

# Development and Validation of a Multi-Body Dynamics Model of the Pro-Neck-Tor Helmet

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## ABSTRACT

*The Pro-Neck-Tor (PNT) helmet was developed to reduce the incidence of cervical spine injuries during head-first impacts. It consists of an inner- and outer-shell that are connected by an internal guide mechanism. In an impact the mechanism deploys and guides the inner shell and head relative to the outer shell, such that the neck moves into flexion or extension. The deployment mechanism is intended to induce flexion in impacts slightly posterior to the vertex of the head, and extension in slightly anterior impacts. The purpose of this work was to develop a multibody dynamics model of the Hybrid III head and PNT helmet that can be validated experimentally, and allows us to assess the functionality of the deployment mechanism. The model simulates a drop tower that was configured to validate the model. Five experimental drops were conducted with the impact surface oriented at three different angles (0°, 15° and -15°), and helmet kinematics were measured using high speed video analysis. The model showed good agreement with experimental kinematic corridors. Agreement was strongest for the perpendicular (0°), and anterior-to-vertex (15°) impact conditions. The quantitative agreement for the posterior-to-vertex (-15°) impact condition was not as strong; however the mechanism deployed in the same manner in the experimental and virtual drops in all impact conditions. The deployment mechanism was able to select an appropriate deployment mode in various impact scenarios. Flexion was induced in posterior impacts, and extension was induced in axial and anterior impacts. According to the model, the deployment direction is governed by the moment that results from the forces at the deployment pins and the occipital condyles. This supports our current understanding of the deployment mechanism. The performance of the model is adequate to warrant its use in the continued development of the Pro-Neck-Tor helmet.*

## INTRODUCTION

Sporting accidents are a leading cause of spinal cord injuries (SCI) (NSCISC, 2006). They have been reported in football (Cantu and Mueller, 2003), mountain biking (Dodwell et al.,

2010), snow sports (Tarazi, 1999), motocross (Gobbi, 2004) and hockey (Tator, 1984). Head-first impact resulting in cervical spine fracture/dislocation is the predominant cause of injury (Cantu, 2003; Tator, 1984; Torg, 1990). When damage to the spine occurs, tissue fragments can enter the spinal canal and compromise the delicate spinal cord (Bohlman, 1979). Typically, this results in partial or complete paralysis. Additional complications may include loss of bowel control or the ability to participate in intercourse (Benevento, 2002). These symptoms can substantially reduce quality of life (Levi, 1995), and there is no cure. It is important that we prevent these injuries, given the devastating consequences.

The inertia of the head is sufficient to constrain the head on impact, and compliant padding can increase this effect (Nightingale, 1996). The cervical spine then becomes trapped between the head and the torso. As the torso continues to move towards the head, axial compressive loads are exerted on the cervical spine. Furthermore, cadaveric experiments have shown that increasing cervical spine alignment increases the forces on the spine during axial loading (Maiman, 1983; Pintar, 1995). Thus, the forward-flexed cervical spine, with the resting lordosis removed, has been generally accepted as the most vulnerable posture in head-first impacts. As eccentricity between the occipital condyles and first thoracic vertebra increases, injury type changes from fracture to soft tissue injury (Maiman, 2002). Studies have suggested that the spine can ‘escape’ injury if the head is able to move out of the path of the incoming torso (Camacho, 2001; Hu, 2008; Nightingale, 1996, 1991).

The Pro-Neck-Tor (PNT) helmet was conceived to reduce the incidence of cervical spine injuries in head-first impacts. The helmet induces head rotation and translation in the sagittal plane, to allow the cervical spine to escape the momentum of the following torso. The protective mechanisms of the helmet are three-fold: the cervical spine is moved away from a vulnerable, aligned posture; impact energy is dissipated through motion of the head and spine; and head constraint is reduced, allowing the head to escape the momentum of the following torso.

