Effect of Manual Wheelchair Caster Stiffness and Energy Absorption on Wheelchair-Occupant Kinematics During a Frontal Impact Using Computer Simulation

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ABSTRACT

Many wheelchair users traveling in motor vehicles are required to or choose to remain seated in their wheelchairs. Studies have shown that casters are particularly prone to failure, if the vehicle were involved in a frontal impact. This study evaluates the use of incorporating energy absorption into the wheelchair casters to improve wheelchair-occupant kinematics. A parametric sensitivity analysis conducted using a previously validated computer crash model suggested that caster stiffnesses between 1750 lb/in and 750 lbs/in along with R and G factors between 0 - 0.5 and 0.75 - 1, respectively can improve wheelchair-occupant kinematics by dissipating the crash energy. Such an approach may present opportunities to reduce wheelchair-seated occupant injury risk in a motor vehicle crash.

KEYWORDS

Wheelchair Safety, Simulation, Caster Design, Caster Stiffness, Energy Absorption

BACKGROUND

There are approximately 2.3 million wheelchair users in the US [1]. The Americans with Disabilities Act (ADA) [2] has led to an increased number of wheelchair users who are seeking transportation in motor vehicles. Wheelchair users who are unable to transfer to a motor vehicle seat must rely on their wheelchair to provide a safe, stable support surface and occupant protection in the event of a motor vehicle crash.

Unlike OEM (Original Equipment Manufacturer) motor vehicle seats, wheelchairs are not always designed to protect occupants from injury during motor vehicle impact. To provide wheelchair occupants with the same level of safety as other vehicle passengers, wheelchairs must be capable of withstanding dynamic crash level forces. Study findings indicate that wheelchair caster/fork assemblies are often incapable of withstanding the forces associated with crash level loading [3, 4]. Although excessive caster/fork bending or fracture exposes wheelchair-seated individuals to increased risk of injury due to an unstable seating surface; controlled bending or failure of components and associated energy absorption can be advantageous in a crash.

Since the late 1960’s, the automotive industry has been incorporating energy absorption systems [5] in vehicles. The crumple zone in cars was one of the first passive safety features adopted by the automobile industry after the introduction of occupant restraints. The crumple zone or deformation zone is a structural feature that absorbs energy upon impact. Engineers designed weak spots in the car's structure to enable the front or rear-end to collapse in a controlled manner on impact. Energy from the impact is then expended in deforming metal or plastic components, often converting it into heat and sound, thereby reducing the force transferred to the occupants and reducing the risk of injury.

Following a similar approach, it may be possible to achieve this proven method of controlled deceleration in wheelchair design. During a frontal impact vehicle collision (20g), as wheelchair occupants tend to move forward and downward, casters (caster and fork assembly) are subjected to loads as high as 8000 N [6]. This makes the caster an ideal component of the wheelchair that can be redesigned to incorporate energy absorption properties. In this preliminary study, we examined the effects of caster design (stiffness and energy absorbing properties) on wheelchair and occupant kinematics, and identified a design that minimized wheelchair and occupant excursions during frontal impact and rebound, using a validated computer simulation model.

METHODS

A previously validated, rigid body, computer crash simulation model representing the 50th percentile male Hybrid III Anthropomorphic Test Device (ATD), seated in an adult manual wheelchair, subjected to an SAE J2249 compliant 20g/30mph frontal impact pulse [7], developed in Articulated Total Body (Advanced Information Engineering Services, Inc., Dayton, OH 45431), was used to evaluate the effects of varying the properties of the caster on wheelchair and occupant kinematics. The ATD was restrained by a vehicle mounted, 3-point occupant restraint system and the wheelchair was secured by a 4-point, belt-type tiedown system [8].

Using a computer model, a parametric sensitivity analysis was conducted to examine wheelchair and occupant kinematics, based on varying caster properties. The caster used in the model had a 7 inch diameter and a 1.25 inch wheel width. A total of three parameters were varied during this study. Firstly, the caster stiffness which primarily affects the loading portion of the crash event was varied from 2750 lb/in to 250 lbs/in from a baseline stiffness of 1750 lb/in with increments of 500lbs/in, while maintaining all other values constant. Investigation into these simulation results led to the elimination of caster stiffnesses that proved potentially harmful to the wheelchair occupant. Using the remaining stiffness values, the two parameters associated with unloading of the caster and rebound of the wheelchair and occupant, were varied as per Table 1. These two variables were the R-factor, and the G-factor.

The R factor is the energy absorption function and is used to specify the amount of energy recovered at the end of unloading. The G factor is the permanent deflection function and is used to model permanent deformation due to contact force. Both R and G values can range from 0 to 1. The equation and graphical depiction of R and G factors are illustrated in Figure 1.

For each simulation performed evaluating the various caster scenarios, the effect on the wheelchair and occupant kinematics were studied. The crash response of the wheelchair was explored by examining the wheelchair CG excursions and caster hub excursions, characterizing the motion of the wheelchair. Wheelchair-occupant response was evaluated by measuring head CG excursions. Excursions in the horizontal plane are represented as x-excursions and excursions in the vertical plane are represented as z-excursions.

