

Improving Earpiece Accelerometer Coupling to the Head

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ABSTRACT

As accurate measuring of head accelerations is an important aspect in predicting head injury, it is important that the measuring sensor be well-coupled to the head. Various sensors and sensor mounting schemes have been attempted in the past with varying results. This study uses a small, implantable acceleration sensor pack in the ear to study impact coupling with the human skull. The output from these ear-mounted accelerometers is compared to laboratory reference accelerometers rigidly attached to the skull of two cadaveric head specimens for both low-amplitude oscillatory tests and high-amplitude impact drop tests. The combination of sensor type and mounting scheme demonstrates the feasibility of using ear mounted sensors to predict head acceleration response. Previously reported progressive phase lag was not seen in this study, with the comparison between ear mounted accelerometers and rigidly mounted head accelerometers ranging from very good to excellent.

INTRODUCTION

Previous research investigating the ability of earpiece mounted triaxial accelerometers to accurately represent head dynamics for low and high-rate head impacts has resulted in contradictory conclusions. In a study of IRL and CART earplug mounted accelerometers in both dummies and human volunteers, earplug accelerometers showed a linear correlation with rigidly mounted accelerometers in predominantly anteroposterior impacts with accelerations up to 10g (Knox, 2004). Higher-rate studies by Begeman et al. (2006) used similar IRL earplug accelerometers in cadaveric specimens, but showed progressive phase lag with increasing frequency when compared to skull measurements, along with up to a 70% peak overshoot. These tests indicate limitations in of skull coupling for the earplugs mounted in the external canal for high rate excitations.

To investigate the limits of ear canal coupling in assessing skull and head accelerations, a second series

of tests was performed using a newly-developed accelerometer package that is small enough to place in the bony ear canal. Results include correlation between the acceleration measurements made using the new package and laboratory instrumentation rigidly mounted to cadaveric specimens for both low and high-rate excitations. Recommendations are made on improving ear/head coupling including the stiffness of the ear-mounting medium and the position of the earplug inside the ear canal.

METHODS

The ear mounted accelerometer units were comprised of three orthogonal Endevco 7269-500 (Endevco, San Juan Capistrano, CA), and the head mounted reference accelerometers were comprised of three orthogonal Endevco 7264B-500. Data was collected using a TRAQ-P data acquisition system with sampling at 10 kHz and anti-aliasing filtering at 3.3 kHz.

Two postmortem human specimens (PMHS) were obtained for this testing through the Virginia State Anatomical Board and other tissue suppliers accredited by the American Association of Tissue Banks. The test protocols were subject to review by the University of Virginia Cadaver Use Committee

For this study, two 50% male specimens were procured. A summary of their anthropometry is shown in Table 1.

Table 1. Specimen anthropometry

Test	Specimen	Gender	Age	Mass (kg)	Stature (cm)
EShake1	M305	Male	57	84.8	175.3
EShake2	M295	Male	68	78.9	182.9

Each PMHS was potted in a box that allowed the specimen to be rigidly gripped by a series of threaded inserts embedded in the potting medium. For this case, the potting medium used was 16 lbs per cubic foot syntactic foam (FOAM-1616, U.S. Composites, West Palm Beach, FL). Ear access, and sufficient space for mounting laboratory sensors at the insertion in the Frankfort plane and mid-occipital plane, was maintained

during potting (Figure 1). Threaded inserts were mounted on three sides of the box, allowing each specimen to be tested in the X, Y, and Z orientations.

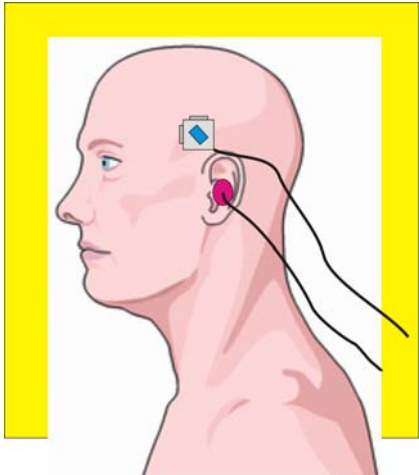


Figure 1. Schematic of potted specimen showing mounted ear accelerometer and laboratory 6-axis accelerometer array.

