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Evaluation of the head-helmet sliding properties in an impact test

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ABSTRACT

The scalp plays a crucial role in head impact biomechanics, being the first tissue involved in the impact and providing a sliding interface between the impactor and/or helmet and the skull. It is important to understand both the scalp-skull and the scalp-helmet sliding in order to determine the head response due to an impact. However, experimental data on the sliding properties of the scalp is lacking. The aim of this work was to identify the sliding properties of the scalp using cadaver heads, in terms of scalp-skull and scalp-liner (internal liner of the helmet) friction and to compare these values with that of widely used artificial headforms (HIII and magnesium EN960). The effect of the hair, the direction of sliding, the speed of the test and the normal load were considered. The experiments revealed that the sliding behaviour of the scalp under impact loading is characterised by three main phases: (1) the low friction sliding of the scalp over the skull (scalp-skull friction), (2) the tensioning effect of the scalp and (3) the sliding of the liner fabric over the scalp (scalp-liner friction). Results showed that the scalp-skull coefficient of friction (COF) is very low (0.06 ± 0.048), whereas the scalp-liner COF is 0.29 ± 0.07. The scalp-liner COF is statistically different from the value of the HIII-liner (0.75 ± 0.06) and the magnesium EN960-liner (0.16 ± 0.026). These data will lead to the improvement of current headforms for head impact standard tests, ultimately leading to more realistic head impact simulations and the optimization of helmet designs.

1. Introduction

Traumatic Brain Injury (TBI) is the leading cause of death for young adults (under 45 years of age) worldwide (Gennarelli, 1993; Jennett, 1998; Coronado et al., 2015; Taylor, 2017). Helmets are effective in reducing head accelerations and velocities, and can therefore contribute to the reduction of head and brain injuries in sport under some (but not all) conditions (Thompson and Patterson, 1998; Povey et al., 1999; Thompson et al., 1999; Attewell et al., 2001; Keng, 2005; Amoros et al., 2012; Hasler et al., 2015). The majority of helmet standard tests measure the reduction in linear acceleration to assess the quality of a helmet (Connor et al., 2016), despite a number of studies suggesting that the rotational acceleration is a better indicator of brain injury (Holbourn, 1943; Gennarelli et al., 1987; Kleiven, 2007; Forero Rueda et al., 2011; Kleiven, 2013). The brain is hypothesised to be more sensitive to shear forces resulting from rotational and linear acceleration, than to compressive forces due to linear acceleration alone (Adams et al., 1982; Gennarelli et al., 1982). Under these assumptions, researchers are now developing new helmet standard tests which incorporate the effect of rotational accelerations. The National Operating Committee for Standards in Athletic Equipment released a new standard for headgear which consists of a linear impactor test evaluating the rotational accelerations which will become active in 2018 (NOCSAE, 2018). This will ultimately lead to helmet designs which are optimised to protect the head against both linear and rotational accelerations. Head-helmet sliding properties represent one of the parameters to consider when optimizing a helmet against rotational acceleration. Using two popular headforms, EN960 Magnesium headform and Hybrid III dummy headform (HIII), a number of authors have examined the effect of the headform-helmet friction over the years (Aare and Halldin, 2003; Finan et al., 2008; Halldin and Kleiven, 2013). The EN960 Magnesium headform does not have an outer layer to simulate scalp tissue; whereas the Hybrid III dummy headform has a vinyl skin. Some researchers have claimed that a lower

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head-helmet friction reduces the rotational acceleration undergone by the head during the impact and therefore the risk of head injury (Aare and Halldin, 2003; Halldin and Kleiven, 2013; Halldin et al., 2013). On the other hand, other works have claimed that a lower head-helmet friction, in some cases, increases the rotational acceleration undergone by the head, depending on impact location and angle (Finan et al., 2008; Ebrahimi et al., 2015). Despite the different opinions on the effect of a lower head-helmet COF, researchers concluded that the material covering the headform, and its sliding properties, are important in determining the head response in oblique helmet impacts (Ebrahimi et al., 2015).

From this perspective, the knowledge of the sliding properties of the scalp is essential for a better understanding of the impact biomechanics. The scalp is the most external part of the head and is the first tissue involved in a head impact. It is free to slide over the skull and it is anteriorly connected with the orbicularis oculi muscles, laterally connected to the frontal process of the zygoma, to the superior aspect of the zygomatic arch and over the mastoid process superior to the attachments of the sternocleidomastoid and trapezius muscles, and in the back of the head it fuses with the superior nuchal line (Tolhurst et al., 1991). Therefore, there are two primary surface interactions at play during an impact, the scalp-skull friction and the scalp-helmet friction.

In the majority of cases, sliding properties of the skin are determined using the ASTM D3702 (Comaish and Bottoms, 1971; Kondo, 2002) or the ASTM D1894 (Gerhardt et al., 2008) standard test. The ASTM D3702 involves the application of a rotational probe to test a surface using the torque to determine the horizontal friction force. The ASTM D1894, instead, involves the application of a translational motion of the probe on a surface to determine the static and dynamic friction. Different normal loads and speeds can be applied in both cases. In the case of a head impact the helmet slides over the scalp and this sliding motion can be better represented using the ASTM D1894. This standard test allows the application of larger sliding distances and minimize unpredictable effects due to the presence of hair.

