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Experiment System of Motorcycle Impact Injury Using Electric Motor Traction

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Abstract

Although motorcycle crash is one of the most common causes of death and injury, there hasn't been a standard experiment system to simulate the generation of the resulting motorcycle impact injuries. A unique motor drive unit (MDU) and motorcycle crash simulation unit (MCSU) were developed to establish a short-track and high-accuracy experiment system of motorcycle impact injury. The control hardware of the MDU consists of a "two DC motors" system and a "two drums, closed-loop, friction transmission" system, and the control software of the MDU has a novel "carriage acceleration profile control program" which was specially set up to prevent the cusp-like pulse and oscillation phenomenon in the acceleration stage close to the uniform velocity. The unique motorcycle sled and energy absorber constitute a novel MCSU. Thirteen vehicle frontal impact tests (50, 64, 80km/h) were carried out to validate the motor traction properties of this experiment system of motorcycle impact injury, while 18 motorcyclist ejection injury simulations (30, 40, 50km/h) and 3 motorcycle-pedestrian impact injury simulations (50km/h) were carried out to examine its simulation capability. Research results show that: (1)Using a unique generation algorithm of the carriage acceleration- and velocity-time curve and unique manufacturing techniques of hardware components, the apparatus presented in this paper has a potential to become the first short-track experiment system of motorcycle impact injury. (2)Due to a high weight capacity with the ability to propel whole vehicles, the MDU can be used in the full motorcycle/full vehicle crash tests or vehicle component sled impact tests.

Keywords*: electric motor traction, motorcycle crashes, impact injury*

1. Introduction

Motorcycle crashes are an increasing public health problem in the present world [1-5]. The motorcyclist ejection injury and motorcycle-pedestrian impact injury are two of the most common injury severitirs of the resulting motorcycle impact injury [6]. Because they are capable of high speeds but offer minimal occupant protection, motorcycles are the most hazardous highway vehicles: they have the highest crash costs per person-mile (NHTSA, 2002)[7]. Per vehicle mile traveled, motorcycle riders have a 34-fold higher risk of death in a crash than people driving other types of motor vehicles, and they also are eight times more likely to be injured (NHTSA, 2007) [8]. The higher risks of injury and death for motorcycle riders have been reported to be associated with a younger age, lack of protection, and poor visibility of the rider and vehicle to other road users [9-12]. A number of studies show that the most important variable affecting mortality in motorcycle crashes is head injury. Thoracic and abdominal trauma as well as pelvic ring fractures associated with long bone injuries appears to be the secondary factors contributing to reduced survival [1], [13-16].

To date, there has been very little information published on the generation mechanism of motorcycle impact injury. According to the computer-based online search to identify English articles about "Motorcycle injury" published from January 1994 to December 2012 in PubMed database, for instance, 1896 articles were available. However, most articles are related to the epidemiological and clinical researches of motorcycle impact injury. Only four (4) articles were

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about the generation mechanism of motorcycle impact injuries [6], [17-19]. One of the reasons is that: there hasn't been a standard experiment system of motorcycle impact injury.

The purpose of this study is to establish a short-track, high-accuracy experiment system of motorcycle impact injury using electric motor traction.

2. Research Method

2.1. Design Approach

(a) L-shaped structural layout. The experiment system of motorcycle impact injury was designed to have a L-shaped structural layout (Figure 1). It has the following operation principle: shown in Figures 1-2, two DC motors respectively drive two drums to mobilize the drag steel rope by friction; the drag steel rope then pulls the motorcycle sled to move along the "test track" from the "test preparation room" to the crash hall. At a pre-defined position, the motorcycle sled is mechanically separated from the drag rope and then a motorcycle crash takes place only by means of the inertia of motorcycle sled.

(b) Technical requirement. Two main components of this experiment system are: motor drive unit (MDU) and motorcycle crash simulation unit (MCSU). The MDU is for driving motorcycle sled, while the MCSU is for simulating motorcycle crashes.

The following MDU kinematics criteria, based on ECE R94 and ISO13232, were used to assure the initial test state of test items:

1. the maximum drag acceleration of motorcycle sled be 0.5 Gs (G: acceleration of gravity) or less;
2. the average drag acceleration of motorcycle sled be 0.3 Gs or less;
3. the drag velocity accuracy be ±2% or less when the impact velocity of motorcycle sled is 40 mph or less than;

Besides, this MCSU was required to simulate the generation of the motorcyclist ejection injury and motorcycle-pedestrian impact injury.