Table 1 and Figure 1 Goes Here

RESULTS

<u>Caster Stiffness Analysis</u>

Analysis of the crash simulations for varying caster stiffness scenarios indicated that a caster stiffness greater than the original model [8] stiffness of 1750 lbs/in, made no significant changes to the wheelchair and occupant kinematics. Simulations of softer casters (i.e. stiffness less than 1750 lbs/in) showed that it was possible to change wheelchair/occupant kinematics during a frontal impact. However, caster stiffnesses lower than 750 lbs/in create a scenario that exceeds the geometrical limits of the caster. Such casters would have to be larger than standard sized casters to allow such excessive deflection. Also caster stiffnesses lower than 750 lbs/in create extreme downward and forward pitching of the wheelchair which can be unsafe given an increased risk of occupant lap belt submarining. Lap belt submarining is characterized by the pelvic restraint slipping upward over the iliac crests and loading the soft abdominal tissues. Submarining can lead to severe internal injuries of organs in the abdominal region [9].

The risk of lap belt submarining of occupants in frontal impacts was assessed in a study that established a torso angle injury criterion as measured from the vertical as 30˚ [10]. Figure 2 shows the torso angle relative to the vertical for different caster stiffnesses. It is evident from the plot that caster stiffness of 250 lbs/in produces a torso angle over 30˚, suggesting a risk of lap belt submarining. Caster stiffness of 750lbs/in or more were found to have a low risk of lap belt submarining. Further analysis in our study included the original caster stiffness (1750 lbs/in) and the stiffness with the potential to have maximum deformation (750 lbs/in) without causing possible injury to the wheelchair occupant.

Figure 2 Goes Here

Energy Absorption/Permanent Deformation Analysis

To reduce the risk of submarining, caster stiffnesses of 1750 lbs/in (original model stiffness) and 750 lbs/in were used to analyze the influence of energy absorption (R) and permanent deflection (G) function to examine wheelchair and occupant kinematics.

Figures 3, 4 and 5 provide caster hub excursions, wheelchair CG excursions and head CG excursions for the stiffness of 1750 lbs/in. Each of the scenarios begins with a forward and downward motion, but differences were observed on rebound and unloading of the caster. Instances occurred where multiple energy absorbing scenarios had an identical response curve. In such cases, one of the trials was used to represent the group with identical responses. Table 2 provides the R and G factor legend for the simulations represented in the plots.

Table 2 Goes Here

In figures 3 and 4, the loading function is represented by the curve, untill maximum deformation is achieved. Thereafter the unloading function is observed, at the end of which variations in permanent deformation are seen. The instances with maximum permanent deformation show the maximum energy absorption.

Figure 3, 4, and 5 Goes Here

Maximum energy absorption is evident in simulation number 20 which has the maximum difference between its initial and final z excursion. This difference between initial and final excursion in the z direction shows permanent deformation. Figure 6, 7 and 8 provides caster hub excursions, wheelchair CG excursions and head CG excursions for the caster stiffness of 750 lbs/in. The excursion of the caster and wheelchair CG in this case shows the additional deformation the caster is experiencing because of its reduced stiffness. Maximum energy absorption is seen in runs 17 and 20.

Figure 6, 7, and 8 Goes Here

The parametric sensitivity analysis of the caster energy absorption/permanent deformation for both caster stiffness scenarios revealed that simulation numbers 3, 4, 7 and 13 were least favorable as there was minimal energy absorption. In contrast simulation numbers 17 and 20 were associated with substantial energy absorption which is evident by the unloading curves and permanent caster deformation.

Table 3 shows a summary of the effects of varying caster properties (caster stiffness, R and G factors) on the outcome measures.

Table 3 Goes Here

DISCUSSION & CONCLUSION

The sensitivity analysis indicates that caster stiffness and caster energy absorption characteristics do influence the wheelchair and wheelchair occupant kinematics during a frontal impact. Caster stiffnesses less than 1750 lb/in, with minimal energy absorption properties (simulation number 3) showed increased rearward (negative z-direction) head CG excursion than instances with energy absorption properties (simulation numbers 4, 7, 13, 17 and 20), whereas caster stiffnesses more 1750 lb/in had no such correlation. The results show that caster stiffness below the original model [8] stiffness of 1750 lb/in is favorable to improve wheelchair and occupant kinematics, although stiffnesses below 750 lbs/in can cause the risk of lap belt submarining. Also an R factor between 0 and 0.5 with a G factor between 0.75 and 1 can improve overall kinematics by removing energy from the wheelchair and occupant during a frontal impact.

This is the first study that investigates a new method of incorporating energy absorption into wheelchairs as a way to improve occupant kinematics during a frontal impact. As wheelchair casters are exposed to high loads during frontal impacts, this study proposes a method that can effectively reduce the impact energy from a crash by absorbing the energy in a controlled and effective manner. Any reduction in crash energy would translate to a reduced injury potential for the occupant.

Limitations of this study include that it has only considered an adult manual wheelchair with the 50^{th} percentile male occupant. A different wheelchair or different sized occupant could produce different results. Future work will focus on studying the effects of caster stiffness on occupant dynamics by evaluating changes in different injury criteria.

In summary, the results of our study suggest that wheelchair caster designs incorporating energy absorbing features may offer an innovative method of controlling wheelchair and occupant response in a motor vehicle crash. Such an approach may present opportunities to reduce wheelchair-seated occupant injury risk in a motor vehicle crash.