Ear mounted accelerometers were inserted into each ear after an injection of Westone SiliClone S-50 impression material. Head mounted 3-axis accelerometer arrays were rigidly mated to the skull of the subjects through the use of aluminum plates screwed directly into the skull.

EAR SENSOR POSITION - Triaxial accelerometer arrays were mounted in each ear using a potting compound designed for making ear canal impressions. The technique involved depositing a sufficient amount of compound to fill the ear canal and a large amount of the outer ear. The ear accelerometers were then inserted into the ear canal, making the exact placement difficult. The placement of each sensor in each ear was later determined through CT analysis, with the summary shown in Table 2.

Table 2. Ear mounted sensor locations

Test Series	Ear	Bony canal diameter (entrance) (mm)	Depth of bony canal (mm)	Sensor from bony canal (mm)
EShake1	L Ear	15.6	20.7	3.8
	R Ear	18.6	27	10.9
EShake2	L Ear	18.1	22.1	8.1
	R Ear	14.3	34.7	21

Post test radiology images of the sensor placement in the left ear of specimen 1 (EShake1) is shown in Figure 2, and the right ear in Figure 3. Specimen 2 (EShake2) radiological images for sensor placement are located in the Appendix.



Figure 2. CT scan of Specimen 1 (EShake1) showing position of left ear mounted sensor.

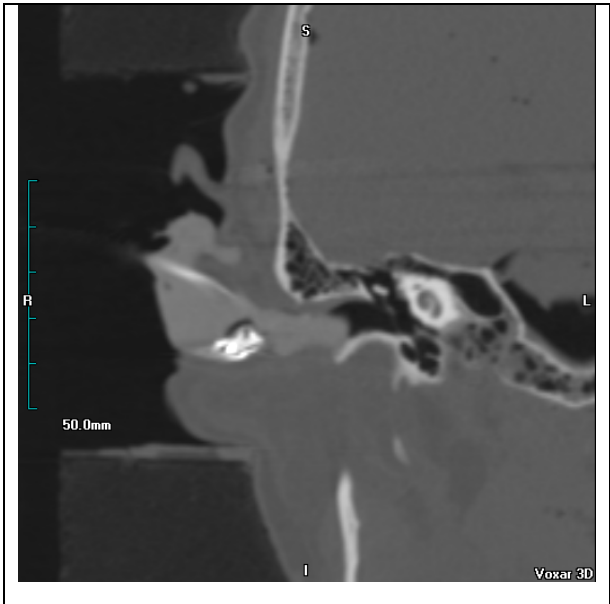


Figure 3. CT scan of Specimen 1 (EShake1) showing position of right ear mounted sensor.

In order to ascertain the local orientation (x, y, z) of each ear mounted accelerometer with respect to the global X, Y, and Z axes of the potted specimen, a procedure was developed that involves placing the specimen in various positions and reading the accelerometer values from each of the axes. Knowing that there should be a 2-G difference from gravity as the specimen is rotated from side to side, the orientation of the sensor in the ear can be determine. The ear mounted accelerometer readings for both specimens are shown in Table 3.