The helmet consists of two concentric shells that are connected by bilateral guide mechanisms. In an impact the mechanism deploys and guides the inner shell and head relative to the outer shell, moving the neck into flexion or extension. Flexion deployment should occur in impacts posterior to the crown of the head. Extension deployment should occur in impacts anterior to the crown of the head. Both flexion and extension deployment are acceptable in horizontal impacts; however, flexion deployment is preferred. Experimental results have demonstrated that these motions can reduce the compressive loads exerted on the spine (Nelson, 2011).

The deployment mechanism must be able to automatically select the appropriate deployment mode in various impact scenarios. The purpose of this work was to develop and validate a multibody dynamics model of the Hybrid III head and PNT helmet that allows us to assess the functionality of the deployment mechanism. The model is intended as a design tool for future optimization of the helmet.

## METHODS

Drop tower experiments were conducted to provide data for verification and validation of a multibody model. The Hybrid III head and PNT helmet were positioned in a drop tower to simulate head-first impacts. The head was oriented with the Frankfort plane aligned horizontally. It was held in place by strings, which slackened on impact. A revolute joint was located at the approximate location of the occipital condyles, and connected to a 16 kg drop carriage. This joint allowed the head to rotate in flexion or extension, while providing control of the magnitude and direction of the loads applied to the head. Drops to positively inclined ( $15^\circ$ ), negatively inclined ( $-15^\circ$ ), and horizontal ( $0^\circ$ ) surfaces were conducted to generate anterior-to-vertex, posterior-to-vertex, and perpendicular-to-vertex head impacts, respectively. Five drops were conducted for each condition, and recorded using high speed video. The outer helmet shell kinematics were measured using 2D image analysis software (TEMA, Image Systems, Sweden). A uniaxial load cell beneath the impact surface measured the impact force. A six-axis load cell at the base of the carriage mass measured the force transmitted through the occipital condyles.

A multibody model was constructed in MSC Adams (MSC Software, Santa Ana, CA) to simulate the drop tower experiments (Figure 1). The geometry of the carriage, helmet, and head were imported directly into the model. Therefore, the simulated apparatus precisely replicates the real world scenario. Impacts were simulated at 2.06 m/s, to match the average velocity of the experimental impacts.

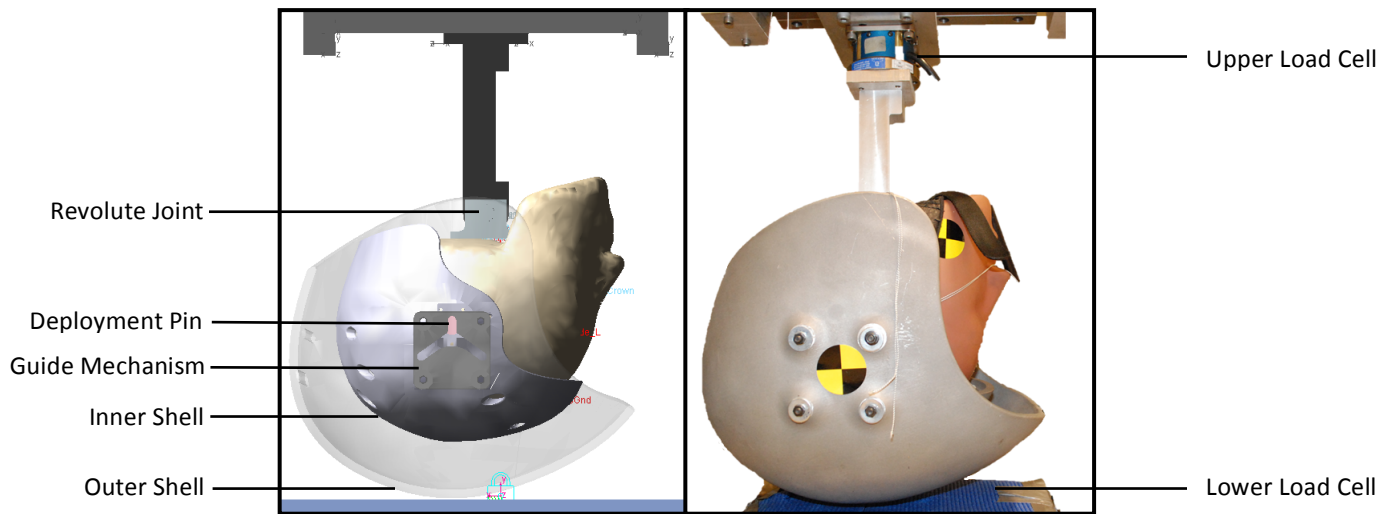


Figure 1: Multibody model (left) of a physical drop tower apparatus (right)