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FIGURES AND TABLES:

Factor	R=0	R=0.25	R=0.5	R=0.75	R=1
G=0	X	X	X	X	X
G=0.25	X	X	X	X	X
G=0.5	X	X	X	X	X
G=0.75	X	X	X	X	X
G=1	X	X	X	X	X

Table1. Matrix of wheelchair caster R and G factor combinations used in the parametric sensitivity analysis. Simulations were performed for each of these scenarios.

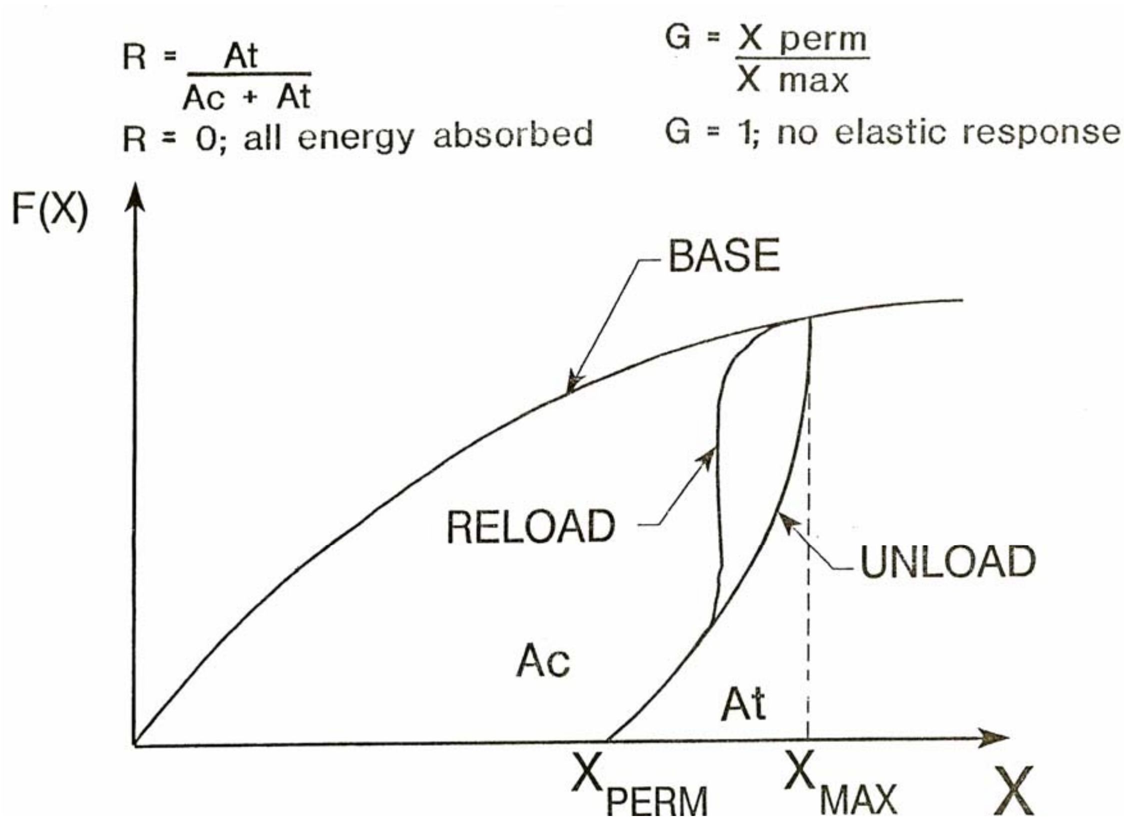

Figure1. An illustration of a force-deformation curve along with the equations for the R and G factors. Diagram depicts a loading function (BASE), an unloading function (UNLOAD), and a reloading function (RELOAD). Also the permanent deformation (X_{perm}), maximum deformation (X_{max}), energy absorbed (A_c) and energy recovered (A_t) are shown.