(c) Design principle. The kinematics equation of this experiment system of motorcycle impact injury can be simplified as

$$M - M_L = k \cdot GD^2 \cdot \frac{dn}{dt} \tag{1}$$

Incorporating the following formulas:

$$GD^2 = G_r D_r^2 + G_l D_l^2 = G_r D_r^2 + (G_{IV} D_{IV}^2 + G_{IS} D_{IS}^2) \tag{2}$$

$$M_L = M_{L0} + M_{LT} + M_{LV} \tag{3}$$

It can be also expressed as:

$$M - (M_{L0} + M_{LT} + M_{LV}) = k \cdot (G_r D_r^2 + G_{IV} D_{IV}^2 + G_{IS} D_{IS}^2) \cdot \frac{dn}{dt} \tag{4}$$

Where:

M, n = Eletro-magnetic torque and rotating speed of DC motors, respectively
M_L, GD^2 = Load torque, flywheel moment of whole system, respectively
k = Transmission coefficient of whole system
M_{L0} = Resistance torque when motors do no-load running
M_{LT} = Resistance torque resulting from mechanical transmissions
M_{LV} = Resistance torque resulting from the linear motion of motorcycle sled
$G_r D_r^2$ = Flywheel moment of rotating parts, consisting of the rotational inertia of mechanical transmission parts and motor rotators
$G_l D_l^2$ = Equivalent flywheel moment of linear motion parts (i.e. the motorcycle sled and drag steel rope) based on the Principle of Momentum Conservation

$G_{IV}D_{IV}^2$ = Equivalent flywheel moment that the mass of the motorcycle sled under linear motion is converted to

$G_{IR}D_{IR}^2$ = Equivalent flywheel moment that the mass of the drag steel rope under linear motion is converted to

