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Testing and evaluation of wheelchair caster assemblies subjected to dynamic crash loading

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Abstract—Wheelchair designs based upon loads applied quasi-statically during normal mobility use are apt to be inadequate to handle the increased level of dynamic crash forces that may be encountered when using the wheelchair as a motor vehicle seat. The purpose of this study was to characterize the integrity of wheelchair caster assemblies under simulated crash conditions. This study utilized dynamic drop (DD) testing, with loading levels and rates adjusted to match those found previously in sled impact testing and computer crash simulations. The results verify that current caster assembly designs may not be able to withstand forces associated with a crash. Five of seven evaluated caster assemblies failed when loaded to 8,007 N, or less, at loading rates seen in sled testing. DD testing used in this study is a valuable tool that can be used in the design of transport wheelchair components.

Key words: *caster design, dynamic testing, transport wheelchair, wheelchair design, wheelchair transportation safety.*

INTRODUCTION

In 1990, the United States Congress enacted the Americans with Disabilities Act (ADA), prohibiting discrimination against people with disabilities in employment practices, public accommodations, and telecommunication services (1). By definition of this legislation, transportation services fall within the public accommodations category. The ADA has wide-reaching implications for transportation services, since it requires both public and private transporters to accommodate people with disabilities who wish to travel in their wheelchairs. Virtually all modes of transportation, including buses, trains, and subways, are required to be accessible.

Motor vehicle seat designs incorporate many features that serve to protect the occupant in a crash. However, many wheelchair users are unable to transfer to a vehicle seat, and are thus unable to take advantage of these safety features. Instead, wheelchair users are often forced to rely upon their wheelchairs, which were most likely not intended to function as vehicle seats.

The structural integrity of a vehicle seat is key to occupant crash protection; that is, the seating system must support the occupant and not undergo catastrophic failure in a crash. When using a wheelchair as a vehicle seat, the seat, seat back, wheels, and other components of the wheelchair must be capable of withstanding dynamically applied crash-level forces. The ANSI/RESNA Subcommittee on Wheelchair and Transportation (SoWhat) is currently drafting a standard for wheelchairs used as motor vehicle seats (2), requiring sled-impact testing to a 20g/30mph frontal crash pulse.

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The Society of Automotive Engineers (SAE), the International Organization for Standardization (ISO), and the Canadian Standards Association (CSA) continue to develop standards addressing wheelchair tiedowns and occupant restraint systems (WTORS; 3-5). The most prevalent securement in public transportation is the four-point strap tiedown system. When rear tiedown points are located below the wheelchair's center of gravity (CG), the chair tends to rotate forward, increasing the loads applied to caster wheels and forks in frontal crashes (6). Sled tests have also shown that caster assemblies can fail under 20g/30mph frontal crash conditions[1] common caster assemblies may not have strength capabilities to withstand these conditions. Caster system failure, through fracture or severe bending, can result in excessive occupant excursion, increasing the risk of injury. Secondary impact with vehicle surfaces can produce serious head and neck injuries (3), and occupant submarining can produce internal injuries from lap belt loading of the soft abdominal tissues (7,8) when casters fail. Submarining can occur when caster failure causes the front of the wheelchair seat and the occupant's lower torso to drop downward, allowing the lap belt to slip upward over the iliac crests and onto the abdomen. Proper caster design can, therefore, influence the risk of injury when using wheelchairs as seats in motor vehicles.

To investigate the effects of a 20g/30mph frontal motor vehicle crash on wheelchair caster assemblies, this study utilized dynamic drop (DD) testing, with loading levels and rates adjusted to match those found previously in sled-impact testing and computer crash simulations (6,9). Such a component test is valuable, since sled testing of a complete assembled wheelchair is costly and can lead to production schedule delays for redesign. DD testing can provide manufacturers and designers a cost-effective preliminary indication as to the performance of their caster assemblies under crash conditions.

Crash Loading Conditions

To simulate crash loading conditions through DD testing, both the magnitude of force and the loading rate should approximate those encountered

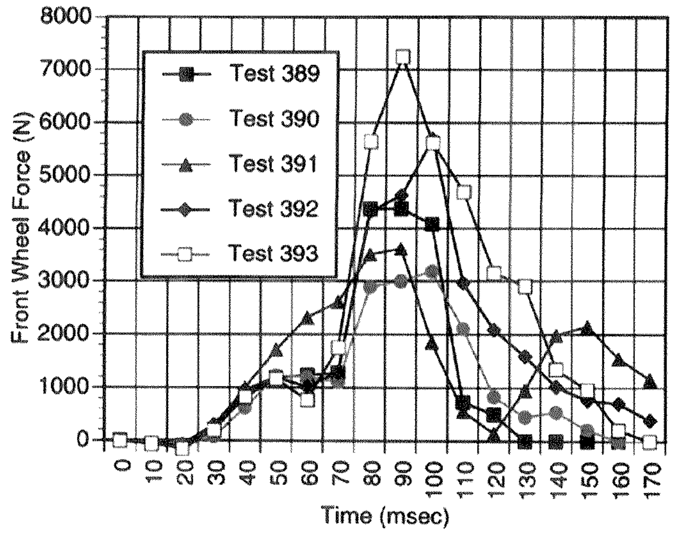

Figure 1.
Front caster wheel force time histories from 20g/30mph frontal impact sled tests (9).

in crash conditions. Front wheel caster assembly load levels and loading rates expected in crash conditions were investigated using both sled testing and computer crash simulation.

