Non-Linear Response of a Post-Mortem Human Subject Pelvis During a Sideways Fall Impact: A Biomechanical Case Study

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I. INTRODUCTION

Hip fracture, in the geriatric context, is prevalent and often leads to catastrophic levels of disability. One approach towards mitigating hip fracture risk is prophylactic strengthening of the vulnerable femur with an orthopaedic augmentation. The efficacy of such augmentations has been investigated in biomechanics studies that simulate a sideways fall from standing, which is how most hip fractures occur [1]. However, these studies lack sufficient representation of the pelvis, a critical medial boundary condition for the femur during sideways falls. Understanding the breadth of pelvis biomechanics in this loading mode is one key to designing effective augmentation approaches. The objective of this work is to describe one complex case of cadaveric pelvis failure and deformation captured in an augmented specimen during a simulated sideways fall impact and to explore the potential implications for future approaches for preventing these catastrophic injuries.

II. METHODS

The donated post-mortem human subject (PMHS) in this case study was a 63-year-old female with bone density classified as osteoporotic (t-score -3.3). A femur-pelvis construct was cast in a mould of ballistic gel shaped to represent their soft tissue. The femur that was impacted was augmented with a commercially available intramedullary nailing system by an orthopaedic trauma surgeon (PG). The PMHS was subjected to an inertia-driven sideways fall impact using a previously developed inverted pendulum simulator (Fig. 1) [2]. Force-time data, pelvic marker deformations and x-ray video of the impact were collected. Pelvis marker deformations were quantified using high-speed videography analysis of markers placed along the pelvis brim on the impacting side (Fig. 2, collected at 5,000 fps). The biplanar x-ray system included two each of x-ray sources, image intensifiers, and high-speed cameras with capture rates of 8,500 fps.

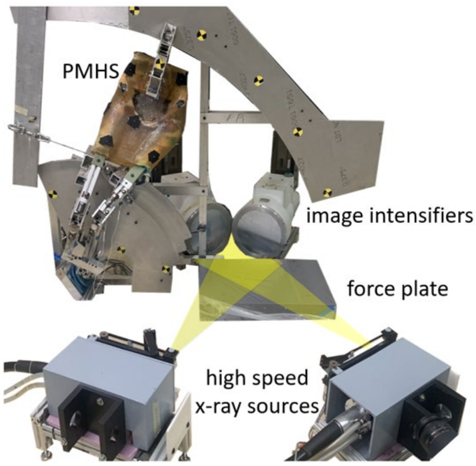

Fig. 1. Experimental sideways fall simulator with high-speed x-ray system components.

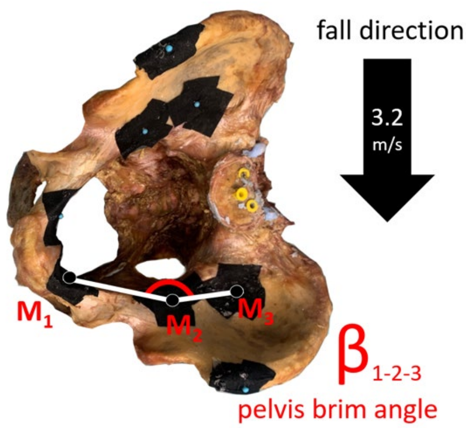

Fig. 2. Schematic showing markers 1–3 used to calculate the pelvis brim angle (β).

III. RESULTS

Post-fall examination of the PMHS revealed damage to the pelvis at the superior pubic ramus on the impacting side (Fig. 3A), and no evidence of hip fracture or damage to the femurs. Analysis of pelvic marker deformation at the impacting pelvic brim and pubic symphysis showed large deformations and bending of the superior pubic ramus initiating shortly after the peak surface impact force of 3.58 kN (8.3 mm and 37˚, respectively, Fig. 3B). These changes were documented to have occurred in a timeframe of less than 10 ms.

