A New Instrumentation Technique for the Cervical Spine of PMHS in Rear Impacts

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ABSTRACT

A newly developed technique to place instrumentation on the anterior aspect of the bodies of the cervical vertebrae and the first thoracic vertebra was proposed to measure detailed neck kinematics in rear impact tests. The instrumentation technique is capable of measuring kinematics at each vertebral level from the second cervical vertebra (C2) to the first thoracic vertebra (T1), while minimizing damage to the neck muscles and soft tissues. Lab trial tests to validate the instrumentation technique were conducted using post mortem human subjects (PMHS) in a rigid rolling chair to simulate 10 km/h rear impact events. Three accelerometers and three angular rate sensors were installed on five of the cervical vertebrae (C3 – C7) to measure the translational (x- & z- direction) and angular (y- direction) displacements during the event. Steinman pins with fiducials were embedded in each vertebral body to record kinematics using a high speed camera (1000 Hz), for comparison with data from the proposed instrumentation (20 kHz). All instrumentation blocks including the fiducials were digitized using a FARO arm, and local coordinate systems were created on each block to measure the initial Euler angles used for transformation of the local coordinates to the global (lab) coordinate system. Results from the lab trial shows that our proposed technique is capable of accurately measuring detailed neck kinematics during rear impact tests. The next phase of this study is to test Post-Mortem Human Subjects (PMHS) in rear impact sled test conditions to quantify the detailed cervical kinematics and generate data which can be used to assess the internal and external biofidelity of the existing rear impact dummies utilizing the NHTSA Biofidelity Ranking System.

INTRODUCTION

Cervical spine injuries in rear impact collisions (e.g., whiplash) are very common and result in enormous societal cost, with estimates on the order of $8.0 billion annually (NHTSA, 2004). Numerous studies have investigated occupant biomechanics and cervical spine injury mechanisms during simulated rear impacts utilizing volunteers (Mertz, 1967; Geigl, 1994; Siegmund, 1997; Ono, 1997; Van den Koonenberg, 1998; Croft, 2007) and/or PMHS (Mertz & Patrick, 1967; Hu, 1977; Geigl, 1994; Kallieris, 1996; Bertholon, 2000; Deng, 2000; Philippens, 2000; Yoganandan, 2000). Other studies have investigated intervertebral kinematics using whole cervical spine specimens on a mini- sled (Panjabi, 1998; Stemper, 2003; Tencer, 2004; Panjabi, 2005). Despite the fact that rear impact events have been studied extensively, there is no consensus as to the exact mechanism of injury or most relevant injury criterion. Proposed soft tissue injury sites vary and include facet joints, capsular ligaments, and intervertebral discs. While the precise location of injury is debated in the literature, there is reasonably good agreement that the injuries occur due to relative rotation and displacement between adjacent vertebrae which exceeds the physiological range of motion (ROM). This illustrates the importance of being able to measure the detailed intervertebral kinematics of the cervical spine during a rear impact event.

A few studies have captured the detailed intervertebral kinematics using a high speed x-ray imaging system (Ono, 1997; Deng, 2000). Although this provides a minimally invasive and visually appealing anatomic view of the cervical spine kinematics in fully intact PMHS or volunteers, it is limited by a small field of view and relatively low acquisition rate. The field of view was 30 cm by 30 cm (2-D kinematics only) with a 90 f/s acquisition rate in the Ono study, and 25 cm by 25 cm (2-D kinematics) and 22.5 cm by 17 cm (dual camera 3-D kinematics) with a 250 f/s acquisition rate in the Deng study. Consequently, using high speed x-ray to measure rear impact cervical kinematics is limited to low-speed tests and/or using a rigid non-yielding seat back.