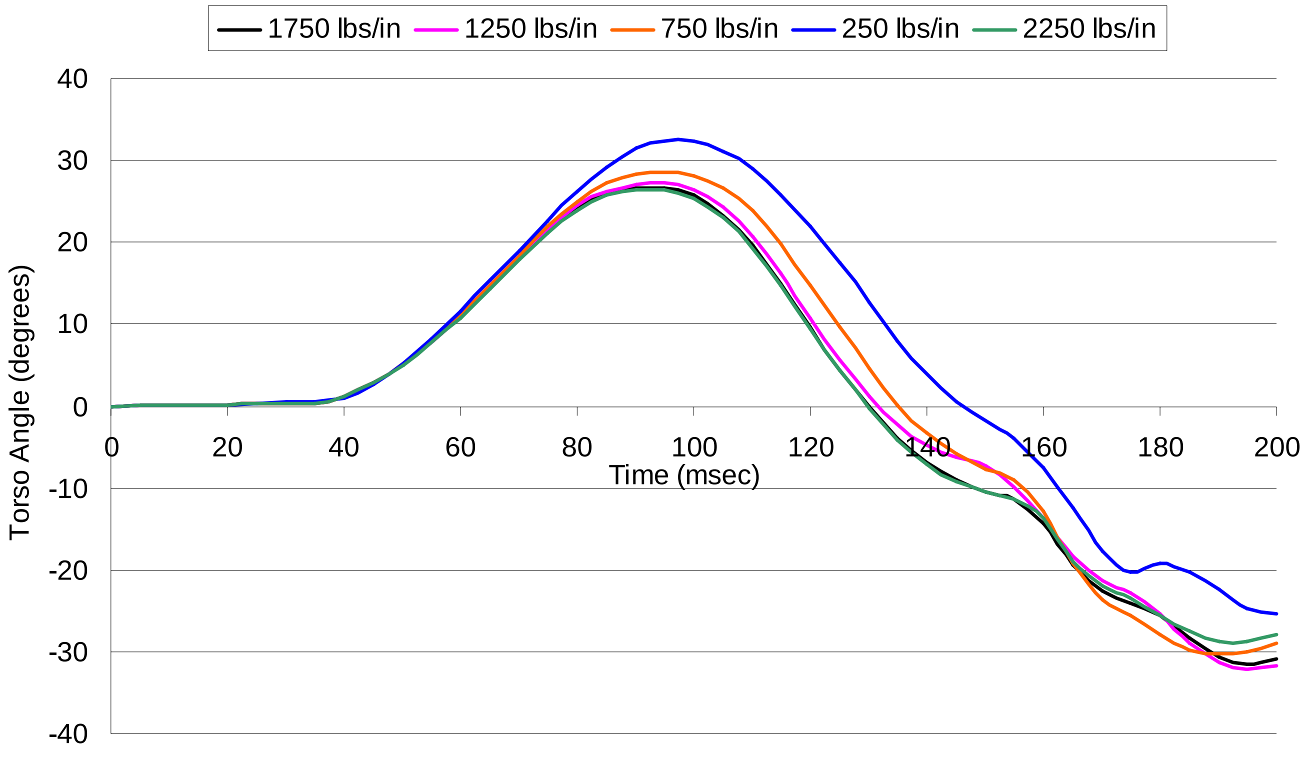

Figure 2. Torso angles relative to the vertical for various caster stiffnesses. A Positive angle indicates rearward torso rotation.

This figure depicts occupant torso angles relative to the vertical, for various caster stiffnesses simulation runs. The x-axis shows the time in milliseconds and the y-axis shows the torso angle in degrees during the simulation. All caster stiffnesses except for the 250lb/in stiffness produce maximum torso angles below the 30˚ criteria [9].

Simulation No.	R	G
3	0.75	0
4	1	0
7	0.5	0.25
13	0.75	0.5
17	0.5	0.75
20	0	1

Table 2. R and G factor legend for the simulations represented in the figures

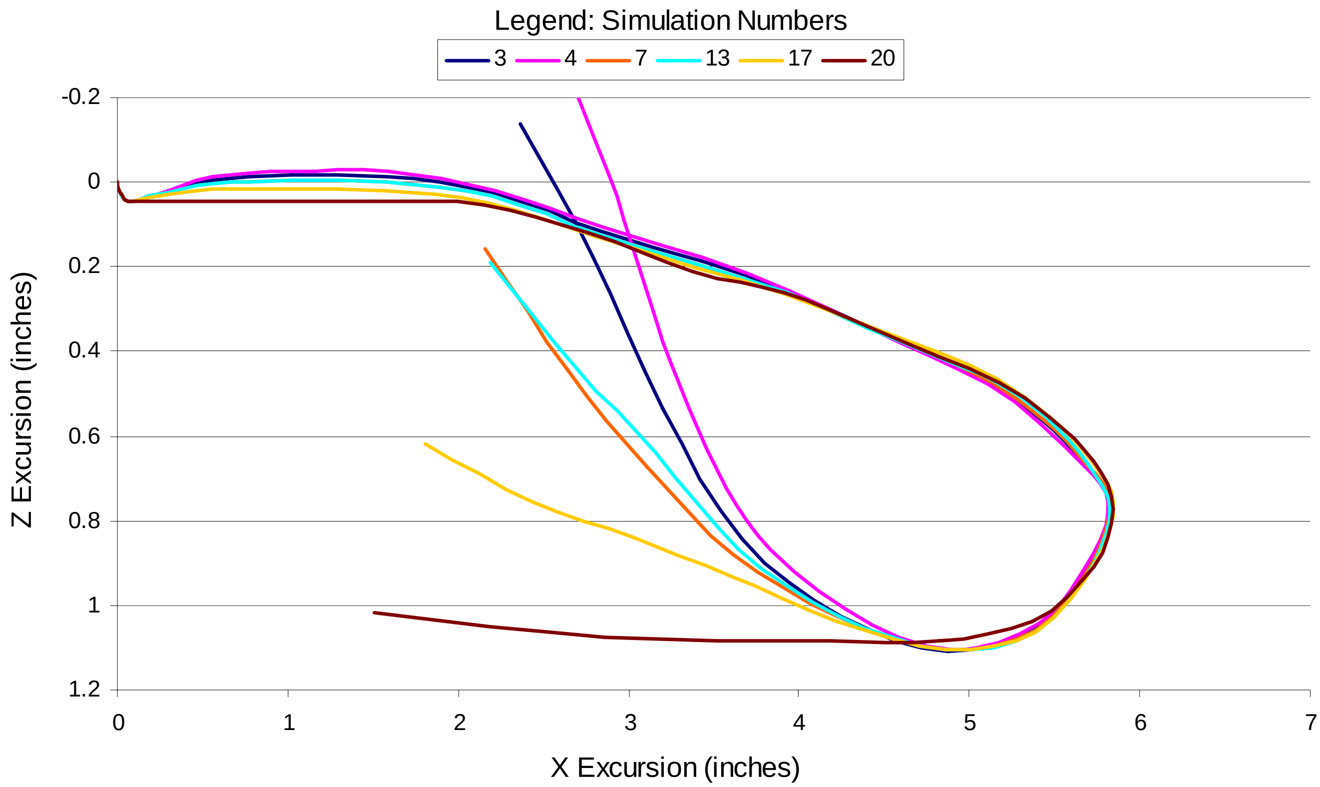

Figure 3. Caster hub X-Z excursions for caster stiffness of 1750 lbs/in (original model stiffness) from time 0 to 120 msec. At x = 0 (inches) and z = 0 (inches), t = 0 (msec)

