Accident Analysis and Prevention 89 (2016) 128–141

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Simulative investigation on head injuries of electric self-balancing scooter riders subject to ground impact

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ARTICLE INFO

Article history:
Received 2 November 2015
Received in revised form 24 January 2016
Accepted 25 January 2016

Keywords:
Self-balancing scooter
Traffic accidents
Ground impact
Brain injuries

ABSTRACT

The safety performance of an electric self-balancing scooter (ESS) has recently become a main concern in preventing its further wide application as a major candidate for green transportation. Scooter riders may suffer severe brain injuries in possible vehicle crash accidents not only from contact with a windshield or bonnet but also from secondary contact with the ground. In this paper, virtual vehicle–ESS crash scenarios combined with finite element (FE) car models and multi-body scooter/human models are set up. Post-impact kinematic gestures of scooter riders under various contact conditions, such as different vehicle impact speeds, ESS moving speeds, impact angles or positions, and different human sizes, are classified and analyzed. Furthermore, head–ground impact processes are reconstructed using validated FE head models, and important parameters of contusion and laceration (e.g., coup or contrecoup pressures and Von Mises stress and the maximum shear stress) are extracted and analyzed to assess the severity of regional contusion from head–ground contact. Results show that the brain injury risk increases with vehicle speeds and ESS moving speeds and may provide fundamental knowledge to popularize the use of a helmet and the vehicle-fitted safety systems, and lay a strong foundation for the reconstruction of ESS-involved accidents. There is scope to improve safety for the use of ESS in public roads according to the analysis and conclusions.

1. Introduction

Electric self-balancing scooters (ESSs), as newly emerging pollution-free transportation tools, are gradually being popularized for short-distance traveling or the last-mile trip after traditional public transportations because of their convenient performance (Blackman and Haworth, 2013). However, the security concerns of the public about ESS are increasing simultaneously because of the many cases of accidents with serious injuries (Keith et al., 2011; Roider et al., 2015). Similar to pedestrians and bicyclists, ESS riders are generally regarded as vulnerable road users (VRUs) because riders may suffer from critical injuries during accidents (Lin and Tsai, 2009; Tsai et al., 2010). According to the World Health Organization statistics, VRUs accounted for approximately 50% of the total fatalities in 2013 (World Health Organization, 2013) worldwide. The latest report also indicates that nearly 270,000 pedestrian deaths on the road occur every year (World Health Organization, 2015). Head injury is one of the research focuses because of its severity and lethality (Yang, 2011b), and it accounts up to 80% of all VRU fatalities in several districts (Edirisinghe et al., 2014; Hui et al., 2014). However, no investigations have been conducted on ESS safety in traffic accidents, although limited studies have focused on self-balancing and yaw control of the ESS (Lin and Tsai, 2009; Tsai et al., 2010). Recently (Xu et al., 2016), pioneered a study on the ESS safety situation in vehicle crash accidents by considering the head–vehicle contact. Compared with pedestrians, ESS riders are more likely to have head contact with higher regions of vehicles and the head–vehicle impact timing in vehicle–ESS crash accidents is tens of milliseconds later than that in vehicle–pedestrian crash accidents under the same impact conditions. This contact time difference may cause different injuries to riders.

Studies on VRU head injuries are mainly focused on pedestrians and cyclists using several methods such as in-depth accident investigation (Otte et al., 2005; Yao et al., 2007; Deck and Willinger,

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http://dx.doi.org/10.1016/j.aap.2016.01.013

2008; Li and Yang, 2010) and numerical accident reconstruction (Xu et al., 2009; Li and Yang, 2010; Peng et al., 2012a; Nie and Yang, 2014; Peng et al., 2014). Research has shown that VRU head injuries are sensitive to various variables, such as vehicle impact speed (Anderson et al., 1997; Yao et al., 2008; Simms and Walsh, 2009; Elliott et al., 2012), vehicle type (Yang, 2003; Ballesteros et al., 2004; Lefler and Gabler, 2004; Han et al., 2012; Kerrigan et al., 2012; Crocetta et al., 2015), VRU moving speed (Crocetta et al., 2015), walking posture (Peng et al., 2012b), and impact location (Maki et al., 2003; Yang et al., 2005; Lin et al., 2007; Yao et al., 2008). The VRU head–vehicle collisions are always on the bonnet, windshield, and A-pillar areas during a crash. Then, human body falls off the car and the head contacts the ground. The coupling effects of head–vehicle contact and head–ground contact cause more difficulty in identifying the head injury mechanism. Preliminary studies have indicated that vehicle speed is the governing factor in the major head injury source (Simms and Wood, 2006; Yang et al., 2007). An effective way to reveal the main cause of the head injury is accident reconstruction based on in-depth vehicle–VRU accidents (Badea-Romero and Lenard, 2013). The finite element method (FEM) is regarded as a useful tool to analyze the injuries caused by head–vehicle contact from the biomechanics perspective (Yao et al., 2008; Peng et al., 2013). In terms of head injury caused by contact with the ground, parameterizations of simulation processes are used to analyze the ground impact effects on head injury (Gupta and Yang, 2013; Gupta, 2014; Crocetta et al., 2015).