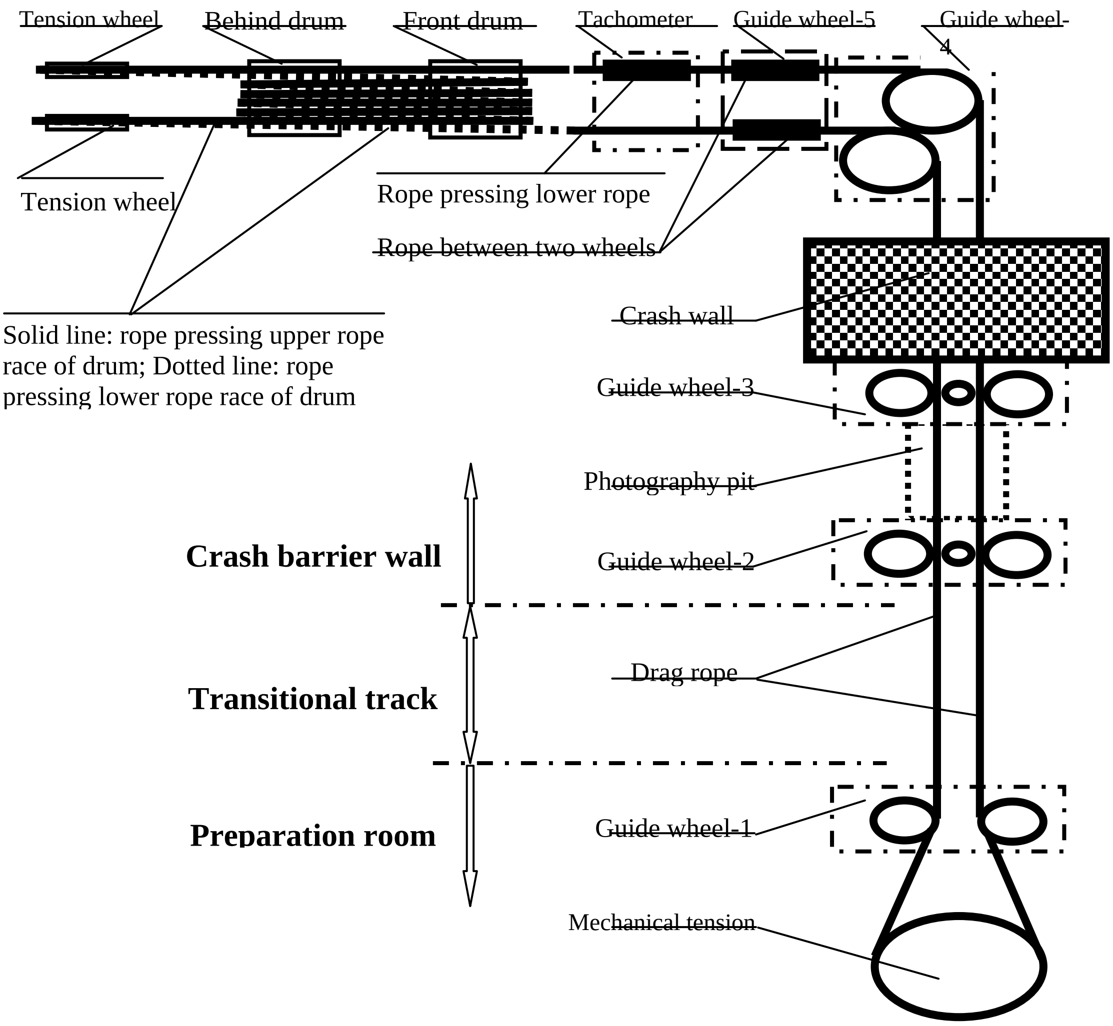

Figure 1. L-shaped Structural Layout of this Experiment System

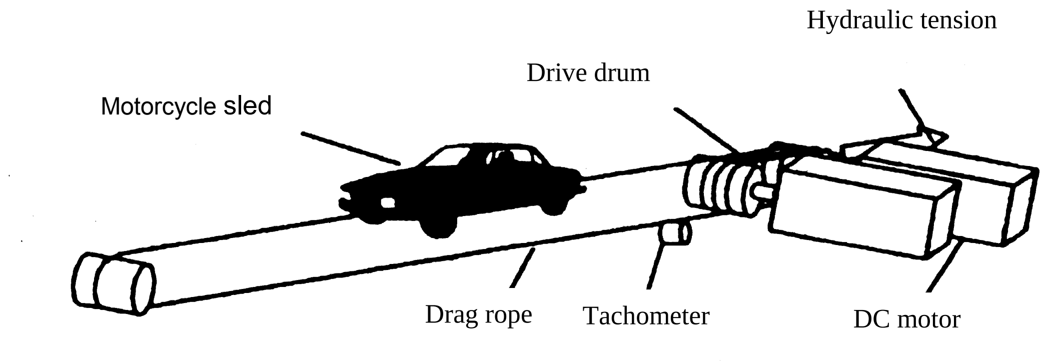

Figure 2. Scheme of Operation Principle of this Experiment System

From the above kinematics equations, the design principles of the MDU [20] are as follows:

1. A unique “Motor Control Strategy” was designed to assure that: the electromagnetic torque (*M*) of two DC motors is stable and reliable while the resistance torque when motors do no-load running (M_{L0}) is approximate to a constant.
2. A unique “Closed-loop Friction Drive Strategy” and “drag sled” and “mini-rail” were designed to assure that: the resistance torque resulting from mechanical transmissions (M_{LT}) and ($G_r D_r^2$) and ($G_{lR} D_{lR}^2$) are approximate to a constant, and the (M_{LV}) is minimal.

Besides, the design principles of the MCSU are as follows:

The unique “motorcycle sled” and “energy absorber” were designed to simulate the generation of the motorcyclist ejection injury and motorcycle-pedestrian impact injury.

2.2. The “two motors” system

(a) General description of the MDU: This MDU consists of a “two motors” system, two drive drum complexes, a drag rope complex, and a hydraulic control complex (Figures 1-3).

(b) DC motors. Two DC motors with the rated power of 225kW (Model: Z4-280-42 DC motors) were served as the power source of this motorcycle experiment system.

(c) Digital DC speed regulating cabinets. Using a force balance control mode, two speed regulating cabinets (Model: Siemens 6RA2487-6DV62-0 Digital DC Speed Regulating Cabinets) provide the identical loading for the related two motors. The cabinet subject to the front motor was defined as the master cabinet and the other subject to the behind motor as the slave cabinet. The master cabinet controls the slave one through communication.

(d) Motor control program. To ensure the reliability of the motor drive unit (MDU), a control computer (CtrC) and PLC (i.e. Programmable Logic Controller) were combined to constitute a 2-stage motor control strategy: First, the CtrC sends various control commands to the PLC; Then, the PLC defines the operation parameters of two motors. The CtrC is connected with the PLC by serial ports. During a drag motion the CtrC runs the specilly-developed “Motor Control Program”. Figure 4 shows the flow chart of motor control program. The “velocity feedback” signal is from the tachometer to measure the linear velocity of drag steel rope.

2.3. Drive drum complex

(a) Drive drum. The drive drums are used to deliver the forward or reverse drag force to the drag steel rope. In order to make sufficient friction force between the drive drums and drag rope, two drums were designed to have a different quantity of rope races whose geometrical sizes were specially manufactured (Figure 3). In fact, the front and behind drum includes 7 and 6 rope races, respectively.

The rotary part of each drum, consisting of a shaft and a hub and two side plates as well as a rim, is supported by two bearing house. Two ends of each drum shaft are respectively connected to the coupling and the brake dic.

