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Short communication

Understanding how pre-impact posture can affect injury outcome in side impact sled tests using a new tool for visualization of cadaver kinematics

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ABSTRACT

The effect of posture and subject-specific factors on injury outcome is an active field of research in injury biomechanics, in particular in automotive safety research where post-mortem human subjects (PMHS) are used as surrogates. Current PMHS tests routinely include acquisition of the subjects' geometry and kinematics. However, combining these two datasets to better understand the injury mechanism is still a challenge. This study investigated the connection between pre-impact posture and resulting injuries in six previously published side impact sled tests (three with a rigid wall and three with an airbag) by creating three-dimensional kinematic animations (3DKA) of the tests. The 3DKA allow qualitative assessment of parameters related to posture and their possible effect on injury outcome. The orientation of the struck scapula and the lateral leaning of the torso were identified as potentially significant parameters. The ranges of variation in these parameters were quantified and compared to the number of rib fractures for each subject: the data suggested a correlation, but there was insufficient data for a probabilistic analysis. The 3DKA were published with this study and are freely available.

1. Introduction

The development of effective countermeasures for side impact depends on a detailed understanding of the response of the human body. The role of the scapula in side impact is of particular interest (Melvin et al., 1998) but it is not yet fully understood.

Recent studies using sled and pendulum tests with post-mortem human subjects (PMHS) have focused on specific factors contributing to PMHS biomechanical response and especially injury outcome: for example, subject size and shape (Yoganandan et al., 2011; Miller et al., 2013), impact location and velocity (Subit et al., 2010), and arm position (Kemper et al., 2008). However, variation in pre-impact posture—such as spine curvature and shoulder position—has not been thoroughly examined. In fact, subject posture is generally assumed to be invariable; computational studies replicating PMHS tests typically consider the subject to be in the target or nominal posture at the time of impact (Park et al., 2013; Pipkorn et al., 2014). This is partly due to a lack of data describing subject position, with the result that the contribution of pre-impact posture to subject response is unknown.

Two recent studies have reported the whole-body response of PMHS to side impact with a rigid wall (Lessley et al., 2010) and with an airbag (Shaw et al., 2014), including the six-degree-of-freedom kinematics of skeletal structures in the PMHS. Injury outcomes varied substantially in these tests, ranging from no injury in two rigid-wall tests and one airbag test (no rib fractures) to moderate injury in one airbag test (2 rib fractures) to serious injury in one rigid-wall test and one airbag test (16 and 9 rib fractures respectively) (Table 1). Examination of intrinsic variation among subjects (e.g. anthropometry and rib fracture tolerance) did not reveal any definite correlation between these factors and the injury outcome, and extrinsic factors, such as pre-impact posture, were not investigated (Lessley et al., 2010, Shaw et al., 2014).

Pre-impact posture, here defined as the relative positions and orientations of anatomical structures immediately prior to impact (time $t=0$), will influence subsequent kinematics and therefore injury mechanisms; however, the extent to which it does so, or even what parameters may be important, are unknown. In this study, we created three-dimensional kinematic animations (3DKA) of the tests by Lessley et al. (2010) and Shaw et al. (2014) by combining subject-specific bone geometry with six-degree-of-freedom bone kinematics recorded during the tests. By neglecting intrinsic variations among PMHS (e.g. anthropometry and material properties) and examining solely kinematics, we hypothesized that we can identify quantitative parameters in pre-impact posture directly connected to the injury

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outcome and qualitative connections between bone motion and subsequent rib fracture patterns.

2. Methods

2.1. Experimental setup—Lessley et al. (2010) and Shaw et al. (2014)

Lessley et al. (2010) and Shaw et al. (2014) described the experiments in detail. Six 50th-percentile male PMHS were tested; three in each impact condition (Table 1). For each test, the subject was positioned in a rigid seat according to the occupant posture specified by the University of Michigan Transportation Research Institute (UMTRI) (Schneider et al., 1983), and a tether system maintained this position until immediately prior to impact. A rigid wall installed on a 1700-kg rail-mounted sled struck the subject on the right side at 4.3 m/s. Shaw et al. (2014) included a large side airbag which deployed fully before impact (Fig. 1).

Table 1
Test matrix with PMHS characteristics and number of resulting rib fractures.

