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Short communication

Lightweight low-profile nine-accelerometer package to obtain head angular accelerations in short-duration impacts

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Abstract

Despite recognizing the importance of angular acceleration in brain injury, computations using data from experimental studies with biological models such as human cadavers have met with varying degrees of success. In this study, a lightweight and a low-profile version of the nine-accelerometer system was developed for applications in head injury evaluations and impact biomechanics tests. The triangular pyramidal nine-accelerometer package (PNAP) is precision-machined out of standard aluminum, is lightweight (65 g), and has a low profile (82 mm base width, 35 mm vertex height). The PNAP assures accurate orthogonal characteristics because all nine accelerometers are pre-aligned and attached before mounting on a human cadaver preparation. The feasibility of using the PNAP in human cadaver head studies is demonstrated by subjecting a specimen to an impact velocity of 8.1 m/s and the resultant angular acceleration peaked at 17 krad/s^2. The accuracy and the high fidelity of the PNAP device at high and low angular acceleration levels were demonstrated by comparing the PNAP-derived angular acceleration data with separate tests using the internal nine-accelerometer head of the Hybrid III anthropomorphic test device. Mounting of the PNAP on a biological specimen such as a human cadaver head should yield very accurate angular acceleration data.

Keywords: Angular acceleration; Nine-accelerometer package; Head trauma; Brain injury

1. Introduction

For head injury quantification and correlation, linear-accelerometer arrays have been used in experiments to determine critical variables such as angular accelerations. Brain injury in the motor vehicle environment has been attributed for over six decades to rotational acceleration (Holbourn 1943; Gennarelli and Meaney 1996; Anderson et al., 2003). Human cadaver or animal models have been used as surrogates in experimental head injury research (Gennarelli 1981; Yoganandan and Pintar 2004). While it is relatively easy to determine the head kinematics (example, displacements at the center of gravity) of a rigid physical model, a biological specimen poses instrumentation challenges. The deformability of the biological surrogate coupled with the difficulty of placing sensors inside the cranium poses problems for the experimentalist. External peripheral instrumentation is the most practical choice in human cadaver and animal models.

A set of six linear accelerometers is theoretically needed to compute the three angular accelerations of a rigid body (Padgaonkar et al., 1975). To obtain the angular acceleration components, it was necessary to solve a system of three nonlinear ordinary differential equations. Liu showed that the set of three nonlinear ordinary differential equations was mathematically unstable according to the Routh–Hurwicz criterion (Liu 1976). Thus, to obtain practical measures of the three components of angular and linear accelerations, redundant sensors are needed. Specifically, the 3–2–2–2

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cluster of linear accelerometers has been proposed to achieve this objective (Padgaonkar et al., 1975). The nine-accelerometer scheme has been used in impact studies using biological models. For example, Cavanaugh et al., used nine accelerometers in human cadaver sled tests for side impact research, although no head acceleration data were reported (Cavanaugh et al., 1990). In a study of diffuse axonal injury using the sheep as an experimental model, Anderson et al., adopted the same scheme with additional instrumentation to determine the dynamics of impact (Anderson et al., 2003). McIntosh et al. used the scheme to determine head and neck injury dynamics using human cadavers (McIntosh et al., 1996). Nahum et al. used it in one human cadaver to determine the effect of impact head protection with a helmet (Nahum et al., 1981). Stalnaker et al. also used a similar scheme to determine human cadaver head impact response (Stalnaker et al., 1977). Although researchers have devised different types of systems using the 3–2–2–2 method for human cadaver applications, a validated standard device does not exist (Hardy, 2000; Yoganandan and Pintar, 2004). Such a proven device is necessary to have confidence in the outcome, i.e., angular accelerations. The objective of this study is, therefore, to develop a nine-accelerometer package and affix it to human cadaver heads at the periphery to determine the angular accelerations during short duration, low and high levels of dynamic contact loading. The feasibility of the device is demonstrated by subjecting an unembalmed head specimen to impact loading resulting in high angular acceleration. The accuracy of the high fidelity device is demonstrated by comparing its response with experiments using the Hybrid III dummy with an internal nine-accelerometer array head.

