Assessing the Accuracy of Biplanar High-Speed X-Ray to Capture Subsurface Implant and Bone Kinematics During a Sideways Fall Impact

Emily K. Bliven, Alexander Baker, Anita Fung, Benedikt Helgason, Pierre Guy, Peter A. Cripton

I. INTRODUCTION

The kinematics of skeletal and other medical structures in post-mortem human subject (PMHS) tests is an essential aspect of understanding and quantifying injury due to impact. This is especially relevant for assessment of non-biologic devices, such as orthopaedic implants, as populations of humans with implanted hardware are increasing worldwide. There is a paucity of data exploring the biomechanics of traumatic injury in humans with implanted hardware, particularly at the high collection rates needed to capture phenomena during impact. High-speed x-ray has been used for capturing skeletal phenomena, such as impact of the mandible [1] or distal radius fracture in a fall [2], in past biomechanics work using PMHS. The presented study applies this tool to a simulated sideways fall, a scenario most likely to cause the common and deadly injury of hip fracture [3]. Beyond the kinematic data offered by this experimental method, it also presents a potential validation data set for finite element models (FEMs). The objective of this work is to evaluate the accuracy of experimental high-speed x-ray data in capturing subsurface implant kinematics in a PMHS sideways fall test, and to assess the potential for its use as a validation source for a corresponding FEM.

II. METHODS

Experimental Testing

An uninjured, fresh-frozen PMHS pelvis-femora construct (female, age 76, osteoporotic bone density) was augmented with an orthopaedic fracture fixation system on the side experiencing the impact to strengthen the femur in a fall. Fiducial markers (stainless steel, Ø=3 mm) were affixed to the femur and pelvis with cyanoacrylate and the PMHS was cast in a subject-specific mould of soft tissue surrogate. The PMHS was subjected to an inertial sideways fall impact from standing height onto a force plate using a previously developed inverted pendulum simulator [4]. The impact was captured with a custom biplanar x-ray system that was equipped with two each of x-ray sources, image intensifiers and high-speed cameras (Fig. 1A and 1B). The PMHS construct and four beads on a calibration cage were digitised with an optical tracking probe prior to the fall test. A threshold for desired tracking accuracy was set to be 1/10 of the diameter of the tracked markers (target value = 0.3 mm).

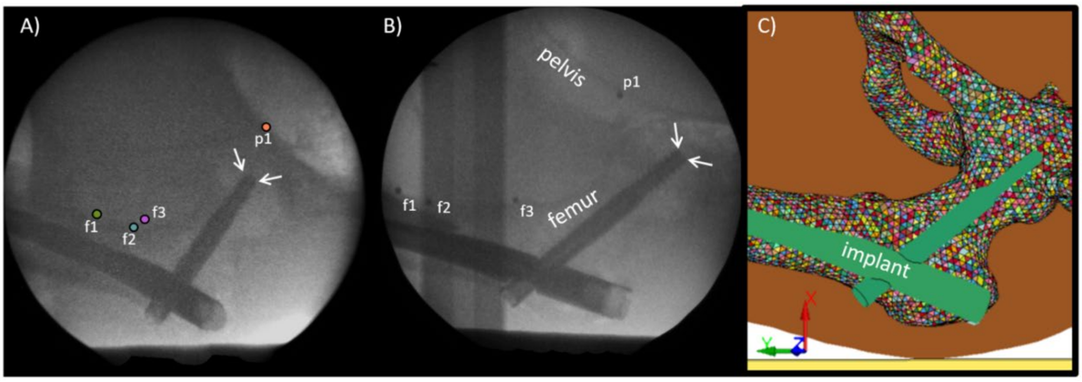

Fig. 1. X-ray views from cameras A) one and B) two, with femur and pelvis markers labelled, and arrows showing the two selected corners of the implant. C) View of FEM and coordinate system axes. All frames are at 0 ms.

Computational Modelling

A corresponding model of the PMHS was constructed and material mapped from CT scan data, as in previously described methods (Fig. 1C) [5]. The explicit, non-linear FEM was run in LS-DYNA with initial and boundary conditions to match those of the experiment. FEM nodes closest to the position of each marker at time = 0 were traced using a postprocessor at 0.2 ms intervals for the purpose of collecting comparative kinematic data.