This figure depicts the caster hub x-z excursions for caster stiffness of 1750 lbs/in. The x-axis shows the x direction (horizontal) displacement in inches, while the y-axis shows the z direction (vertical) displacement in inches. The R = 0 and G = 1 scenario (simulation 20) produced maximum energy absorption demonstrated by the greatest permanent deformation maintained during the unloading of the caster.

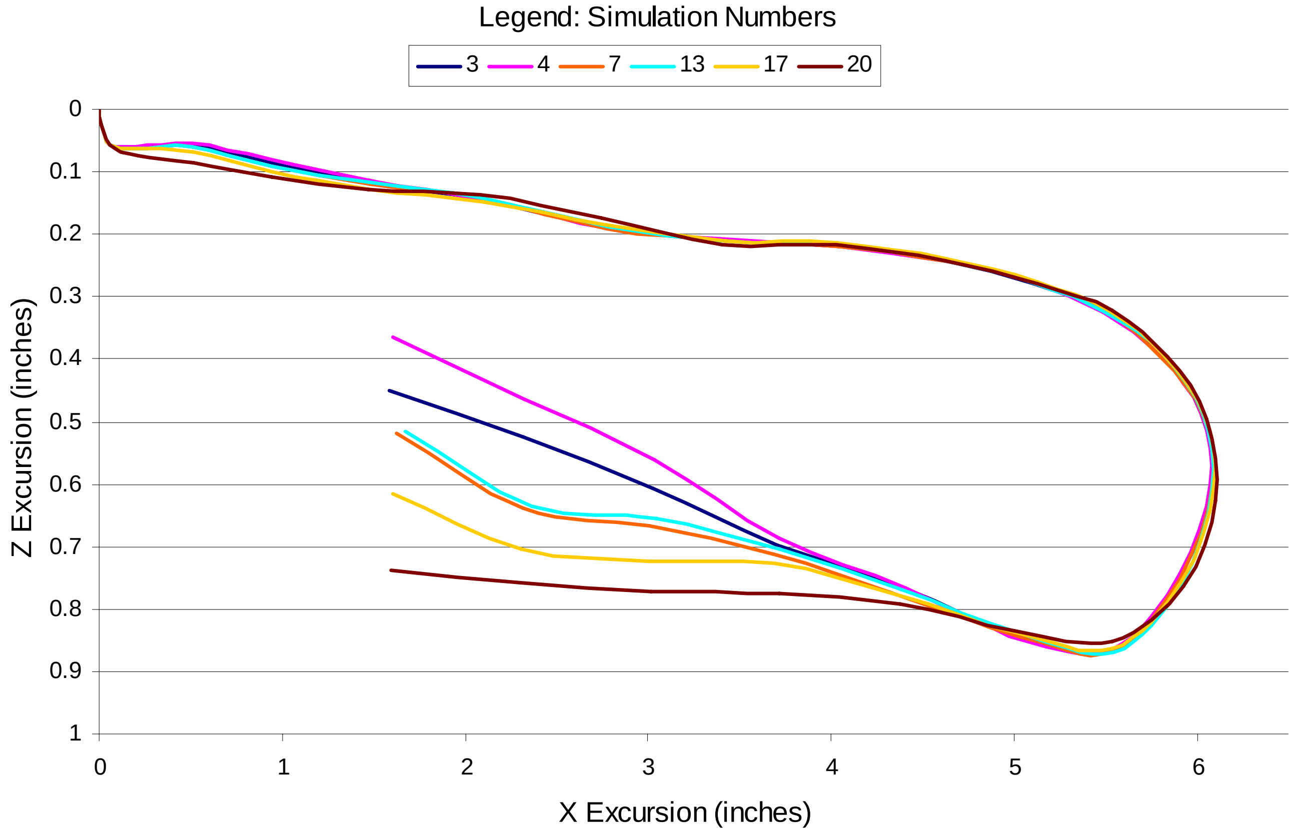

Figure 4. Wheelchair CG X-Z excursions for caster stiffness of 1750 lbs/in (original model stiffness) from time 0 to 120 msec. At x = 0 (inches) and z = 0 (inches), t = 0 (msec)

This figure depicts the wheelchair CG x-z excursions with caster stiffness of 1750 lbs/in. The x-axis shows the x direction (horizontal) displacement in inches, while the y-axis shows the z direction (vertical) displacement in inches. The R = 0 and G = 1 scenario (simulation 20) produced maximum energy absorption demonstrated by the greatest permanent deformation maintained during the unloading of the caster.