Intervertebral kinematics have also been studied by mounting isolated cervical spine specimens to a mini-sled, applying a horizontal acceleration, and obtaining the kinematics using high speed video (Panjabi, 1998; Stemper, 2003; Tencer, 2004; Panjabi, 2005). In these studies (with the exception of Stemper, 2003) the muscles and skin were removed from the spine specimens so that only the ligamentous spine was evaluated, although the Panjabi studies did incorporate spring-cable muscle force replicators. A common headform was also attached to the upper end of each spine specimen tested in these studies, rather than using the actual head for each subject. Stemper (2003) tested entire human head-neck complexes, allowing for the individual inertial properties of each subject's head to be maintained, and the skin and musculature were left intact (with the exception of a small portion removed to facilitate placement of retroreflective targets). Obtaining the intervertebral kinematics using isolated spine specimens provides a detailed anatomical view of the cervical kinematics which does not limit the severity of potential test conditions, but the acquisition rate for high speed video is still somewhat limited (typically 1000 f/s), and thoracic interaction with the automotive seat back along with the kinematic effects of "ramping" can not be analyzed. Also, the upper thoracic spine (i.e., lower end of the specimen) must be fixed so kinematic effects due to rotation of the thoracic spine (e.g., T1) can not be accounted for.

Bertholon et al. (2000) measured 2-D cervical kinematics by installing mounting blocks containing two accelerometers and an angular rate sensor on the anterior aspect of the second and fifth cervical vertebrae (C2 and C5) as well as T1. Implementation of instrumentation such as accelerometers and angular rate sensors to measure the cervical kinematics allows for measurements at a sufficiently high sample rate, does not limit the severity of potential test conditions, and allows for full-body PMHS testing in any seating environment. Installation of the instrumentation on the anterior aspect of the vertebral bodies, rather than the posterior spinous process, resolves a major issue in rear impact testing involving the interaction of the instrumentation with the seat back and/or head restraint. However, Bertholon et al. only measured partial kinematics of the cervical spine (i.e., C2 & C5 only) and the kinematics were limited to 2-D. Also, dissecting the anterior part of the neck to install the instrumentation without damaging muscles which may or may not contribute a passive role to neck kinematics in extension (e.g., sternohyoid, sternothyroid, omohyoid, mylohyoid, and/or digastic muscles) is difficult. The authors stated that a fine dissection was required and there were no muscular injuries, but detailed information for the dissection procedure was not provided in the paper.

The objective of this study is to propose and validate a new instrumentation and dissection technique in which instrumentation capable of measuring 3-D kinematics (3 accelerometers, 3 angular rate sensors) are installed on the anterior aspects of each cervical vertebral body with no muscular damage. The instrumentation is installed by dissecting the lateral aspect of the neck to enter the retropharyngeal space and gain access to the anterior aspect of the vertebral bodies. This instrumentation technique should allow for full-body PMHS to be tested in realistic seating environments (i.e., modern yielding seat backs) at any impact severity, while capturing the 3-D intervertebral kinematics of the entire cervical spine. The kinematic data obtained from this instrumentation should prove useful in the investigation of rear impact injury mechanisms and aid in the development and evaluation of injury criteria.

METHODS

Neck instrumentation

In order to measure the detailed intervertebral kinematics of the cervical spine in rear impact tests, a new technique is proposed which allows for installation of accelerometers and angular rate sensors on the anterior aspect of the cervical vertebral bodies without disrupting the musculature of the neck. It is important not to damage the muscles in the neck during the dissection so that the passive resistance of the musculature is maintained during the neck extension that will occur in rear impact. Due to the extensive musculature in the anterior portion of the neck this was accomplished by entering the retropharyngeal space from the lateral aspect of the neck, thus providing access to the anterior aspect of the cervical vertebral bodies (Figure 1). Specifically, an incision was made on the anterior border of the sternocleidomastoid (SCM) muscle to access the lateral retropharyngeal space, and then the retropharyngeal space was expanded to make room for instrumentation by pushing the trachea and esophagus anteriorly, separating them from the cervical vertebrae. Custom instrumentation mounts were screwed into the anterior aspect of the vertebral bodies and were designed to wrap around to the lateral side of each vertebra, as shown in Figure 2(a). In order to measure the translational and rotational displacements of the cervical vertebrae during the event, three accelerometers (Endevco model 7264; Entran model EGEB6Q-2000$) and three angular rate sensors (DTS ARS-1500) were installed to each mount, either with all six sensors on one instrumentation block (22 x 22 x 11 mm) or with the three accelerometers and three angular rate sensors on two separate blocks (15 x 15 x 11 mm). The custom instrumentation mounts were wrapped around alternating sides of the neck, and the corresponding instrumentation block configurations were staggered to ensure sufficient clearance between instrumentation on adjacent vertebrae during the rear impact tests (Figure 2(b) and Table A1).

