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Evaluation of a laboratory model of human head impact biomechanics

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ABSTRACT

This work describes methodology for evaluating laboratory models of head impact biomechanics. Using this methodology, we investigated: how closely does twin-wire drop testing model head rotation in American football impacts? Head rotation is believed to cause mild traumatic brain injury (mTBI) but helmet safety standards only model head translations believed to cause severe TBI. It is unknown whether laboratory head impact models in safety standards, like twin-wire drop testing, reproduce six degree-of-freedom (6DOF) head impact biomechanics that may cause mTBI. We compared 6DOF measurements of 421 American football head impacts to twin-wire drop tests at impact sites and velocities weighted to represent typical field exposure. The highest rotational velocities produced by drop testing were the 74th percentile of non-injury field impacts. For a given translational acceleration level, drop testing underestimated field rotational acceleration by 46% and rotational velocity by 72%. Primary rotational acceleration frequencies were much larger in drop tests (∼100 Hz) than field impacts (∼10 Hz). Drop testing was physically unable to produce acceleration directions common in field impacts. Initial conditions of a single field impact were highly resolved in stereo high-speed video and reconstructed in a drop test. Reconstruction results reflected aggregate trends of lower amplitude rotational velocity and higher frequency rotational acceleration in drop testing, apparently due to twin-wire constraints and the absence of a neck. These results suggest twin-wire drop testing is limited in modeling head rotation during impact, and motivate continued evaluation of head impact models to ensure helmets are tested under conditions that may cause mTBI.

Introduction

Of the 2–4 million sports-related mild traumatic brain injuries (mTBI) in the US each year, over half occur in football (Gessel et al., 2007; Langlois et al., 2006; Lincoln et al., 2011). Football helmets are worn to mitigate the risk of injury, but their purpose, function, and efficacy are the source of much debate. Some studies suggest modern helmets may not protect against mTBI better than helmets developed 20–80 years prior (Bartsch et al., 2012; Cantu et al., 2012; Rowson et al., 2013; Viano et al., 2012). This controversy has motivated the question: are helmets effective in conditions that cause mTBI?

Rapid head rotation is thought to cause mTBI by shearing brain tissue and straining axons in tension (Gennarelli et al., 1998; Giordano and Kleiven, 2014; Holbourn, 1943). In primates, translational acceleration induced traumatic coma only when combined with rotational acceleration (Ommaya and Gennarelli, 1974). Animal, physical, analytic, and finite element models found that the severity and direction of head rotation was commensurate with traumatic coma, neurological impairment, tissue strain, and diffuse axonal pathology (Gennarelli et al., 1982; Kleiven, 2006; Margulies et al., 1990; Margulies and Thibault, 1992; Smith et al., 2000). These findings have motivated direct measurement of human head rotation during head impact (Bartsch and Samorezov, 2013; Camarillo et al., 2013; Rowson et al., 2011) and the development of criteria to predict mTBI using rotation measurements (Newman, 1986; Newman et al., 2000b; Ommaya and Hirsch, 1971). In a field study of football mTBI (Hernandez et al., 2014), criteria that used rotation measurements predicted injury better than the translation-only criteria used in safety standards (Gadd, 1966; Versace, 1971).

Despite studies implicating rotation in mTBI, helmet safety testing may not model head rotation in football head impacts. For 40 years, helmet safety standards defined by the National Operating Committee on Standards for Athletic Equipment (NOCSAE)

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(NOCSAE, 2012a,b) have used a drop test that was developed to reproduce severe TBI conditions commensurate with head translational acceleration (Gurdjian et al., 1953, 1966). However, laboratory drop testing has been used to model mTBI risk, as in the STAR rating system (King, 2012; Rowson and Duma, 2011, 2012) and other recent helmet efficacy studies (Forbes et al., 2013; Johnston et al., 2014; Rowson et al., 2013). Although drop testing suitably models the frequency characteristics of translational acceleration in football head impacts (Gwin et al., 2010), drop testing and other laboratory models such as horizontal linear impacting (Camarillo et al., 2013; Hernandez et al., 2013; NOCSAE, 2006; Rowson et al., 2011; Viano et al., 2012) and pendulum testing (Bartsch et al., 2012; Pellman et al., 2003), have not been demonstrated to reproduce human head rotation in football head impacts because no such methodology exists.