In the model, contact forces arise in two locations: between the outer helmet shell and ground; and between the deployment pin and the guide. Contact forces in Adams are calculated using a spring-damper contact model. The contact behavior is defined by four input parameters: stiffness,  $k$ , damping,  $\zeta$ , force exponent,  $e$ , and penetration depth,  $d$ . Penetration depth determines when full damping is turned on in the solver, and was set at the default value of 0.01 mm. The force exponent is material dependent, and was chosen based on the recommended value for aluminum-aluminum contact, 1.5. The stiffness and damping values for helmet-ground and pin-

guide contact were tuned independently to match the force response in the  $0^\circ$  experimental impacts. The model was then validated for the  $0^\circ$ ,  $15^\circ$ , and  $-15^\circ$  impact conditions, based on the kinematics of the outer helmet shell. The deployment mode was also evaluated to ensure the simulated helmet response matched the real-world behavior. The model was then used to assess the functionality of the helmet, and determine the factors that govern deployment.

## RESULTS

Two impact peaks result when the helmet contacts the ground. The first occurs when the outer helmet shell contacts the impact platform. The second arises when the deployment pin contacts the top of the deployment guide. This is observed in both the experimental and simulated drops. However, the model response is sensitive to changes in the contact stiffness and damping parameters (Figure 2).

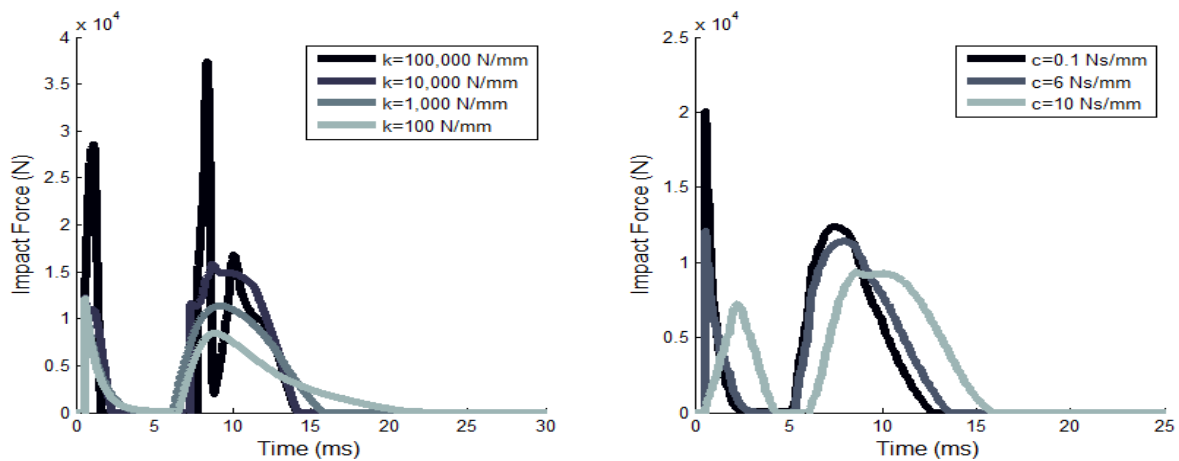


Figure 2: The impact force of the model is sensitive to changes in the contact stiffness (left) and damping (right) parameters

The head-ground contact parameters were adjusted until the initial impact peak matched the experimental value. The pin-guide contact parameters were then tuned to approximately match the second impact peak, while preventing unrealistic penetration between the deployment pin and guide. This caused the magnitude of the second impact peak to exceed the experimental value (Figure 3). The final contact parameters are provided in Table 1.

