] was introduced in 1990 to assure that all people with disabilities are granted equal opportunity to integrate into society. Part of the ADA mission is to establish equivalent safety with respect to transportation, so that all individuals may pursue employment, education, and recreation. There are 3.3 million adult wheelchair users in the U.S. [2], and a substantial number may not be able to transfer from their wheelchair to a motor vehicle seat during transport. These wheelchair users should have the same level of transportation safety as persons using motor vehicle seats.

Wheelchairs are primarily designed to be mobile, and are often not intended to serve as motor vehicle seats, especially in a crash. ANSI/RESNA WC19 [3] wheelchairs have been designed to sustain frontal impact crashes, but because of differences in rear impact loading [4] and dynamics, they may not be able to sustain a rear impact crash. Previous studies have been conducted, investigating rear impact pediatric wheelchair and occupant behavior [5,6], but very little is known about adult wheelchair and occupant response in rear impact. Initial testing done at the University of Michigan Transportation Research Institute (UMTRI) found catastrophic failures [7] when ANSI WC19 wheelchairs were subjected to a rear impact crash pulse (25–32 km/h, 12–14 g) [8]. Rear impact collisions account for 43.5% of all motor vehicle crash related injuries [9] and 5.4% of fatalities [10]. Therefore it is important to further investigate the effects of rear impact collisions on the occupant, wheelchair, and wheelchair tiedown and occupant restraint system (WTORS). Sled testing is one method to perform this investigation, but has certain drawbacks. Sled test limitations include their time consuming nature, relatively high costs, and the inability to provide detailed wheelchair structure loading data. Computer simulation modeling addresses some of these limitations and can be an effective tool to supplement sled testing.

Computer simulation has been used previously to study wheelchair and seat loading during frontal impact conditions [11–15]. These studies used validated computer simulation models to investigate loading patterns imposed by frontal impact to aid in the design of crashworthy pediatric and adult wheelchairs. Rear impact models were also previously developed for an adult manual wheelchair as well as a surrogate wheelchair base (SWCB), but neither of these models was validated [16,17]. Therefore, the purpose of this study was to develop a validated rear impact computer simulation model of a commercial, adult-occupied, manual wheelchair. This model will serve as a valuable tool to investigate wheelchair and WTORS loading in rear impact, which can aid in the design and development of wheelchairs suitable for rear impact.

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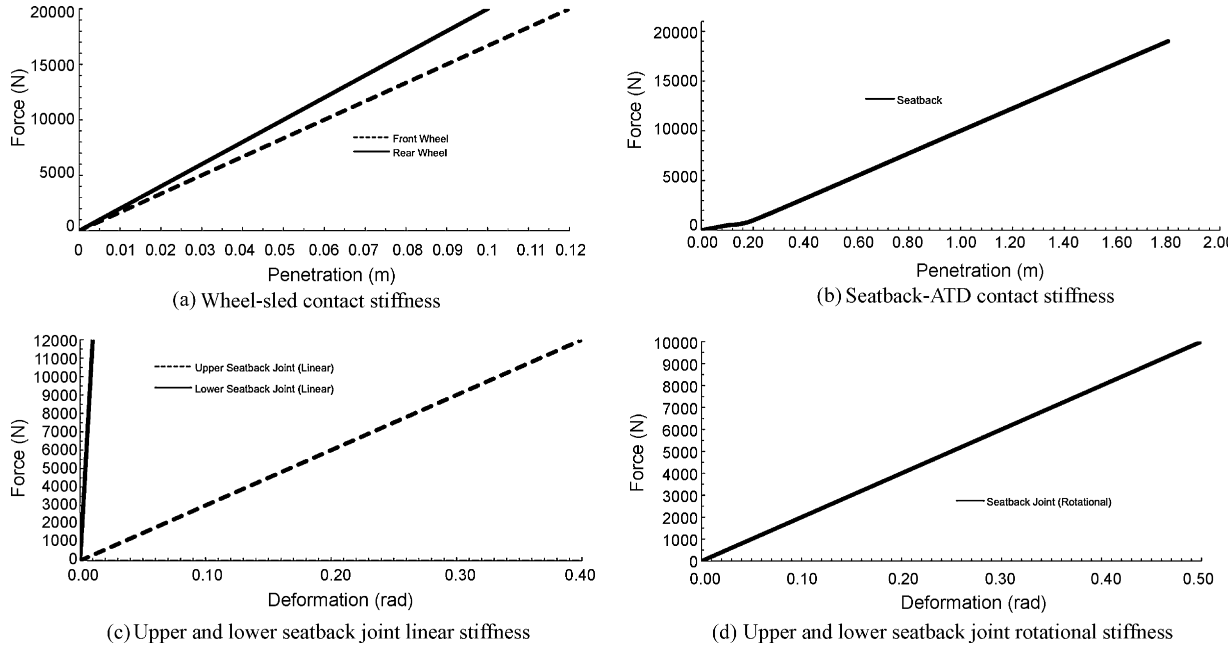

Fig. 1. Key computer model stiffness characteristics. (a) Wheel-sled contact stiffness; (b) seatback-ATD contact stiffness; (c) upper and lower-seatback joint linear stiffness; (d) upper and lower-seatback joint rotational stiffness.