Figure 1 provides front wheel force time histories as measured during a series of 20g/30mph sled tests evaluating a manual wheelchair (29.5 kg) occupied by a 75 kg, 50th percentile male anthropomorphic test device (9). The wheelchair was secured using four-point strap-type tiedowns, and the occupant was restrained using both lap and

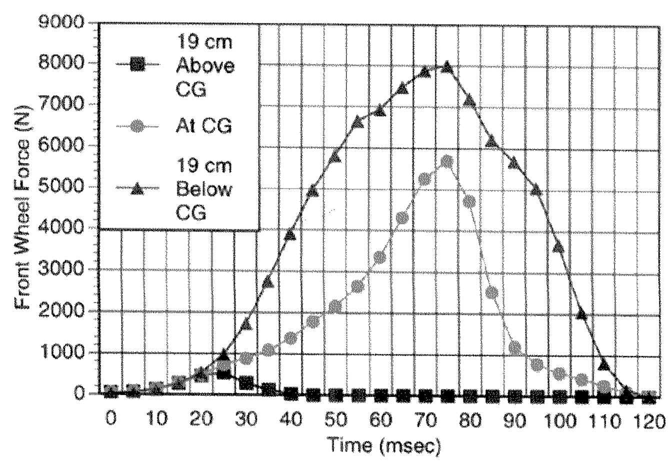

Figure 2.
Front caster wheel force time history for varying rear securement point locations in 20 g/30mph frontal impact computer simulations (6).

[1]Personal communication with Greg Shaw, PhD, Transportation Safety Lab, University of Virginia, Charlottsville, VA; Feb 1996.

Table 1.
Front wheel loading conditions.

Source	Load	Rate
Sled Tests (9)	3,843-7,882	67-262
Computer Simulations (6)	534-8,087	111-133

Load=range of loading, in N; Rate=rate of loading, in N/ms.

shoulder belts. Front wheel loads varied from 3,843 N to 7,882 N, while the rate of wheel loading varied from 66.7 N to 262 N/msec. Differences in loading can be attributed to different seating and securement configurations, as well as test-to-test crash pulse variations.

Computer simulations of a similarly secured wheelchair and occupant subjected to a 20g/30mph frontal crash pulse were also consulted to predict wheel loading conditions. These simulations used a 50th percentile male (75 kg) anthropomorphic test dummy seated in a representative 85-kg power wheelchair. Computer simulations showed that caster loading is dependent upon location of rear tiedown attachment relative to the CG of the wheelchair (6). **Figure 2** indicates the front wheel force time histories with respect to the rear tiedown attachment location: as securement is moved below the wheelchair CG, the wheelchair rotated forward in the frontal crash, leading to increased front wheel loading (7). In computer simulations, tiedown points located below the CG led to forward rotations resulting in an 8,087-N caster load. Placing rear securement points above the wheelchair CG led to a substantial reduction in front wheel loading, since the wheelchair and its occupant rotated rearward onto the rear wheels. Front wheel loading was minimized in this scenario to 534 N. Loading rates varied from 111 N/msec to 133 N/msec depending upon securement location.

Table 1 summarizes the range of caster loads and the rate of loading found in the described computer simulations and sled tests under 20g/30mph frontal crash conditions. Based upon these findings, DD testing goals were to apply a 6,672-N vertical load at a rate seen in sled testing and simulations.

METHOD

Six types of commonly used caster assemblies were dynamically loaded to simulate motor vehicle crash conditions using a drop tester. **Table 2** describes the assemblies tested, and **Figures 3a** and

Table 2.
Evaluated caster assembly details.