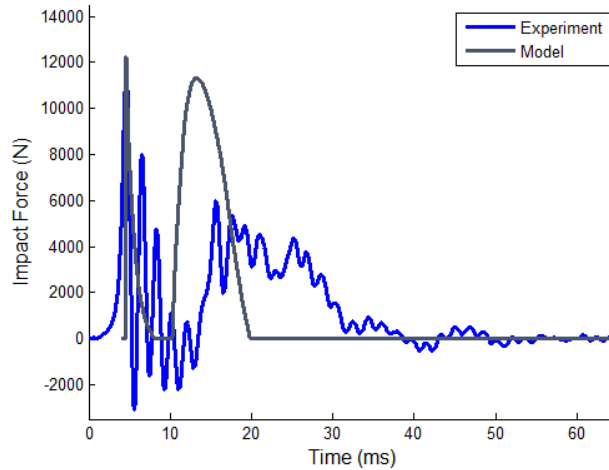


Figure 3: The model (gray) force response matches the experimental (blue) force response during the first impact peak. The agreement weakens during the second impact peak.

Table 1: Final contact parameters after tuning

	Penetration Depth, $d$ (mm)	Force Exponent, $e$ (unitless)	Stiffness, $k$ (N/mm)	Damping, $c$ (Ns/mm)
Helmet-Ground	0.01	1.5	1000	5.96
Pin-Guide	0.01	1.5	2000	1.5

Figure 4 shows the results of the model validation. The experimental and simulated data were aligned at the time of peak force development, measured at the base of the carriage mass. The model results fell close to the experimental corridors in the  $0^\circ$  and  $15^\circ$  impacts. The agreement was less strong in the  $-15^\circ$  impact condition. In this case, the experimental drops produced larger motions, although the model tended towards similar patterns of motion. Still, the deployment mode observed in the model matched that observed experimentally in every impact condition.