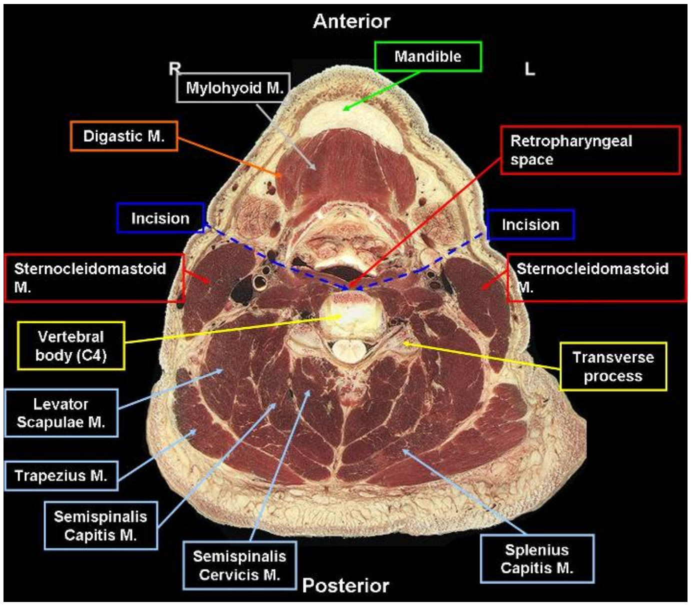
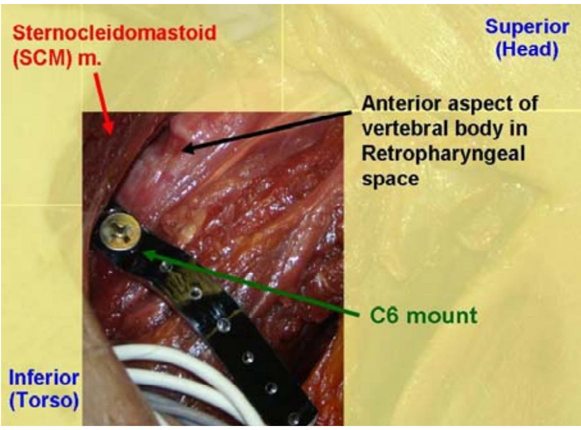


Figure 1: Neck anatomy and dissection flow (http://www.netanatomy.com/).



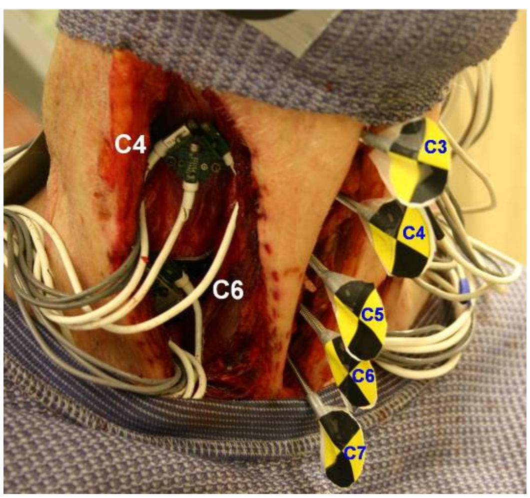
(a) Custom instrumentation mount screwed on C6

(b) Instrumentation configuration (CT 3D reconstruction)

Figure 2: Cervical instrumentation.

