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Sled Test Trials of 3-D Point Tracking System

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ABSTRACT

Accurate tracking of the 3-D movement of crash test subjects is challenging. Optical systems, although they are limited to line-of-sight applications, have the potential to offer greater accuracy than other non-contact technologies. The University of Virginia Center for Applied Biomechanics (CAB) recently evaluated an optical 3-D point tracking system provided by Vicon Peak with the initial intended use of recording the torso kinematics of restrained cadavers in a simulated frontal impact. The Vicon system is a video-based optoelectronic stereophotogrammetric system that simultaneously records the movement of spherical retroreflective markers. Processing software calibrates the movement capture volume, generates 3-D movement time-history data, and produces data visualization graphics. In two trial test series, involving a seated Hybrid III 50th percentile male dummy restrained by a customized lap and shoulder belt and knee bolster, the camera system was capable of recording marker positions at 1000 Hz. The cameras were arranged so that multiple cameras were able to "see" each of the 50 markers placed on the dummy's head, torso, pelvis, and shoulder belt. In the second trial, the Vicon cameras were paired with high intensity light rings that allowed the simultaneous recording of quality high speed video images. The Vicon system tracked the markers with few occlusions, periods during which less than two cameras were able to see any one marker. Peak chest deflection (movement of the anterior thorax toward the spine) measured by the Vicon system differed by 0.7 to 4.4 mm in comparison to three measurements at the same locations recorded by internal dummy instrumentation. This was within the confidence bounds of the internal dummy instrumentation for these trials. Lateral movement of the sternum with respect to the spine measured by the Vicon system differed from 15.2 to 17.6 mm with respect to internal dummy instrumentation measurements. The lateral movement differences prompted a more careful ongoing investigation of Vicon system accuracy.

INTRODUCTION

Reducing the chance of automotive crash injury is predicated on understanding human response in a crash. However, measuring human (cadaveric) response in simulated crashes is challenging. Frontal crashes at 48 km/h are short duration, approximately 120 ms, and involve complex total body movement and interaction with occupant restraints. We are currently investigating thoracic response resulting from shoulder belt loading with a specific focus on the relative movement and deformation of the shoulder, clavicle and anterior ribcage. Also of interest is the role of inertial loading on ribcage geometry and spinal deformation.

In order to successfully characterize cadaver torso-restraint interaction, we have been searching for a point tracking system that is capable of recording the 3-D movement of at least 50 points circumferentially distributed on the subject and shoulder belt. Other system criteria include sub-millimeter accuracy for the three dimensional position of a marker within the capture volume and a sampling frequency of at least 500 hz. Precise quantification of human cadaver response under inertial loading is essential for establishing performance targets for physical (crash dummies) and computational human models.

Given a sizable investment in high speed video imagers, we first investigated ways to use our existing cameras to record 3-D motion. Such a system was developed by TNO using FalCon software (ref http://www.falcon.de/falcon/pdf/eng/datasheet/tno_3d.pdf). However replicating such a system in our lab requires the ability to tightly synchronize our cameras, something we are unable to do because of the variety of models in our inventory.

Other options for 3-D point tracking were investigated (Table 1). Of these options, only one, a video-based optoelectronic stereophotogrammetric system (Figure 1) (Chiari et al., 2005) that uses passive markers, appeared sufficiently developed to meet our needs (Table 2). This system uses an array of high speed cameras to track the position of spherical retroreflective markers (Figure 2). The system includes software that corrects for lens distortion and parallax (Figure 3), establishes camera positions and a coordinate system, automatically tracks point trajectories, and provides options for completing point trajectories interrupted by occlusions. Analysis software is available to create visualization models from the 3-D trajectory data. Motion Analysis Corp. and Vicon Peak provide optoelectronic stereophotogrammetric systems. The Vicon system was the focus of our investigation and testing.

Table 1. 3-D Point Tracking Systems.

Method of Operation	Pros	Cons
Orthogonal Electromagnetic Fields	Does not require line of sight.	Too slow, inaccurate. Affected by electromagnetic fields and metal.
Measurement of Mechanical Linkages	Accurate.	Cumbersome hardware on subject.
Ultrasonics	Less expensive.	Too slow, inaccurate. Requires line of sight.
Inertial Tracking	Does not require line of sight.	Inaccurate.
Video Signal Processing	Fast, accurate.	Requires line of sight.