(b) Expansion sleeve. The expansion sleeve is for mechanically connecting the drum shaft to the hub or brake disc. To maintain the hub in contact with the drum shaft, this apparatus allow the high-strength bolts to be tightened and thereby produce sufficient pressure or friction force between the adjacent interface surfaces.

(c) Coupling. A VULKAN FLEXOMAX-G flexible coupling was applied to make a transmission connection between the DC motor and drive drum. The flexible behavior of rubber coupling components not only prevents the local drum-motor transmission system from enduring impulse loading, but also reduces the noise produced by the direct interface between two metal components (i.e. motor shaft and drum shaft).

(d) Brake disc. The brake discs are for braking the inertia rotation drum shafts after the DC motors are instructed to stop. The control hydraulic pressure to brake discs is supplied by the specially-developed hydraulic pump station. The brake disc of each drive drum is connected with the exposed cantilever of drum shaft and is fixed on the bearing house through a transitional plate.

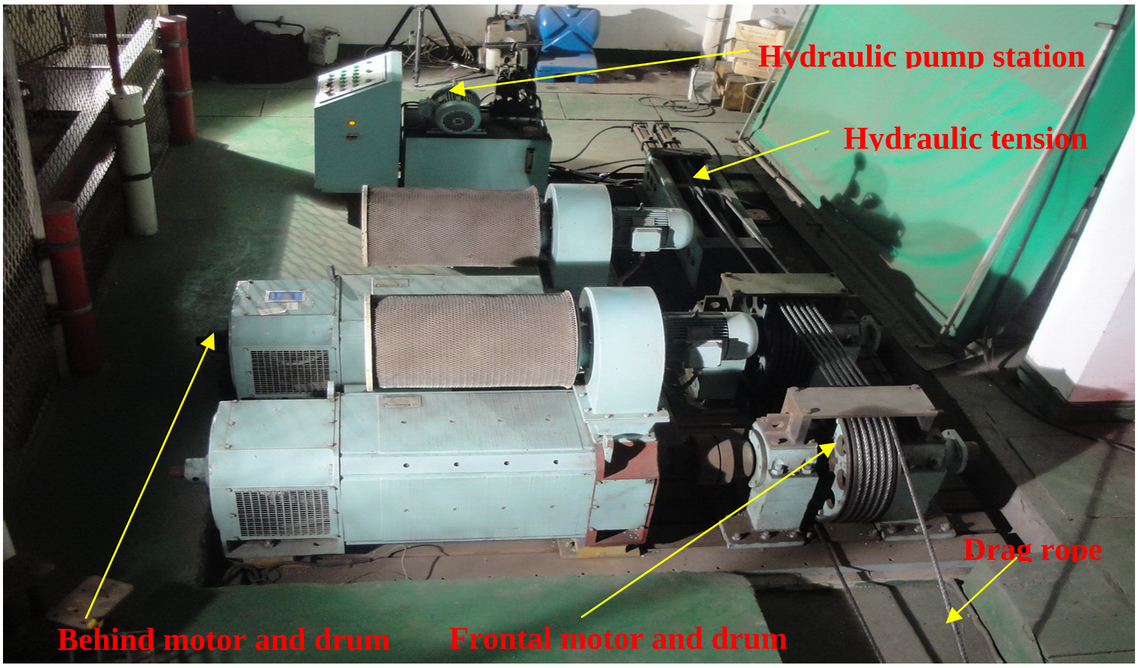

Figure 3. The “two motors” System and Drive Drun Complex (See Online Version For Colours)

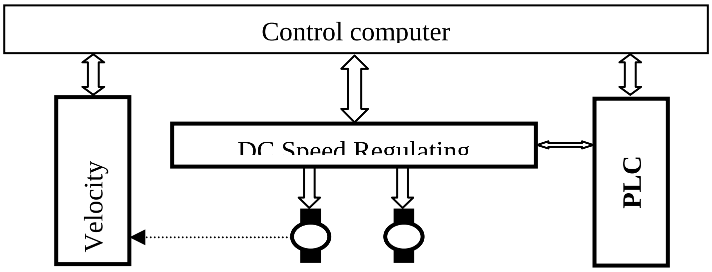

Figure 4. Flow Chart of Motor Control Program

2.4. Drag rope complex

(a) Drag rope loop: shown as Figure 1.

(b) Tension devices. The hydraulic tension device was designed to make a precision alignment of tension force of drag rope, while the mechanical tension device to do a rough alignment. This hydraulic tension device was placed behind the behind drum (Figures 1-3). During a tension operation, the drag rope was firmly pressed into the rope races of drive drums so that the torque of DC motors can be transmitted to the drag rope.