Data Processing

Single x-ray frames of an undistortion grid and calibration cage were captured for undistortion and experimental space calibration. The exposure factors of the system were set to 150 mA, 4 kV and camera settings to 80 µs exposure and capture rate of 8,500 fps. Fiducial marker positions and lag screw corner features were tracked over the first 30 ms of the impact and exported in 3D using XMALab software [6]. The x-ray kinematic data were transformed to the same coordinate system as the fall simulator (and corresponding FEM) using direct linear transforms, and then filtered with a Savitzky-Golay filter with a window length of 9 and degree 2 polynomial. To investigate the ability to measure femur-implant motion, the distance between the lag screw corners and the centroid of the triangle made by femur markers 1–3 was calculated at time = 0 and at the instance of peak force.

III. INITIAL FINDINGS

The four fiducial markers were tracked throughout the impact with a resolution of 0.213 mm/pixel and average reprojection error values of < 0.15 mm, as calculated in XMALab (Table I). No reprojection errors were calculated for the implant corners, as they were tracked by manual selection. Transformation of the x-ray data using the digitised calibration cage was associated with a root mean square error of 5.26.

TABLE I

AVERAGE REPROJECTION ERRORS IN MARKER TRACKING (MM)

Femur 1	Femur 2	Femur 3	Pelvis
.142 ± .101	.135 ± .097	.095 ± .072	.084 ± .069

The FEM nodes' paths were visually similar to those of the fiducial markers measured with the x-ray, but exhibited consistent variations in the latter part of the impact. This can be observed in the lower parts of the curves in Fig. 2B, where the FEM data show a small 'rebound' of the femur after initial impact, in contrast to the curves taken from the x-ray data. Between time = 0 and time of experimental peak force (4,010 N at 10 ms) the FEM and experiment showed similarly small increases in femur-implant distance values of .19 and .29 mm, respectively. These changes are 0.2% (FEM) and 0.3% (experiment) larger than the initial distance values.

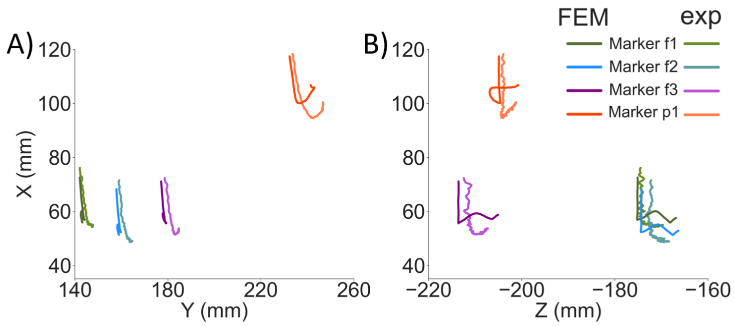

Fig. 2. Experimental marker and FEM node positions tracked over 30 ms in A) X-Y and B) X-Z planes.

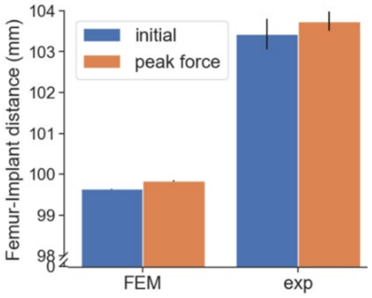

Fig. 3. Average distances from femur marker centroid to screw corners.

IV. DISCUSSION

These preliminary n=1 data demonstrate the ability to track bone-affixed markers with reprojection errors below our target accuracy value and at capture rates sufficient for a fall impact. Furthermore, the changes in femur-implant distance were well-aligned between the experiment and FEM, an encouraging sign for how the screw thread-to-bone contacts are defined in the FEM (fully bonded). These results suggest that this experimental data may be an acceptable source for future FEM validation; however, approaches for reducing the transformation error are recommended. These include digitising more beads on the x-ray calibration cage, higher density markers (i.e. tantalum), and affixing markers to the implant. Limitations include the use of corner features as a surrogate for implant motion, and the inability to place markers closer to the femoral neck or head.

The presented method and preliminary results offer the ability to expand on our understanding of bone and implant biomechanics during a traumatic impact, as well as towards improving prediction models like FEMs. Obtaining such data is essential to reducing injury due to impact and improving relevant interventions.

V. REFERENCES

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