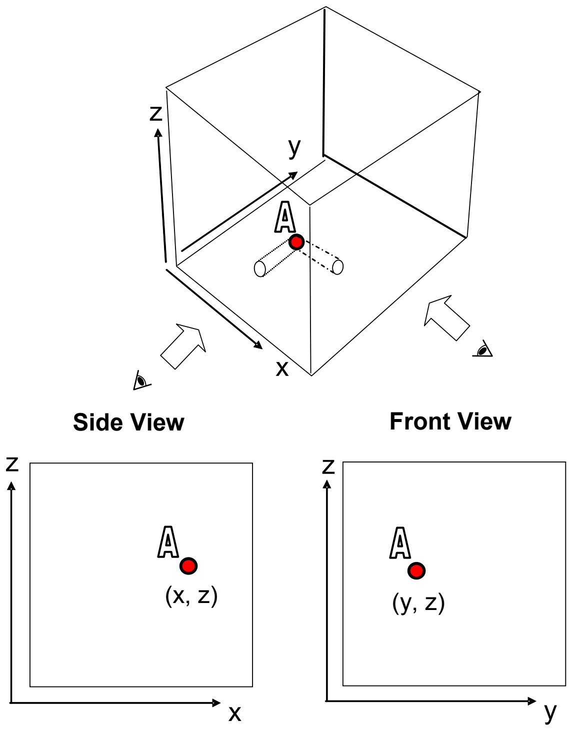

Figure 1: Principles of optoelectronic stereophotogrammetry: The 3-D location of point A can be determined by the combination of information supplied by two planar views (cameras). In this example, the side view provides x and z coordinates and the front view provides y and (redundant) z.

Table 2. Video Signal Processing Systems Using Marker Tracking.

System Description	Examples
Software and procedures to integrate existing high speed cameras	Image Express (www.sensorsapplications.com), FalCon (www.FalCon.de)
Dedicated high speed cameras and software	
Active markers (LEDs)	Atracsys (www.**atracsys**.com)
Passive markers (retro-reflective)	Motion Analysis Corp. (www.**motionanalysis**.com), Vicon (www.**vicon**.com)

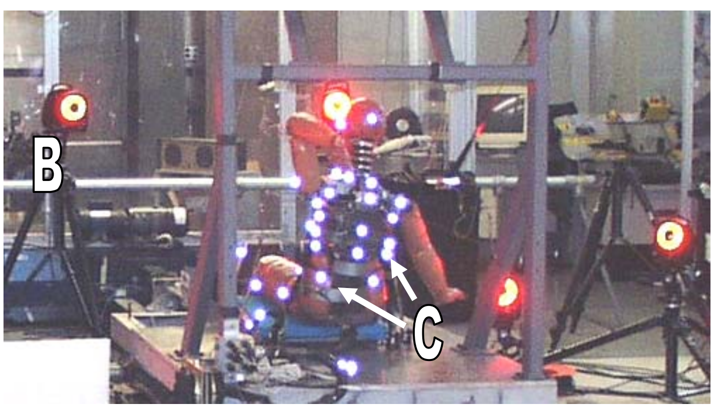

Figure 2: Cameras with LED light ring (B) and retro-reflective markers (C).

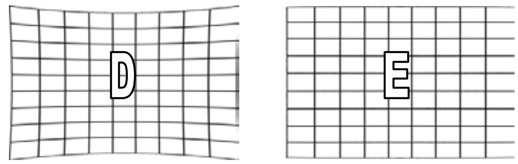

Figure 3: Camera lens distortion (D) corrected by software (E).

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METHODS

Vicon System

In the trial periods at UVA, the system consisted of multiple MX13 cameras capable of capturing 480 f/s at full frame (Figure 4). Higher frame rates require a reduction in frame area. In our tests, the cameras recorded at 1000 f/s with a modest reduction in frame area.

- 1.3 million pixel resolution
- 484 f/s full frame
- 10,000 f/s maximum frame rate.

Figure 4: Vicon MX13 camera with LED light ring (A).

Test Fixture and Parameters

The buck and seat for the Hybrid III 50th percentile male ATD were constructed to maximize the visibility of the markers relative to the cameras (Figure 5). The back and head supports for the ATD consisted of a wire mesh. The knee bolster limited upward knee movement that was likely to hide torso markers from one or more cameras. The ATD was restrained by an aftermarket shoulder belt and lap belt. Approximately 11 cm of slack was introduced into the shoulder belt to simulate belt spool-out without allowing excessive forward torso rotation, another potential cause of marker occlusion.

The buck, oriented to simulate a full frontal impact, was accelerated to 48 km/h before being decelerated to a stop by a hydraulic decelerator over a distance of approximately 630 mm. Contact of the piston rod end with a rigid barrier defined the beginning of the crash event (T_0) and produced a trigger signal for both the data acquisition and Vicon systems.