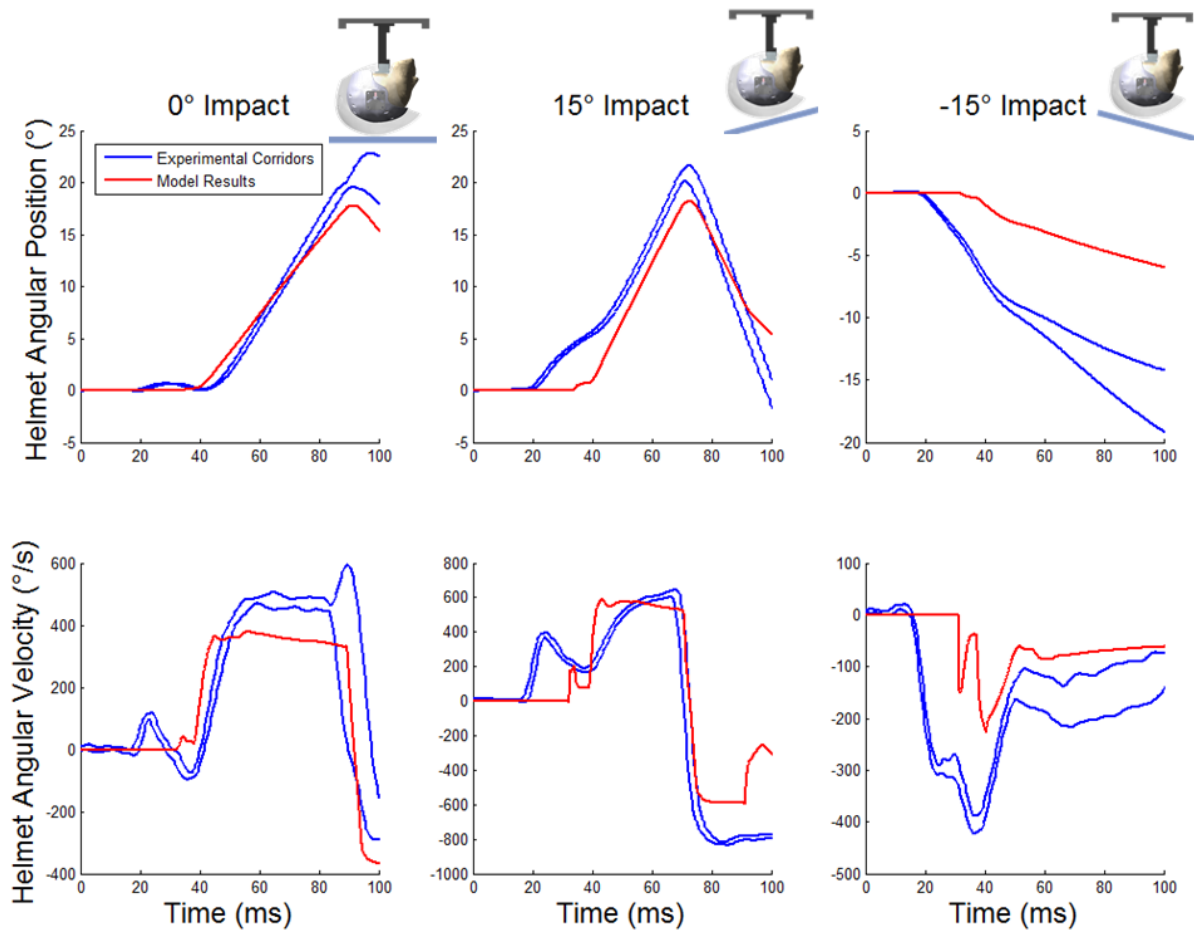


Figure 4: The model response (red) was compared to experimental corridors (blue) for the outer shell angular position and angular velocity. The model showed good agreement with experimental results.

The differences between the virtual and measured responses in the  $-15^\circ$  impacts may be due to differences in the initial head and helmet positions. The orientations of the head and helmet relative to each other, and relative to the overall apparatus, were not quantified. Therefore, the positioning of the head and helmet in the model may not accurately reflect the experimental configuration. Figure 5 shows the model kinematics when the head and helmet are flexed forward four degrees, prior to simulation. This results in better agreement with the experimental kinematics. These changes did not alter the behavior of the deployment mechanism, or otherwise affect our analysis of helmet functionality. Thus, the differences observed in the  $-15^\circ$  impacts appear minor.

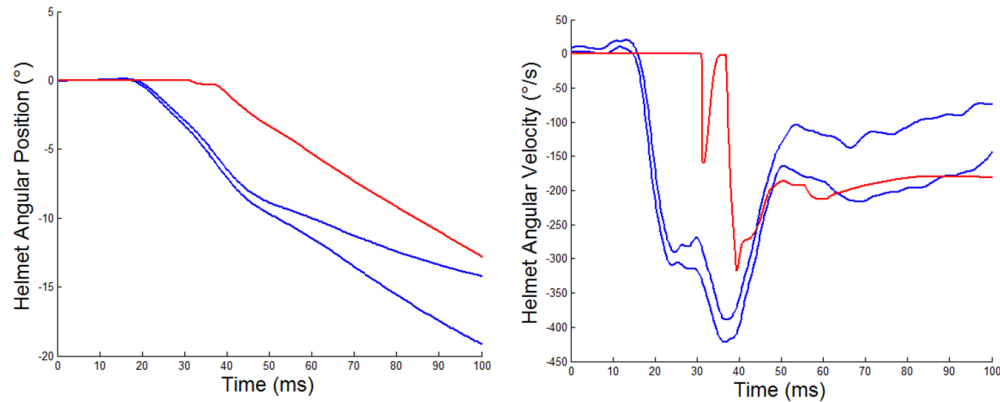


Figure 5: Agreement between the model (red) and experimental (blue) kinematics is improved when the head and helmet are initially flexed forward by four degrees

The model was used to demonstrate how the deployment mechanism functions. Forces are transmitted to the head through the deployment pins and the occipital condyles. These forces give rise to moments, which cause the head to rotate in flexion or extension and initiate the corresponding deployment mode. In  $+15^\circ$  and  $0^\circ$  impacts, a predominantly positive moment results in extension deployment. In  $-15^\circ$  impacts, a negative moment results in flexion deployment. Figure 6 shows the resultant moments throughout each impact.

