

Hybrid III Head/Neck Analysis Highlighting Nij in NCAP

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ABSTRACT

Nij, a function of upper neck forces and moment, plays a dominant role in the vehicle's star rating under the new NHTSA NCAP front impact program. This is mainly due to an artifact in the mapping of the Nij into the "risk" value used in the star rating, and the fact that the neck region is not weighted appropriately to reflect its real world significance relative to the other body regions in the NCAP rating. New test data also show that compared with the 50th male driver Nij, the 5th female passenger Nij is significantly more challenging to contain and therefore it is more dominant in the star rating.

This paper describes the Hybrid III dummy head and neck impact response and provides a method to determine the external force acting on the head. The force and its acting point on the head are determined from head acceleration, angular acceleration, and the upper neck forces. This paper also analyzes the neck bending mechanism and the associated forces, and how the thorax rotation and translation can affect the upper neck forces. It discusses how the airbag shape and stiffness can affect the external force acting point and direction, and how the force affects the neck internal forces. The analyses have focused on the response of the 5th female dummy neck due to the aforementioned practical difficulty with its Nij. The analytical methods presented should aid in the understanding of vehicle restraint systems.

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1. INTRODUCTION

With the NHTSA's introduction of the new NCAP 5-star rating system [1] starting with 2011 MY vehicles, the front impact star rating is based on ratings of the head, neck, thorax and femur regions. To achieve a 5-star rating for the driver or passenger, the assessment values for each body region, on average, have to be about 30%, or lower than the corresponding FMVSS 208 regulatory limits. In doing so, one particular difficulty has to do with the Nij. This, unfortunately, is mostly artificial and justified by neither biomechanics nor field accident data. As shown in [Figure 1](#) where the probability of injury (1(a)) and their derivatives (dP/dI, 1(b)) for the four injury criteria are plotted against their values normalized by their respective FMVSS 208 limits, the neck injury risk* as a function of Nij used by the NHTSA rises most quickly up to 0.3 in the normalized value; and unrealistically, the injury risk* is 3.8% at zero Nij (this is a result of the logistic fit for the function). This concern had been raised before the finalization of the new NCAP [3, 4]. If the responses at the other three body regions are controlled to

the same level of 3.8% - corresponding to zero Nij, the vehicle will be rated borderline between 3 and 4 stars. This illustrates that the Nij unduly outweighs the other criteria in the rating system.

Actual test results recently have become available, and these have made the above concerns more than a theoretical consideration. [Figure 2\(a\)](#) plots the passenger RRS ("Relative Risk Score" [1]) versus Nij for 2011MY vehicle tests by the NHTSA. The close correlation between the RRS and Nij reveals a dominant effect of Nij on the star rating. Of the 62 vehicle tests, 7 of them were rated 5 stars for the passenger. These cases are as shown in [Figure 2\(b\)](#) where the four body regions' relative contribution is plotted as a stack bar. In these 5-star vehicles, the Nij overwhelms even the head and chest which are the most critical body regions.

*Note that in general, the "injury risk" functions are derived from laboratory experiments. They are often far from precise due to lack of reliable biomechanical data, parametric fit procedures, and the choice of relevant mechanical responses - for an example, see Nusholtz et al. [2] on neck injury. The term "injury risk" is used here with this caveat.

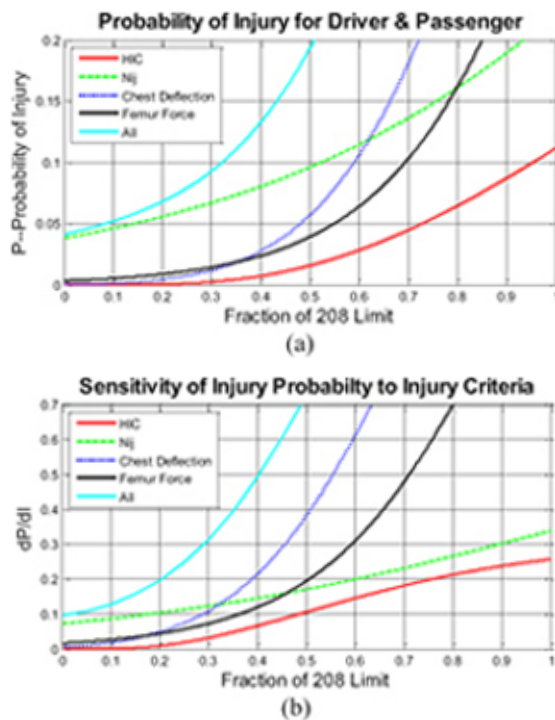


Figure 1. (a) Injury risk* functions and (b) their sensitivity for driver and passenger.