Lab validation test

In order to validate the proposed instrumentation technique a 10 km/h impact trial was conducted using a PMHS seated in a rigid rolling chair. An 82 year old male subject (weight: 72.1 kg, height: 175 cm) was used in this validation test. The subject's anthropometry measurements are provided in Table A2. The neck was dissected and each of the cervical vertebrae from C3 to C7 was instrumented as described in the previous section. The anterior portion of the neck was also dissected so that Steinman pins with attached fiducials could be drilled into the anterior aspect of each of the vertebral bodies (C3 to C7) to record kinematics using a high speed camera (Figure 3(a)). This required that a portion of the anterior neck including the trachea, esophagus, and hyoid bone was split in half along a superior to inferior mid line. Since it was not possible to install the Steinman pins on the C2 or T1 vertebra due to interference with the chin and sternum respectively, instrumentation blocks were also not installed on C2 or T1 for this validation test. It should be noted that although the realistic response of the neck may have been compromised by the additional anterior dissection, and that complete kinematics were not obtained because of the C2 and T1 omissions, the purpose of this study was to validate the instrumentation for a given vertebral level by comparing the kinematics from the high speed video with the kinematics obtained from the instrumentation. Therefore five separate vertebral levels (C3 – C7) were deemed sufficient for this purpose. Once validated, however, the additional anterior dissection will not be necessary in future tests, thus avoiding any disruption of the anterior neck musculature. The kinematics at C2 and T1 will also be measured in future tests.



(a) C4 and C6 instrumentation and Steinman pins with fiducials


(b) Lateral view of test set-up

Figure 3: Rear impact lab trial test.

The rigid rolling chair was positioned against a pneumatic ram system so that the chair would move forward when the ram system was fired, resulting in extension of the subject's neck . The subject's head was supported by a harness that was attached to an electromagnetic system such that the head would be released just prior to the event (Figure 3(b)). After positioning the subject, three points on each instrumentation block were digitized by a Faro arm device (Faro Arm Technologies, Lake Mary FL) in order to define the initial 3D orientation of the instrumentation blocks. The fiducials on the Steinman pins were also digitized so that the data from the instrumentation could be transformed to the fiducials. High speed video (1000 fps) was recorded so that the kinematic data from the Steinmann pin fiducials could be compared to the kinematic data from the instrumentation. To provide a quantitative measure of this comparison, first the mean square error (MSE) was calculated and the square root taken to obtain the root mean square deviation (RMSD), as in Equations 1 and 2. The RMSD was then divided by the range of the observed values (i.e., data obtained from the instrumentation) to obtain the normalized root mean squared deviation (NRMSD), as shown in Equation 3. The NRMSD effectively provides an average percent error over time between the kinematic data obtained from the two methods (i.e., video and instrumentation).

$$MSE = \frac{\sum_{i=0}^{n} (Instrumentation_i - Video_i)^2}{n} \tag{1}$$

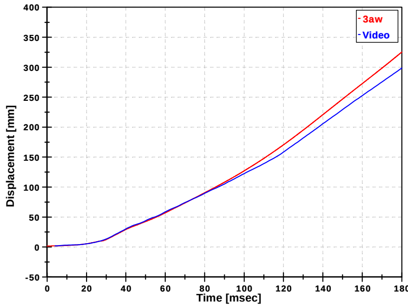
$$RMSD = \sqrt{\frac{\sum_{i=0}^{n} (Instrumentation_i - Video_i)^2}{n}} \tag{2}$$

$$NRMSD = \frac{RMDS}{x_{\max} - x_{\min}} \tag{3}$$

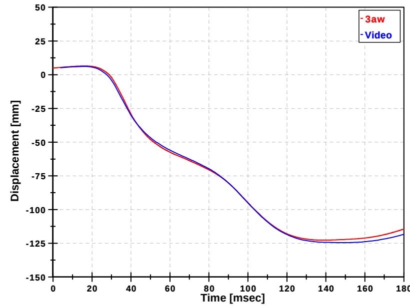
where, $Instrumentation_i$ and $Video_i$ are the ith data point obtained from the instrumentation and the ith data point obtained from the high speed video analysis, respectively. n is the total number of data points and x_{max} and x_{min} represent the maximum and minimum values of the data obtained from the instrumentation, respectively.