Table 3. Two-G Ear Sensor Orientation Protocol

Test Series	Specimen Orientation	Ear Sensor	Accelerometer Readings (G)		
			X	Y	Z
EShake1	Sit up	Right	-4.7	-173.7	-61.2
		Left	-61.2	-101.3	6.08
	Left Side	Right	-6.1	-173.9	-62
		Left	-61.7	-102.6	5.4
	Right Side	Right	-4.4	-172.4	-62.3
		Left	-60	-102	6.66
	On Back	Right	-4.67	-173.9	-62.8
		Left	-61.4	-102.6	6.82
	Face Down	Right	-5.83	-172.4	-61.4
		Left	-60.2	-102.2	5.1
EShake2	Sit up	Right	-3.5	-172.4	-61.1
		Left	-3.5	-99.9	7.1
	Left Side	Right	-4.3	-173.9	-60.6
		Left	-7.3	-99.8	5.9
	Right Side	Right	-4.9	-172.1	-61.9
		Left	-14.9	-100.6	7.86
	On Back	Right	-4.37	-173.6	-62.2
		Left	-15.8	-101.3	6.7
	Face Down	Right	-5.1	-172.4	-60.4
		Left	-7.5	-99.13	7.0

These accelerometer readings were post-processed to transform the local accelerations from the ear mounted sensors to the global SAE coordinate system (Figure 4).

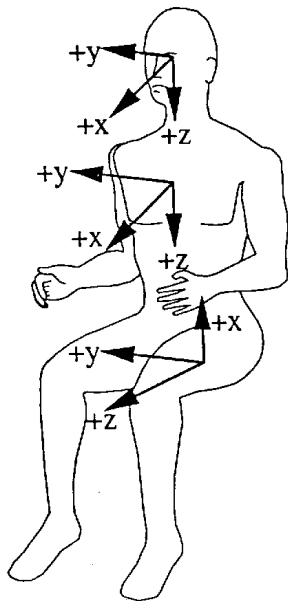


Figure 4. SAE coordinate system used for all tests.

This allows the local accelerations (x, y, z) to be transformed to the global coordinate system (X, Y, Z) of the specimen by the form

$$\begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{Bmatrix} x \\ y \\ z \end{Bmatrix}$$

The transformation matrix for the right ear of the first test specimen (EShake1) is

$$a_{ij} = \begin{bmatrix} 0.444 & -0.631 & -0.638 \\ -0.760 & -0.649 & 0.0659 \\ -0.474 & 0.378 & -0.797 \end{bmatrix},$$

the transformation matrix for the left ear of the first test specimen (EShake1) is

$$a_{ij} = \begin{bmatrix} -0.519 & -0.254 & 0.822 \\ -0.776 & -0.228 & -0.595 \\ 0.326 & -0.940 & 0.00806 \end{bmatrix},$$

and the transformation matrix for the right ear of the second test specimen (EShake2) is

$$a_{ij} = \begin{bmatrix} 0.355 & -0.470 & -0.814 \\ -0.301 & -0.744 & 0.606 \\ -0.907 & -0.387 & -0.116 \end{bmatrix}.$$

Due to the failure of one of the accelerometers in the left ear of the second specimen, the coordinate transformation could not be performed. Except for this case, all other transformed ear accelerations are provided in the Appendix.

For the low frequency tests, a hydraulically operated vertical shaker unit was employed. This unit is adjustable both in amplitude as well as frequency, although amplitude was held constant for this test series. Each of the three axes was tested for low and high shaking. This setup is shown in Figure 5.

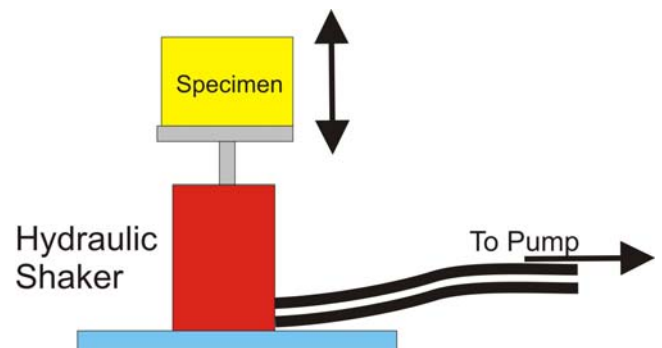


Figure 5. Vertical Shaker Fixture

For high-G testing, a drop tower device was used. Again, each specimen was tested in the X, Y, and Z axes, and dropped from two different heights to achieve two levels of acceleration. This fixture is shown in Figure 6.