2. Methods

The pyramid shaped nine-accelerometer package, termed PNAP, was fabricated from aluminum (7075). The 3–2–2–2 accelerometer-based PNAP design consisted of three sets of biaxial accelerometers (Entran model EGE-73B, Fairfield, NJ) mounted to the triangular base of the pyramid and one triaxial accelerometer mounted at its vertex. The three base arrays constituted the biaxial 2–2–2 components, and the vertex contained the triaxial component of the 3–2–2–2 configuration. The base width and vertex height dimensions of the PNAP were 82 and 35 mm, respectively. To mount the PNAP to an experimental model of the human head, 28×12 mm symmetrical flanges protruding from each side of the triangular pyramid base were welded. The flanges thus became an integral part of the PNAP. Each flange had two symmetrically drilled four-millimeter diameter screw holes at a distance of five millimeters from each outboard side; in other words, the clear distance between the two holes in each flange was 10 mm. The flanges were oriented downward at an angle of 70° from the horizontal base of the pyramid. Anchoring these flanges with six orthopedic screws ensured rigid fixation to the skull bone. To minimize the mass, 17 mm diameter holes were drilled on each face of the pyramid; the resulting weight of the PNAP was 65 g. Fig. 1 shows a photograph of the entire system with accelerometers and flanges.

To demonstrate the feasibility of using the PNAP in impact experiments, an intact unembalmed human cadaver head was instrumented with the PNAP at the right temporo-parietal surface, and triaxial accelerometers were mounted at the vertex, frontal, and occipital regions. Fig. 2 shows the schematic of a human head with three triaxial accelerometers and the PNAP affixed to it. The pyramid base of the PNAP was secured to the skull through the skin by the three protruding flanges. For this purpose, two holes in each flange of the PNAP were screwed with six orthopedic screws to secure the device to the skull bone. The compact design and use of six screws at three locations fit the local anatomy of the human cadaver head. Positions and orientations of accelerometers were determined using a FaroArm digitizer device. The right-handed Cartesian-based anatomical system of reference was defined as follows: the $+x$-axis line joins the CG to the line connecting the inferior orbital rims in the midsagittal plane, $+z$-axis is orthogonal to the x-axis in the inferior-superior direction, and $+y$-axis is orthogonal to the x–z plane in the right to left lateral direction. The preparation was impacted using a free fall technique so as to contact the

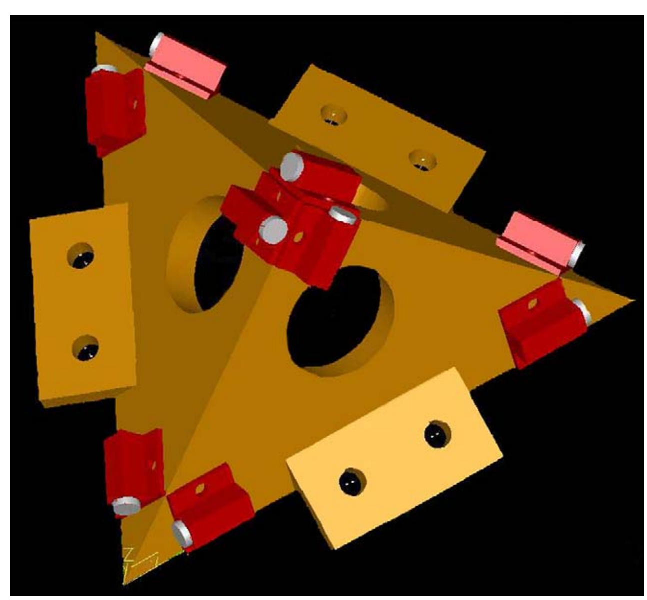

Fig. 1. Photograph of the triangular pyramidal nine-accelerometer package (PNAP) along with accelerometers at the four corners. The weight of the device is 65 g.