A number of studies have focused on the COF of the skin, concluding that skin friction depends on the type and physical properties of the contacting materials, on the body region, on the physiological skin conditions (e.g. hydration state, sebum level) and on mechanical contact parameters (e.g. normal load, sliding velocity) (Zhang and Mak, 1999; Tang et al., 2008; Derler and Gerhardt, 2012); while ethnicity and gender do not affect the COF (Sivamani et al., 2003). Age does not affect the COF (Sivamani et al., 2003); however, late age (80 years in men, post menopause for women) has been shown to affect the sebum level (Pochi et al., 1979), which affects the COF. Researchers have generally performed friction tests under small contact pressure; Fotoh et al. (2008) reports a COF of 0.8 ± 0.5 between a steel sphere and the forehead under a normal force of 0.1 N, while Christensen and Nacht (1983) reports a COF of 0.12–0.22 between a Teflon wheel and the forehead under a normal force of 1.96 N. However, the contact pressure between the helmet and the scalp can reach values up to 0.7 MPa, which represents the plateau value for the expanded polystyrene (EPS) foam of the helmet (Di Landro et al., 2002). At this point, the foam deforms, absorbing a large amount of energy, without increasing the contact pressure on the head.

Currently sliding properties of the scalp are not accurately represented in either artificial headforms or numerical head models. Artificial headforms do not always include a scalp-like material (Magnesium EN960) and if they do, it is a polymeric layer rigidly attached to the headform (HIII, NOCSAE, FOCUS headforms). In numerical head models, scalp tissue is generally modelled as a linear elastic material rigidly connected to the skull (Zhang et al., 2001; Horgan and Gilchrist, 2003; Belingardi et al., 2005; Deck and Willinger, 2008), except for the model developed by Kleiven et al. which represents the scalp with two layers, a hyperelastic and an elastic layer (Kleiven, 2007; Fahlstedt et al., 2015).

The aim of this work is to determine the sliding properties at play between the internal liner of a helmet and cadaver human heads and compare them with the sliding properties of the magnesium EN960 and HIII headforms. The results presented here will lead to the development or modification of headforms for head impact standard tests with the aim of improving helmet design. Additionally, they will be used in finite element simulations to better understand the effect of friction during a head impact.

2. Methods

Friction tests were performed on cadaver human heads, Hybrid III headform (HIII) and magnesium EN960 headform at KU (Katholieke Universiteit) Leuven, Belgium.

2.1. Head preparation

The ethics committee within KU Leuven approved the use of human cadaver heads for testing (Ethical approval n. NH0192017-02-02). Five Caucasian human heads with hair were obtained from the KU Leuven Anatomy Centre (age 73–86); three males and two females. The heads were decapitated between the C4 and C5 vertebra and rinsed with a 0.9% NaCl solution via the vena jugularis and the carotis interna and externa. The blood vessels were emptied using a 55 cc syringe with air. The blood vessels, the carotis and the jugularis were sealed with ethibond 2/0 to avoid extensive loss of body fluids. No fixation was used. The heads were subsequently packaged in an airtight bag and frozen at −18 °C. Five days prior to testing, the heads were brought to 2 °C to allow slow defrosting and to preserve the quality. On the day of the experiment, the eyes and mouth were sealed with ethibond 2.0; the nose was not sealed to allow internal pressure release if needed. The heads were transported and stored in the test lab at 4 °C until one hour before the start of the experiments. After performing the experimental tests on the head with hair, each head was shaved and the same experiments were performed on the shaved head at a room temperature of 21 ± 2 °C.

2.2. Set-up description

The customised experimental set-up was developed based on the ASTM D1894 friction test method. The set-up (Fig. 1) consists of a Schenck horizontal fatigue machine (25 kN load cell) coupled with

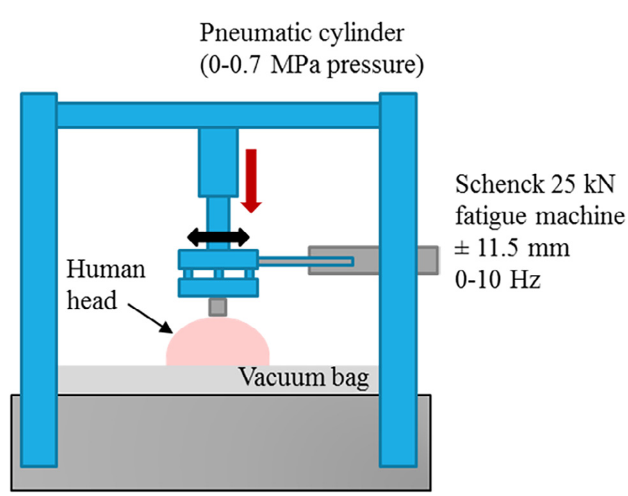

Fig. 1. Experimental set-up for the friction tests.

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