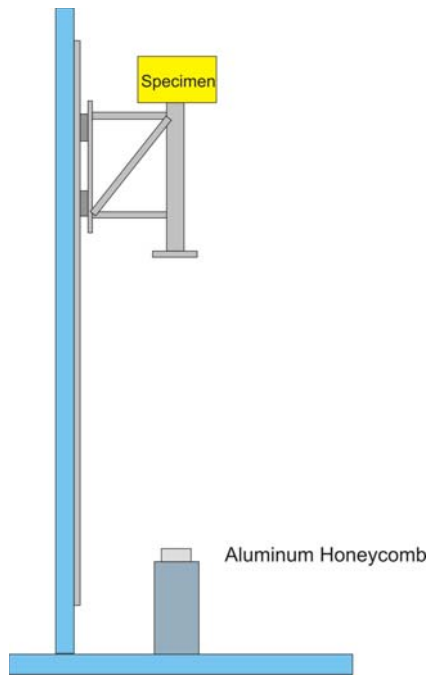


Figure 6. Drop Tower Fixture

Table 4. Test Matrix

Test	Description	Direction of Load	Type of Load
EShake1_1	Low Frequency (6.2 Hz)	X-axis	S-Wave Generator
EShake1_2	High Frequency (9.5 Hz)		
EShake1_3	Low Frequency (6.2 Hz)	Y-axis	
EShake1_4	High Frequency (9.5 Hz)		
EShake1_5	Low Frequency (6.2 Hz)	Z-axis	
EShake1_6	High Frequency (9.5 Hz)		
EShake1_7	Low Height (812.8mm)	X-axis	Drop Tower
EShake1_8	High Height (1371.6 mm)		
EShake1_9	Low Height (812.8mm)	Y-axis	
EShake1_10	High Height (1371.6 mm)		
EShake1_11	Low Height (812.8mm)	Z-axis	
EShake1_12	High Height (1371.6 mm)		
EShake2_1	Low Frequency (6.2 Hz)	X-axis	S-Wave Generator
EShake2_2	High Frequency (9.5 Hz)		
EShake2_3	Low Frequency (6.2 Hz)	Y-axis	
EShake2_4	High Frequency (9.5 Hz)		
EShake2_5	Low Frequency (6.2 Hz)	Z-axis	
EShake2_6	High Frequency (9.5 Hz)		
EShake2_7	Low Height	X-axis	

	(812.8mm)		Drop Tower
EShake2_8	High Height (1371.6 mm)		
EShake2_9	Low Height (812.8mm)	Y-axis	
EShake2_10	High Height (1371.6 mm)		
EShake2_11	Low Height (812.8mm)	Z-axis	
EShake2_12	High Height (1371.6 mm)		

RESULTS

SENSOR DATA - SAE standard coordinate system is used for these tests. Typical sensor data, comparing ear mounted accelerometer data with head mounted accelerometers, will be presented here. Accelerations recorded during the low and high frequency shaker tests were filtered with an 8 pole Butterworth filter set to 100 Hz, with an additional notch filter of an 8 pole Butterworth between 60 Hz and 80 Hz. The accelerations recorded during the high-G drop tests were filtered with an 8 pole Butterworth filter set to 1650 Hz (CFC 1000). Results from the x, y, and z-axis head mounted accelerometers are compared to the transformed x, y, and z-axis ear mounted accelerations. For this report, tests EShake1_2, 4, 6, 8, 10, and 12 are analyzed. EShake2_2, 4, 6, 8, 10, and 12 are compiled in the Appendix to this report.

