Journal of Biosensors & Bioelectronics
ISSN: 2155-6210

Lessley, et al., J Biosens Bioelectron 2011, S1
DOI: 10.4172/2155-6210.S1-002

Research Article | Open Access

Assessment and Validation of a Methodology for Measuring Anatomical Kinematics of Restrained Occupants During Motor Vehicle Collisions

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Abstract

Efforts to improve restraint design for human occupant protection require a detailed knowledge of human kinematic response. However, to improve the current understanding of human kinematic response to restraint loading it is necessary to obtain a more detailed knowledge of how structures within the body such as individual ribs and vertebrae move during an impact event. Video-based optoelectronic stereo photogrammetric systems (OSS) have recently been employed for kinematic measurement during simulated vehicle collisions with restrained post mortem human surrogates (PMHS). Application of this methodology requires specialized optical sensor hardware to be surgically attached to anatomical structures of interest such as acromia, ribs orvertebrae. The hardware supports retro reflective spherical targets which are visible to the OSS. The recorded target motions are then transformed to the underlying anatomical structures to quantify the trajectories of individual bone centers throughout the impact event. This study presents the results of seven tests that were conducted to practically assess the efficacy of this emerging methodology for measuring anatomical kinematics during impact loading. The tests used a 16-camera 1000Hz OSS and a single simulated anatomical structure with attached target hardware to quantify the uncertainty in the calculated trajectory of the bone center. Specifically, the tests assessed the intrinsic optical error associated with the OSS, and also evaluated the ability of the rigid body transformation to reproduce a directly measured bone center trajectory. The tests also assessed the effect of compliance in the assumed rigid connection between the visible target hardware and underlying bone on the transformed trajectories. The results demonstrate robust performance of a novel methodology combining state-of-the-art optoelectronic technology, specialized target hardware, and rigid body transformation to obtain kinematic measurements of anatomical structures within the human body which are not visible or accessible for direct measurement during an impact event

Keywords: Optoelectronic; Kinematics; Anatomical rigid body; Skeletal

Introduction

Road traffic injuries are a well-established public health problem and are a leading cause of death globally. While increased seat belt usage and advances in restraint design have substantially improved the injury outcome for restrained occupants, injuries and fatalities are still occurring nonetheless. Ongoing efforts to further mitigate injuries to restrained occupants require a more complete understanding of how the human skeletal system moves and deforms while interacting with the occupant restraint system during a vehicle crash. However, in order to improve the current understanding of human kinematic response to restraint loading it is necessary to obtain a detailed knowledge of how specific structures within the body such as individual ribs and vertebrae move during an impact event. Accurately quantifying the motion of such anatomical structures during an impact event is a difficult yet essential task in effectively characterizing human kinematic response, and is also necessary for quantifying injury risk and developing optimal countermeasures for human protection. Accomplishing this goal, however, requires improved methods for measuring these vital kinematic responses during impacts.

Kinematic measurements during high-rate events such as vehicle collisions have historically been accomplished using two-dimensional (2D) video analysis from conventional high-speed video imaging [1,2]. Recently however, in the field of impact biomechanics, the use of high-rate video-based optoelectronic stereo photogrammetric systems (OSS) has been combined with specialized retro reflective target hardware to provide kinematic measurement of specific anatomical structures in restrained post mortem human subjects (PMHS) during simulated vehicle collisions[3,4]. Using this methodology, the OSS tracks the displacements of visible four-target clusters rigidly attached to a specific underlying bone as illustrated in Figure 1. The collected cluster trajectory is then transformed to the corresponding bone center (Figure 2) using a rigid body transformation. The advantage of this methodology is that it provides detailed 3D trajectories of specific skeletal structures that are within the body such as individual vertebrae and ribs which are not directly visible or accessible for measurement by other available means.