Test	Wheel	Caster Fork
A5a & b	12.7 cm Poly	Extruded Aluminum
B2	15.2 cm Pneu	Extruded Aluminum
C4	12.7 cm Poly	Stamped Steel
D8	20.3 cm Pneu	Extruded Steel
D7 & D7a	20.3 cm Pneu	Extruded Aluminum

Poly=polyurethane; Pneu=pneumatic; all hubs were plastic

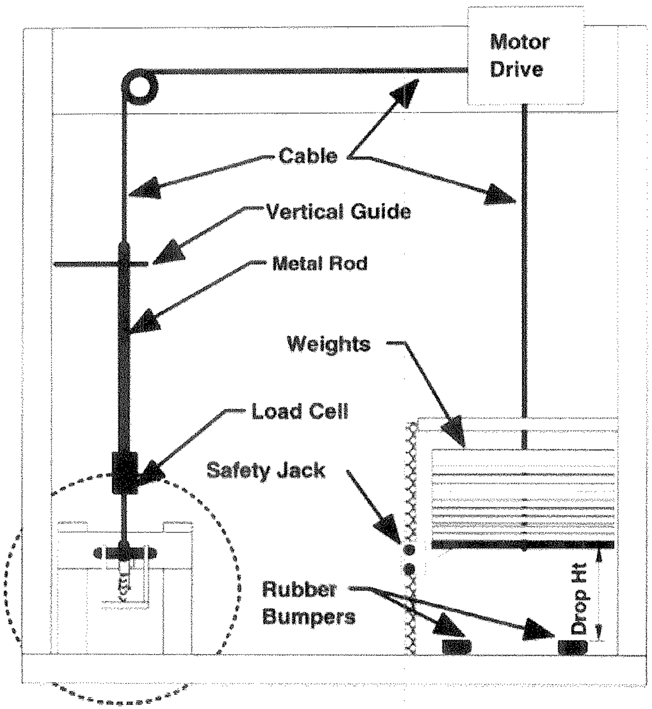

Figure 3a.
Dynamic drop tester and caster assembly test fixture.

3b provide a diagrammatic representation of the drop testing equipment and caster assembly test fixture. The DD testing device consists of a structural frame supporting a motor-driven cable connected to a stack of weight plates; the motor raises the weights to a predetermined height. The number of plates and their drop height are variables selected according to the desired loading profile. Once the weights are raised to that height, a locking mechanism is used to fix their position, and a manual safety jack is placed beneath them. For this study, the weight and drop height were fixed at 158.75 kg and 17.78 cm, respectively. A second cable, independent of the motor drive unit, passes through pulleys mounted at the top of the support structure, and a vertical guide rod (see **Figure 3a**) was then connected from the weights to the point of load application, in this case the caster assembly test fixture. A load cell, annually calibrated by the manufacturer, was mounted in-line with the vertical guide rod just above the point of load application and connected to a data acquisition system used to record load-time history during the event. Data were subsequently filtered in accordance with SAE J211, Instrumentation for Impact Test.

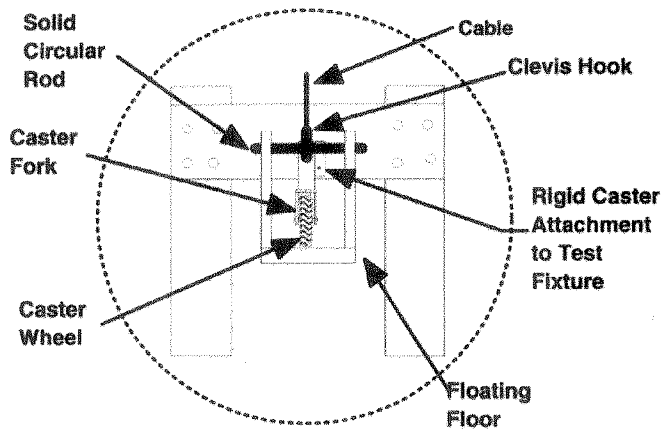

Figure 3b.
Detail of caster assembly test fixture shown in **Figure 3a.**

A test fixture positioned at the point of load application was designed to apply load vertically upward on a caster mounted in the drop tester (**Figure 3b**), simulating the caster wheel being driven downward into the vehicle floor in a crash. The caster was arranged in the fixture so that it was in contact with the false floor. This test fixture was fixed to the drop test equipment base at the point of load application. To apply the test, the safety jack was removed from beneath the raised

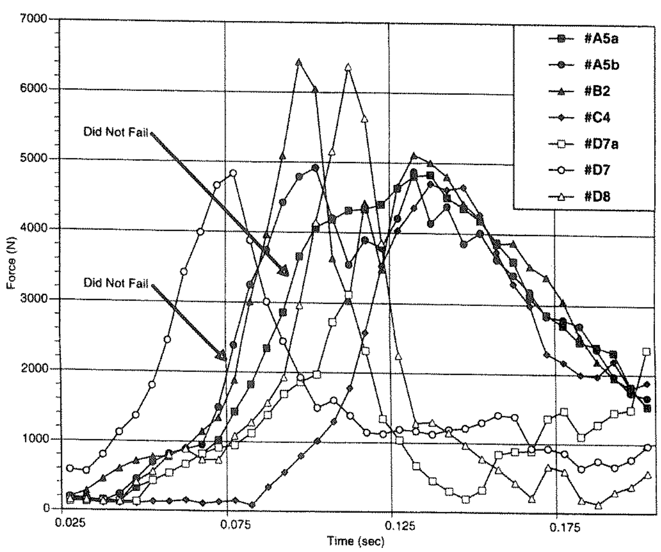

Figure 4.
Drop test force time histories for each caster assembly.