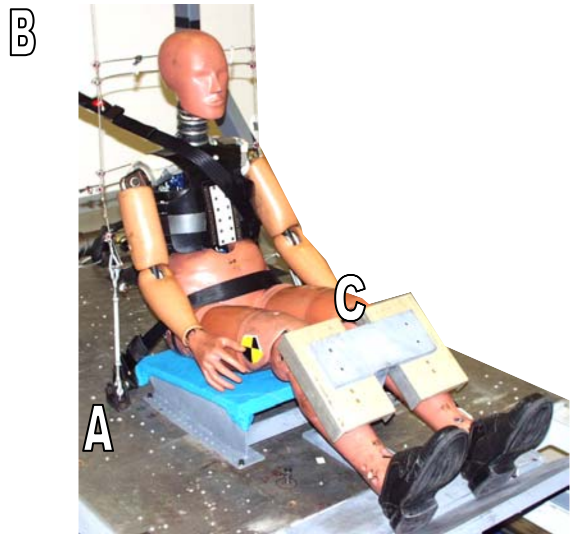


Figure 5: Hybrid III 50th percentile male ATD on rigid planar seat (A). Wire mesh back and head supports (B). Knee bolster (C).

General Test Procedures

In preparation for the sled tests, spherical markers of 14 mm in diameter were affixed to the dummy (without torso skin), shoulder belt, knee bolster, and seat. Four markers on the anterior ribcage were positioned over internal deflection instrumentation attachments or contact points (Figure 6). Several markers were taped to the spine box. The cameras were arrayed around the sled buck impact site and aimed in such a way as to capture the maximum number of markers throughout the impact event.

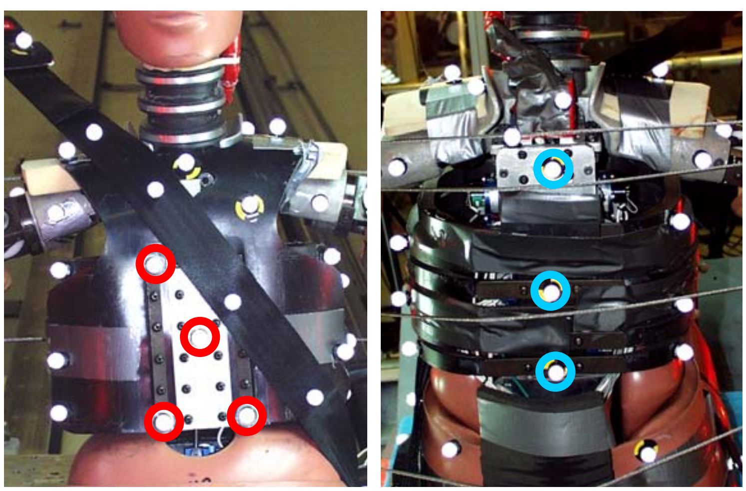


Figure 6: Thorax and shoulder belt marker placement. Red circles indicate markers placed over contact points for internal deflection instruments that measure the change of displacement of the anterior chest relative to the spine. Blue circles indicate markers on the spine.

Calibration of the capture volume, a procedure that defines the locations of the cameras and linearizes camera measurements, is a two-step process that preceded data capture.

Shortly after the test, video images of marker movement were generated to assess data capture performance including the continuity of marker trajectories (Figure 7). For example, markers that flicker on and off during replay indicate marker occlusion. The analogue dummy and Vicon data were post-processed to evaluate the agreement of calculated Vicon marker position in comparison to internal dummy chest deflection instrumentation with respect to the change in distance between the anterior thorax and spine (Figure 6).

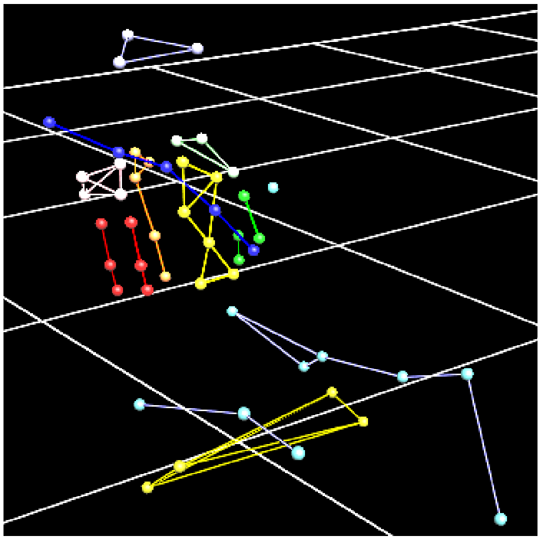


Figure 7: Visualization of marker location. Blue - shoulder belt. Upper yellow - anterior ribcage.