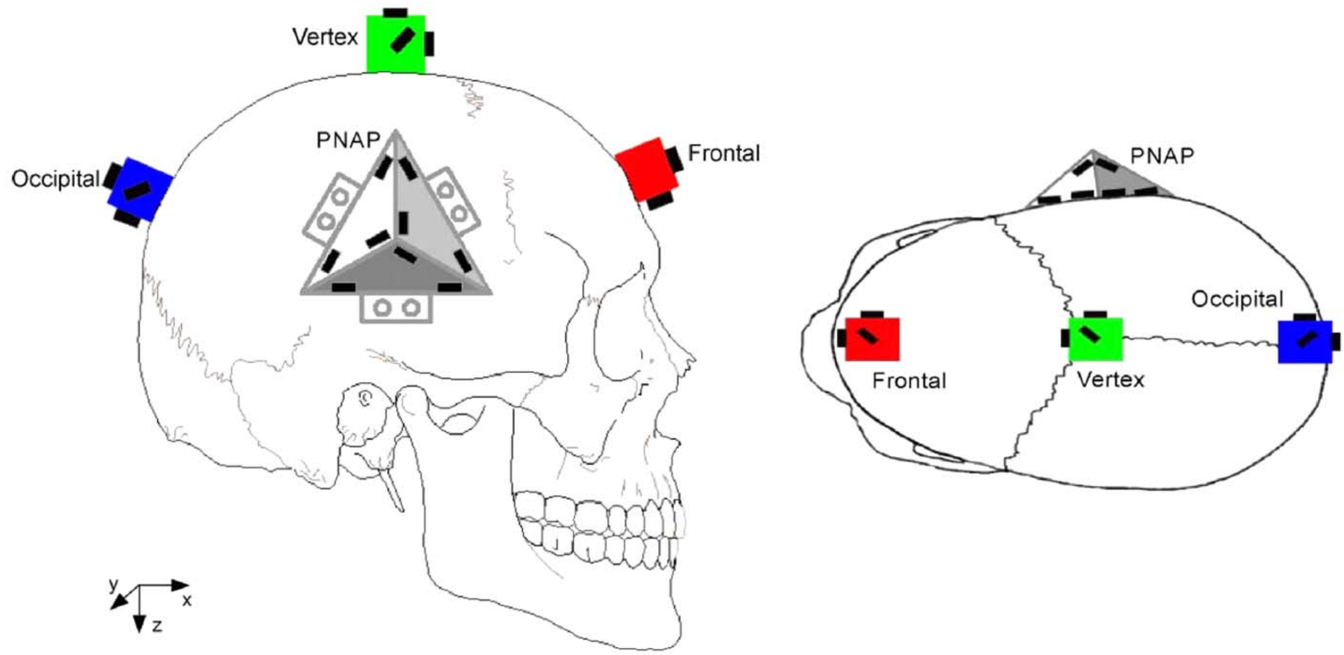

Fig. 2. Schematic of the human skull with the affixed triangular PNAP and three triaxial accelerometers (shown as rectangles).

temporo-parietal region of the head. Accelerometer signals were gathered at a sampling rate of 12,500 Hz, and filtered according to the Society of Automotive Engineers specifications. X-ray and close-up computed tomography (CT) images were obtained before and after impact to identify pathology, if any. Angular acceleration time histories were computed using signals recorded from the PNAP. Resultant CG accelerations were separately computed using the PNAP, frontal, vertex, and occipital triaxial accelerometer signals. For this purpose, angular accelerations were first derived from PNAP-recorded data. Angular velocities were determined by integrating angular acceleration traces. Using geometrical locations of accelerometers and principles of rigid body kinematics, CG accelerations were computed separately using the frontal, vertex, and occipital accelerometer signals. In addition, CG accelerations were computed using the vertex triaxial accelerometer of the 3–2–2–2 PNAP. This process resulted in four discrete computational results for CG acceleration time histories.

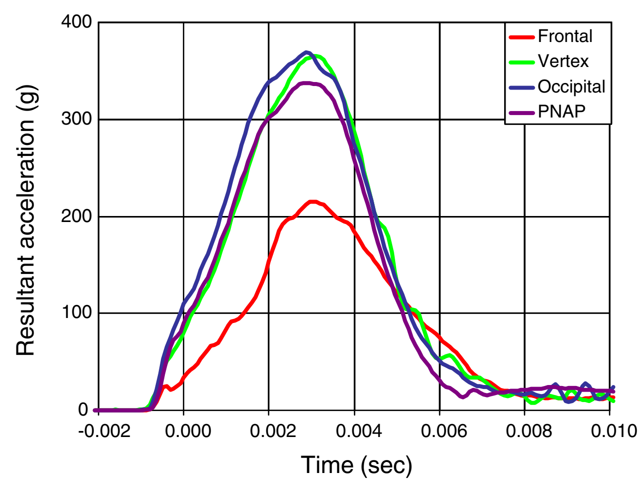

Fig. 3. Resultant head accelerations (at the sensor location) computed using data from each individual triaxial accelerometer and the PNAP.