Table 3.
Caster assembly test results.

Test	Fail	Comment	Force	Rate
A5a	N		4,844	102
A5b	N	Mounting bolt bending	4,937	133
B2	Y	Fractured wheel hub	6,552	218
C4	Y	Severe caster fork bending	4,760	84
D8	Y	Fractured fork mounting post	6,388	213
D7	Y	Fractured caster fork	4,884	133
D7a	Y	Sheared fork mounting screws	7,629	89

Force=maximum applied force, in N; Rate=rate of load application, in N/ms.

weights, an alarm sounded, and a switch was activated to disconnect the lifting cable from the weights, dropping them to the base. As the weights fell from their predetermined height, the second cable attached to the weights pulled the false floor of the test fixture upward into the bottom of the caster wheel. Rods passing through the test fixture floor constrained fixture movement to vertical, and the data acquisition system recorded the load history during the event. This process was repeated for each of the caster assemblies shown in **Table 2.**

RESULTS

Table 3 provides the results of caster testing using the DD tester, the maximum applied load, and the rate of caster loading. **Figure 4** provides a force-time history for each of the casters. Four (Tests B2, C4, D8, and D7) of the seven caster assemblies tested failed at less than 6,672 N loading. An additional failure (Test D7a) occurred at 7,629 N and a loading rate of 89 N/msec. Failures associated with Tests B2 and D8 had the largest rates of loading, 218 N/msec and 213 N/msec, respectively. Other failures occurred at loading rates ranging from 84 to 133 N/msec. Casters that did not fail (Tests A5a and A5b) had loading rates of 102N/msec and 133 N/msec, and loads of 4,844 N and 4,937 N.

As indicated, failure modes include fracture of wheel hubs and caster forks, extreme bending of caster forks, and shearing of mounting hardware. **Figure 5** shows the results of a 6,552 N load

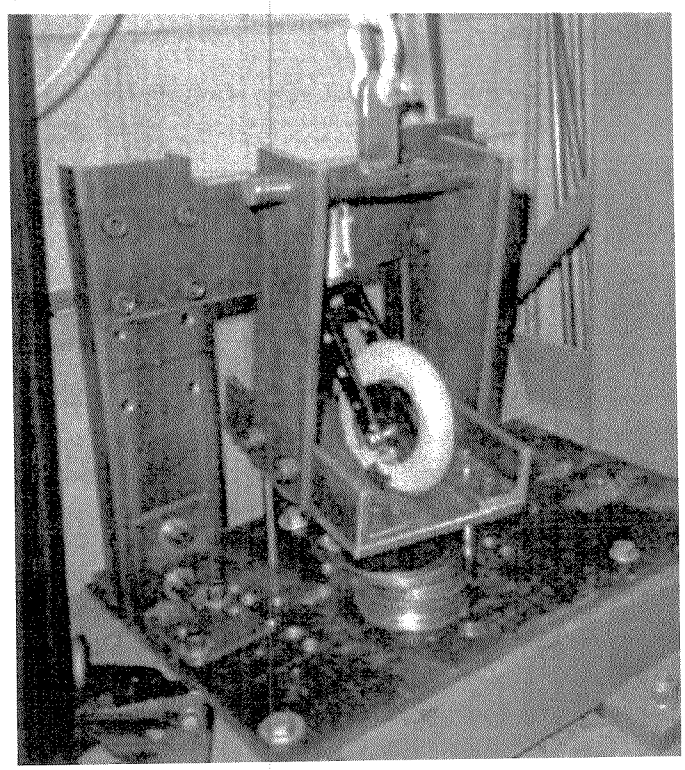

Figure 5.
Test B2 resulting in a fractured wheel hub.

applied in Test B2 before removing the caster assembly from the test fixture. In this test, the plastic wheel hub fractured. **Figure 6** shows the results and means of failure in Test D7 (fractured caster fork), Test B2 (fractured wheel hub) and Test C4 (severe bending of caster fork). **Figure 7** shows the mounting post fractured in Test D8.