TRIAL A

Specific Test Procedures. The first trial utilized 11 cameras with LED strobe rings for marker illumination (Figure 4). Most of this first trial was spent assessing Vicon system performance with higher than recommended levels of ambient light, required for parallel use of our existing high speed video cameras. Some test conditions demand high quality high speed images in addition to the point tracking that Vicon provides. Our 60,000 watt tungsten halogen lighting arrays brilliantly illuminated the test volume. The Vicon cameras were unable to isolate marker reflections from other brightly reflecting surfaces that included both the dummy's vinyl skin as well as unpainted metal, a potential problem for even normal high speed cameras that utilize ambient lighting. Due to the extent of these spurious reflections, standard methods of eliminating them such as painting with a flat dark color and digitally masking areas within the field of view, a procedure that permanently blinds a camera to a specified area, were not feasible. Changing the camera ring lights from near infrared to visible red LEDs also failed to produce good results.

Reducing the intensity of our lighting array failed to improve Vicon performance. Spurious reflections disappeared only when using a much less powerful alternative lighting array consisting of fluorescent tubes (Figure 8**;** Table 3). Fluorescent light was chosen under the assumption that the cameras would be less sensitive to cooler temperature illumination.

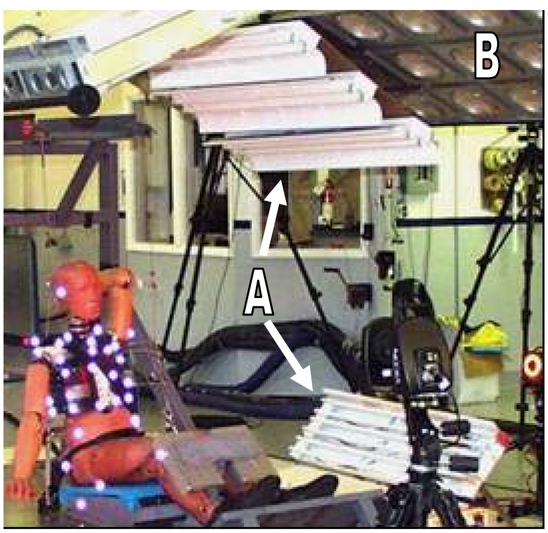


Figure 8: Fluorescent lights (A), an alternative to the existing incandescent tungsten-halogen array (B).

Table 3. Lighting Options.

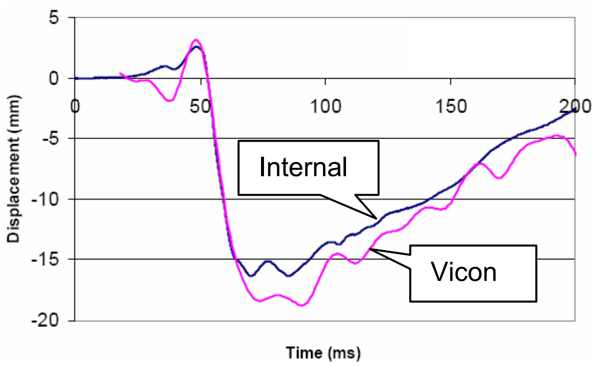
	Lamp Type	Color Temperature Degrees Kelvin	Total Watts	Total Lumens (Estimated)	Comment
Standard Arrays	Tungsten Halogen PAR	3200	60,000	1, 260, 000	Sixty lamps, in two arrays. Independent switching for groups of three.
Alternative Array	Fluorescent Tube (Daylight)	6500	480	27,000	Twelve 48” (120 cm) tubes in six fixtures.

Because the fluorescent tubes produced approximately 2 percent of the illumination of the original array, we reduced the high speed video frame rate from 1000 to 250 f/s and increased the exposure time. This resulted in a poor quality high speed image (Figure 9).

Figure 9: Frame from video camera with the subject illuminated by the fluorescent lights.

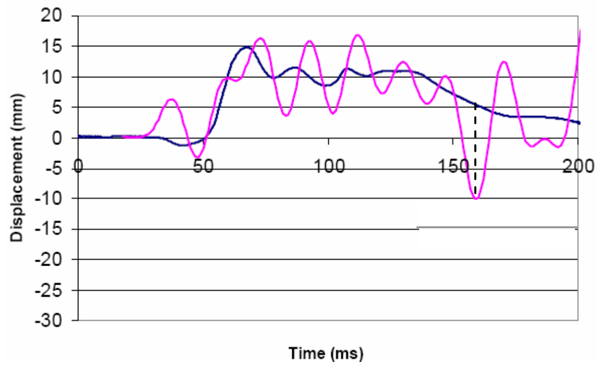
Trial A Results. Agreement between chest deflection values calculated using Vicon marker data and internal instrumentation was good for sternum movement toward the spine (local occupant x-axis). Peak values were within 1 to 3 mm for each measurement method and the corresponding time-history traces were similar (Figure 10). However, anterior chest movement lateral to the spine (local occupant y-axis) varied in both peak value and corresponding time-history pattern. The Vicon traces exhibited a prominent oscillation that was not evident in the internal instrument traces.