3. Results

The specimen was dropped from a height of 3.3 m (impact velocity 8.1 m/s). Post experiment X-ray and CT images showed no skull fractures. Inspection of the fixation region following the test indicated no loosening of the fixation. As shown in Fig. 3, the resultant acceleration time histories from the triaxial accelerometers had a pulse width of approximately eight ms, although amplitudes varied with the location of measurement. Peak resultant accelerations were the lowest with the frontal accelerometer set (210 g) and the highest with the occipital set (360 g). Angular acceleration histories computed from the PNAP had pulse durations of approximately six ms (Fig. 4). Peak rotational acceleration of 11,510 rad/s^2 occurred early in the impact event. Angular accelerations were computed from PNAP signals. Using these angular accelerations and linear triaxial acceleration signals recorded from the frontal accelerometer, head CG accelerations were obtained. This process was repeated for the vertex and occipital accelerometers, resulting in three CG acceleration curves. In addition, using recorded signals from the

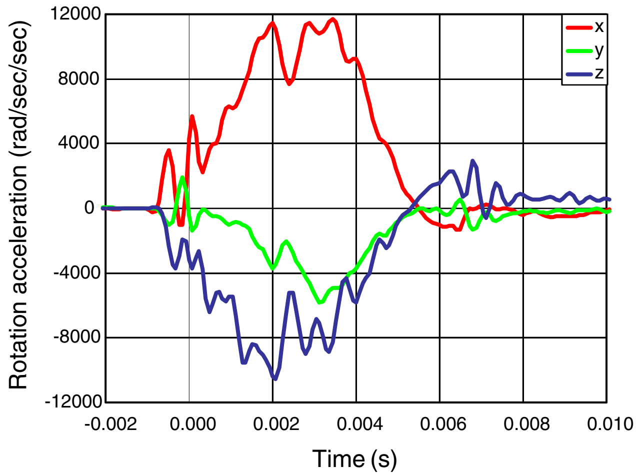

Fig. 4. Rotational head accelerations time were histories computed using data from the PNAP.

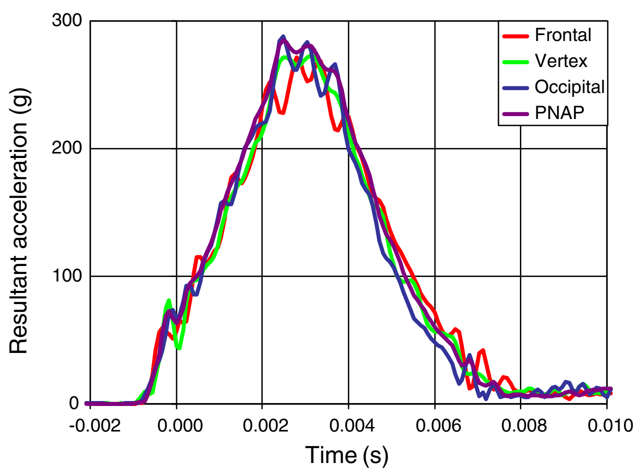

Fig. 5. Resultant head CG acceleration data. First angular accelerations were computed from PNAP signals. Using these angular accelerations and linear triaxial acceleration signals recorded from the frontal accelerometer, head CG accelerations were obtained. This process was repeated for the vertex and occipital accelerometers, resulting in three CG acceleration curves. In addition, using recorded signals from the apex triaxial accelerometer set of PNAP and computed angular acceleration from PNAP, head CG accelerations were obtained, resulting in four curves.

apex triaxial accelerometer set of PNAP and computed angular acceleration from PNAP, head CG accelerations were obtained. This resulted in four curves, shown in Fig. 5. Resultant CG acceleration histories (Fig. 5) matched extremely well with a mean peak acceleration of 272 g, and the maximum difference was $<5\%$ between any two-sensor sets.