Our objective was two-fold: (a) describe methodology for evaluating laboratory head impact models using field measurements, and (b) use this methodology to investigate the degree to which laboratory twin-wire drop tests model human head rotation in American football head impacts. To that end, we compared six degree of freedom (6DOF) measurements of football head impacts to drop tests performed at typical impact sites and velocities. Using stereo high speed video, we compared 6DOF measurements of a single football head impact to a drop test reconstruction.

Materials and methods

Field measurements

We measured 421 American football (video-confirmed) head impacts in 6DOF using instrumented mouthguards (Fig. 1A) (Hernandez et al., 2014). These head impacts were collected from 30 collegiate football players over 15 games and practices of varying intensity (66 total athlete-events). Of these head impacts, two resulted in the diagnosis of mTBI by a sideline clinician: one loss of consciousness (LOC) injury, and one self-reported injury. Human subjects protocols were approved by the Stanford Institutional Review Board (IRB No. 21304). All head impacts were confirmed in video as player head contact with another head, body, or ground. The kinematic accuracy of the instrumented mouthguards was previously characterized in laboratory testing (Camarillo et al., 2013; Hernandez et al., 2014).

To understand aggregate field trends, we reconstructed a single head impact that was measured in high resolution on the drop test. Stereo high speed video of a single in vivo head impact was collected to estimate initial impact conditions (impact location on helmet and relative impact speed) that were used to set up a laboratory reconstruction of the impact. As part of a routine football practice drill, two players lined up approximately 3 m apart and engaged in head-to-head contact following an auditory

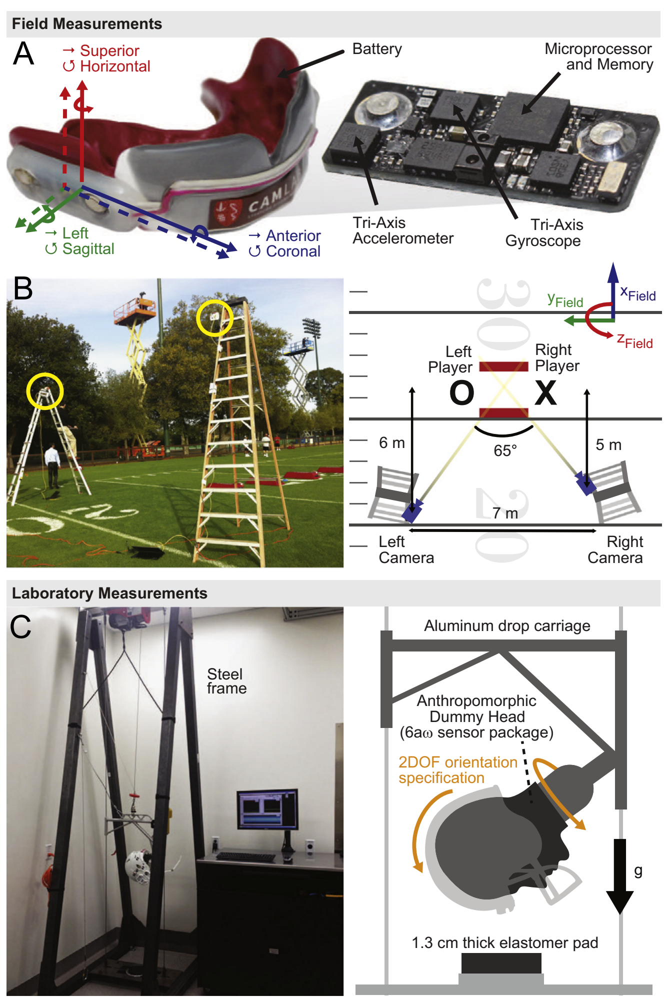

Fig. 1. Field and laboratory data collection. (A) Custom-fit mouthguards measured head impacts in full six degree of freedom (6DOF) using a tri-axis accelerometer and tri-axis gyroscope. (B) stereo high speed video cameras were 7 m apart, 3.5 m elevated above the field, at a 5–6 m down-field distance from the impact, and formed a 65° triangulation angle. (C) Twin-wire drop test and anthropomorphic dummy head.

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