(c) Measurement of linear velocity of drag rope. Shown as Figure 1, the drag rope was tensioned and firmly pressed into the rope races of the tachometer wheel. During a drag motion, the drag rope allows the tachometer wheel to rotate and thereby the opto-electrical encoder which is co-axial with the tachometer wheel outputs the pulse signals representing the rotary velocity of the tachometer wheel. Of course, these pulse signals can be used to calculate the linear velocity and linear acceleration of the drag rope.

2.5. Hydraulic control complex

The apparatus (Figures 1-3) provides a stable, adjustable control pressure for the hydro-cylinder of the hydraulic tension device or the brake disc. Its hydraulic pump station has a complete hydraulic control system to maintain in contact with the general control system.

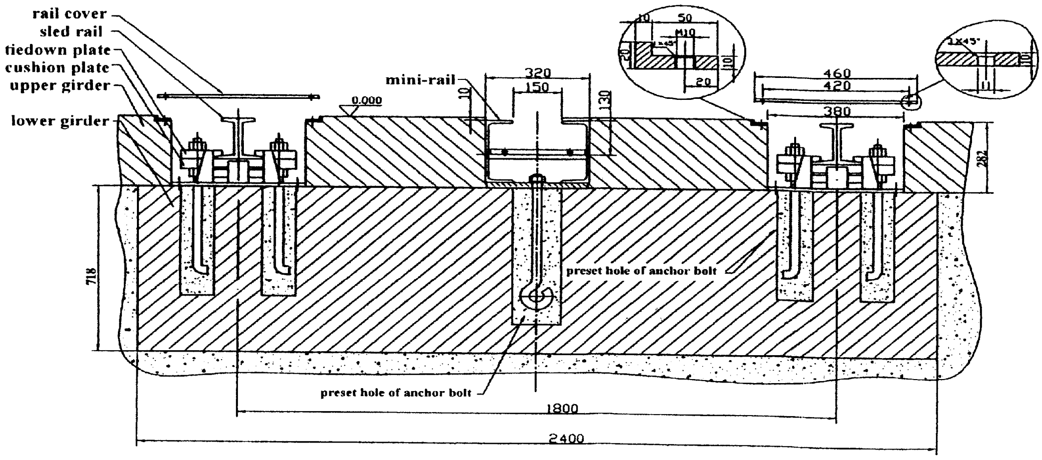

Figure 5. Cross-section View of the Mini-Rail (Geometric Dimensioning unit is mm)