4. Discussion

Accurate determinations of angular accelerations in impact tests using biological specimens are badly needed for improvements in vehicular design and injury criteria development. Researchers have used different versions of the nine- and additional accelerometer (ranging from 15 to 24) systems for automotive crash applications (Hardy, 2000). Other forms of nine-accelerometer arrays had substantial local vibrations in their computed angular accelerations. Local vibrations may occur because of insecure mounting and/or accelerometers attached to a cantilevered arm projecting away from the base of the 3–2–2–2 array (McIntosh et al., 1996). Authors have suggested different filtering techniques (e.g., 200 Hz cutoff) to reduce the effect of high-frequency vibration (McIntosh et al., 1996). However, such techniques are not according to SAE standards. Using their 3–2–2–2 triangular mount in human cadaver testing, Hardy et al. showed that data filtered using "class 180-Hz profile" decreases peak angular acceleration data by as much as 92% when compared with data filtered at class 1 kHz (Hardy et al., 2001). These filters produce significantly lower actual peaks, thus, affecting the accuracy of impact data. Because local vibrations are minimized, the PNAP obviates the need for non-standard signal processes.

In order to demonstrate that the determined angular acceleration is accurate, separate tests were conducted using a Hybrid III dummy with a nine-accelerometer array head (NAAH). The present PNAP was mounted at the outer periphery of the dummy. The Hybrid III has precision-machined accelerometer mountings inside the dummy head. Fig. 6 shows the comparison between the angular acceleration data obtained from the PNAP and internal NAAH instrumentation. As can be seen, an excellent match was obtained, and the peaks differed by less than two percent.

The PNAP also showed an excellent match at lower levels of acceleration. Fig. 7 shows the match between the angular acceleration data from the present PNAP and NAAH instrumentation inside the Hybrid III head. Similar to the case of high acceleration (Fig. 6), the PNAP data agreed very closely with NAAH data, with peaks differing by approximately less than 1% between the two measures. Thus, the present PNAP is validated for both low and extreme acceleration levels.

Additional checks for angular accelerations were made. Resultant accelerations at all the locations of the other three traiaxial accelerometer mounts were computed using PNAP data and compared with resultant accelerations at respective mounts for the extreme acceleration level test. Comparison plots shown in Figs. 8–10 for the frontal, occipital, and left side locations further indicate an excellent agreement, similar to Figs. 6 and 7. These multiple validation processes confirm the accuracy of accelerations of the present PNAP.

Figs. 6 and 7 comparing the PNAP to Hybrid III NAAH dummy angular accelerations clearly showed

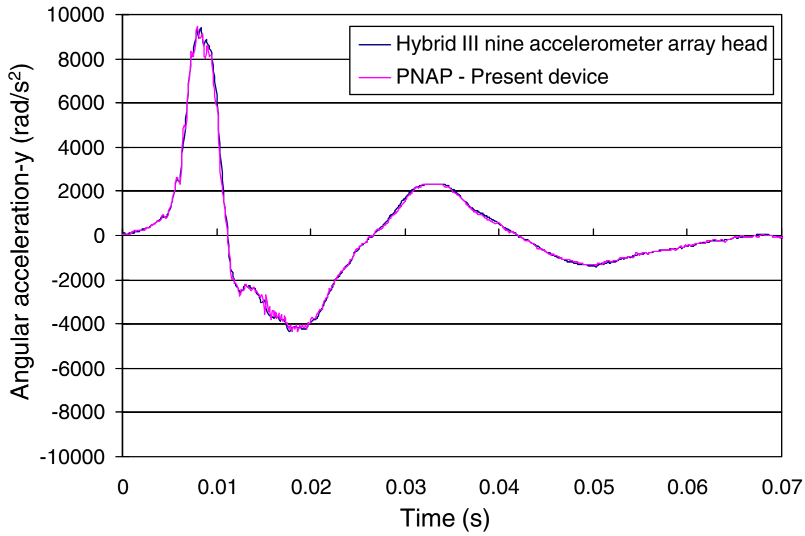

Fig. 6. Comparison of angular acceleration data from the PNAP with the Hybrid III dummy equipped with an internal nine-accelerometer array head (NAAH). Virtually identical responses can be noted from the two devices.