Test condition	Subject ID	UVA test ID	Stature (cm)	Mass (kg)	Number of rib fractures
Rigid wall	S1	1413	166	59.9	16
	S2	1414	182	63.1	0
	S3	1415	182	68.9	0
Rigid wall with airbag	S4	1569	168	93.4	0
	S5	1570	175	98.0	2
	S6	1571	165	67.6	9

2.2. Kinematic measurement

An optoelectronic stereophotogrammetric system tracked the impacting wall and clusters of reflective markers rigidly attached to the skull, pelvis, bilateral scapulae, and the T1, T6, T11, and L3 vertebrae (Fig. 1). Transformation matrices relating the marker clusters to the underlying bones were calculated from hardware schematics, digital scans of the cluster assembly, and computed tomography (CT) scans of the instrumented PMHS. The motion of the underlying bones was calculated from the motion of the marker clusters using the transformation matrices (Lessley et al., 2010; Shaw et al., 2014).

2.3. Three-dimensional kinematic animation development

Three-dimensional kinematic animations (3DKA) of the tests were developed using OpenSim, an open-source musculoskeletal simulation software platform (Delp et al., 2007). For each bone, a six-degree-of-freedom (6DOF) rigid body was defined, the motions of the bone were prescribed from the measured test kinematics, and a reconstruction of the bone geometry was superimposed on the rigid body. The 6DOF rigid bodies were combined in an OpenSim model file, which

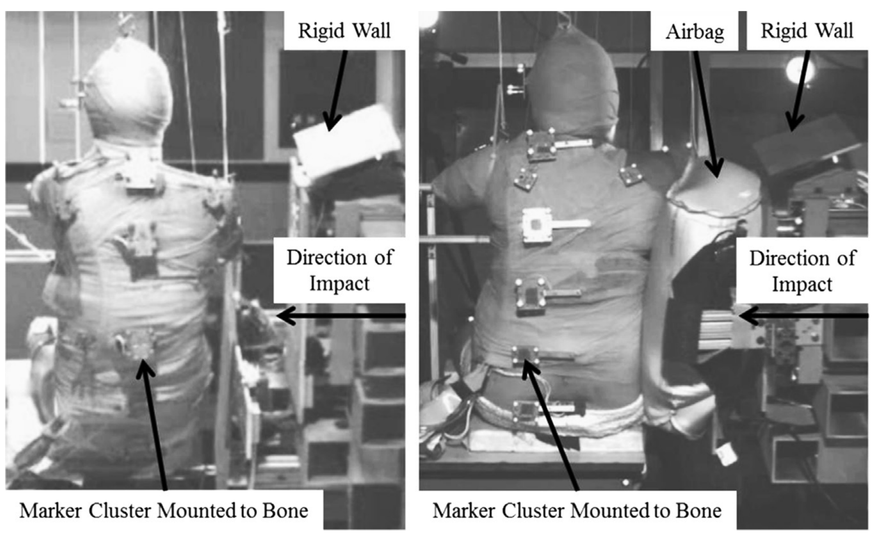

Fig. 1. (Left) Rear view of side impact sled tests with a rigid wall (Lessley et al., 2010). (Right) Rear view of side impact sled tests with a rigid wall and an airbag (Shaw et al., 2014). Each test series included three PMHS.

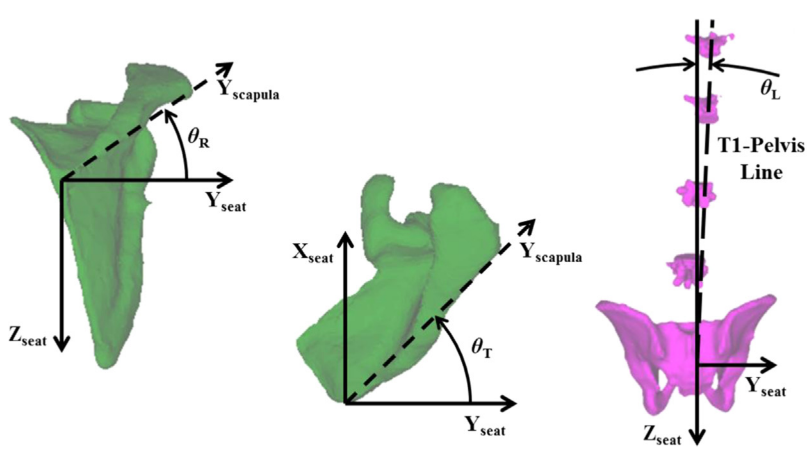

Fig. 2. Definition of pre-impact scapula and spine orientation angles. (Left) Rear view of scapula in seat (global) reference frame with rotation angle θ_R. (Center) Top view of scapula in seat reference frame with traction angle θ_T. (Right) Rear view of spine with pelvis in seat reference frame with lateral lean angle θ_L; the black dashed line passes through the local origins of the pelvis and the T1 vertebra.