HIGH FREQUENCY INPUT - The high frequency response of the ear mounted accelerometer arrays compared favorably to the rigidly mounted head 3-axis arrays (Figure). For the high frequency input applied in the X-axis, both right (Figure 7a) and left side (Figure 8a) accelerations compare well in the X-axis, although the right side ear accelerometer tends to over predict the oscillation in the negative phase. Y-axis and Z-axis accelerations for an applied X-axis high frequency input all have a magnitude of approximately ± 1 g with varying measured frequencies (Figures 7b,c and 8b,c). Similar patterns are seen in the Y and Z-axis accelerometers from high frequency inputs in the Y and Z-axis (Figures 9, 10). Again, significant progressive phase lag is not seen in these tests.

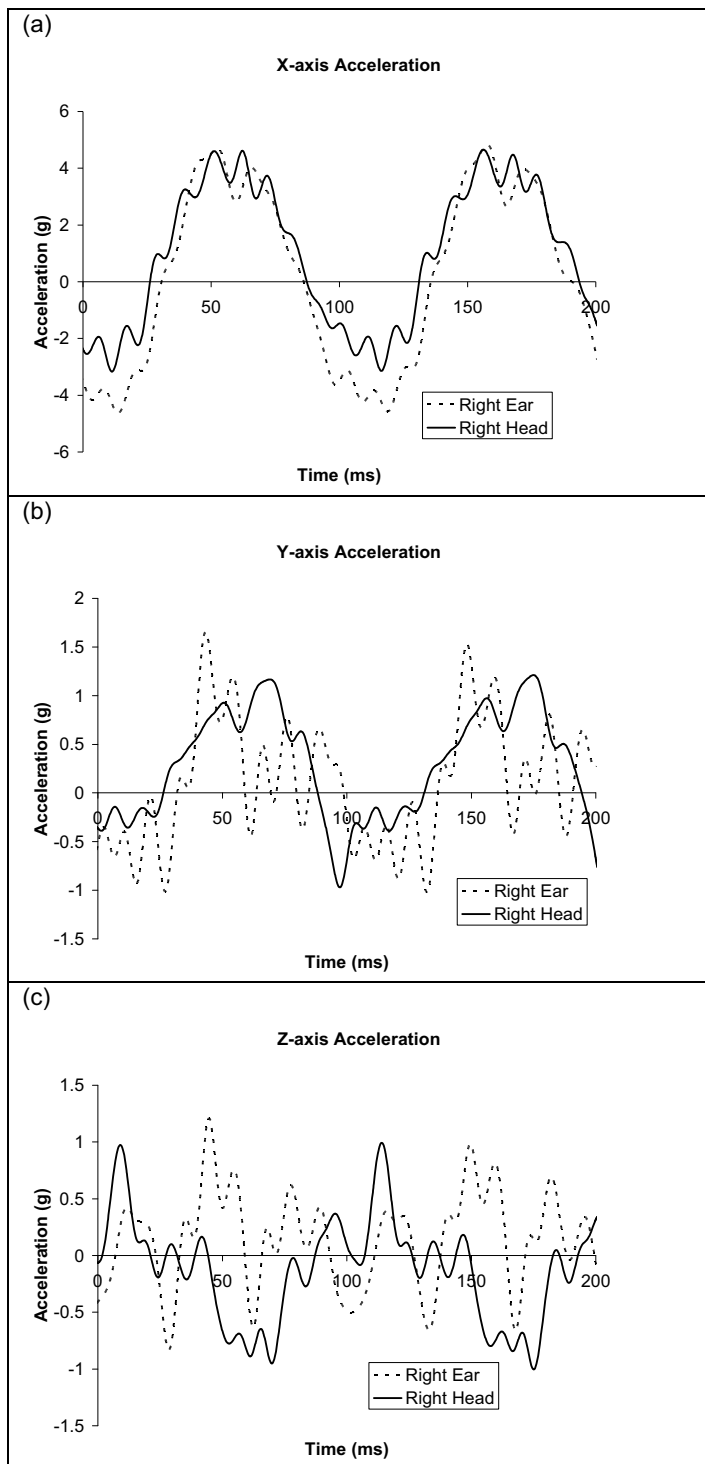


Figure 7. (a) X-axis accelerations from the right ear sensor, right head array; (b) Y-axis accelerations from the right ear sensor, right head array; (c) Z-axis accelerations from the right ear sensor, right head array. Input acceleration was from high frequency input excitation in the X-axis (EShake1_2).