DISCUSSION

Study test results suggest that current wheelchair caster assemblies may not be capable of withstanding forces associated with a 20g/30mph frontal crash without failure. Quite different from the loading conditions found in normal mobility, dynamic loading encountered in a crash introduces complex stresses, and material properties may vary significantly from their reported static values under these stresses. Material strength characteristics have been found to vary depending upon impact velocity. Yield strength and ultimate strength typically increase under high loading rates (10). For many steels, the dynamic yield point is increased to the level of the dynamic ultimate strength for impact velocities between 15.24 m/d snf 30.48 m/s. At these impact velocities, materials can exhibit brittle behavior. Aluminum alloys, however, do not typically realize the same increases in ultimate strength under dynamic conditions that are seen in steel. The ability of a metal to absorb energy under impact loading conditions is also important in describing material response and varies depending upon materials and treatment processes. Hardened or quenched steel often exhibits a decrease in energy absorption at impact velocities at or above 30.48 m/s. Cold rolling steel increases its energy absorbing capability at impact velocities near 30.48 m/s, but diminishes with increasing impact velocities. Annealed steels show an increase in their ability to absorb energy under impact, except when impact velocities are greater than 38.10 m/s. Fracture toughness and ultimate strength are also important in impact loading and are used as design criteria in fracture prevention. Dynamic fracture toughness is influenced by loading rate, and generally

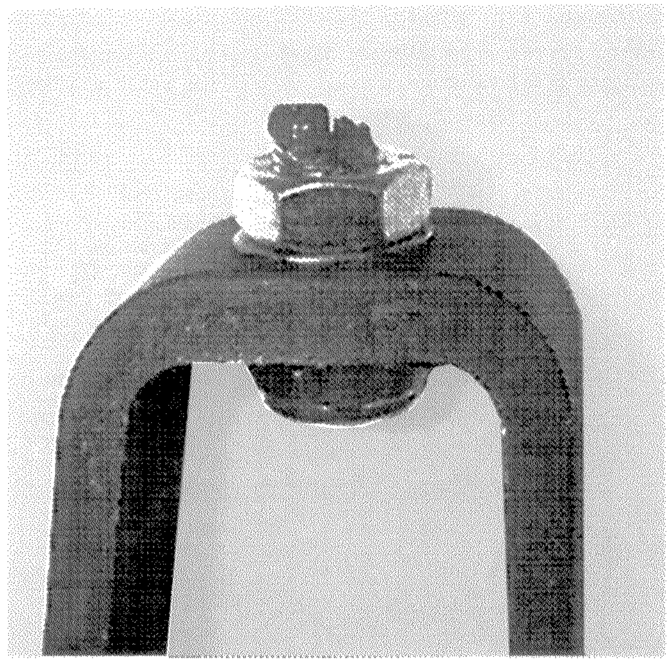

Figure 7.
Test D8 failure: fractured mounting post.

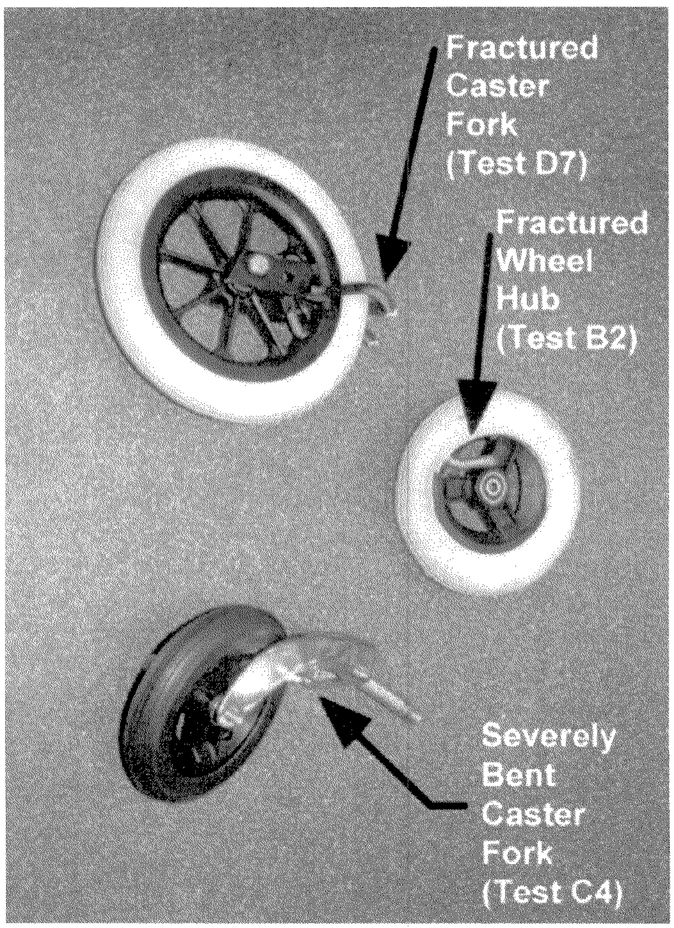

Figure 6.
Test D7, B2, and C4 caster assembly failures.

decreases under impact in most metals. Each of these factors that varies under impact loading must be accounted for when designing transport wheelchair components.