The introduction of video-based optoelectronic stereo photogrammetry for PMHS impact loading is relatively recent, however, it has long been utilized in non-impact motion biomechanics applications such clinical gait analysis [5-16]. The objective in movement analysis is the reconstruction of anatomical motion in the global OSS reference frame (Figure 2), however, it is generally accepted that a primary limitation of such movement analysis is error in single target position data and the propagation of this error to the estimation of the desired anatomical motion [5,6]. Considerable effort has been

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Received September 15, 2011; **Accepted** November 10, 2011; **Published** November 17, 2011

Citation: Lessley D, Shaw G, Riley P, Forman J, Crandall J (2011) Assessment and Validation of a Methodology for Measuring Anatomical Kinematics of Restrained Occupants During Motor Vehicle Collisions. J Biosens Bioelectron S1:002. doi: 10.4172/2155-6210.S1-002

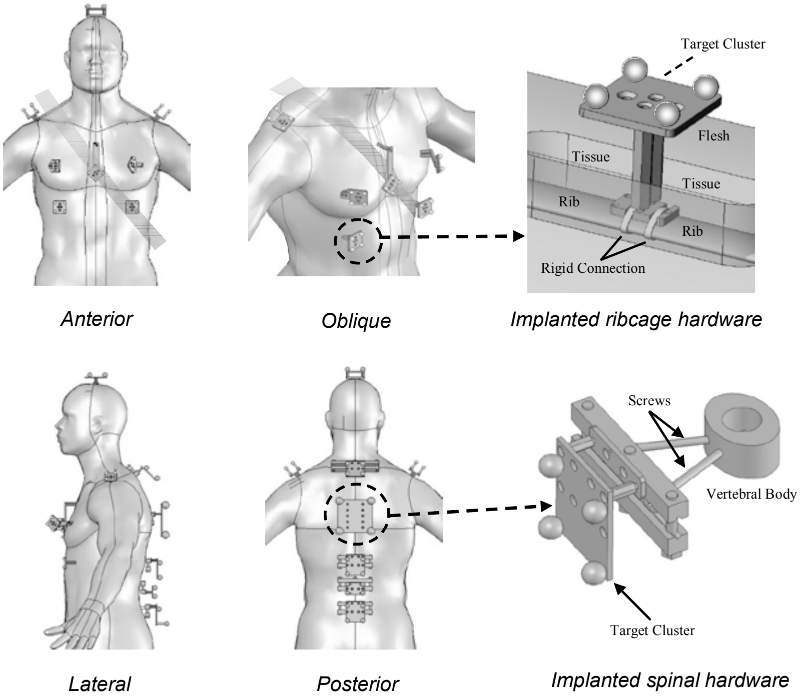

Figure 1: Surgically implanted retro reflective target hardware.

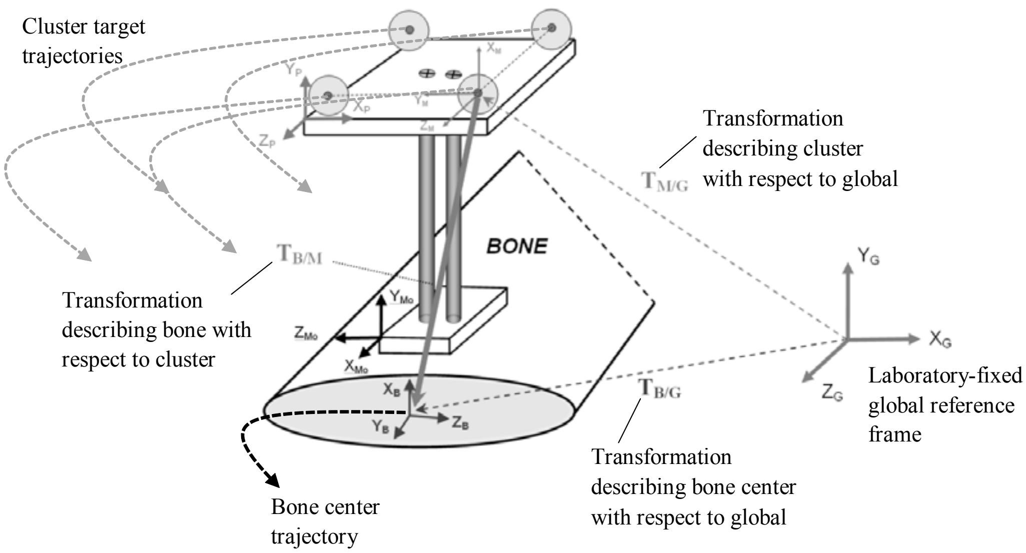

Figure 2: Rigid body transformation. At a given anatomical location the trajectory of the visible target cluster is transformed to the bone using a coordinate transformation.

made to quantify and reduce instrumental errors as well as to set forth experimental guidelines regarding estimating anatomical motion from remotely placed targets [6,7].

