

Comparison of Responses of the Flex-PLI and TRL Legform Impactors in Pedestrian Tests

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ABSTRACT

Injuries to the lower extremities are one of the major issues in vehicle-to-pedestrian collisions. To evaluate pedestrian lower extremity protection, the Transport Research Laboratory (TRL) legform impact tests have been conducted according to the specifications in the EU directive. The TRL legform impactor consists of a tibia and a femur steel shaft connected by deformable knee bars. A Flexible Pedestrian Leg-form Impactor (Flex-PLI), which has flexible femur and tibia, is examined in the Global Technical Regulation (GTR). Previous studies compared the responses of both impactors; however, the relation between the tibia acceleration in the TRL legform impactor and the maximum bending moment in the Flex-PLI (both injury measures are for the tibia fracture) is not understood sufficiently. In this study, using finite element (FE) analyses, the injury measures of the TRL legform and the Flex-PLI were compared with those of the human FE model in impact with a simple large car model to identify which injury measures of the two impactors are reasonable to predict injury risk to pedestrian lower extremity.

The rigid body model was used to gain a theoretical understanding of the injury measures of the impactors. Based on the equations of motion of the rigid body model, physical parameters were identified that relate with the injury measures. The tibia acceleration relates with the bumper force and the spoiler force. The bending moment depends on the equation that is expressed by the force and distance of the bumper and the spoiler energy absorber. Therefore, the tibia acceleration and the bending moment are different design parameters. The knee bending angle depends on the moment around the tibia center of gravity. Analyses of the TRL legform, Flex-PLI and human FE models were conducted; and it was shown that the injury measures in the FE models were affected significantly by the physical parameters determined in the rigid body model.

The responses of the TRL legform, the Flex-PLI, and human FE models were compared with changing vehicle parameters. The trend was comparable for the three models. However, when the bumper energy absorber was soft and its bottoming-out occurred, the tibia acceleration in the TRL legform increased sharply, whereas the bending moment in the Flex-PLI did not increase. In the human FE model, when the bumper energy absorber bottomed out, the stress of the tibia that made contact with the bumper energy absorber was still small. As far as changing parameters of the large car in the present study, the responses of the Flex-PLI are more comparable with the human FE model than those of the TRL legform impactor; and it is likely that the Flex-PLI can predict injury risk more reasonably than the TRL legform impactor.

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INTRODUCTION

In vehicle-to-pedestrian collisions, the frequency of lower extremity injuries is high [1], and the leg protection is important for pedestrian protection. For a protection of lower extremities, a regulatory test has been developed in which a legform impactor is impacted against a bumper to evaluate the performance of a vehicle. In the European Union (EU)

regulation (DIRECTIVE 2003/102/EC), the legform impact test has been conducted using a legform impactor developed by Transport Research Laboratory [2]. The TRL legform impactor has a steel femur and tibia body, which are connected by knee bars. The fracture risk of the tibia bone is evaluated from the tibia acceleration measured at the upper end of the tibia, and the knee ligament damage risk is

evaluated from the knee bending angle and knee shear displacement. In the EU regulation phase II (No 78/2009), the acceptance level of the tibia acceleration is 170G, the knee bending angle is 19 degrees, and the knee displacement is 6 mm [3]. In car-to-pedestrian collisions, it is pointed out that the leg can bend during impact. Though the acceleration was used as an injury measure to evaluate the tibia fracture in the TRL impactor, a tibia fracture can occur not from shear force but from bending of the tibia. On the other hand, Japan Automobile

Research Institute (JARI) and Japan Automobile Manufactures Association (JAMA) has developed a flexible pedestrian legform impactor (Flex-PLI) [4]. In the United Nations Working Party on Passive Safety (GRSP), the pedestrian legform impact test using the Flex-PLI has been discussed regarding its introduction into the Global Technical Regulation No. 9 [5]. In the Flex-PLI, the tibia and femur are flexible and thereby have a comparable characteristic of bending with human bone. The fracture risk of the tibia bone of the Flex-PLI is evaluated from the bending moment, and the knee ligament damage is evaluated from the elongation of the knee wire. At present, a tibia bending moment of 340 N·m, medial collateral ligament (MCL) elongation of 22 mm, and anterior cruciate ligament (ACL) elongation of 13 mm are proposed as the acceptance levels of the Flex-PLI [6].

It has been pointed out that Flex-PLI is more biofidelic than the TRL legform impactor from its basic design concept [4]. The ground clearance of the Flex-PLI impactor was set to 75 mm in order to have comparable kinematic behavior of human FE model based on computer simulations [6,7]. A comparison between the TRL legform and Flex-PLI was examined in some studies based on experiments [8,9]. Zander [8] also showed that good results of injury measures with a Flex-PLI were similar to those obtained with the TRL legform impactor, and would not necessarily lead to a change of a vehicle's front design already developed for good performance of injury measures by the TRL legform impactor. Matsui et al. [9] compared injury measures of both impactors from eight test vehicles with various frontal shapes. They concluded that there was a correlation of injury measures of both impactors. A correlation coefficient of knee injury measures between two impactors (knee bending angle of TRL legform impactor and the knee ligament elongation of Flex-PLI) was high (0.82). However, for the tibia fracture measures (i.e., the acceleration of TRL legform impactor and the tibia bending moment of Flex-PLI), the correlation coefficient was lower (0.57). Both the tibia acceleration and the tibia bending moment are injury measures to evaluate the tibia fracture risk, the correlation between the two injury measures was not so high, and it is not still clear whether the both injury measures are comparable. To replace the TRL legform by Flex-PLI in the pedestrian safety regulation, it is essential to evaluate the relation between the tibia acceleration of the TRL legform impactor and the tibia bending moment of the Flex-PLI.