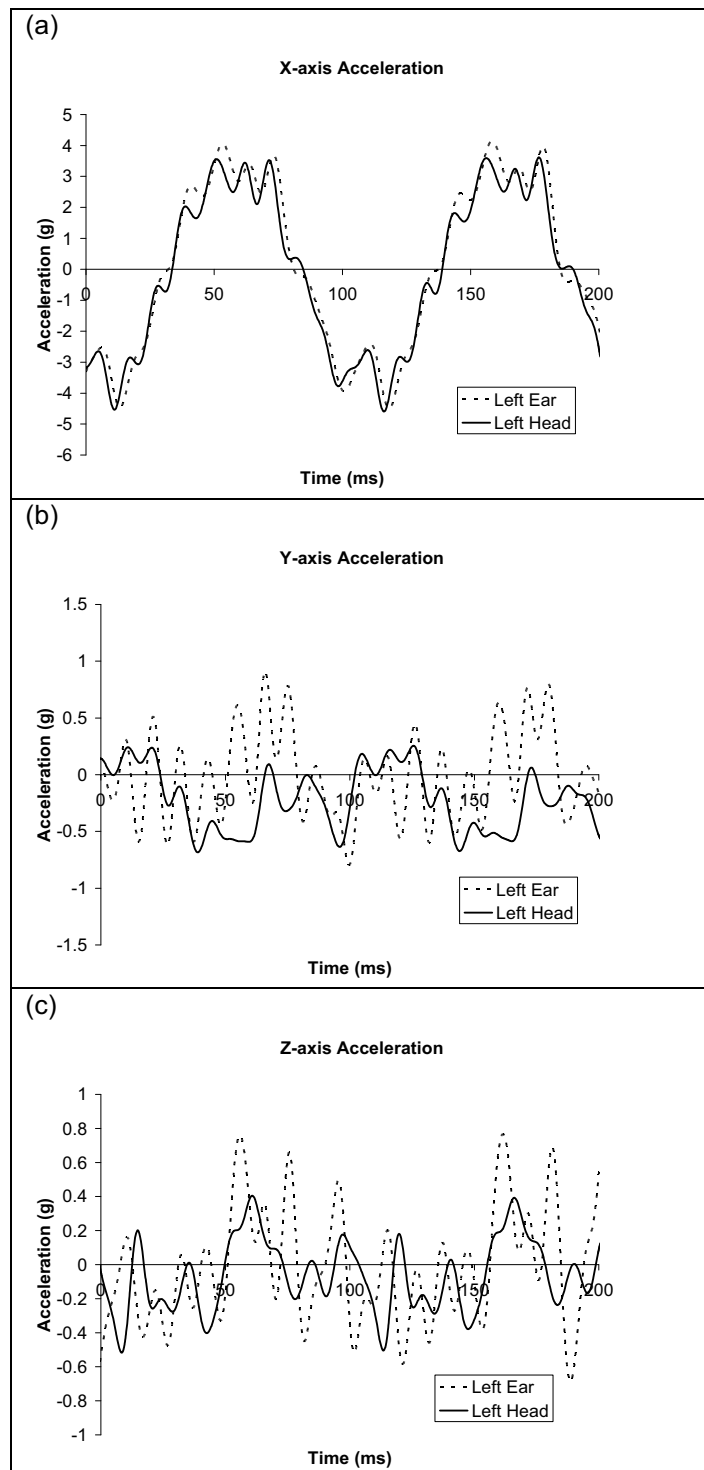


Figure 8. (a) X-axis accelerations from the left ear sensor, left head array; (b) Y-axis accelerations from the left ear sensor, left head array; (c) Z-axis accelerations from the left ear sensor, left head array. Input acceleration was from high frequency input excitation in the X-axis (EShake1_2).