Throughout the development of the presented methodology for measuring anatomical motion during impact loading, an ongoing concern and design consideration has been that the combination of OSS error and unintended compliance in the cluster-to-bone connection could lead to unreasonable uncertainty in the calculated anatomical trajectories. This study presents the results of seven tests that were conducted to practically assess the efficacy of an emerging methodology for measuring anatomical kinematics during impact loading. The threefold objective of this study is as follows: 1) to evaluate the quality of single target data collected from a standard OSS configuration used during impact conditions; 2) to demonstrate the ability of the rigid body transformation to use remotely measured target data to reproduce a known bone center trajectory; and 3) to assess the effect of compliance in the assumed rigid connection between the target cluster and bone on the transformed trajectory of a desired anatomical location. The combination of these factors provides the magnitude of uncertainty with which anatomical motion can currently be measured during impact loading.

Methods

To assess the efficacy of the optoelectronic kinematic measurement methodology presented by [3], seven tests were conducted using a single target cluster attached to a simulated bone segment which will be referred to as the "bone" from here on. The premise of the conducted tests was to utilize a test condition that allowed the motions of the target cluster and bone center to be measured simultaneously, thus providing a method to compare the calculated bone center motion from the target cluster to the actual bone center motion measured directly. This comparison quantified the uncertainty in the calculated motion and also identified the most substantial contributors to the total uncertainty.

To accomplish this in the seven presented tests, the motion of the bone center was measured directly by a 16-camera OSS (Vicon, MX series, Oxford, UK) via two reflective targets rigidly attached to opposing sides of the cylindrical bone surface. The mean position of these targets on the rib surface provided a direct measure of the position and motion of the bone center for all tests. In each test this directly measured motion of the bone center served as the "actual" motion and was compared to "calculated" motion of the bone center derived from the attached target cluster using the rigid body transformation described by [4].

The details of the seven conducted tests are summarized in Table 1. In Test 001 the bone with rigidly attached marker cluster was manually driven over a 0.635m trajectory at approximately 5 m/s. This test was used to1) assess the ability of the of the rigid body transformation to reproduce the directly measured bone center trajectory and 2) to assess single target data quality associated with the OSS. Tests 002 – 007 were used to explore the effects of unintended compliance in the cluster hardware, or in its attachment to the bone, on the accuracy of the calculated motion of the bone center. In all tests the OSS captured the target trajectories at 1000Hz. Prior to the testing the OSS was calibrated [17-19] using a manufacturer supplied software based algorithm (Vicon, IQ 2.5, Oxford, UK) such that the root mean squared error was < 0.4 mm over the capture volume. All test conditions are illustrated in Figure 3.

TEST #	Test Description	Hardware Description	Rate	FApplied(N)	Cluster center to bone center dist. (mm)
001	Single Target Data Quality assessment	Standard	Dynamic	NA	105.9
002	Rotational compliance assessment	Standard	Dynamic	NA	95.4
003	Bending compliance assessment	Standard	Quasi-Static	22	95.4
004	Bending compliance assessment	Standard	Quasi-Static	44.5	95.4
005	Rotational compliance assessment	Modified	Dynamic	NA	89.3
006	Bending compliance assessment	Modified	Quasi-Static	22	89.3
007	Bending compliance assessment	Modified	Quasi-Static	44.5	89.3

Table 1: Test matrix and summary of conducted tests.

Rigid body transformation assessment

During an actual PMHS impact test, the bone center of interest for kinematic measurement is within the body and hidden from view. This requires that its motion be determined from the visible cluster motion via rigid body transformation. Here, in the assessment test however, both the cluster and bone motions were able to be directly tracked during the same dynamic event. The collected cluster data were used as an input to the rigid body transformation described by [3] to obtain a calculated trajectory of the bone center to be compared with the actual (directly measured) bone trajectory. Specifically, referring to Figure 3, the collected cluster target data were transformed to the bone center, which was taken to be the mean position of two targets attached to opposing sides of the simulated bone surface. Comparison between the calculated and actual bone center trajectories provided a practical verification and quality assessment of the calculated data obtained from the rigid body transformation.