X-Axis Deflection

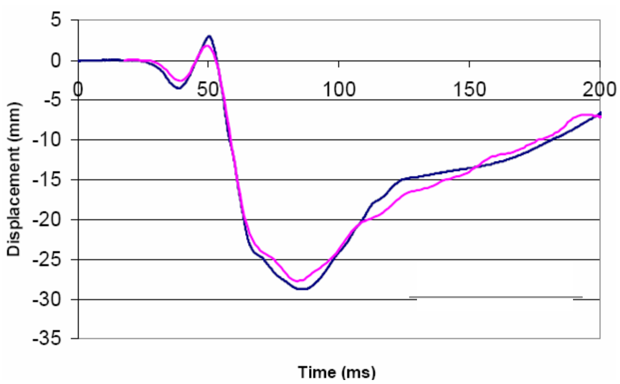


Upper Right
Difference in Peak Values: 2.4 mm

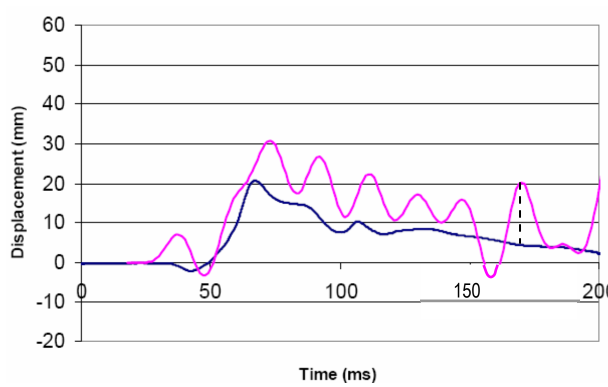
Y-Axis Deflection



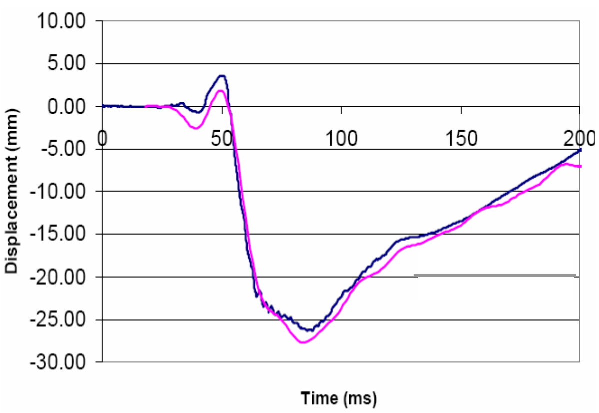
Upper Right
Difference in Peak Values: 2.1 mm
Maximum Difference in Values: 15.3 mm @ 159 ms



Lower Left
Difference in Peak Values: 1.3 mm



Lower Left
Difference in Peak Values: 10.1 mm
Maximum Difference in Values: 15.2 mm @ 169 ms



Central Sternum
Difference in Peak Values: 1.3 mm

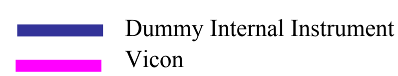


Figure 10: Trial A test deflection results. Negative x-axis values indicate the anterior ribcage moved toward the spine. Positive y-axis values indicate anterior ribcage movement to the dummy's right.

TRIAL B

Specific Test Procedures. A second trial was conducted in order to address the lighting challenge and unexplained y-axis response in the initial trial. The second trial utilized 12 cameras with Pallites (tungsten halogen light rings) in place of the visible red LED strobe rings (Figure 11). Vicon staff indicated that the non-standard Pallites had solved a similar lighting problem.

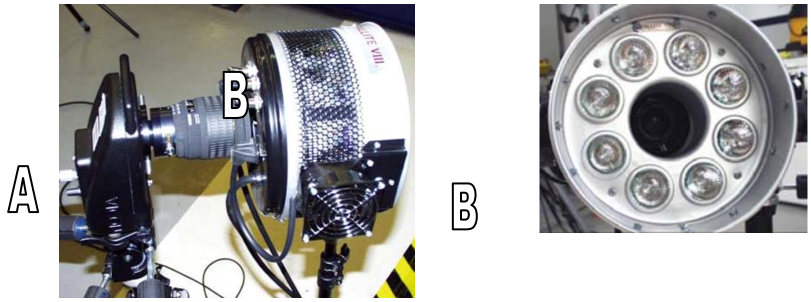


Figure 11: Vicon camera (A) with Pallite light ring (B).

A marker array was mounted on the upper spine box in order to provide a better defined local coordinate system for calculation of anterior chest motion relative to the spine. A poorly defined local reference y-axis in the previous trial was thought to be the cause of the y-axis oscillation. (Figure 12). Aside from lighting and marker set differences, Trial B replicated Trial A hardware and procedures.