The criticality of the head and chest, and the relatively limited role of the neck in terms of serious and fatal crash outcome, are recognized in the literature. For example, Frampton et al. [5] showed that for frontal crashes, only 7% of the fatalities sustained an AIS 4+ injury in the neck, while much higher percentages sustained AIS 4+ injuries at the head and thorax. Another analysis by Laituri et al. [6] estimated that the rate of sustaining AIS3+ levels of injury in “NCAP-type” real-world crashes for the neck is 1%, compared with 5% and 19% for the head and chest. This indicates that, of the four body regions considered in the NCAP testing, the neck had the lowest life-threatening injury probability in the field.

Another way to look at this concern is to compare the RRS of the 62 vehicle front impact tests with that of the side impact tests (61 kph MDB, and no Nij involvement) as plotted in Figures 2(c) and (d). They show that the 5-star side impact vehicles fill the whole RRS range between 0 and 0.67 while the 5-star front impact vehicles can hardly achieve the RRS under 0.5 (The lowest RRS for the passenger is 0.59) - because of the Nij involvement. The NHTSA summarized [7] the 2011 NCAP side impact tests and concluded that the average star ratings for the side MDB- and side pole-tested vehicles certifying to the new FMVSS 214 regulation were 5 stars, while for the front impact tests, the average ratings were 4 stars for the driver side and 3 stars for the passenger

side. The disparity here is rooted in the elevated role of the Nij, and indeed it is a manifestation of the issue with it.

The above analysis and data form a strong argument that the way the Nij is included in the new NCAP system should be revised because it ultimately weakens the final rating as an indicator of occupant protection. A revision should address both the injury risk* function and the weight on the neck region in the overall calculation so that the field significance of the neck is appropriately reflected relative to the more prominent roles of the head and thorax. This notwithstanding, at the current time, the status quo means that for vehicle manufacturers to achieve a good star rating, considerable and careful efforts have to be made to control the Nij response.

This study analyzes the mechanisms through which neck force and moments are generated. It shows how accelerometers and angular rate sensors can be used on the dummy head and chest to obtain additional information as how the external resultant force acts on the head, how the restraint influences the chest, and how the resulting motion of the chest can affect the Nij.