RESULTS

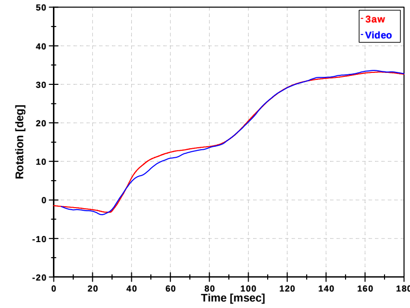
The input acceleration pulse and velocity for the lab validation test are presented in Figure B1. Data from the proposed instrumentation was transformed to the Steinmann pin fiducials at each point in time using Euler angles (2-1-3). The transformed data (translational motion in the X and Z as well as rotational motion in the Y direction according to SAE J211) and the data from the high speed video analysis for C3 and C4 can be found in Figure 4 (see also Appendix B for C5 through C7). Qualitative evaluation of these curves reveal relatively good agreement between the cervical kinematics obtained from video with the kinematics obtained from the instrumentation.



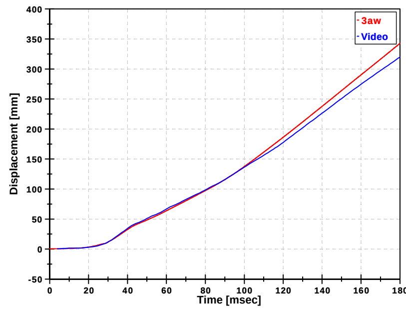
(a) C3 X-displacement (NRMSD = 3.52%)



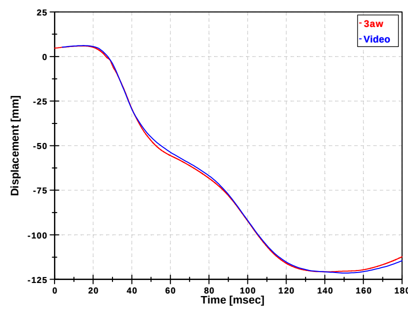
(b) C3 Z-displacement (NRMSD = 1.27%)



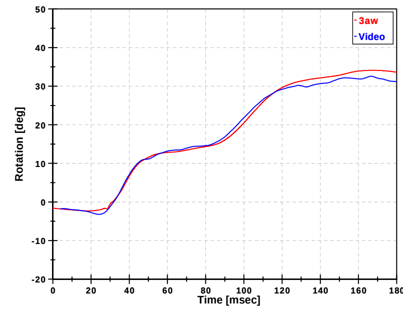
(c) C3 Y-rotation (NRMSD = 2.25%)



(a) C4 X-displacement (NRMSD = 2.60%)



(b) C4 Z-displacement (NRMSD = 0.90%)



(c) C4 Y-rotation (NRMSD = 3.00%)

Figure 4 Comparison of transformed instrumentation data with video analysis for C3 and C4

To quantify this agreement, the NRMSD was calculated over the first 180 ms at each vertebral level, and the results are shown in Table 1 along with the corresponding MSE and RMSD values. The NRMSD was under 5% for every kinematic measure (X- and Z-displacement & Y-rotation) at C3 through C6, and for both displacement measures at C7, indicating that there was less than 5% error between the two methods. The NRMSD value for the C7 Y-rotation was 11.1%, which indicated much higher disagreement between the two curves. Close inspection of the video revealed that the C7 fiducial was partially hidden behind the C6 fiducial which may have affected the video analysis results for the rotation. In fact, the maximum peak rotations for C7 from the instrumentation and the video analysis were 28.2 degrees and 23.5 degrees, respectively. However, the average peak rotations of the cervical vertebrae from C3 through C6 as determined by the instrumentation and video were 31.99 ± 1.96 degrees and 32.05 ± 1.24 degrees, respectively. This indicates that the 28.2 degrees of rotation obtained from the instrumentation may be more realistic than the 23.5 degrees of rotation obtained from the video analysis, thus providing further evidence that there may have been an issue tracking the C7 fiducial. Based on these results, the proposed instrumentation appears to be capable of measuring detailed cervical kinematics in rear impacts.