Single target data quality assessment tests

Prior to the test described above the bone and attached target cluster were digitized using a FARO arm (FARO, model N10, Lake Mary, FL). The digitized data were used to create a high-quality digital representation of the physical target cluster to be spatially compared with collected target position data from the OSS (Figure 4). For each frame of collected data, the center positions of the four targets from the digital representation were optimally fit to the collected single target data using a least squares pose optimization [20-23] as illustrated in Figure 4. Deviations, δi(t), between the digital representation and the collected target data provided measures of single target error for the four targets comprising the cluster. Additionally the known diagonal distances between targets on the cluster for each optical frame were

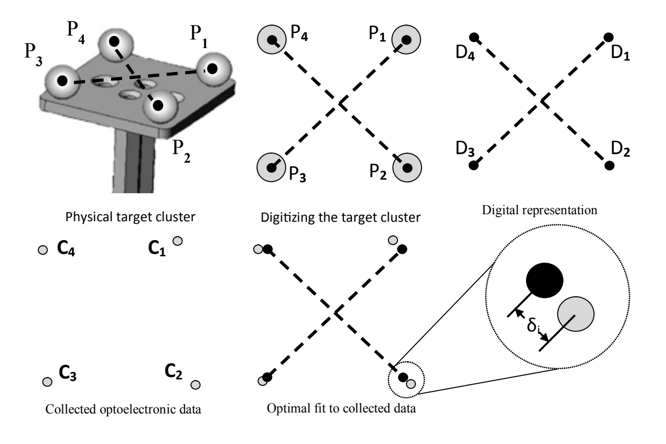

Figure 3: Single target data quality assessment.

$$\Delta_{Diag_t}(t) = \overline{A_1A_3}_{Optical}(t) - \overline{A_1A_3}_{Digita\_representation} \quad (1)$$

$$\Delta_{Diag_t}(t) = \overline{A_2A_4}_{Optical}(t) - \overline{A_2A_4}_{Digita\_representation} \quad (2)$$

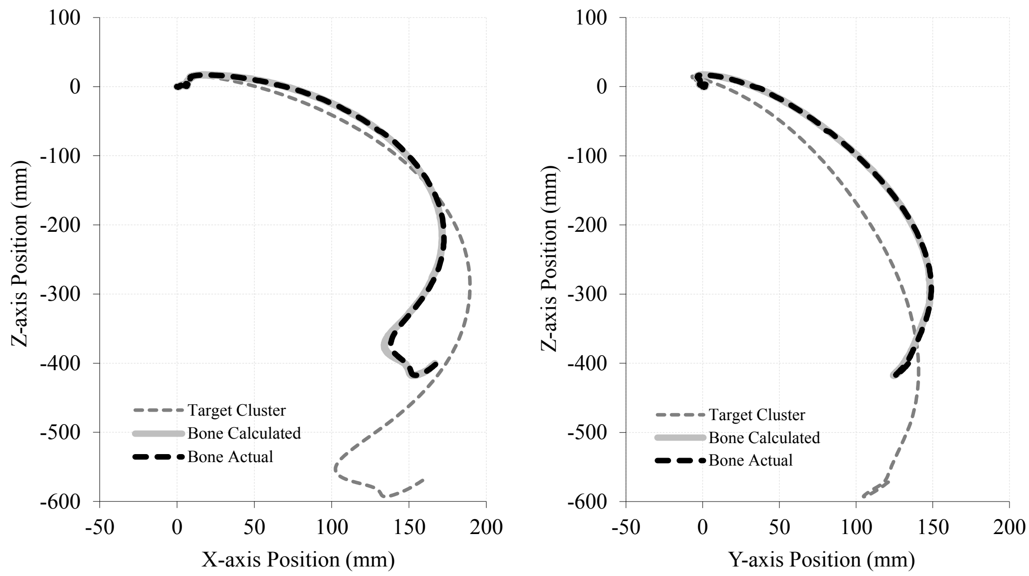

Figure 4: Rigid body motion assessment results. Views of trajectories in both the Z-X and Z-Y planes.