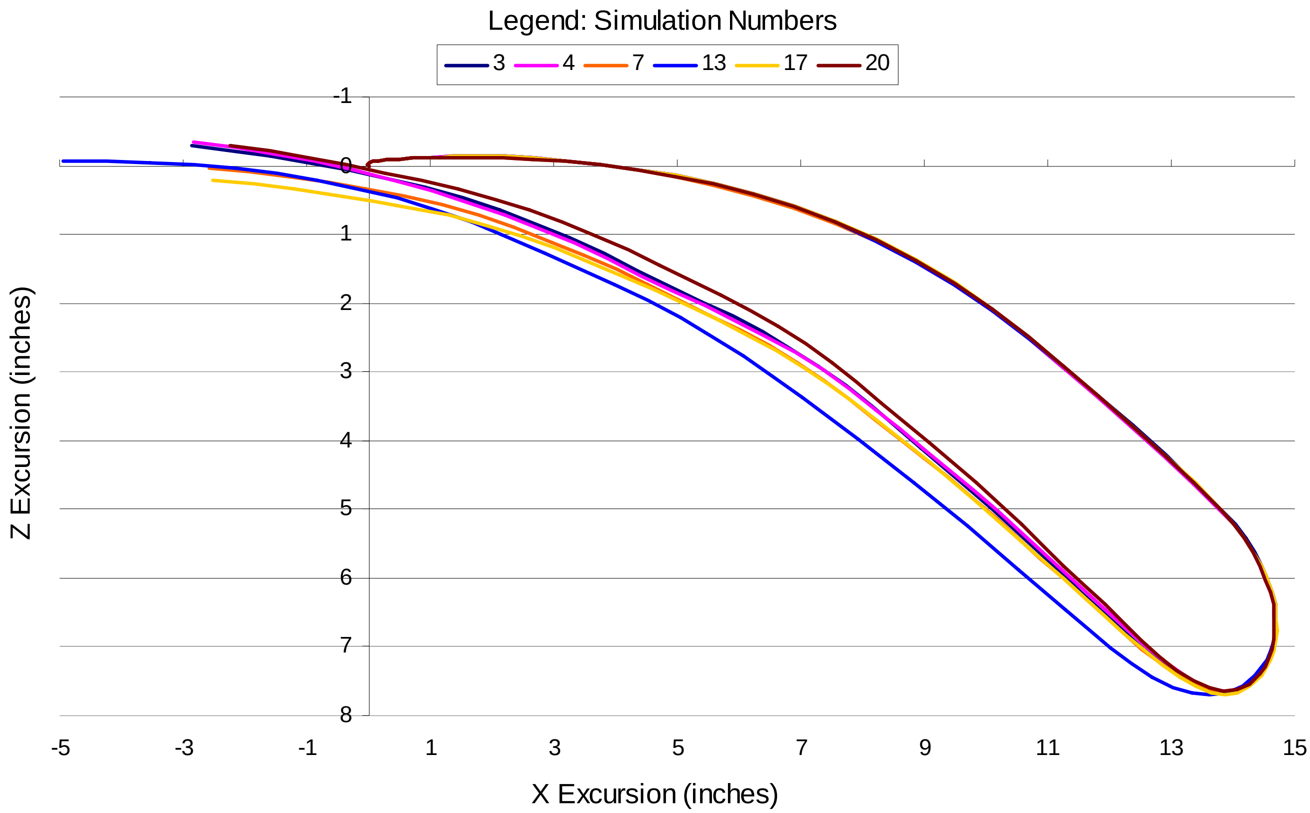

Figure 5. Head CG X-Z excursions for caster stiffness of 1750 lbs/in (original model stiffness) from time 0 to 200 msec. At x = 0 (inches) and z = 0 (inches), t = 0 (msec)

This figure depicts head CG x-z excursions for a caster stiffness of 1750 lbs/in. The x-axis shows the x direction (horizontal) displacement in inches, while the y-axis shows the z direction (vertical) displacement in inches.