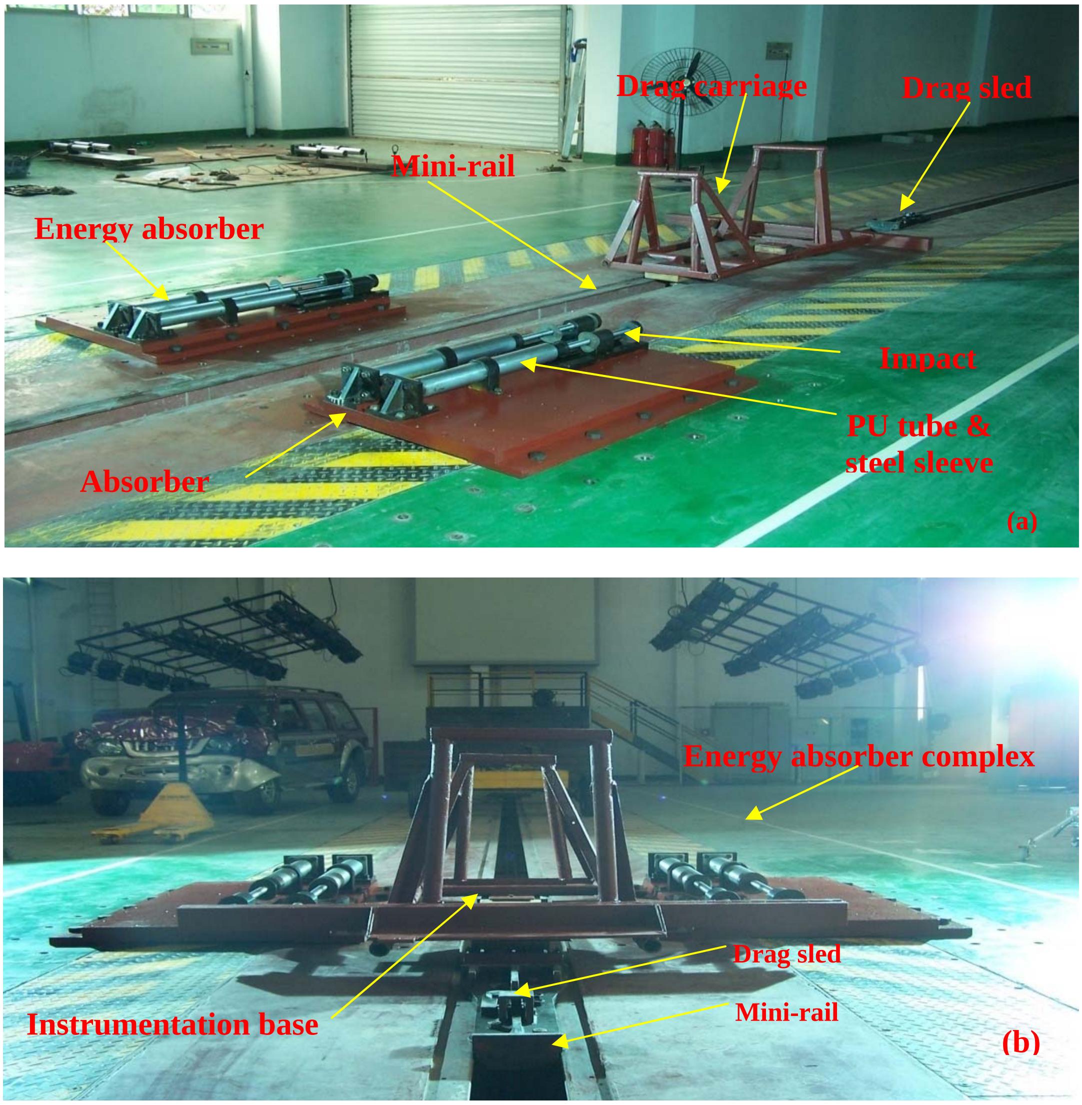

Figure 6. Set-up of Motorcycle Crash Simulation Unit (see online version for colours)
(a) Drag Carriage and Energy Absorber Complex; (b) Motorcycle Crash Hall

2.6. Drag sled and mini-rail

The drag sled is mounted on a 75-m long mini-rail (Figure 5), which was made up of the custom-forged channel steel sections of 25c type.

The technical requirements of this mini-rail are as follows:

1. The upper surfaces of this mini-rail should be horizontal and the elevation difference between be ±2mm or less;
2. The gauge of two upper surface edged should be 150_{0}^{+1}, and both the overall longitudinal and vertical linearity of two edges should be ±2 mm or less.

This drag sled is a key component of the MDU. The novel structure was designed to connect the drag steel rope with the motorcycle sled so that they can be firmly connected during drag motion and automatically separate from each other at a pre-defined separation position (Figure 6).

2.7. Motorcycle crash simulation unit

(a) Motorcycle sled. The motorcycle sled consists of a test motorcycle, motorcycle carriage (Figure 6), and locking fixture. During a test, the motorcycle sled is propelled by the MDU and slides along the mini-rail. When this sled arrives at a pre-defined position a motorcycle crash test is carried out.

The locking fixture has a novel structure to assure that the motorcycle sled and drag sled can be firmly connected during a drag motion and automatically separate from each other at a pre-defined separation position.

(b) Energy absorber. The required sled deceleration pulse is achieved by means of an energy absorber. This energy absorber consists of two or more re-usable polyurethane tube devices placed in parallel inside steel pipes, which are rigidly attached to the fixed base plate (Figure 6). Deceleration occurres when two or more steel shafts on the energy absorber, which are fitted with olive-shaped ends, are impacted by the motorcycle sled and rammed inside the polyurethane tubes, absorbing the impact energy.

2.8. Validation tests

To validate the motor drag properties of this experiment system of motorcycle impact injury, six 50-kph sled frontal impact tests and six 64-kph and one 80-kph full vehicle frontal impact tests were carried out according to ECE R94 and ISO13232.

In per sled tests a standard sled was dragged to impact the energy absorber of polyurethane-tube type attached to a solid crash barrier wall at a 50-kph speed (Figure 7) [21], while in per vehicle tests a full-scale vehicle (weighing approximately 680 kg or 1200 kg) was propelled to impact the solid crash barrier wall at a 64- or 80-kph speed.

Figure 7. Dummy Frontal Impact Sled Test (see online version for colours)

2.9. Animal (pig) experiments

To examine the simulation capability of this experiment system of motorcycle impact injury, 18 motorcyclist ejection injury simulations (Figure 8; the ejection velocities ≈ 30, 40, 50 kph) [6] and 3 motorcycle-pedestrian impact injury simulations (Figure 8; the impact velocities ≈ 50 kph) were carried out. Digital high-speed color videos are used to photographically record each event.

Figure 8. Animal Experiment Models (see online version for colours)
Left: Motorcyclist Ejection Injury; Right: Motorcycle-Pedestrian Impact Injury.