2. Methodology

The intent of this study was to develop and validate a model to simulate a common rear impact scenario for the purposes of estimating WTORS and seatback loading. A manual wheelchair was chosen because wheelchair users most frequently utilize manual wheelchairs for mobility [18]. With consult of a wheelchair supplier, a widely used commercial manual wheelchair with the most common options was selected. A 50th percentile Hybrid III anthropomorphic test device (ATD – 78.3 kg) represented the wheelchair-seated occupant.

Three sled tests were conducted using identical, ANSI/RESNA WC19, reinforced, manual, folding, X-braced frame wheelchairs (25.1 kg) which were subjected to a rear impact crash pulse at UMTRI. The manual wheelchair had to be reinforced to sustain rear impact loads. A previous study by Manary et al. [7] showed that many wheelchairs that were crashworthy in frontal impact (ANSI/RESNA WC 19 compliant) exhibited failures in rear impact. The wheelchair's frame and seatback cane tubing were reinforced with solid steel rods, while the front securement point nuts and bolts were upgraded to Society of Automotive Engineers (SAE) grade 8. The crash pulse (25.8 km/h, 14 g) was as described in the proposed ISO/TC 173 rear impact standard [8]. The wheelchair was secured using surrogate 4-point strap-type tiedowns [19], while the ATD was restrained using a surrogate vehicle-mounted 3-point lap and shoulder belt occupant restraint system. Multiple views of the sled tests were captured using Kodak HG 2000 high-speed digital cameras (1000 frames/s). High contrast markers were placed on the wheelchair and ATD to track kinematic response, while all other time histories were acquired and filtered in accordance with SAE J211 [20].

The model was developed in MADYMO^{TM} (MAthematical DYnamic MOdeling), which is an advanced software engineering tool developed by TNO (Delft, Netherlands). MADYMO^{TM} has combined capabilities of finite element and rigid multi-body modeling. Multi-body modeling can be used for the simulation of gross motion of systems of bodies connected by kinematic joints, while finite element techniques can be applied to simulate structural behavior. While rigid bodies within MADYMO^{TM} are assigned inertial properties, they are often “encased” by ellipsoids with geometric specifications; this gives the body a certain “shape.” Ellipsoids can then interact with the surrounding ellipsoids and their respective bodies. A model can consist of rigid bodies, finite element bodies, or a combination of the two [21].

The wheelchair frame, wheels, seat, and seatback were modeled in MADYMO^{TM} using rigid multi-body ellipsoids. The masses of these wheelchair components were measured and their moments of inertia were determined; both were incorporated into the model. In the case of the wheelchair frame, frame tubing inertial properties were lumped together and represented in one body. The moments of inertia of individual frame components were combined using the parallel axis theorem while their masses were simply summed and represented in the model with a single body having the inertial properties of the entire wheelchair frame. The seat was modeled using one ellipsoid surface linked to the seat body, while the seatback was modeled with two bodies and two ellipsoid surfaces (upper and lower-seatback) each connected to the wheelchair by translational/revolute joints. This allowed for different effective seatback stiffness at the upper-seatback vs. the lower-seatback. The contact properties of the ATD and seatback were the same for the upper- and lower-seatback. Key stiffness properties of wheelchair components are shown in Fig. 1(a–d).

A validated ellipsoid ATD representing the 50th percentile male Hybrid III was imported from the MADYMO^{TM} TNO database. The 50th percentile ellipsoid ATD has 37 rigid bodies connected by numerous revolute, translational, revolute/translational, and spherical joints. The ATD segment inertial properties, joint and segment stiffness, as well as additional properties have been measured quasi-statically [22]. This Hybrid III ellipsoid ATD has been validated by TNO using a series of tests, including a frontal impact sled test (48 km/h, 20 g) [22]. Fig. 2 shows the wheelchair model and the imported 50th percentile male Hybrid III ATD.

The wheelchair in the model was secured with front and rear tiedowns modeled as belt segments [A]. The 50th percentile Hybrid III ATD [B] was imported from a TNO database into the MADYMO^{TM} model. The lap and shoulder belts [C] were modeled with finite element belts, while the wheelchair seatback [D] was modeled with two ellipsoid surfaces (one representing the upper-seatback and