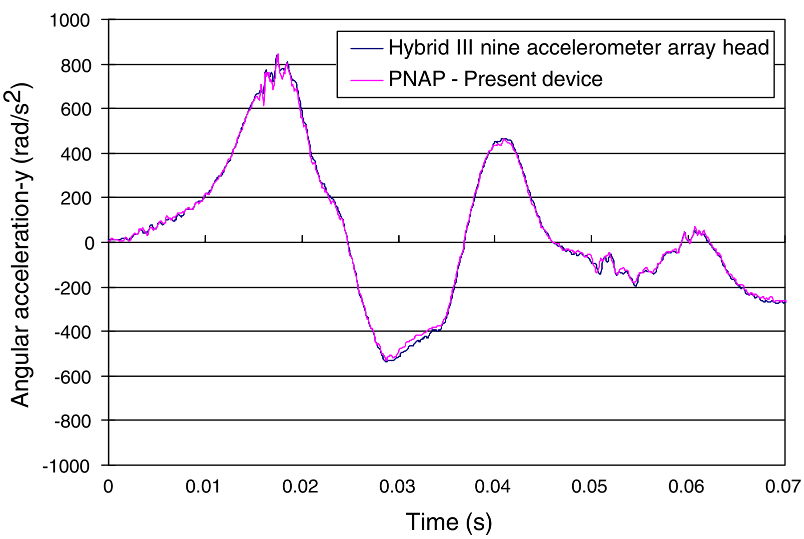

Fig. 7. Comparison of angular acceleration data from the PNAP with the Hybrid III dummy equipped with an internal nine-accelerometer array head (NAAH). Similar to the case of high acceleration (Fig. 6), the PNAP data agreed very closely with NAAH data even at lower levels of acceleration.

that both signals virtually overlay over each other. Furthermore, vibration problems do not exist or are at least minimized to a great extent even when the signals are filtered at 1650 Hz. This obviates the need to resort to other types of filters (e.g., 180 and 200 Hz) used in previous studies (McIntosh et al., 1996; Hardy et al., 2001). Thus, it can be concluded that the PNAP eliminates the need for non-standard signal conditioners because local vibrations are minimized and do not interfere with actual accelerometer recordings, as demonstrated from the results of this experimental study.

It should be noted that the 3–2–2–2 accelerometer setup is well known. The Wayne State University triangular mount is different from the present PNAP, although in principle, both use the 3–2–2–2 accelerometer pattern. The present device, in contrast to the cited triangular mount, has three flanges with two screw holes in each flange to allow firm fixation into the human cadaver head preparation. As indicated previously, we are not aware of any publication that has systematically compared angular accelerations from the cited mounted array with the Hybrid III NAAH dummy to demonstrate yield the similar accuracy and high fidelity performance. Currently described devices indicate the need for other forms of filtering. For example, Hardy et al. stated: “to eliminate resonance of the head and the 3–2–2–2 mount system, the kinematics data

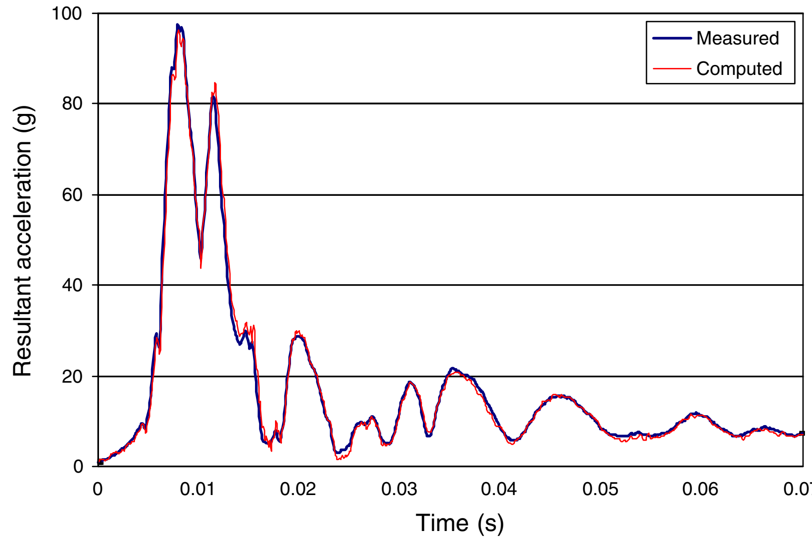

Fig. 8. Resultant accelerations at the location of the frontal triaxial accelerometer mount computed using PNAP and compared with resultant accelerations from signals recorded from the frontal triaxial accelerometer.

