Evaluating the Reliability of Multibody Models of Micromobility Users: Comparison with ATD Reconstructions and Real-World Accident Footage

Marianne Guesneau, Oscar Cherta-Ballester, Valentin Honoré,
Yvan Petit, Pierre-Jean Arnoux, Nicolas Bailly

I. INTRODUCTION

Over the last two decades, accidents involving bicycles [1] and e-scooters [2] have risen sharply in Europe, highlighting the need for a better understanding of the crash dynamics and impact conditions to enhance rider protection. Multibody modeling enables simulation of diverse accident scenarios, with relatively low computation time, to determine impact conditions on the human body. However, these models are typically developed, calibrated, and validated based on pedestrian or car occupant data, and are not specifically designed to represent micromobility crash dynamics. Their ability to reproduce human kinematics in these crashes still needs to be evaluated. This study analyses the kinematics of two multibody models -a cyclist and an e-scooter rider- by comparing them to real-world accident footage and anthropomorphic test device (ATD)-based crash tests.

II. METHODS

Studied Crash Cases

Three controlled crash experimental tests were conducted using a standing Hybrid III 50th percentile male ATD: (1) an e-scooter colliding with a curb [3-4], (2) a stationary bicycle laterally impacted by a moving car, and (3) a moving bicycle colliding with the front wheel of a stationary vehicle. All experimental tests were recorded at 1000 fps using high-speed cameras. In parallel, three real-world crashes were analyzed: (4) an e-scooter curb impact, (5) an e-scooter–car collision, and (6) a bicycle–car collision. The videos were recorded at 30 fps using surveillance or smartphone cameras. Kinovea software was used for motion tracking. The displacement and velocity of the car and the most visible part of the rider (head or back) were tracked ,from the first contact of the bicycle/e-scooter against the obstacle to the initial head or windscreen impact (see case 2, fig. 1), following the method of Shishov et al. [5]. A 2D grid calibrated using vehicle dimensions or ground markers was used to scale the pictures.

Multibody Reconstructions

The MADYMO 50th percentile male pedestrian model from TNO Automotive was used to simulate all cases. The geometry of an existing car model [6] was adjusted to match the video car dimensions. The e-scooter model, developed by [3], had a mass of 13 kg and included a rigid body with six ellipsoids and flexible wheels to dissipate energy. The bicycle model was developed based on the geometry of a commercially available bike (Riverside 120 M, Decathlon). The model has a mass of 15 kg and includes 3 rigid bodies and 14 ellipsoids. The contact stiffness properties were obtained from experimental test data [7]. For real accidents, the micromobility vehicle and car's motion, including braking, were extracted from video data and used as initial conditions for the models. Kinematic accuracy was evaluated using root mean square error (RMSE) between tracked and simulated rider displacements. Fall duration, fall distance, and impact velocities (of the head or back) were also compared. In case 6, analysis was limited to qualitative comparison of the rider's posture, as the rider did not fall within the camera's plane.

III. INITIAL FINDINGS

The reconstructed crashes showed good overall agreement with video data. The rider's posture was consistently comparable between simulations and videos, with some minor differences. In both ATD and real e-scooter falls (1 and 4), the model's arms detached from the handlebar slightly earlier than in the videos. In case 5, the pedestrian model's back appeared slightly more arched than in the footage (fig 1). In cases 2 and 3, the ATD's legs seemed more rigid than in the multibody model, remaining straighter upon impact. The opposite was observed in the real bicycle-car collision (6), where the rider's legs appeared stiffer in the model than in the video.

M. Guesneau (e-mail: marianne.guesneau@univ-eiffel.fr; tel: +33(0)4 91 69 89 05) is a PhD student in Biomechanics employed by In&motion at the LBA, Aix-Marseille University and University Gustave Eiffel, France. N. Bailly and P-J. Arnoux are affiliated to LBA, Aix-Marseille University and University Gustave Eiffel, France. O. Cherta-Ballester is Lead Researcher and V. Honoré is Chief Technical Officer at In&motion, France. Y. Petit is Professor at the ETS, Montreal, Canada.

Regarding impact speeds, fall durations and distances the computed errors ranged from 0% to 25% (see table 1) except for impact speed of case 5, with an error of 39%. The case 2 was the most accurate, while the case 3 had the highest horizontal RMSE (0.38 m, table 1).