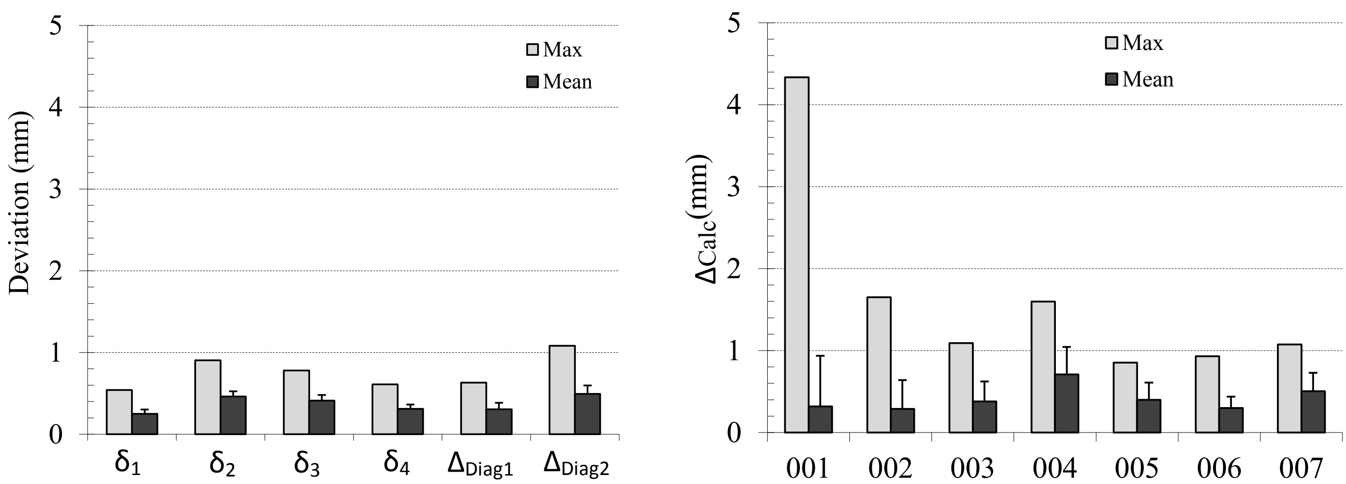

Figure 6: Summary of single target data quality asssessment(left) and ΔTrans from all tests (right).

compared with those of the digital representation (Equations 1 and 2) as an alternate measure of single target error [8,9,15,23,24].

Hardware compliance assessment

In conjunction with the OSS kinematic measurement methodology, a range of specialized hardware configurations are utilized for PMHS tests to support the retro reflective target clusters [3]. Of these hardware configurations, the greatest potential for compliance exists at the anterior ribcage measurement locations which require hardware that is strapped to the rib rather than screwed to prevent stress concentrations that could lead to fracture. Thus, the anterior ribcage hardware was considered a worst case and was selected to serve as the tested hardware in the presented tests 002 - 007.

Test fixture and setup

A test fixture was constructed to rigidly support the simulated bone segment. The target cluster was attached to the bone using a representative range of hardware configurations commonly employed to optically measure anterior ribcage displacement in whole-body PMHS tests (Figure 1). Specifically, two hardware configurations were used. The “standard” configuration (Figure 3) and a geometrically similar but slightly more compliant configuration referred to as the “modified” configuration. Each configuration was rigidly attached to the rib using the same securement straps used to attach the hardware to the rib in PMHS tests.

Test condition

The test conditions selected for the assessment tests were based on the two most likely modes of hardware compliance which were considered to be 1) rotation around the rib and 2) bending due to inertial loading during the impact event. The rotational and bending compliance assessment tests are illustrated in Figure 3. For the rotational tests the hardware was driven through an angle of approximately 100 degrees using a manually tensioned nylon cable connected just beneath the target cluster, however only the initial 20 degrees of rotation were selected for analysis based on maximum rotation estimates from the PMHS tests. For the bending compliance tests, the simulated inertial load, FApplied, was nominally either 22.5 N or 43 N for a given test. The selected values for FApplied are based on estimates of inertial loading from conducted PMHS sled tests. 22.5 N was selected using the product of the maximum resultant sternal acceleration and the maximum hardware mass (56.5 grams), and is considered a reasonable worst case. 43 N was selected for duplicate tests to evaluate the effect of doubling the initial worst case estimate. A detailed summary of all conducted tests and conditions is provided in Table 1.

Data processing and compliance error assessment

For each test, cluster data was collected by the OSS. During post-processing each frame of collected cluster data was transformed to the bone center to determine its position, referred to as the "calculated" bone center. The calculated position was then compared to the measured bone center position, referred to as the "actual" bone center. At the start of each test the calculated and measured positions were coincident; however, the induced rotation or deformation of the hardware caused the calculated bone center position to deviate from the actual bone center position. This deviation, ΔCalc, between calculated and actual bone center positions was taken as the magnitude of the measurement uncertainty due to hardware compliance.