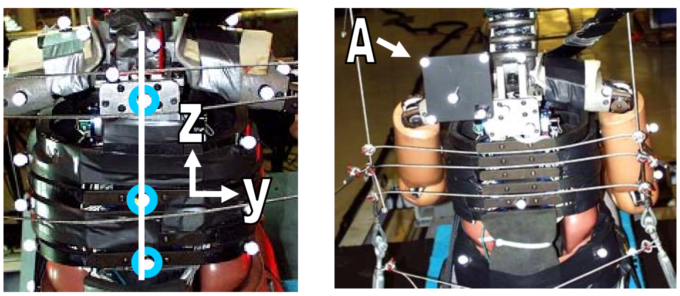


Figure 12: Spine marker arrays.

Trial A spine markers poorly defined the y-axis and the y-z plane as they were essentially aligned along the z-axis of the spine.

Trial B marker array (A), provided a 100 mm marker offset in the y-axis.

Trial B began with the seated dummy and buck parked in the capture volume. A series of Vicon marker captures with various lighting conditions were conducted. The initial test involved our 60,000 watt lighting arrays oriented to provide optimal subject illumination in addition to the 12 Pallites associated with the cameras (Table 4). This combination proved to be too much illumination for the Vicon system. However, raising our arrays approximately 2 meters reduced the surface reflections enough to allow the cameras to distinguish the markers. This configuration provided sufficient illumination for acceptable high speed images recorded at 1000 Hz (Figure 13).

Table 4. Lighting Options Trial B.

	Lamp Type	Color Temperature Degrees Kelvin	Total Watts	Total Lumens (Estimated)	Comment
Standard Arrays	Tungsten Halogen	3200	60,000	1, 260, 000	Sixty PAR lamps, in two arrays. Independent switching for groups of three.
Pallite (Single)	Tungsten Halogen	3200	2400	50,400	A light ring with eight projector bulbs.
Pallites (12)	Tungsten Halogen	3200	28,800	604,800	

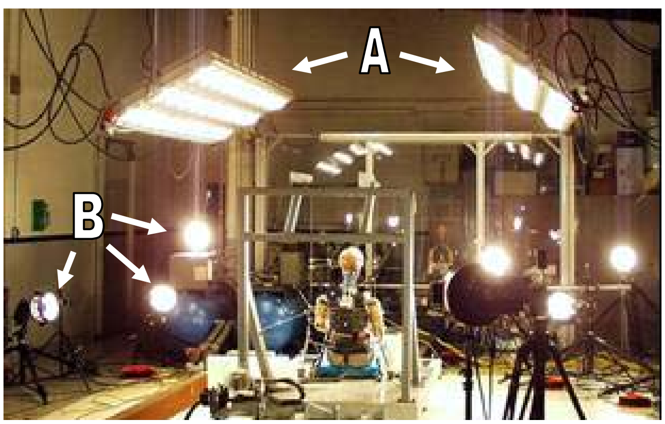


Figure 13: Illumination for Trial B tests.
A - 60,000 watt lighting arrays
B - Pallites

Trial B Results. As in Trial A, agreement between local occupant x-axis chest deflection calculated using Vicon marker data and internal instrumentation generally was good (Figure 14). However, as observed in the prior trial, local occupant y-axis deflection varied in both peak value and time-history pattern.