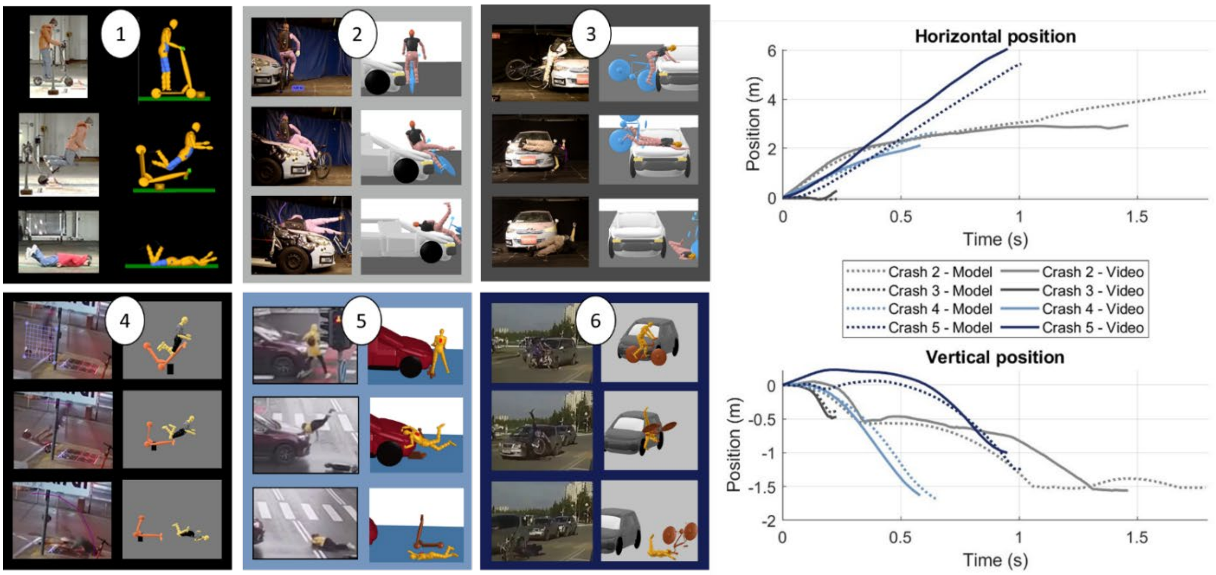

Fig. 1. ATD (1-3) and real-life (4-6) crashes with their reconstructions. Evolution of horizontal and vertical position are shown for crashes 2-5. These curves are presented in [4] for crash 1 and are not available for crash 6.

TABLE I.
KINEMATIC PARAMETERS MEASURED ON THE VIDEOS AND ON THE MULTIBODY SIMULATIONS.

Case	Vehicle velocity (km/h)	Impact velocity abs. error (m/s)	Fall duration abs. error (s)	Fall distance abs. error (m)	Vertical RMSE (m)	Horizontal RMSE (m)
1	E-scooter: 21.6	Head: 1.1 (15 %)	0.00 (0 %)	0.06 (2%)	0.20	0.22
2	Bike: 0; Car: 29.7	Head: 1.1 (16 %)	0.01 (5%)	0.03 (23%)	0.05	0.06
3	Bike: 23.6; Car: 0	Head: 0.0 (0 %)	0.24 (18%)	0.23 (8%)	0.23	0.38
4	E-scooter: 15.4	Head: 0.7 (16%)	0.07 (12%)	1.00 (16%)	0.11	0.25
5	E-scooter:7.2; Car: 26.7	Back: 2.1 (39%)	0.15 (13%)	0.53 (25%)	0.17	0.16

IV. DISCUSSION

Comparing model simulations with crash test and real-world data highlights the strengths and limitations of each approach. ATD crash tests provided controlled impact speeds and high-resolution footage for precise tracking but lacked realism due to the ATD's rigidity and absence of reflexes. In these reconstructions, the discrepancies between the model and the videos may be due to the use of a human model rather than an ATD model. Real-world accident videos captured natural reflexes and environmental conditions but suffered from low camera resolution and suboptimal angles, leading to less precise initial conditions [8] and therefore greater displacement errors compared with the crash tests. The model closely matched the rider posture over time, confirming that it reproduced well the global kinematics of real accidents. Minor deviations—such as premature hand detachment from the e-scooter handlebars—suggest further refinements are needed. The pedestrian-based multibody model is not optimized for micromobility crash simulations and does not account for rider-specific behaviors, including protective reflexes (~1 second), which may occur during these crash sequences. Overall, combining both data sources strengthens confidence in the model's ability to replicate crash dynamics. Future work should evaluate sensitivity to input variations such as impact speeds and rider posture, as explored in other studies [8].

V. REFERENCES

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