Table 1: Quantitative results – MSE, RMSD, and NRMSD

Cervical Spine	MSE (mm^2 or deg^2)	RMSD (mm or deg)	NRMSD (%)
C3Dx	129.77	11.39	3.52
C3Dz	2.69	1.64	1.27
C3AnDy	0.67	0.82	2.25
C4Dx	79.23	8.9	2.60
C4Dz	1.19	1.09	0.90
C4AnDy	1.19	1.09	3.00
C5Dx	99.07	9.95	2.95
C5Dz	24.90	4.99	4.11
C5AnDy	1.30	1.14	3.40
C6Dx	41.58	6.45	1.90
C6Dz	2.09	1.45	1.37
C6AnDy	1.56	1.08	3.16
C7Dx	33.15	5.76	1.65
C7Dz	18.27	4.27	3.58
C7AnDy	13.65	3.69	11.10

CONCLUSIONS

In this study a new instrumentation and dissection technique was proposed and validated in which instrumentation capable of measuring the detailed intervertebral kinematics (3 accelerometers, 3 angular rate sensors) are installed on the anterior aspects of each cervical vertebral body with no muscular damage. This is accomplished by dissecting the lateral aspect of the neck to access the anterior vertebral bodies through the retropharyngeal space. The instrumentation was validated by conducting a 10 km/h rear impact test with a PMHS in a rigid rolling chair. Initial 3D orientation of the instrumentation was defined by digitizing points on the instrumentation block. Steinman pins were drilled into the anterior portion of the cervical vertebral body, and fiducials were attached to the end of the pins to record the motion of the cervical vertebrae using high speed cameras. Data from the instrumentation was transformed to the fiducials and compared with results from the video analysis. The ability of the proposed instrumentation to successfully capture the detailed cervical kinematics was quantified by calculating the NRMSD, which provides an average percent error over time, and the results were below 5% in 14 of the 15 comparisons. The lone exception is likely a result of difficulty tracking the rotation of the C7 fiducial. The proposed instrumentation appears to be capable of measuring the detailed cervical kinematics, and will allow for full-body PMHS to be tested in realistic seating environments (i.e., modern yielding seat backs) at any impact severity. The data obtained from this instrumentation in future testing should prove useful in the investigation of rear impact injury mechanisms and aid in the development and evaluation of injury criteria.

ACKNOWLEDGEMENTS

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APPENDIX A

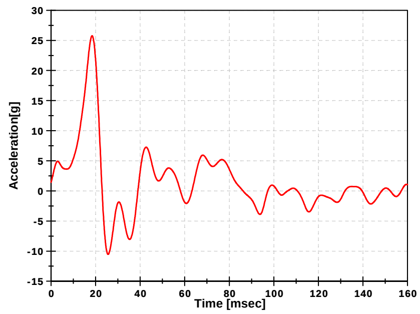
Table A1: Instrumentation block configurations

Cervical Spine	Location	Type
C3	Left anterolateral	1 block, 6 sensors
C4	Right anterolateral	2 blocks, 3 sensors each
C5	Left anterolateral	2 blocks, 3 sensors each
C6	Right anterolateral	1 block, 6 sensors
C7	Left anterolateral	1 block, 6 sensors

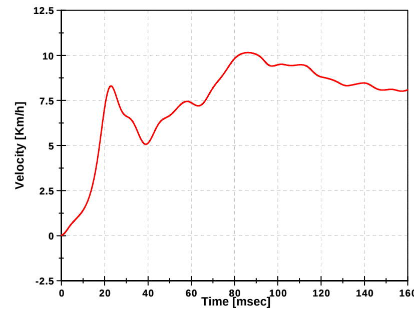
Table A2: Anthropometry

Anthropometry	PMHS01 (cm)
Stature	175
Seated height	89
Head height	21.5
Head length	17
Head breadth	14.9
Neck circumference	40
Neck width	11.5