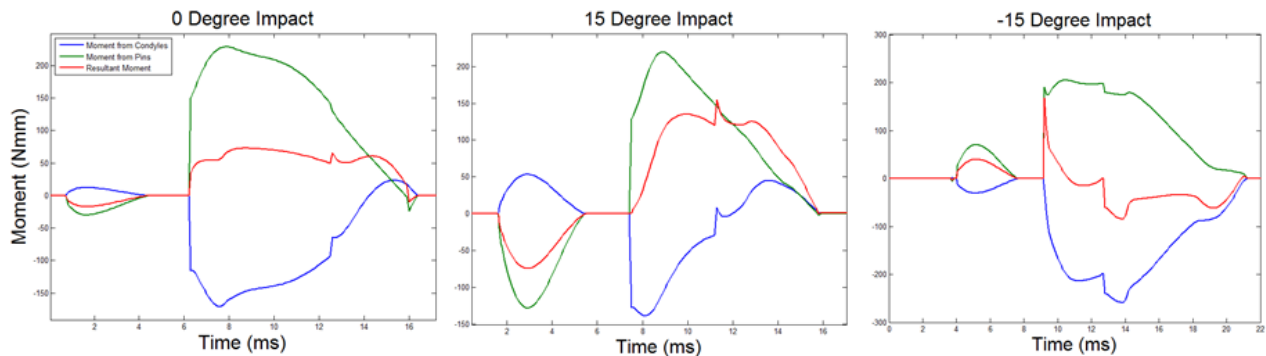


Figure 6: Deployment mode is governed by the resultant moment (red) on the head from the loads at the occipital condyles (blue) and deployment pins (green). The moments that arise at 2-4 ms occur prior to the pin contacting the guide, and do not influence deployment. Positive moments are extension moments, and negative moments are flexion moments.

The moment produced by the occipital condyles opposes the moment from the deployment pins. The net moment on the head is therefore small. While this is sufficient to produce some motion throughout impact, the majority of head motion occurs after the impact forces have developed.

## DISCUSSION

The spring-damper contact model in Adams is a simplification of real-world contact mechanics. Although loosely based on Hertz contact theory, the input parameters cannot be calculated theoretically. As demonstrated, these parameters can be tuned to approximately match experimental measurements. However, there are tradeoffs between matching experimental data, achieving reasonable model behavior, and maximizing computational efficiency. Contact behavior is also dependent on the geometry, velocity, and mass of the bodies involved. Therefore, the model has limited ability to predict contact forces in situations beyond what it was tuned for. The user should exercise caution when interpreting absolute forces derived from this model. However, it may be reasonable to perform analyses based on relative force responses.

Despite the limitations associated with determining contact forces, the model agreed well with measured kinematics. Most importantly, the helmet deployed in the same manner in both the virtual and physical tests. Although the forces in the model do not perfectly represent the experimental behavior, the model could still be used to understand how the applied forces influence deployment. This is adequate to warrant the use of this model in future development of the PNT.

Automatic selection of an appropriate deployment mode occurred in every impact. Forces at the occipital condyles and deployment pins produce a moment on the head that initiates deployment. However, these forces appear to be in precarious balance, as the resultant moments are small. Presumably, as the magnitude of the moment decreases, the deployment time will increase, which increases the likelihood that the spine will be injured before appreciable head motion can occur. Future design improvements should seek to initiate head motion earlier, in order to maximize the potential for injury prevention.

## CONCLUSIONS

This model demonstrated good agreement with kinematic measurements. It confirmed that the deployment behavior of the helmet is governed by the moment about the head, and demonstrated that the PNT is capable of selecting an appropriate deployment mode in different impact scenarios. The model is believed to be sufficient for use as a design tool in the continued development of the PNT helmet. However, in light of the limitations associated with multibody modeling, future design work should not take place exclusively within the virtual environment. Physical testing is recommended to support the analysis of future designs.

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