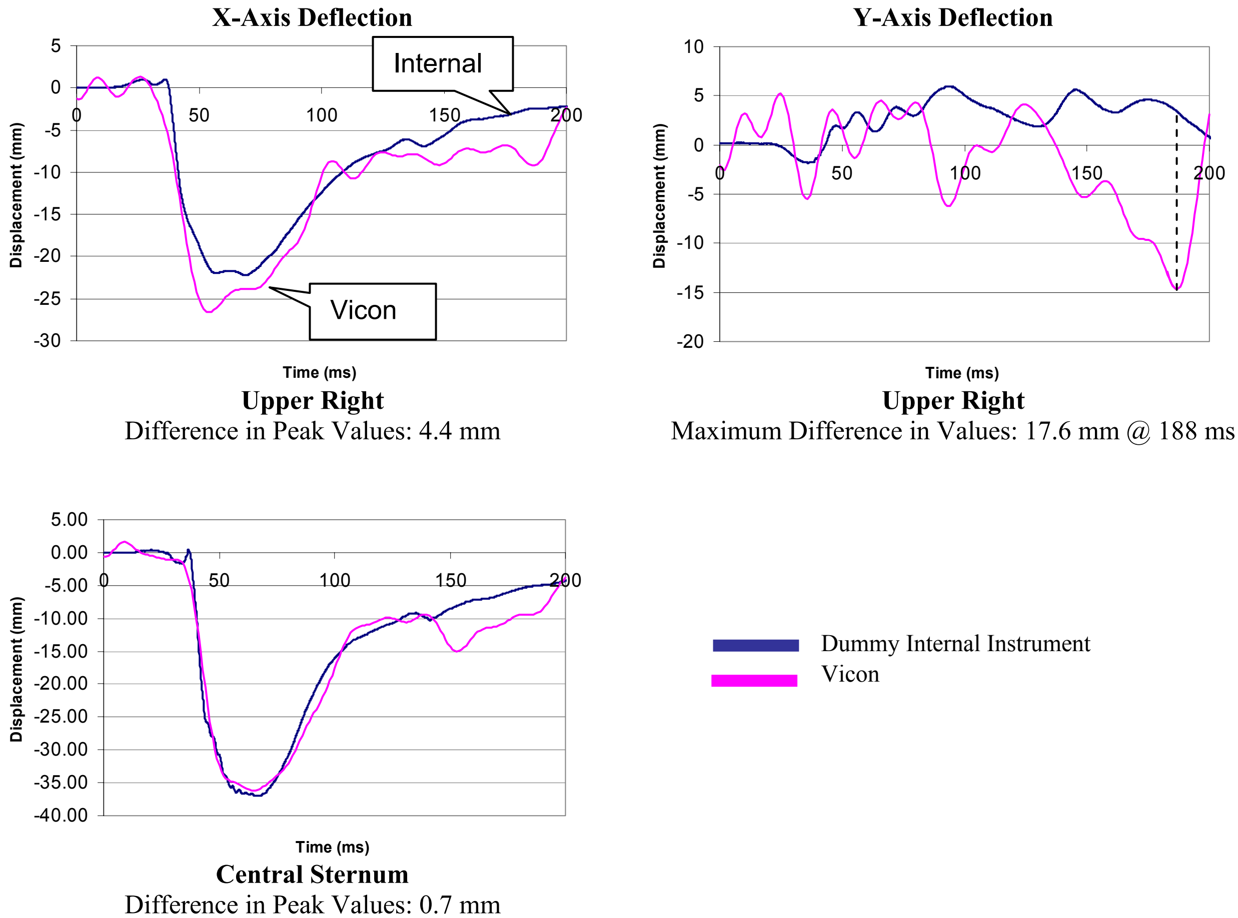


Figure 14: Trial B test deflection results. Negative x-axis values indicate the anterior ribcage moved toward the spine. Positive y-axis values indicate anterior ribcage movement to the dummy's right.

DISCUSSION

Lighting. The combination of CAB lighting arrays positioned farther from the capture volume and the 12 Pallites met the challenge of illumination sufficient for acceptable high speed video quality but not so intense as to degrade marker identification. However, the Pallites complicate camera set up. Because of fears that the Pallite fan vibration may affect image quality, the Pallites were independently mounted on separate stands in front of the cameras rather than being clamped to the camera tripods. Each Pallite requires two 110v power cords. Along with the camera cables and tripods, the accommodations for the Pallites create a cluttered test space. Better integration of the Pallites is required to minimize tripping hazards and to streamline infection control procedures for testing of cadaver subjects.

Comparison with Dummy Internal Deflection Instrumentation. The comparison of the Vicon and internal dummy sensor deflection was intended to be a convenient way to evaluate the Vicon results with respect to familiar and relevant measurements rather than a definitive test of Vicon accuracy. The finding that the peak x-axis deflection calculated by the Vicon and the internal instruments were within 4 mm of each other and that the time-history traces were similar but did not overlay suggests that the Vicon data capture and post processing could replicate the dummy measurements within reasonable error bounds. One source of "error" was marker placement relative to the monitored points on the anterior ribcage. For example, the marker trajectory was similar to but not coincident with that of the anchor point of the potentiometer string (Figure 15).