Although people have used ESS for short-distance transportation on city roads for quite a long time, relevant laws and regulations are still not published by the traffic management bureau. Consequently, people riding ESS on the roads without helmets or any other protection device may pose a potential safety risk to themselves. This study aims to evaluate the brain injuries of ESS riders during a secondary head collision, i.e., head–ground impact. First, numerical models of the traffic accident scenes are established based on the MADYMO (TASS, 2010) platform. In finite element (FE) reconstruction impact models of head–ground collisions are computed using LS-DAYNA (Hallquist, 1998). The Abbreviated Injury Scale (AIS) is used as the evaluating indicator of brain injury based on injury biomechanics and quantitative degrees of injury (AAAM, 1985). Comprehensive parametric studies involving two representative ESSs and five types of vehicles on head–ground injury are also conducted to fully investigate ESS rider safety.

2. Methods

2.1. Traffic accident scenarios

The proposed research process for ESS rider safety is divided into several steps. Earlier research analyzing the head injuries caused by vehicle contact (Xu et al., 2016) has been conducted. By contrast, we mainly focus on ground contact in the present study. To evaluate the brain injury risks of single-wheel and double-wheel riders during head–ground impacts, MADYMO, the most commonly applied numerical simulation software to study crash safety during accidents in previous literature (Simms and Wood, 2006; Yao et al., 2008; Carter and Neal-Sturgess, 2009; Peng et al., 2012a; Nie and Yang, 2014), is used to model and simulate the entire impact processes of impact accidents. For example, a vehicle driving at a speed of 10 m/s brakes at a sustained rate by the time it hits the ESS rider on its side. The lateral impact is set as the baseline vehicle-ESS crash scenario because of its extremely high frequency and proportion (accounting for over 90%) in vehicle–VRU collisions (McLean et al., 1996; Yao et al., 2008; Yan et al., 2011). The intersection of facing directions between human and vehicle is $\pi/2$ (shown in Fig. 1). The ESS rider hit by a vehicle with braking action falls to the ground earlier than that in cases without braking action. To avoid cases in which the human body flips over the vehicle roof and thus leading to a more complicated situation, cars are designated with a continuous brake with a 0.8 g deceleration, which indicates for the brake response of occupants, and a good friction contact is assumed between road and tire (Heinrichs et al., 2004). In addition, vehicle impact speeds, vehicle–ESS contact angles, vehicle–ESS contact positions, and human sizes are parameterized to investigate the human dynamic mechanisms and brain injuries under different impact conditions with constant deceleration.

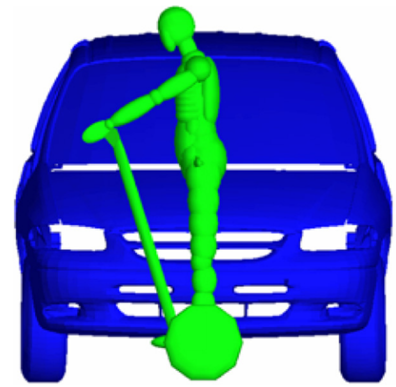

Fig. 1. Description of the baseline vehicle–ESS crash scenario.

To meticulously examine the brain injuries of ESS riders, the processes of head–ground impact are reconstructed and simulated using FEM. This method is commonly accepted in impact safety research (Lei et al., 2009; Yang, 2011a; Han et al., 2012), such as in investigating the head response during head–windshield contact (Yao et al., 2008; Xu et al., 2010, 2011a,b; Peng et al., 2014) and simulating skull dropping tests (Shaoo et al., 2015).

2.2. Human model

The 50th percentile male pedestrian model available in the MADYMO database (Automotive, 2001), which is a widely and the most used dummy model in the field of numerical accident reconstruction and analysis, is chosen as the ESS rider model in the baseline scenario because of its excellent performance in human body kinematics and injury analysis. The 95th percentile male pedestrian model and the 5th percentile female pedestrian model are used to represent ESS riders as the control group. These two human models with different anthropometries are also commonly applied in the VRU safety analysis (Crocetta et al., 2015). Fig. 2 shows the three human models used. More detailed information are presented in Ref. Automotive (2001).

2.3. ESS model

The two most common types of ESS (a single-wheel ESS and a double-wheel ESS) are considered in this study. The numerical model of the single-wheel ESS is modeled by three ellipsoids to depict the external shape. Fig. 3(a) and Table 1 illustrate the rough profiles of the single-wheel model and the stiffness parameters, respectively.

Another typical and widely used ESS is chosen as the representative of the double-wheel model. Six ellipsoids are modeled to describe the outer surface of the ESS body, including a controlling bar component and a couple of wheels. The multi-body model double-wheel ESS and its outside dimensions are presented in Fig. 3(b), with the stiffness setting shown in Table 2.