Caster assemblies tested failed in various modes. Caster forks failed through either extreme bending or metal fracture. Although controlled bending can be advantageous in a crash, since it absorbs energy, the level of bending seen in Test C4 is excessive and could lead to an unstable wheelchair seat surface. Both the stamping process and the use of soft ductile metals were most likely responsible for the severe yielding of this fork. The aluminum extruded fork and 20.3 cm diameter wheel evaluated in Test D7 failed due to fork fracture. Failure occurred at 4,884 N. This particular caster fork had a substantially reduced cross-sectional area, compared with others evaluated. Although the specific type of aluminum alloy used in this fork is uncertain, one source indicates that ultimate dynamic strengths of aluminum alloys vary from 106,183 kPa to 472,997 kPa, depending upon alloy type and treatment process used (10). It is estimated that the fork failed at a stress near 117,215 kPa.

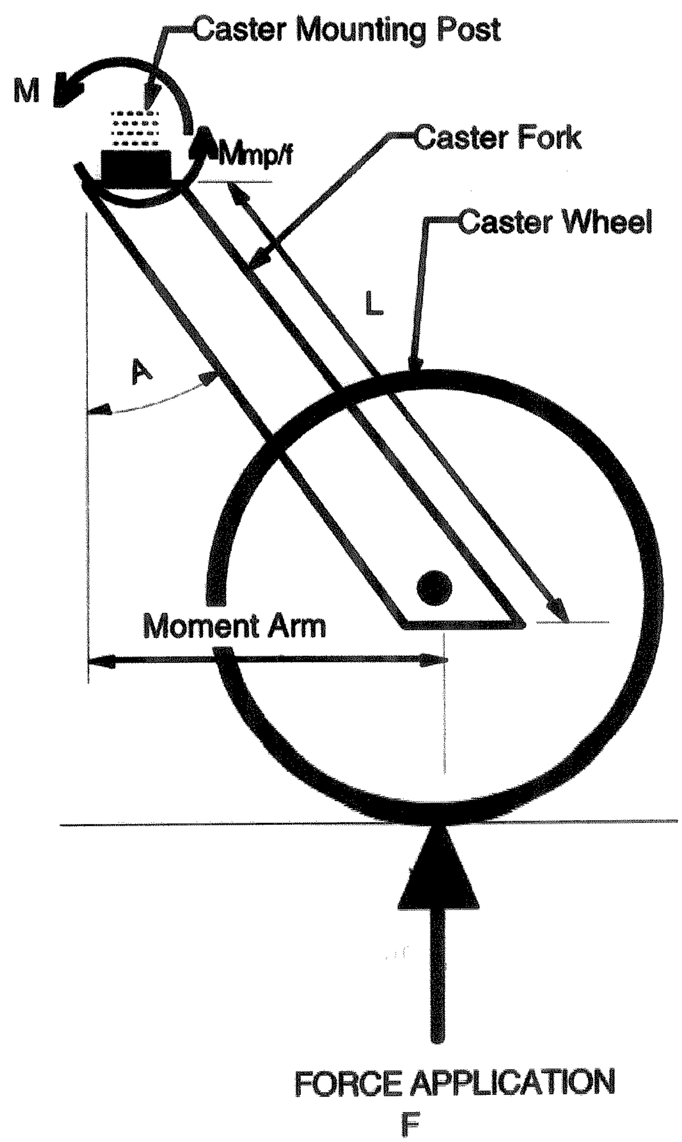

Figure 8.
Mmp/f=F(Moment Arm): forces and moments applied to caster assembly during dynamic drop testing. Moment Arm=[sin(a)]L, where L=caster fork length.

Loading produced through DD testing is applied to the caster wheel vertically, creating a moment at the mounting hardware. The moment applied at the caster mounting post-caster fork interface (Mmp/f) is dependent upon the caster fork length and its angle from vertical, or the moment arm (**Figure 8**). As the length of the moment arm increases, the moment applied to the mounting post/hardware similarly increases. In Tests D7a and D8, mounting hardware failed under loads of 6,388 N and 7,629 N, respectively. Mounting screws (four) used in Test D8 were limited in size (Size 5, 3.2 mm diameter) by the holes provided in the caster mounting hardware. All screws sheared under test conditions. The Test D8 caster assembly consisted of a 20.3 cm diameter wheel, extruded steel fork, and a 12.7-mm hardened steel mounting post. In this test, the threaded mounting post fractured due to the resulting moment. It is estimated that a 314 N-m moment was applied to the mounting hardware during testing. Depending upon the grade of the mounting bolt, static tensile strength can vary from 413,700 kPa through 1,172,150 kPa. Bolts of grade 5 through 8 are hardened through quenching and tempering. Hardness increases with increasing grade number. An SAE grade 8 bolt has a hardness of 352 BHN, whereas a grade 5 bolt has a hardness of 302 BHN (11). It is unclear as to the actual grade of the mounting bolt used in Test D8, but through observation it is certain that the bolt underwent hardening, placing it in the grade 5 to 8 range.