Results

Seven assessment tests were successfully conducted using a range of kinematic measurement hardware configurations and test conditions. Results of the rigid body transformation assessment (Test 001) are illustrated in Figure 4 providing comparison of trajectories of the target cluster, calculated bone center, and actual bone center. The OSS single target data quality assessment (also from Test 001) resulted in deviations, δi, that ranged from 0.2 mm to 0.5 mm on average for targets 1 - 4 over the duration of the test event. In addition, mean values for the diagonal distance deviation, ΔDiag, ranged from 0.3 mm to 0.5 mm with peak values ranging from 0.6 mm to 1.1 mm. A summary of results for single target position data quality is provided below in Figure 4.

Rotational compliance tests (Test 002 and 005) resulted in peak deviations of the calculated bone center, ΔCalc, of 1.7 mm and 0.9 mm for the standard and modified hardware configurations respectively. Bending compliance tests with the standard hardware (Test 003 and 004) resulted in peak ΔCalc values of 1.1 mm and 1.6 mm for the 22 N and 44.5 N tests respectively. Bending compliance tests with the modified hardware (Test 006 and 007) resulted in peak ΔCalc values of 0.9 mm and 1.1 mm for the 22 N and 44.5 N tests respectively. A summary of the ΔCalc results for all tests is provided below in Figure 4.

Discussion

Applications for detailed kinematic response data range from the development of advanced restraint systems to improving existing crash test dummies. Kinematic response also plays a foundational role in the development of improved computational models which are powerful tools for developing optimal countermeasures for human protection; however, the efficacy of such tools is highly dependent on how well they emulate the human response that they are intended to represent. Thus, it is not only imperative to accurately characterize human kinematic response and but also to validate the sensors and methodologies with which such responses are measured.

This study provides necessary assessment and validation of an innovative methodology for measuring anatomical kinematics during impact loading. The results of the tests presented here demonstrate the fundamental effectiveness of the rigid body transformation to predict the trajectories of anatomical structures within the body during impact loading which are not directly visible or accessible for measurement. Additionally, the test results provide the quantified uncertainty magnitudes associated with the three major contributors for the overall uncertainty occurring in anatomical kinematic results for the impact loading environment. These contributors are: 1) single target position error; 2) propagation of the single target position error to the anatomical frame through coordinate transformation; and 3) compliance in the assumed rigid connection between the visible target cluster and the underlying bone.

Effectiveness of the rigid body transformation

Since the anatomical structures most useful for kinematic measurement are within the body, and are not visible for measurement, the motion of the attached cluster must be transformed to the underlying anatomical structure to provide the desired trajectory. The accuracy of the resulting trajectory will depend on the quality of the collected cluster data, the distance between the cluster and underlying bony structure, and also the distance between individual targets on the cluster [23]. The feasibility of the presented methodology is decided by whether or not adequate performance can be achieved using cluster dimensions limited by spatial constraints for placement on the body during tests involving impacts. Using cluster and hardware dimensions representative of those used in actual PMHS sled tests [3] the results of Test 001 illustrates the fundamental ability of the rigid body transformation to successfully predict the actual (directly measured) anatomical trajectory. Figure 4 indicates good qualitative correlation in which the calculated and actual bone trajectories are nearly coincident.

Quantitative assessment reveals that the peak value of deviation, ΔCalc, between trajectories was 4.3 mm. While this value is small relative to the peak resultant displacement of the trajectory, it clearly demonstrates the tendency of the transformation process to amplify the modest single target position error, which was < 0.5 mm on average across parameters δi and ΔDiag. Such amplification of OSS error is an unavoidable consequence of coordinate transformation. While the results of the evaluation test generally indicate excellent performance of the rigid body transformation, the demonstrated sensitivity to even low levels of intrinsic OSS error highlights the necessity of ensuring that the highest OSS single target data quality be obtained.