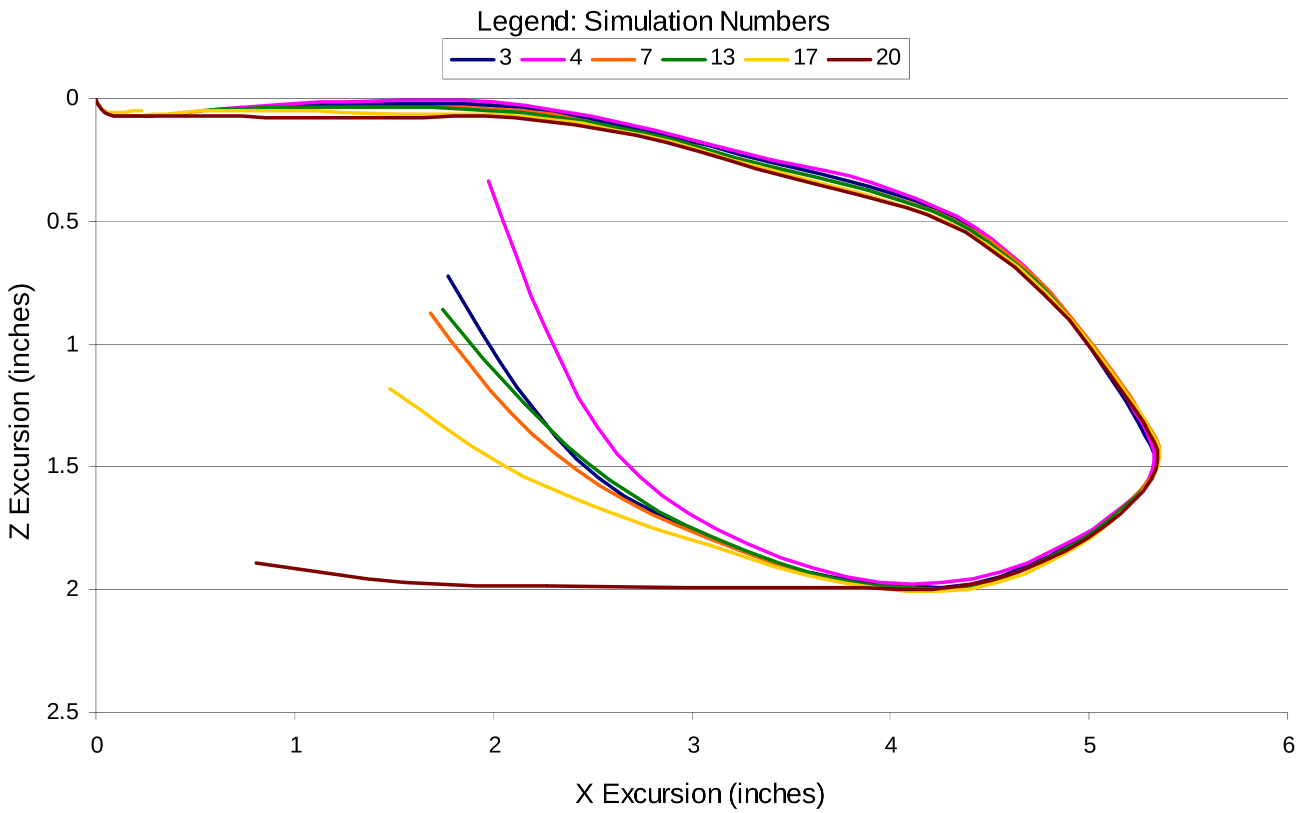

Figure 6. Caster hub X-Z excursions for caster stiffness of 750 lbs/in from time 0 to 120 msec. At x = 0 (inches) and z = 0 (inches), t = 0 (msec)

This figure depicts the caster hub x-z excursions for caster stiffness of 750 lbs/in. The x-axis shows the x direction (horizontal) displacement in inches, while the y-axis shows the z direction (vertical) displacement in inches. The R = 0 and G = 1 scenario (simulation 20) produced maximum energy absorption demonstrated by the greatest permanent deformation maintained during the unloading of the caster.

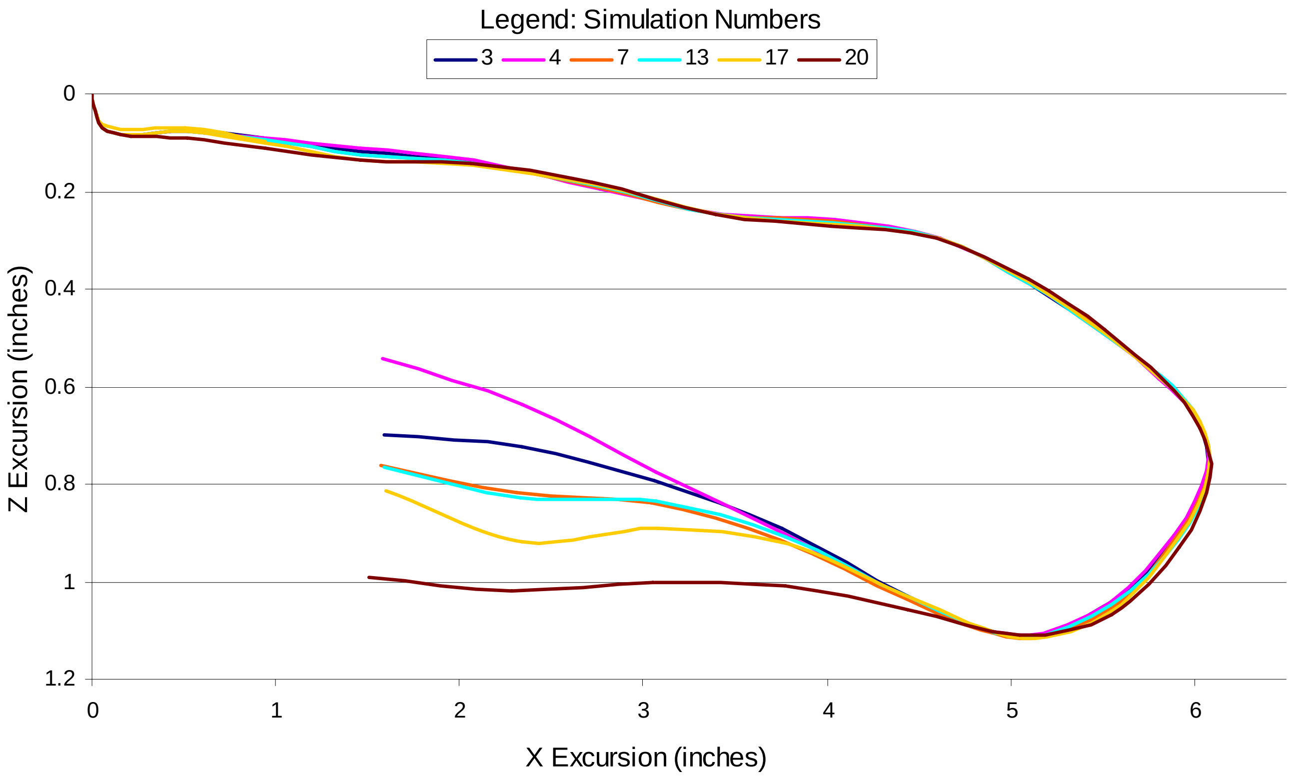

Figure 7. Wheelchair CG X-Z excursions for caster stiffness of 750 lbs/in showing from time 0 to 120 msec. At x = 0 (inches) and z = 0 (inches), t = 0 (msec)