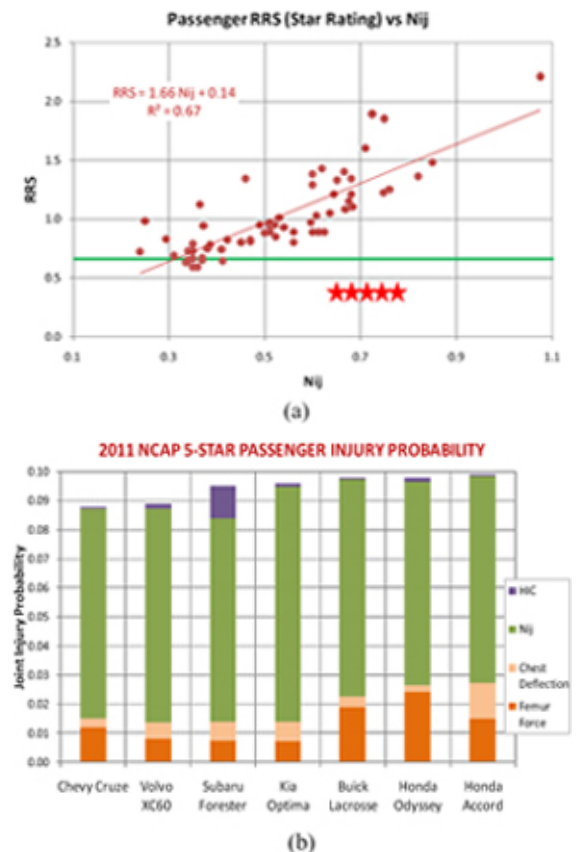
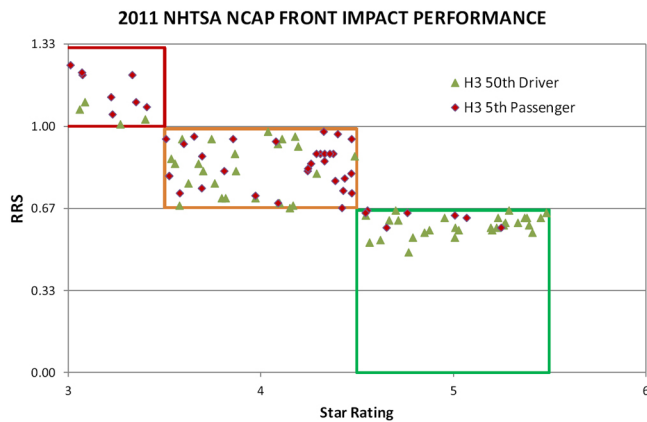
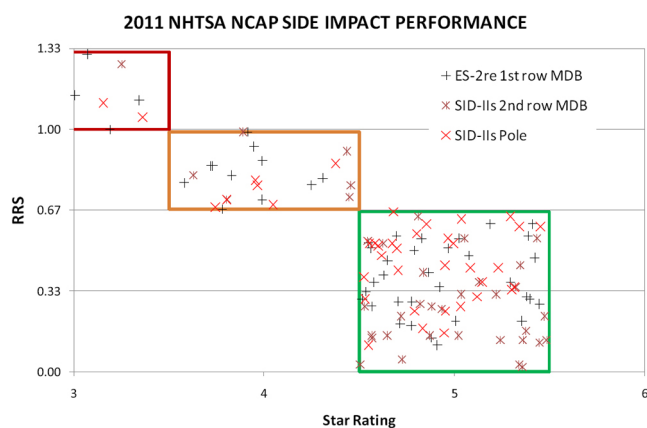


Figure 2. NHTSA 2011 NCAP test results. (a) Passenger RRS vs Nij; (b) Body region contributions for 5-star passengers;

*Note that in general, the “injury risk” functions are derived from laboratory experiments. They are often far from precise due to lack of reliable biomechanical data, parametric fit procedures, and the choice of relevant mechanical responses - for an example, see Nusholtz et al. [2] on neck injury. The term “injury risk” is used here with this caveat.



(c)



(d)

Figure 2 (Cont'd). NHTSA 2011 NCAP test results. (c) Front impact RRS; (d) Side impact RRS.

2. HEAD-NECK ANALYSIS

2.1. HEAD-NECK MECHANISM, UPPER NECK FORCE AND NIJ DEFINITION

Shown in Figure 3 is a drawing of the Hybrid III 50th male head. The 5th female head is similar but with different dimensions and weight [8]. The relative location of the head accelerometers and load cells also are given. At the occipital condyle is a cylindrical pin which can transfer the upper neck shear force and axial force to the load cell. But the neck moment around the transverse y-axis M_y has to be transferred by the two rubber nodding blocks (Figure 3), as indicated in Figure 4. Figure 4 also shows a perspective view of the Hybrid III 5th percentile female dummy's head, neck and thorax spine. The lower neck is rigidly connected with the thorax spine. The neck is a flexible rubber cylinder with slits on the front side, so that its resistance to the extension bending moment is weaker than that to the flexion bending moment.

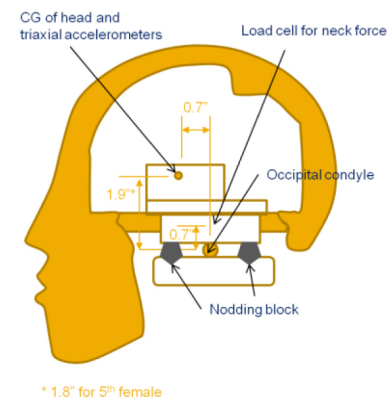


Figure 3. Mechanism of the Hybrid III head.