APPENDIX B

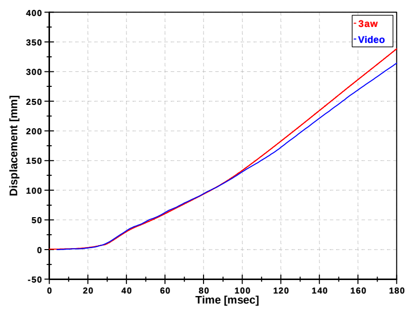


(a) Input acceleration pulse

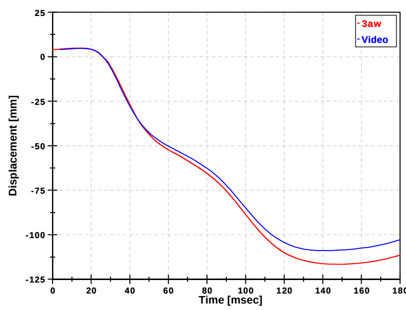


(b) Input velocity

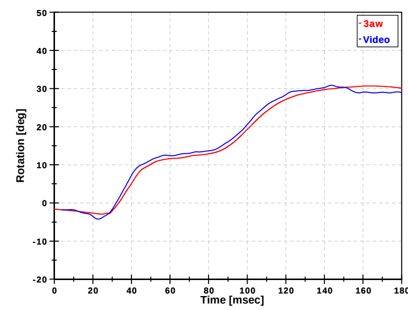
Figure B1: Input acceleration pulse and velocity.



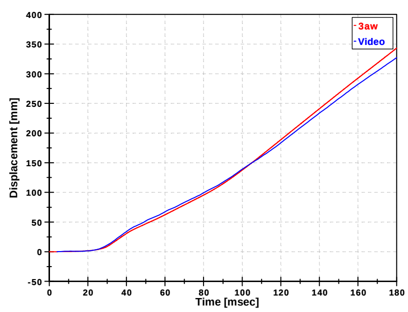
(a) C5 X-displacement
(NRMSD = 2.95%)



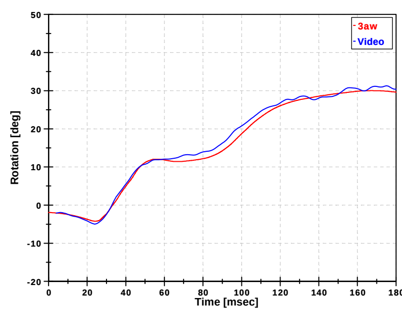
(b) C5 Z-displacement
(NRMSD = 4.11%)



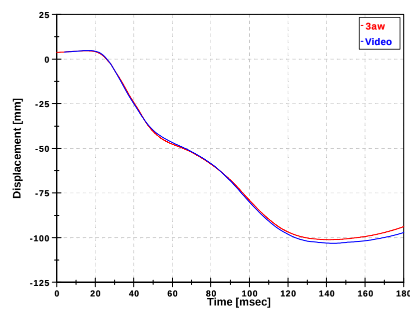
(c) C5 Y-rotation
(NRMSD = 3.40%)



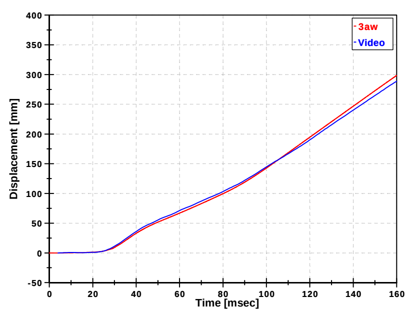
(a) C6 X-displacement
(NRMSD = 1.90%)



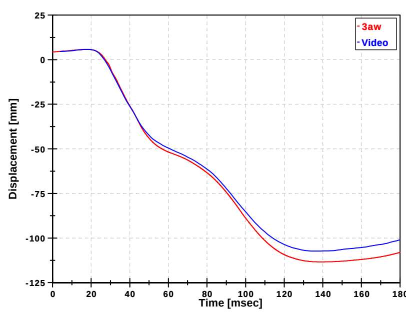
(b) C6 Z-displacement
(NRMSD = 1.37%)



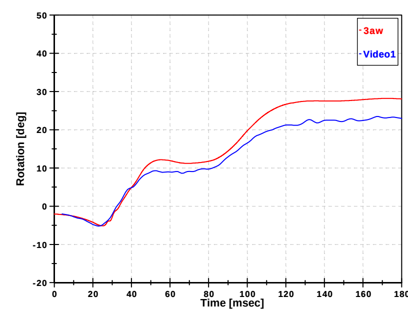
(c) C6 Y-rotation
(NRMSD = 3.16%)



(a) C7 X-displacement
(NRMSD = 1.65%)



(b) C7 Z-displacement
(NRMSD = 3.58%)



(c) C7 Y-rotation
(NRMSD = 11.10%)

Figure B2: Comparison of transformed instrumentation data with video analysis for C5 through C7.

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