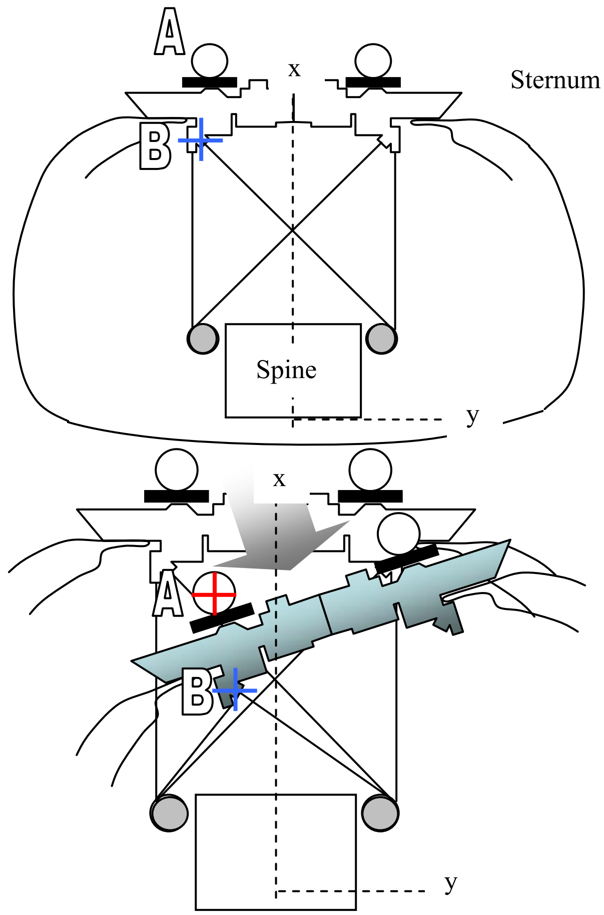


Figure 15: Cross section of Hybrid III dummy chest from above showing marker placement effect on y-axis movement. Rotation of the sternum in response to belt loading differentially affects the y-axis movement of the marker (A) relative to that of the string pot attachment point (B) with respect to a spine-based coordinate system. In the undeflected state, the marker is closer to the x-axis; in the deflected state, the attachment point is closer.

However, the differences in the y-axis results late in the event (Figures 10 and 14), are large enough to warrant further investigation. We evaluated the Vicon system's 3-D accuracy in a more controlled dynamic test and found no difference in accuracy between x and y axis movements. Peak values of marker movement along all three axes varied no more than 1.5 mm from the actual movement as estimated using data from a static test with a digital caliper. This accuracy was similar to that reported for an earlier Vicon system (Chiari et al., 2005). Marker displacement in a quasi-static test was recorded by Vicon to be within 0.185 mm of the caliper value, approximately the caliper test-to-test measurement variation.

Further inspection of the Trial B data, specifically, the behavior of the markers on the array mounted on the upper spine box, indicated that the (unfiltered) distance between the markers changed up to 4.5 mm during the event. This was unexpected as the markers were securely mounted to a rigid aluminum plate.

Instability of the position of the array markers, used to define the spine location, reduced the accuracy of the calculated relative movement between the spine and markers on the anterior chest in all axes.

This finding prompted a series of controlled tests which are ongoing. The objective of these tests is to determine Vicon system accuracy for our specific sled test environment and to develop strategies to minimize error. Preliminary findings indicate that marker position error, less than one millimeter in static tests, increases when the markers move. Error also increases when marker trajectories are not calculated by the same set of cameras throughout the event. This can occur if the marker moves out of the field of view of a camera, i.e. as the buck and dummy move down the track, or if an object obscures the view of the marker from one or more cameras. Unfortunately, our test set up and the need to monitor markers placed circumferentially on the subject, involves changing sets of cameras.

CONCLUSIONS

The UVA trials suggest that the Vicon system has the potential to be a valuable tool with which to track the 3-D trajectories of points during dynamic events such as sled tests. Enhanced by the use of Pallites, the system allowed the recording of simultaneous high speed video images. However, further investigation is required to define system accuracy and to develop strategies to enhance it.

ACKNOWLEDGEMENTS

Vicon Peak generously provided the equipment and staff time required for the two trials in addition to responding to numerous technical questions over the last year. UVA research direction and support was provided by the National Highway Traffic Safety Administration.

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DISCUSSION

PAPER: **Sled Test Trial of 3-D Point Tracking Systems**

PRESENTER: ***Greg Shaw, University of Virginia Center for Applied Biomechanics and Vicon Peak***

QUESTION: *Guy Nusholtz, Daimler Chrysler*

Some time about 20 years ago, I tried to investigate a similar type of process and it seems like the same problems that I had, you're having, and I basically predicted that within five years, it'll all be fixed and we'll be doing everything with 3-D video. So far, it seems like it's pretty stagnant. It's just around the corner and a couple software fixes will continue to fix it. Do you really think that, that this, a lot of these are gonna be solvable? We originally did 3-D film. I've done 3-D film with hand-tracking and everything, and that works reasonably well because you got an operator, which is interpreting where things need to be. But in this case, I'm assuming you're completely automatic.

ANSWER: This is automatic.

Q: In fact, you retro-flex. You have a problem with the targets crossing and not being able to distinguish which target could be and a number of other issues associated with the resolution, but it's been around for a long time.

A: Yes.

Q: And the software to do this has been around for a long time.

A: That is true and we're encouraged because the x-axis information and the static measurements that we've taken are sub-millimeter. I mean we actually have put a caliper on things. So you know, why the y-axis.