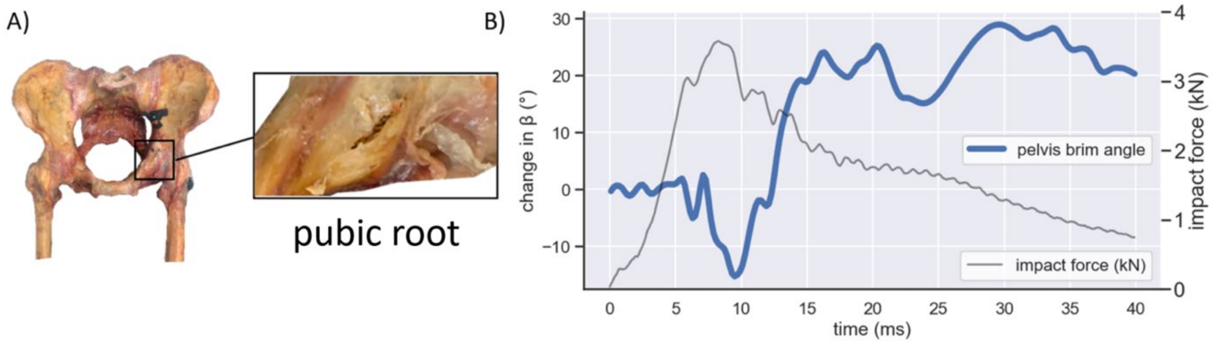

Fig. 3 A) Fracture outcome on PMHS pelvis. B) Plot of surface impact force and change in β over time.

Observation of the x-ray video confirmed these deformations (Fig. 4), displaying an S-shaped deformation pattern propagating along the superior pubic ramus on the impacting side throughout the fall event, particularly visible between 16 ms and 30 ms timepoints. The ramus returned to the undeformed 0 ms configuration past 40 ms data, as shown in Fig. 3B. Later analysis of post-fall CT scans suggested the potential for further pelvis damage not previously visible, interpreted as discontinuities in voxels, which was indicative of cortical bone damage. No deformations of the augmented femur were visible in the x-ray video of the impact.

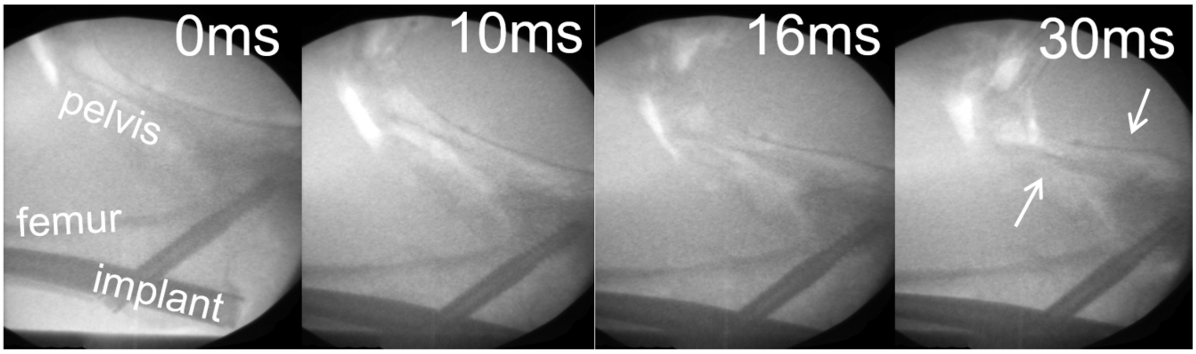

Fig. 4. X-ray video frames showing pelvis deformations on the impacting side over 30 ms of the impact. No pelvis deformations are visible at 0 ms, and arrows indicate the discussed deformations at 30 ms.

IV. DISCUSSION

The significant deformations and bending observed in this pelvis are consistent with dynamic buckling corresponding with decreases in impact force. This mechanism as a force response has been previously documented in other parts of the human body, such as the cervical spine [3], although this structure is multi-articulated to a greater extent than the pelvis. These findings expand on other work characterising the non-linearity of the pelvis under lower forces [4], highlighting the ability of the pelvis to exhibit non-linearity at higher loads. This is further enhanced by offering the real-time visualisation of this phenomenon as it occurs within a biofidelic soft tissue surrogate.

Classifying pelvis response and fracture potential is imperative when investigating prophylactic femoral augmentations. Pelvic fracture is preferred to femur fracture as a clinical outcome in falls because it is associated with far less operative morbidity and possibly mortality; often, patients do not require surgery and can mobilise fully and immediately once pain is controlled. However, to optimise femoral augmentation systems, any increased likelihood of pelvic fracture associated with augmenting the femur must be assessed. This case study demonstrates the high tolerance of the pelvis to significant deformation at high rates, with the ability to sustain only a nondisplaced and relatively small fracture. The strength of the conclusions in this study are limited by the sample size of n=1. Although the created fracture mirrors fracture patterns seen clinically in a low energy pelvis fracture in frail individuals, the clinical prevalence of pelvis fractures in augmented femurs has not been widely documented. Understanding the biomechanics of such injurious events is essential to advance effective treatment and prevention strategies.

V. REFERENCES

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