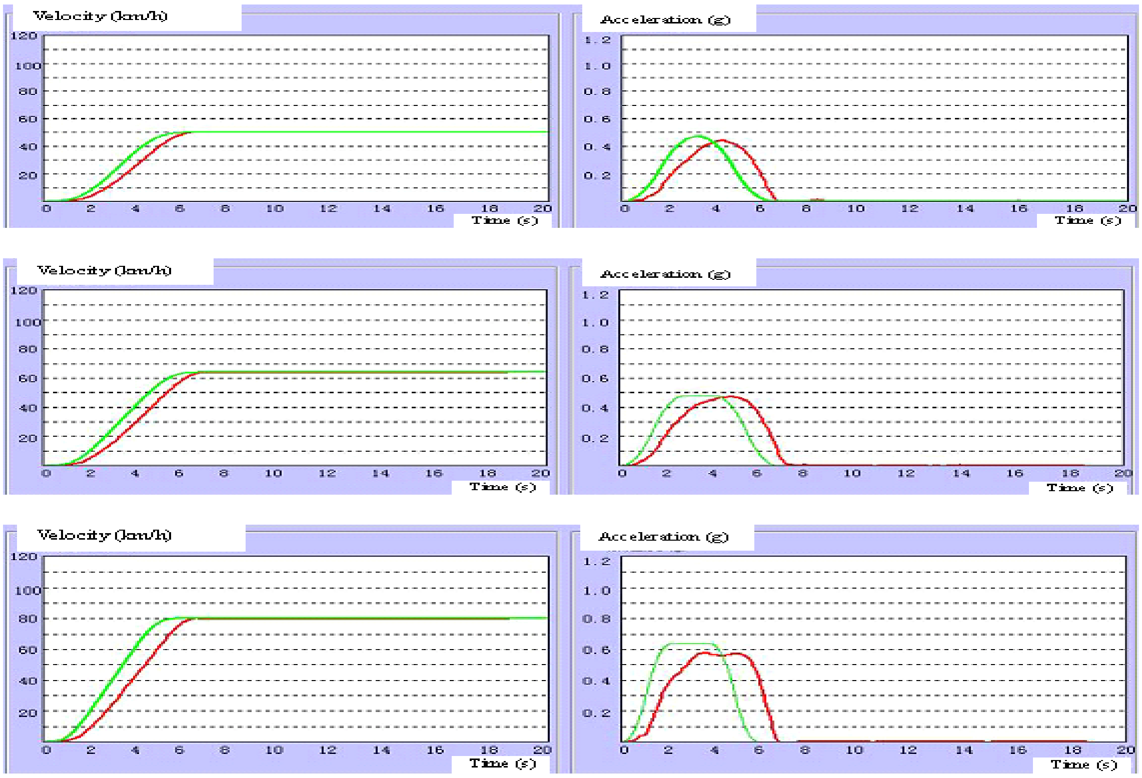

Figure 9. Drag Acceleration Profiles In Validation Tests (see online version for colours)
Upper: 50 km/h; Middle: 64 km/h; Lower: 80 km/h. Green Line Represents The Pre-Defined Values, And Red Line Represents The Actual Measurement Values

3. Results and Analysis
3.1. Validation test results

Table 1 and Figure 9 show that this experiment system of motorcycle impact injury is sufficient to manage the demands for high velocity motorcycle crashes. In fact, the maximal crash velocity of this experiment system is up to 120 km/h while the motorcycle sled assembly weigh 1500 kg.

In Table 1, V_{imp} and $A_{\max}^{drag}$ and A_{avg}^{drag} are respectively the impact velocity and maximum drag acceleration and average drag acceleration of test sleds prior to the impact, while $A_{\max}^{imp}$ is its longitudinal maximum deceleration during the impact. L_a is the acceleration distance of motorcycle sled.

Table 1. Validation Test Data

	Input variables			Output parameters	
	$V_{imp}\ (km/h)$	$A_{\max}^{drag}\ (G)$	$A_{avg}^{drag}\ (G)$	$A_{\max}^{imp}\ (G)$	$L_a\ (m)$
Pre-defined	50	0.48	0.24	---	---
Actual-1 (n = 6)	49.874±0.317	0.462±0.012	0.208±0.019	30.557±1.247	38.6±1.013
Pre-defined	64	0.49	0.29	---	---
Actual-2 (n = 3)	63.867±0.209	0.478±0.010	0.231±0.047	No data	52.9±1.307
Pre-defined	80	0.64	0.40	---	---
Actual-3 (n = 1)	79.75	0.585	0.357	No data	63.1

3.2. Animal experiment results

(a) Motorcyclist ejection injury. From high-speed videos, the generation of motorcyclist ejection injury was divided into three phases:

1. Impact phase: The motorcycle sled was dragged up to a pre-defined velocity and then impacted the energy absorber of polyurethane tube type.
2. Ejection phase: The motorcyclist surrogate (animal) placed freely on the motorcycle in a riding posture was ejected forward, accompanying with the rotation motion in the air.
3. Land phase: The head and shoulder and thorax of ejected animal impacted in turn the hardy ground.