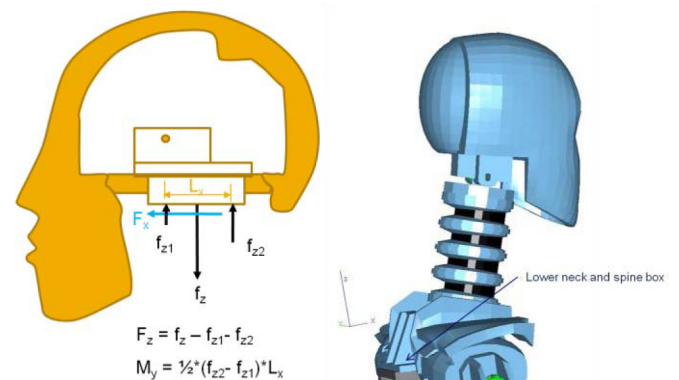


Figure 4. Upper neck force and Hybrid III head, neck and thorax spine.

Because the occipital condyle is under the upper neck load cell, its M_{y0} moment is different from the load cell output M_y by an amount of shear force F_x multiplied by the moment arm 0.7", or 0.01778 m, as follows:

$$M_{y0} = M_y - 0.01778 F_x \text{ (Nm)} .$$

In the rest of this paper, the neck moment in all the schematic drawings represents the bending moment at the occipital condyle.

The flexion and extension moments cannot be accurately judged by the head rotation (Figure 5(a)); although, a head rearward rotation tends to cause extension moment and a forward rotation flexion moment. The internal force directions depend on the free body the force is referred to. As shown in Figure 5(b), the forces are in pairs with respect to the head and the neck, all positive in the SAE sign conventions.

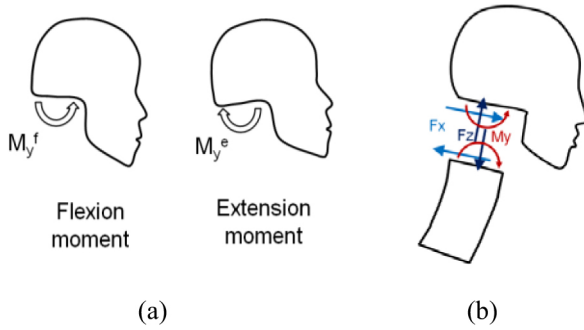


Figure 5. (a) Upper neck flexion and extension moments; (b) Positive F_x , F_z and M_y in SAE sign convention.

Typical transducers for the HIII dummy head and neck are (1) the triaxial accelerometers at the head CG measuring the x-, y- and z-accelerations of the head; (2) upper neck load cells for x- and y-shear forces F_x , F_y and axial force F_z ; and (3) upper neck load cells for x-, y- and z-moment M_x , M_y and M_z . Assuming the occupant's motion is in the x-z plane, as is typically the case for the front rigid barrier impact with belted occupants, only the x- and z-accelerations, neck forces and M_y moment are significant and used. Consistent with this, the N_{ij} in frontal NCAP is defined as follows:

$$N_{ij}(t) = \frac{F_z}{F_{zc}} + \frac{M_{yo}}{M_{yoc}}$$

Eq. 1

M_{yo} is associated with F_x as defined previously, and F_{zc} and M_{yoc} are constants depending on the dummy size. For the 5th percentile female, the N_{ij} at 0.25, 0.30 and 0.35 is shown in Figure 6(a). These values span the range needed to achieve a 5-star front passenger rating. Depending on the axial force and moment types in computing $N_{ij}(t)$, the final N_{ij} criterion can be due to tension-extension (N_{te}), tension-flexion (N_{tf}), compression-extension (N_{ce}), or compression-flexion (N_{cf}), and can be written as ("max" means the maximum value through the time duration):

$$N_{ij} = \max \{N_{te}, N_{tf}, N_{ce}, N_{cf}\}$$

For the 5th percentile female, bringing in the normalizing values of 4.287 kN, -3.880 kN, -67 Nm, and 155 Nm for tension, compression, extension and flexion respectively, Equation 2 is obtained:

$$N_{ij} = \max \{0.0107 |M_{yo}| - 0.0042 M_{yo} + 0.246 |F_z| - 0.012 F_z\},$$

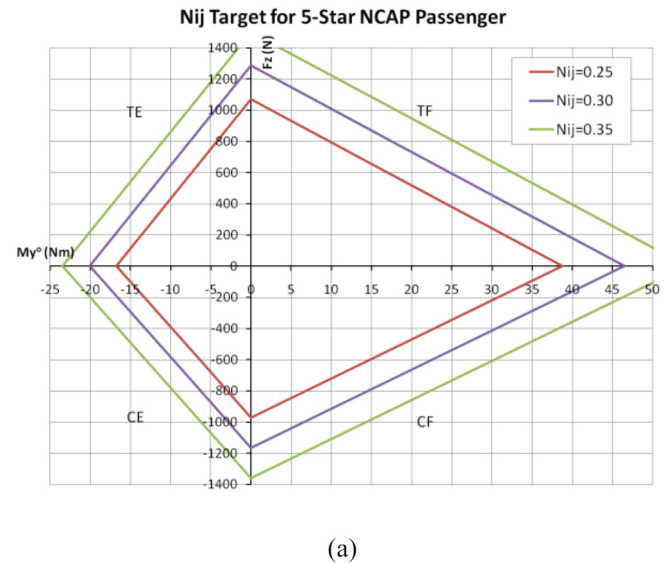
Eq. 2

where M_{yo} is in Nm and F_z in kN, and here and in the rest of this text, the SAE sign convention for the dummy is followed.

Typically N_{te} is dominant for the 5th percentile passenger in the NCAP test (as shown in Figure 6(b)), which plots the

passenger N_{ij} in the F_z -versus- M_y space for the 62 NCAP vehicle tests mentioned in Figure 2), and the neck tension force contribution to N_{ij} can account for up to 0.234 F_z (Eq. 2 with $F_z > 0$) while the extension moment can account for up to 0.015 $|M_{yo}|$ (Eq. 2 with $M_{yo} < 0$). Therefore, reducing the axial force can be as important as the moment in reducing N_{ij} (Data of tests in Figure 6 show that the maximum axial force criterion almost never controls the neck rating - the axial force effect is through N_{ij}). Figure 6(c) shows the same data but normalized to clarify the contributions of F_z and M_y to the N_{ij} for each test. Figure 6(b) shows most of the N_{ij} is in tension-extension mode, some is in compression-extension mode (several of these occurred when the head and chest rebounded and contacted the headrest/seatback). Figure 6(c) reveals that generally the M_y contributes more than F_z in the N_{ij} calculation. Nonetheless, the effect of F_z cannot be ignored, and in fact a high extension moment is frequently associated with a high neck tension.

Figure 6(d) shows the correlation between the neck tension force and N_{ij} for the 50th percentile driver and the 5th percentile female passenger for the same 62 tests. The correlations are not strong, but considering that the tension forces here are the peak forces, not the actual F_z in the N_{ij} calculation, and quite a few of N_{ij} in the 62 tests are due to the neck compression force, this correlation suggests that the neck tension force should not be neglected in dealing with N_{ij} .



(a)

Figure 6. 5th female passenger N_{ij} as a function of neck axial force and moment. (a) Typical N_{ij} range for 5-star passenger rating;