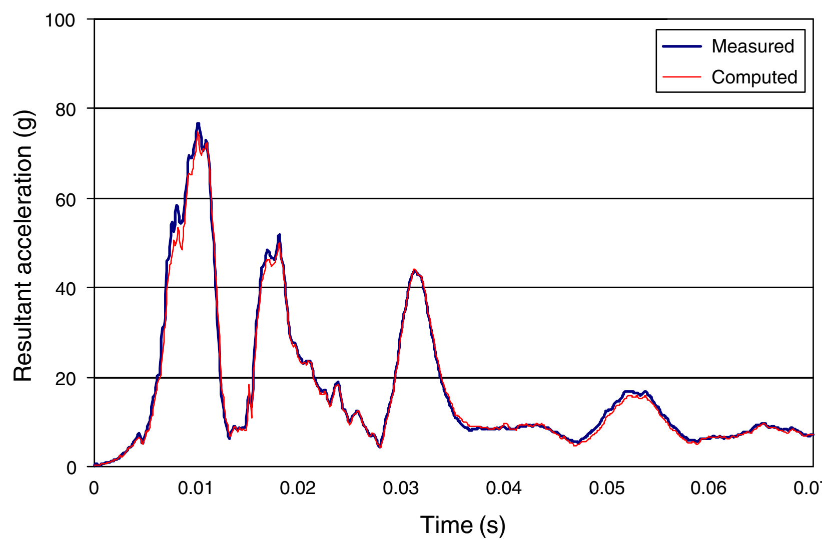

Fig. 9. Resultant accelerations at the location of the occipital triaxial accelerometer mount computed using PNAP data and compared with resultant accelerations from signals recorded from the occipital triaxial accelerometer.

were filtered using a channel class 180 Hz profile'' (Hardy et al., 2001). McIntosh et al. used a 200 Hz filter and stated: ''this filtering also minimized the effect that high frequency skull vibrations may have had on angular acceleration calculations'' (McIntosh et al., 1996). In contrast, the present PNAP provides better data with high fidelity and eliminates the need to use non-standard SAE filters, reflecting the efficacy of the device to record data from short duration impact acceleration exposures, another important difference between the two systems. In addition, the design of the present PNAP is lightweight (65 g) and compact. No weight data could be found for the Wayne State University triangular mount. Another device termed RBKTA, designed by Wayne State researchers intended for human cadaver preparations weighed ''under 90 g''.

The present PNAP can be used in experiments involving biological preparations such as human cadaver heads, and is not primarily intended to be used with the Hybrid III dummy head. Because the Hybrid III head already has a well-proven accelerometer system, it was used in experiments only to demonstrate PNAP fidelity and accuracy.

Selecting the 8.1 m/s (30 km/h) contact impact velocity demonstrated the feasibility of using the PNAP under high angular-acceleration conditions. At this level of impact, the human skull responds with deformations and non-uniform ''in-bending'' of the cranial bone

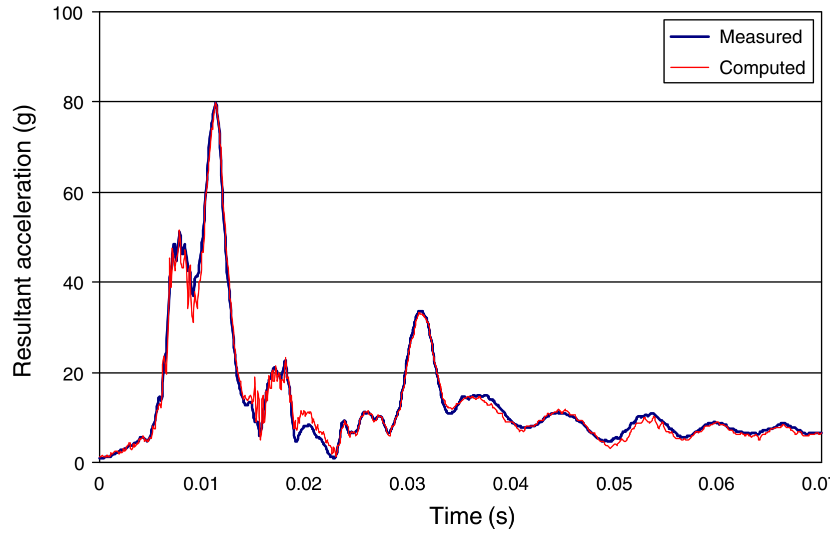

Fig. 10. Resultant accelerations at the location of the left side triaxial accelerometer mount computed using PNAPs and compared with resultant accelerations from signals recorded from the left side triaxial accelerometer.