Besides, varying degree of injuries focusing on the liver, heart, lung and spleen were found. There existed a significant positive correlation between ISS (Injury Severity Score) and the ejected velocity of the motorcycle drivers (ISS = 16.7±2.9 for 30 km/h, 25.0±0.0 for 40 km/h, 37.3±1.0 for 50 km/h).

The above experiment results are similar to the actual motorcyclist ejection events.

(b) Motorcycle-Pedestrian impact injury. From high-speed videos, the generation of motorcycle-pedestrian impact injury included three phases:

1. Impact phase: The test motorcycle mounted on the motorcycle sled was dragged up to a pre-defined velocity and its front wheel then impacted the right tibia of the erect pedestrian model, in which the head-neck model was replaced by the head-neck complex of living animal (pig) and other components were simulated by a custom-made physical model similar to the Hybrid III 50% dummy.
2. Ejection phase: The whole pedestrian model revolved round the motorcycle front wheel, and was then ejected forward, accompanying with the rotation motion in the air.
3. Land phase: Within a certain dsitance from the initial impact point, the head-shoulderof test animal impacted the hardy backgroung or the feet and head and shoulder impacted in turn the hardy background.

The above experiment results are also similar to the actual motorcycle-pedestrian crash events.

3.3. Contributions of this study

(a) The first short-track experiment system of motorcycle impact injury. The experiment system of motorcycle impact injury has a 75-meter test track and high-accuracy carriage velocities and accelerations. This system has also a unique motorcycle sled and energy absorber and thereby has a capability of simulate the generation of the motorcyclist ejection injury and motorcycle-pedestrian impact injury. It is notable that to date there hasn't been a standard experiment system of motorcycle impact injury. Only a few whole motorcycle crash test system were reported in the previous literatures. The possible shortest track of motorcycle crash test is 122-meter long in China [22].

Hence, this device has a potential to become the first short-track experiment system of motorcycle impact injury.

(b) Unique motor control strategy. The control hardware of the MDU has a "two DC motors" system and a "two drums, closed-loop, friction transmission" system and thereby assure the reliability of the MDU.

The control software of the MDU consists of a novel "carriage acceleration profile control" program. The program inputs the target operation parameters of DC motors and designs a carriage velocity- and acceleration-time curve. The interesting contribution is that: the generation algorithm of the carriage acceleration- and velocity-time curve was specially set up to prevent the cusp-like pulse and oscillation phenomenon in the acceleration stage close to the uniform velocity. Noted that though such a cusp-like pulse or oscillation phenomenon generally occurred in the previous automobile traction systems, they had a sufficiently long traction distance for speed regulation to meet the speed control accuracy requirements. This generation algorithm has been proven to assure that the MDU has the high-accuracy carriage velocities (e.g. V_{imp} = 49.874±0.317 km/h) and accelerations (e.g. $A_{\max}^{drag}$ = 0.462±0.012 Gs) within a short drag distance.

(c) Unique manufacturing techniques.

1. The knot-work of the drag steel rope was specially made to ensure a similar diameter between the rope knot and other rope parts and thereby a smooth slide between drag rope and any rope races.
2. The optimal match between the "drag rope-drive drum" interface area and the tension force of drag rope was specially set up to generate a stable, reliable drag velocity or acceleration.
3. The mechanical structure of the drag sled was subtly designed to assure a novel connection between the motorcycle sled and drag rope: they are firmly connected during a drag motion while they are automatically separate from each other at a pre-defined separation position.

3.4. Limitations of this study

Crash pulses during the motrocyclist ejection simulations could not completely simulate the typical or standard motorcycle-barrier crashes. Animal experiment models could not completely simulate the injury characteristics of actual motorcycle impact injury.

4. Conclusion

(1) Using a unique generation algorithm of the carriage velocity- and acceleration-time curve and unique manufacturing techniques of hardware components, the apparatus presented in this paper has a potential to become the first short-track experiment system of motorcycle impact injury.

(2) Due to a high weight capacity with the ability to propel whole vehicles, the DC motor drive unit can be used in the full motorcycle/full vehicle crash tests or vehiclar component sled impact tests. Future research should improve the motorcycle crash simulation pulse and animal experiment model.

Acknowledgements

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