Head kinematics during experimental e-scooter falls

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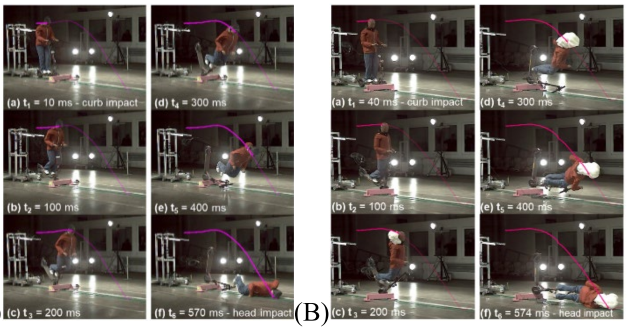
I. INTRODUCTION

Over the last few years, the use of e-scooters has become highly popular in many cities around the world. The rapid growth of e-scooter use is associated with a sharp increase in accidents and hospitalisations: the injury risk for e-scooter users is 112 injured/million kilometres (167 times greater than for cars) [1]. Among those injured, about 20% suffered a head injury [2], which is the leading cause of traumatic death. Recent epidemiological studies have shown that the most frequent accident scenario is a simple fall (79%), caused by a loss of balance, excessive speed or poor road conditions (e.g. tram tracks, potholes) [2]. A few studies have reproduced numerically typical e-scooter falls due to a pothole or a kerb, using a multibody model or a finite element model, providing the first insights into fall kinematics and head impact characteristics [3-5]. However, no experimental e-scooter fall reconstruction has been described and there are very limited data available regarding the head impact conditions and injury mechanisms involved in these accidents. This lack of knowledge makes it difficult to properly evaluate and design current and future protections. The objective of this work, therefore, is to experimentally reproduce two e-scooter accidents to study the kinematics of the head during the fall and the head impact conditions.

II. METHODS

Two configurations of a typical e-scooter fall were reproduced experimentally. The scenario comprised a forward fall induced by the collision of the front wheel with a kerb. A sled test was used to propel a Hybrid III 50th Male Anthropomorphic Test Device (ATD) (1.75 m, 78 kg) standing on an e-scooter. The e-scooter (ESA 1919 EKFV, KSR Group GmbH) was 1.08 m long, 1.14 m high, with 24 cm diameter wheels, and a mass of 13 kg. A structure was designed to guide the ATD and e-scooter up to the point of release (Fig. 1). After the release, the e-scooter and the ATD moved autonomously at a speed of about 22 km/h (6 m/s), which is within the range of e-scooter speed limits in Europe (between 20 km/h and 25 km/h) [6]. The e-scooter then impacted a 140 mm high metallic kerb that was placed at 50 cm from the release point to induce a forward fall. Two impact configurations were tested: (1) with the kerb being placed perpendicular to the e-scooter trajectory and the ATD wearing a beanie (configuration 1); and (2) with the kerb being placed at an angle of 55° to the e-scooter trajectory and the ATD wearing a Hövding 3 airbag (configuration 2). The tests were filmed with a high-speed camera at 1000 fps (Redlake Motion Os7) and head acceleration was recorded using 3 axis accelerometers at a sampling rate of 20 KHz. Head displacement and speed during the fall were measured using the Kinovea software (http://www.kinovea.org) [7] and using a calibration grid, a feature that is built-in in Kinovea, to calibrate the images.



(C)

	Config. 1 90°	Config. 2 55° airbag
Normal impact speed (m/s)	5.5 (±0.4)	5.4 (±0.2)
Tangential impact speed (m/s)	4.6 (±0.7)	5.3 (±0.4)
Head acceleration (g)	581	103
HIC	5282	169

Fig. 1. (A) Fall kinematics of the ATD in configuration 1. (B) Fall kinematics of the ATD in configuration 2. (C) Summary of head impact speed, peak acceleration and HIC.

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III. INITIAL FINDINGS

In configuration 1, contact between the e-scooter's wheel and the perpendicular kerb initiated the tilt forward of the e-scooter and both a forward projection and a sagittal rotation of the ATD (Fig. 1 (A)). The ATD rotated forward, leading to a slight increase of head tangential velocity up to 6.6 (± 0.6) m/s before a decrease to about 4.6 (± 0.7) m/s at impact. It also led to a large increase in normal head velocity up to 5.5 (± 0.4) m/s at 437 ms. The left knee of the ATD first touched the ground 515 ms after the initial contact between the wheel and the kerb followed by the frontal region of the head (at 560 ms). The head acceleration at impact was 581 g and the head injury criteria (HIC_{36}) was 5282, well above the injury assessment reference value (IARV) of 1000 [8]. In configuration 2, the wheel rotated and stopped at the contact with the angled kerb (t_1). The e-scooter then tilted forward with the handlebar turned to the left, which induced the forward projection of the ATD with both forward and sideways rotations (Fig. 1 (B)). The ATD impacted the ground sideways, first on the elbow (t_1 + 481 ms) and then on the temporal part of the head protected by the airbag (t_1 + 534 ms). The tangential and normal head velocities at impact were 5.3 (± 0.4) m/s and 5.4 (± 0.2) m/s, respectively. The Hövding 3 airbag started inflation 200 ms after the e-scooter/kerb impact and finished inflation 90 ms later. It was fully inflated at impact. The head acceleration at impact was 103 g and the head injury criteria (HIC_{36}) was 169, well below the IARV.

IV. DISCUSSION

The normal head impact speed for the two configurations was between 5.4 m/s and 5.5 m/s. This is within the impact speed used in standard tests for bicycle helmets (ASTM F1447) (EN 1078), suggesting that those standards are appropriate to evaluate protections for this crash scenario. However, the impact speed was not only normal to the ground but oblique, with a tangential impact speed component of about 5 m/s. This tangential impact speed is not considered in the current standard evaluation, even though it might induce rotational head acceleration, which is also correlated with head injury risk [9].

In the unprotected configuration, the peak acceleration and HIC of the head were well above every IARV for severe head injuries [8]. This is consistent with the numerous severe head traumas due to e-scooter falls reported in the literature [2]. This study does not allow for a proper evaluation of the effect of the Hövding 3 airbag in reducing the head acceleration, because the head impacts in configurations 1 and 2 were not the same (frontal vs. temporal) due to the distinct fall kinematics induced by the different positions of the kerb. However, the head impact speeds in configurations 1 and 2 were similar (less than 5% difference for normal impact speed). Yet, the peak head acceleration was approximately 6 times slower and the HIC was 31 times lower with the airbag. This suggests that the Hövding 3 airbag can reduce the risk of injury to the head during this type of crash. Further tests would have to be performed to quantify the effect of the airbag on the head acceleration and risk of injury at impact. Additionally, the duration of the fall before head impact was about 550 ms, which is well above the detection and inflation time of most airbags [10]. Indeed, the Hövding 3 airbag tested in this study detected the e-scooter fall and was fully inflated before the head impact.

The main limitation of this study is the small number of crash tests performed: only two crash configurations were reproduced. Those two crash configurations provide the first insight into the head kinematics during a typical e-scooter crash scenario, but they do not allow for a comprehensive evaluation of the effect of the Hövding 3 airbag on head acceleration and risk of injury. Additionally, only the head linear acceleration was recorded, although the head also sustains high rotational head accelerations, as it can be deduced from the oblique kinematics of the head impact. Further work should focus on reproducing similar e-scooter crashes in order to evaluate protective devices (helmet, airbags, etc.) and on other crash scenarios, such as a collision with a vehicle, a scenario that also represents a large number of head injuries [2].

V. REFERENCES

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