The dynamic response of plastics is also of concern in casters exposed to crash conditions since wheels are often constructed using plastic hubs. The thin-walled hub in Test B2 failed by brittle fracture at 6,552 N. Normally ductile plastic components may fail in a brittle fashion at relatively low strains when exposed to increased rates of loading (12). At low rates of loading, a ductile plastic can tolerate overloads because of its ability to redistribute load through yielding. At high loading rates, energy absorption is decreased and failure can be catastrophic. Plastics are known to undergo a ductile-to-brittle transition associated with high strain rates. Material properties and response of plastics under impact conditions are difficult to quantify, since they are dependent upon strain rates, temperature, and component geometry.

DD testing represents an effective means for evaluating component dynamic response. Differences in loading between drop testing and sled testing include the following. DD testing introduces a purely vertical load to the caster wheel at the floor interface. In sled testing, the wheelchair rotates forward, compressing the caster into the sled at an angle that varies slightly from vertical. This can lead to a greater moment at the caster mounting hardware in drop testing than in sled testing. The caster fork loading path in drop testing may also be slightly altered from sled testing loading. Another difference may be introduced through rigidly mounting the caster assembly in the drop test; in sled testing, the caster assembly is mounted to a more flexible wheelchair. However, this difference can be eliminated by matching loading rates, as was accomplished in this series of DD tests.

Factors such as wheelchair and occupant weight, rear securement location, and crash severity can influence loads applied to casters. As indicated by **Figure 2**, rear securement point location can be used as a strategy to reduce forward wheelchair rotation in a frontal crash, thereby reducing caster loads (6). The influence of weight on caster loads was also studied using computer simulation, with results shown in **Figure 9**, that verify that increased wheelchair and/or occupant weight will lead to greater caster loads. Increasing wheelchair and occupant weight from 115 kg to 206 kg produced a corresponding increase in caster load from 7,295 N to near 8,452 N. It should be noted that securement configuration in these simulations was constant, positioned at the same level of the wheelchair CG. As previously shown, locating the securement points below the wheelchair CG will further increase predicted caster loads.

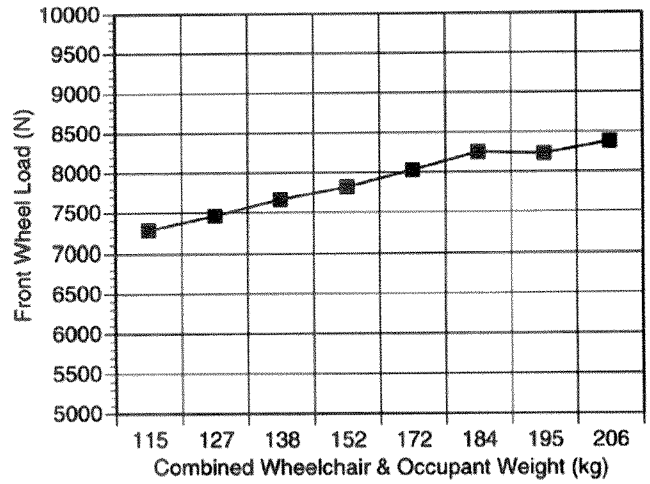

Figure 9.
Front caster wheel peak loads versus combined wheelchair and occupant weight in 20g/30mph frontal impact computer simulations with the rear securement point located at the same level as the CG. Varying securement point heights will influence wheel loads.

Insight into caster performance can also be gained through a review of standards testing conducted to simulate normal mobility conditions. Casters are evaluated for normal mobility function as part of the static, impact, and fatigue strength tests for wheelchairs (ISO 7176-08). Impact strength testing for casters is done by allowing a 10 kg pendulum with center of percussion 1 m from the pivot point to strike the caster's mid-line. The release angle is dependent upon the mass and seating dimensions of the wheelchair. A release angle of 45° is common for manual wheelchairs, while 60° is more common for powered wheelchairs (13). Previous results show that most caster assemblies can withstand this test (13). The impact strength test is designed to simulate running into a curb or obstacle while driving the wheelchair. Caster assemblies also undergo fatigue testing (ISO 7176-08). Caster assemblies experience repeated loading while on the double-drum tester and curb drop tester. These loads are intended to be smaller than those applied in the impact tests. Caster assemblies have been found to fail during fatigue testing (14,15). The results of (13-15) support the findings in this study, in that there may be a need to examine the design of some caster assemblies to improve impact strength, fatigue life, and crash worthiness.