(Gennarelli and Meaney, 1996). The peak linear acceleration of 272 g is approximately equivalent to an impact force of 12 kN on a 50th percentile male body mass. This level of impact loading is close to the threshold of bony injury, although fracture did not occur in the present study (Yoganandan and Pintar, 2004). Thus, the PNAP is capable of performing well at high impact levels wherein cranial deformations closely approximate fracture threshold limits. Of course, should fracture occur and propagate near or between fixation points, the performance of any device will not be fully reliable; the present device is no exception.

The purpose of the present study was to develop a nine-accelerometer package by adopting proven methods of using a 3–2–2–2 system of linear accelerometers. Although the Entran model accelerometer (weight 1 g) was used in the development of the PNAP, it can be replaced with other equivalent models or manufacturers (e.g., Endevco, Inc.). It is possible to use the frontal, occipital, and vertex triaxial accelerometers as the nine-accelerometer cluster and obviate the use for the PNAP. In theory, the three-triaxial cluster should suffice for computing angular and CG accelerations. However, computations assuming principles of rigid-body kinematics do not provide accurate results if used in human cadaver and other biological models. This is because the cluster is attached to three regions of the cranium and variations in local deformability characteristics of different regions of the human head affect recorded accelerations. Furthermore, practical difficulties exist in terms of accurately locating accelerometers including precise alignment issues during mounting procedures on the human cadaver head. Studies have shown that orthogonal alignment is critical, and the attachment and placement of the sensors affect outcomes (Padgaonkar et al., 1975). The PNAP assures accurate orthogonal characteristics because all accelerometers are prealigned and attached before mounting on the human cadaver preparation.

It is well known that angular accelerations are computed using the arm length and differences between relative magnitudes of linear accelerations (Padgaonkar et al., 1975, Eqs. (9)–(11) in the original paper). Increasing the distance between the accelerometer locations by enlarging the device accentuates the difference in linear acceleration magnitudes and increases signal to noise ratio. On the other hand, increasing the distance from the sensor mass to the center of the mass of the body to be measured increases the (unwanted) mass moment of inertia of the body segment by raising the profile; thus, decreasing the biofidelity of the body segment in rotation. In addition, practical constraints dictate the size of any 3–2–2–2 array used on human cadaver preparations. Furthermore, secondary computations such as forces and moments at the occipital condyles that are routinely done in impact simulations demand accurate determinations of moments of inertia and related quantities. Therefore, miniaturization, i.e., lightweight and low profile, is necessary and the PNAP is suitable in such applications.

Secure mounting is another important issue. A secure mounting is achieved with the PNAP with three flanges extending out as an integral part of the pyramid at its base. Anchoring these flanges with six orthopedic screws insured rigid fixation to the skull bone. Although two orthopedic screws were used to secure the head in each flange, and this method was found to be efficacious to demonstrate the feasibility of the present PNAP in human cadaver impact experiments, it is also possible to use other securing methods such as machine screws and helicoids depending on the requirements or constraints of future cadaver tests. The three-flange design can easily accommodate changes in screw mounting operations. As shown in the present study, even at high impact velocity (8.1 m/s) and high resultant angular accelerations (approximately 17,000 krad/s^2), the PNAP remained rigidly secured to the head during and following the impact event. Because the current PNAP is lightweight (65 g), low profile (82 mm base width, 30 mm vertex height), has secure fixation, and uses a triangular pyramidal nine-accelerometer design, researchers can efficaciously use the device in head injury and other impact biomechanics applications. Mounting of the PNAP on a biological specimen such as a human cadaver head should yield very accurate angular acceleration data.

As indicated in the Introduction, the purpose of the study was to demonstrate the present PNAP device with its validation, compact design, lightweight, and other features, which was done using controlled Hybrid III NAAH experiments and show its feasibility for human cadaver head impact applications by conducting an additional human cadaver head impact test. The study was not aimed at characterizing cadaver head behaviors in the frequency domain including resonance/antiresonance and impedance responses. While this may appear to be a limitation, such characterizations are considered by the authors of this study as future research, and the present PNAP can be used with more confidence than any other system for determining head angular accelerations.

Acknowledgments

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