This figure depicts the wheelchair CG x-z excursions for caster stiffness of 750 lbs/in. The x-axis shows the x direction (horizontal) displacement in inches, while the y-axis shows the z direction (vertical) displacement in inches. The R = 0 and G = 1 scenario (simulation 20) produced maximum energy absorption demonstrated by the greatest permanent deformation maintained during the unloading of the caster.

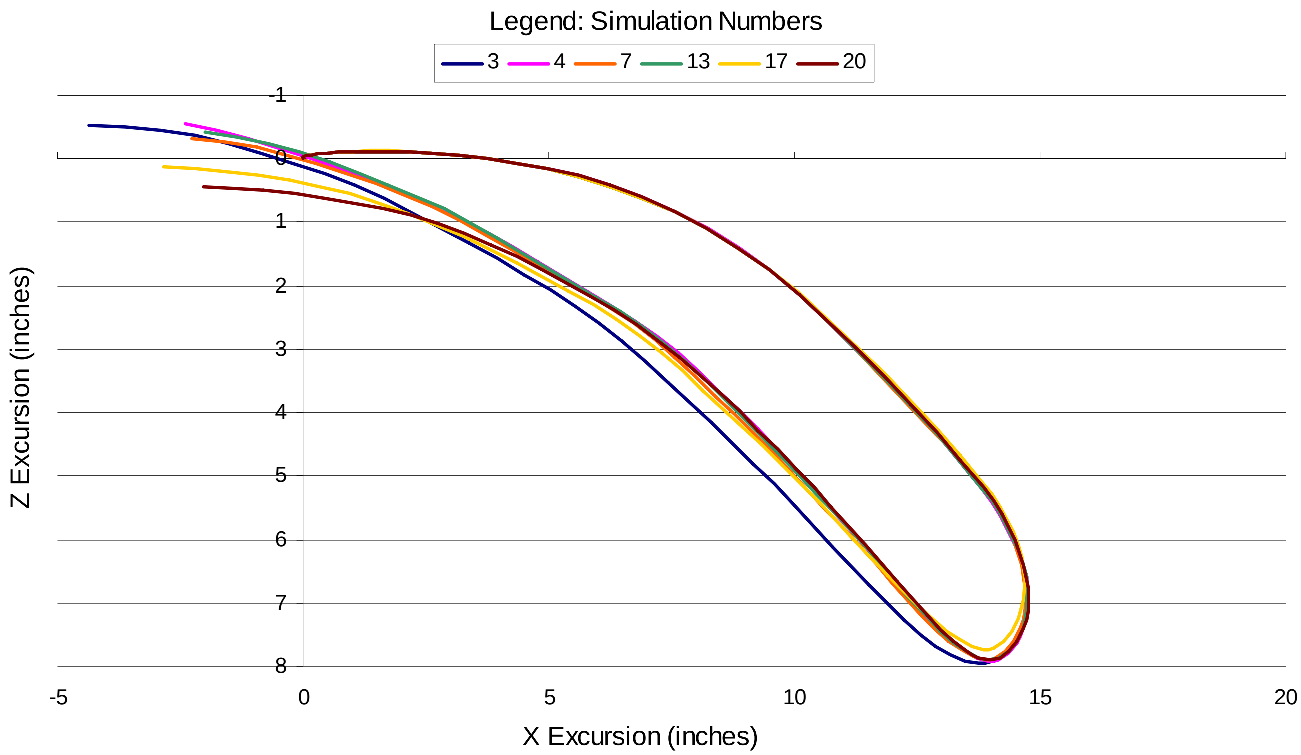

Figure 8. Head X-Z excursions for caster stiffness of 750 lbs/in from time 0 to 200 msec. At x = 0 (inches) and z = 0 (inches), t = 0 (msec)

This figure depicts head CG x-z excursions for caster stiffness of 750 lbs/in. The x-axis shows the x direction (horizontal) displacement in inches, while the y-axis shows the z direction (vertical) displacement in inches.

Caster Stiffness (lbs/in)	R factor	G factor	Caster hub peak excursion Z (inches)	Wheelchair CG peak excursion Z (inches)	Head CG peak excursion Z (inches)
1750	0 - 1	0 - 1	-0.41 – 1.01	0.365 – 0.737	-0.335 – 0.209
750	0 - 1	0 - 1	0.34 – 1.88	0.542 – 0.99	-0.564 – 0.441

Table 3. Effects of varying caster properties on the outcome parameters

This table shows the range of peak excursions in the z-direction (variation in permanent deformation) experienced by caster hub, wheelchair CG and head CG for the two caster stiffness scenarios with the R and G factors varying from 0 to 1.