Some data have been collected in the loads experienced by casters during normal mobility (16). Vertical loads on a single caster can approach 512 N during normal driving conditions with manual wheelchairs. These loads are considerably lower than those experienced by caster assemblies during a 20g/30mph crash. Because of the disparity in loads experienced during normal mobility conditions and crash scenarios, it may be necessary to examine caster assemblies engineered specifically for use on wheelchairs designed as seats in motor vehicles. This area requires further investigation as to suitable caster assembly materials and designs that will meet the desires of consumers for daily activities and be safe for transport in motor vehicles. Future caster assemblies may benefit from the use of composite materials and high-strength steel or aluminum alloys (17).

Wheelchair manufacturers must be aware of the increased loading placed on wheelchair components in a crash and must modify design criteria accordingly. DD testing can serve as a valuable and cost-effective tool in the preliminary evaluation of wheelchair component crash integrity. Drop testing is flexible, since loading levels and rates can be adjusted to match those found in sled impact testing. However, complete assembled wheelchairs intended for transport must be sled tested following the ANSI/RESNA WC-19 frontal crash test protocol (2).

CONCLUSIONS

Computer simulations and sled tests indicate caster crash loads can be as high as 8,007 N, while drop testing produced failures at, or less than, this level of loading. Such failures can permit occupant submarining or excessive occupant excursions, which can increase the risk of injury. Caster assembly designs must anticipate the increased loads and dynamic application of loads that occur in a crash. Transport wheelchair caster loads can vary depending upon crash severity, combined wheelchair and occupant weight, and securement configuration. Caster failures observed in this study suggest that current designs may not be able to withstand crash loading conditions and may not be crashworthy.

Since material properties of both metals and plastics vary significantly under impact, special design considerations are warranted. Metal treatment processing can also affect material response to dynamic loading. Hardening, commonly found in caster forks and mounting posts, improves wear resistance of components, but substantially reduces the energy-absorbing capabilities of material. Such conditions increase the risk of fracture. Annealing or cold rolling of metal components can actually serve to increase energy absorption of a material depending upon impact velocity. DD testing described in this study can be a useful tool in predicting the caster assembly crash response. Such testing can be cost effective when used prior to sled testing of a fully assembled transport wheelchair.

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REFERENCES

1. Architectural and Transportation Barriers Compliance Board. Americans with disabilities act (ADA): accessibility guidelines for transportation vehicles. Federal Register; 1991;56(173, Sept):36 CFR, Part 1192.
2. ANSI/RESNA Subcommittee of Wheelchairs and Transportation. Wheelchairs used as seats in motor vehicles. WC-19; Dec 1998.
3. Society of Automotive Engineers. Wheelchair tiedowns and occupant restraints (WTORS) for use in motor vehicles. SAE J2249; 1996.
4. International Standards Organization. Wheelchair and occupant restraint system for use in motor vehicles. ISO 10542-1; Nov 1997.
5. Canadian Standards Association. Mobility aid securement and occupant restraint systems for motor vehicles. CSA Z605; Nov 1994.
6. Bertocci GE, Hobson DA, Digges, KH. Development of transportable wheelchair design criteria using computer crash simulation. IEEE Trans Rehabil Eng 1996;4:171-81.
7. Leung Y, Tarriere C, Lestrelin D, et al. Submarining injuries of 3 pt. belted occupants in frontal crashes. SAE Paper No. 821158; 1982.
8. Viano D, Arepally S. Assessing the safety performance of occupant restraint systems. SAE Paper No. 902328; 1990.
9. ANSI/RESNA Subcommittee of Wheelchairs and Transportation. Seating insert eval sled tests. Charlottesville, VA: University of Virginia Auto Safety Lab; 1996.
10. Collins J. Failure of materials in mechanical design; analysis prediction, prevention. 2nd ed. New York: John Wiley & Sons; 1993.

11. Shigley J. Mechanical engineering design. 3rd ed. New York: McGraw Hill; 1977. p. 248.
12. Trantina, G., Nimmer R. Structural analysis of thermoplastic components. New York: McGraw Hill; 1994.
13. Cooper RA, Robertson RN, VanSickle DP, Stewart KJ, Albright S. Wheelchair impact response to ISO test pendulum and ISO standard curb. IEEE Trans Rehabil Eng 1994;2(4):240-6.
14. Cooper RA, Robertson RN, Lawrence B, et al. Life-cycle analysis of depot versus rehabilitation manual wheelchairs. J Rehabil Res Dev 1996;33(1):45-55.
15. Cooper RA, Gonzalez J, Lawrence B, Renschler A, Boninger ML, VanSickle DP. Performance of selected lightweight wheelchairs on ANSI/RESNA tests. Arch Phys Med Rehabil 1997;78(10):1138-44.
16. VanSickle DP, Cooper RA, Gonzalez J. SMARTHUB and SMARTCASTOR: force and moment sensing wheelchair wheels. Proceedings 19th Annual IEEE/EMBS International Conference, Chicago, IL: CD-ROM; 1997.
17. Cooper RA. A perspective on the ultralight wheelchair revolution. Technol Disabil 1996;5:383-92.

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