Single target data quality

The results of the single target data quality assessment (Test 001) demonstrate robust performance of the OSS to track the position of individual targets throughout the duration of a high-rate dynamic event. This is indicated by the average values of δi and ΔDiag which were limited to a range from 0.2 mm to 0.5 mm (Figure 4). While peak deviations were as great as 1.1 mm, the S.D. of 0.1 mm indicates the majority of the deviation distribution is substantially < 1.0 mm. This finding of limited single target position error is substantiated by the fact that independent parameters (δi and ΔDiag) to quantifying this error yielded similar results (Figure 4). The low values of δi indicate only minimal adjustments are required to optimally fit the digital representation to the collected single target position data at each time step [20-23]. This is substantiated by the correspondingly low ΔDiag values indicating minimal optical distortion of the cluster during the dynamic event. A number of studies in the literature have been devoted to quantifying performance of commercially available OSS [8-14]. While single target error for the current study is at the low end of the reported range in the literature, it should be noted that current OSS technology is utilized for the current study. Furthermore, the cluster was tracked under qualitatively "good" conditions for which all targets were visible to more than two cameras at all times during the dynamic event. This finding of such modest distortion magnitude under dynamic conditions, however, is particularly important to the application of the presented methodology. The reason being that single target position error associated with the OSS is unavoidably propagated (and likely amplified) to the anatomical location through the process of coordinate transformation.

Hardware compliance

At a given anatomical location the visible target cluster is supported by stiff, light-weight hardware that is securely attached to the underlying bone. This supporting hardware experiences inertial loading during the test which causes bending and/or movement of the hardware relative to the bone. This compliance is not accounted for in the rigid-body-motion analysis which assumes the connection between the cluster and bone to be completely rigid, however, some hardware compliance does inevitably exist. The results of Tests 002 - 007 quantify the effects of such compliance on the accuracy of anatomical kinematic results for a range of hardware configurations typical of those currently used in PMHS sled tests. Figure 4 (Tests 002-007) provides a summary of the deviations, ΔCalc , resulting from compliance in the connection between the cluster and the underlying bone during the compliance assessment tests. For these tests (Tests 002-007) peak values for ΔCalc ranged from 0.9 mm to 1.7 mm. The conducted tests explored the effects of the most extreme conditions of inertial loading and movement of the hardware relative to the bone which were believed to be achievable during actual PMHS impact tests. Thus, based on these results, a reasonable upper limit for ΔCalc , attributable exclusively to hardware compliance, is 2 mm.

Interpretation relative to anatomical kinematics

The results of these seven reported tests provide a practical assessment of the magnitude of uncertainty associated with anatomical kinematic results obtained using the presented methodology. The overall uncertainty, specific to the utilized hardware, depends on a combination of the factors explored in these seven reported tests. Based on the results, the most conservative estimate is to combine the observed peak values of ΔCalc occurring from both transformational and hardware compliance effects, or 4.3 mm + 2.0 mm = 6.3 mm. While the quantified level of anatomical uncertainty is substantially greater than that associated directly with the OSS, it is not unreasonable for most kinematic measurement applications where it is necessary to measure the motion of the anatomical structure, such as for impact loading. Given that the presented methodology provides the ability to track the motion of the actual anatomical structures, the anatomical uncertainty quantified here is likely small in comparison to conventional methods that only approximate anatomical motion using an external representation for which just skin artifact alone can be substantially greater even for non-impact conditions [25].

It should be emphasized that the results provide a valuable practical assessment for the general magnitude of uncertainty in anatomical kinematic results. To be specific, however, requires an independent investigation for each anatomical measurement location taking into account the specific hardware geometry and OSS performance considerations [4]. Thus, providing a single uncertainty value applicable to wide range of PMHS test conditions is not possible. The presented tests were, however, designed to represent the most challenging conditions encountered during impact loading with good cluster visibility. Thus, the obtained results do provide a reasonable upper uncertainty bound for anatomical kinematics in the global reference frame when good cluster visibility is achievable. The results soundly demonstrate the feasibility of the presented methodology for measuring anatomical kinematics during impacts. While no such method is free of error, the determined resultant uncertainty upper bound of +/- 6.3mm is substantially less than typical variations in subject impact response [1,3]. Thus, the presented methodology has sufficient resolution to characterize the response it is intended to measure and represents a valuable tool for the injury biomechanics researchers.

Conclusion

This study presents a necessary validation of an innovative methodology for measuring anatomical kinematics during impact loading. Specifically, the results confirm the fundamental ability of rigid-body transformation to use remotely measured target data, external to the body, to determine motions of underlying structures within the body. In addition to validating the fundamental methodology, the study comprehensively quantifies the magnitude of overall uncertainty in the final kinematic results, by accounting for the individual uncertainty contributions associated with the OSS, rigid-body transformation, and compliance of the hardware attaching visible target clusters to the underlying bone.

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