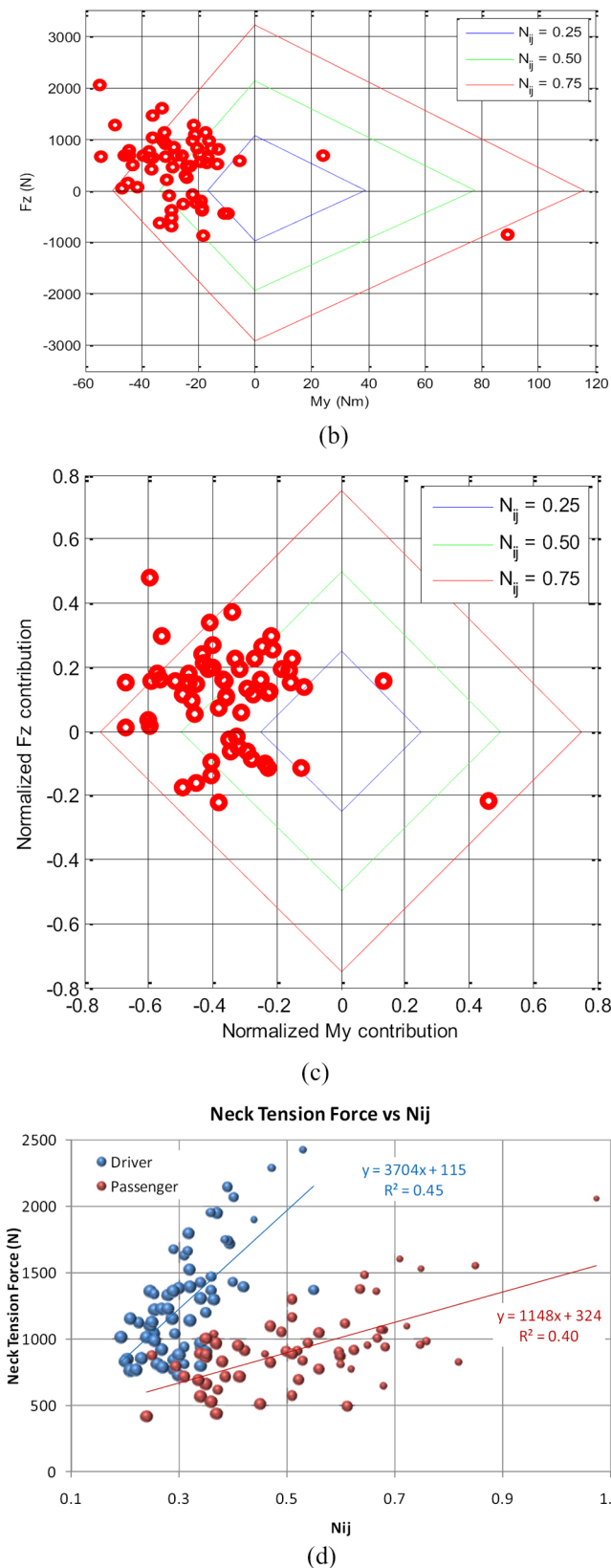


Figure 6 (Cont'd). 5th female passenger Nij as a function of neck axial force and moment. (b) Passenger Nij for the 62 vehicles tested by NHTSA (2011); (c) Normalized My and Fz; and (d) Neck tension versus Nij for the driver and passenger of the 62 vehicles (larger bubbles indicate higher star ratings).

2.2. EXTERNAL FORCE DETERMINED BY DYNAMIC EQUILIBRIUM OF THE HEAD

In a typical NCAP test, M_y and F_z develop through different mechanisms in three possible phases characterized by the head contact conditions throughout the impact duration. As depicted in Figure 7, there are three possible phases of loading. Figure 7(a) illustrates Phase I, where the external force is absent. This occurs before head contact with the airbag. Figure 7(b) illustrates Phase II, where external force from the airbag acts on the head. Finally, Figure 7(c) illustrates Phase III, where the head is first free from external force as the dummy rebounds. But it receives contact force from the headrest towards the end when head contact occurs.

Figure 7(d) is a schematic illustration of the upper neck F_z and M_y , abstracted from responses of a large number of NCAP tests with the solid curves representing a more desirable scenario (For reference, Figure 7(e) shows the 4 tests with the lowest Nij and the 4 with the highest Nij.). In Phase I, the neck is the only load path for the head, and the upper neck force is purely a function of the relative motion between the head and chest. After this, in Phase II, the external airbag force on the head is a strong factor on the neck force. In this phase, the neck axial force is typically in tension first and then in compression after the head plunges into the PAB. The neck moment can be in flexion or extension; however, to get to about the same Nij, the flexion moment can be about 2.3 times as large as the extension, as can be seen in Figure 6(a). In Phase III, the head and chest rebound and the head may contact the headrest or other hard points and cause a high Nij (sometimes the head may not contact anything but the Nij is due to the neck extensive stretch). Analyses of the kinematics and equilibrium of the head are given below.

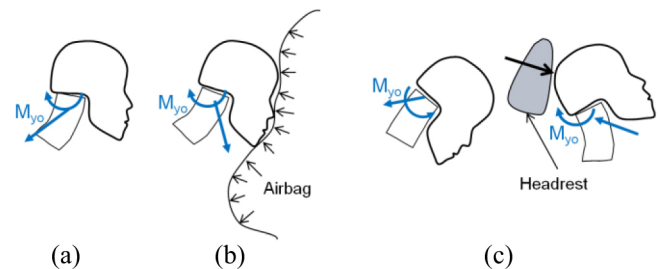


Figure 7. Three phases for possible passenger's Nij (arrows represent neck force). (a) Phase I: Before airbag contact; (b) Phase II: Airbag contact; (c) Phase III: Head rebound to possible head to headrest/surface contact.