The Flex-PLI has been discussed as a replacement for the TRL legform impactor in pedestrian test. In order to discuss the effectiveness for pedestrian injury reduction through vehicle design change by using the Flex-PLI, it is necessary to understand difference in the response and injury measures of both legform impactors with vehicle design changes. In this research, the injury measures of the TRL legform impactor and the Flex-PLI were compared through theoretical analysis and mathematical simulations. Based on the equations of motion of the rigid body model, the predominant parameter of injury measures of the TRL legform impactor was determined. Finite element (FE) analysis was also conducted, and responses of the TRL legform impactor, Flex-PLI, and human FE model were compared for a simple car model. From these simulations, it is possible to change design parameters systematically, and the factors that affect the injury measures can be examined. The correlation between the injury measures of the two legform impactors can be investigated from a theoretical aspect, which has not been evaluated in experiments yet.

RIGID BODY MODEL OF TRL LEGFORM IMPACTOR

The rigid body model was used to gain a theoretical understanding of the injury measures of the impactors. The equations of motion of the rigid body model were derived; and from the equations of the motion, the vehicle design parameters that can affect the injury measures of the legform impactor were determined. Then, it was possible to identify the reasons that made differences in tibia acceleration and tibia bending moment in the experiments of Matsui's study [9].

MODEL AND VALIDATION

In the structure of the TRL legform, the steel shafts of tibia and femur are joined by deformable knee bars. They are surrounded by confor foam 45 and skin (neoprene foam and nylon cloth). An accelerometer is mounted on the non-impacted side of the upper tibia (66 mm below knee joint center). Forces from the car structures are applied to the femur shaft and tibia shaft, through which acceleration of the tibia is generated and the knee is bent. This motion is expressed from the 2-dimensional rigid body model shown in [Figure 1](#) [10]. The rigid body of femur and tibia is connected by revolute joint, and forces are applied from car structures. The impactor flies freely and impacts against the car, and there are no forces applied from the ground. The variables used in this model are described in [Figure 1](#). This model assumes small rotation of impactor, and it is necessary to change angles of impactor and change the angle of force from energy absorbers when the impactor angles of θ_1 and θ_2 are large. The shear displacement of the knee was not included in this model because injuries to the cruciate ligaments are not so common in vehicle-pedestrian collisions, and occur when an MCL is ruptured [11]. The model expresses 2-dimensional

motion, and cannot be applied for 3-dimensional motion where for example the legform is impacted at the corner of the car and it moves in a lateral (y) direction.

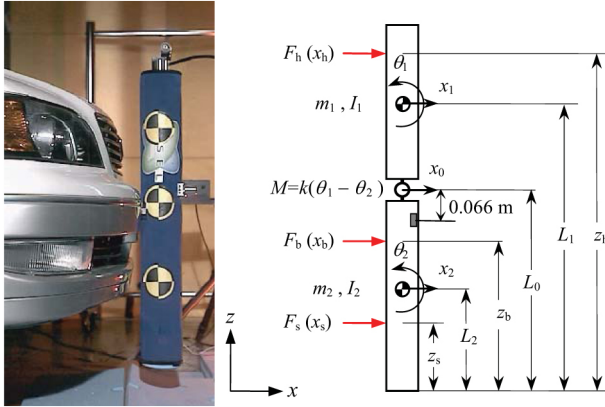


Figure 1. Rigid body model of TRL legform impactor.

The mass and inertia of the femur shaft and tibia shaft are denoted as m_1 , I_1 , m_2 , and I_2 . The force from the hood, bumper, and spoiler to the impactor is denoted as F_h , F_b , and F_s . Assuming that the angle of the femur shaft θ_1 and that of the tibia shaft θ_2 from the vertical axis is small, the equations of motion of the impactor are described as follows.

$$\begin{pmatrix} m_1 + m_2 & -m_1(L_1 - L_0) & m_2(L_0 - L_2) \\ -m_1(L_1 - L_0) & I_1 + m_1(L_1 - L_0)^2 & 0 \\ m_2(L_0 - L_2) & 0 & I_2 + m_2(L_0 - L_2)^2 \end{pmatrix} \begin{pmatrix} \ddot{x}_0 \\ \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & k & -k \\ 0 & -k & k \end{pmatrix} \begin{pmatrix} x_0 \\ \theta_1 \\ \theta_2 \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ L_0 - z_h & 0 & 0 \\ 0 & L_0 - z_b & L_0 - z_s \end{pmatrix} \begin{pmatrix} F_h \\ F_b \\ F_s \end{pmatrix} \quad (1)$$

The knee bending angle of the impactor, θ , is expressed as:

$$\theta = \theta_1 - \theta_2 \quad (2)$$

The acceleration at the tibia accelerometer mounted position, a_A , is

$$a_A = \ddot{x}_0 + 0.066 \ddot{\theta}_2 = \ddot{x}_2 - (L_0 - L_2 - 0.066) \ddot{\theta}_2 \quad (3)$$

The tibia acceleration at the height z from the lower edge of the tibia shaft, $a(z)$, is

$$a(z) = \ddot{x}_0 + (L_0 - z) \ddot{\theta}_2 \quad (4)$$

For the tibia shaft, the force from the bumper force, spoiler force, and inertia force of the tibia shaft is applied, and the bending moment $M(z)$ is classified by the height z from the lower edge of the tibia. That is,

$$(i). \quad 0 \leq z \leq z_s$$

$$M(z) = \frac{m_2}{L_0} \int_0^z \{ \ddot{x}_0 + (L_0 - z') \ddot{\theta}_2 \} (z - z') dz' \quad (5)$$

$$(ii). \quad z_s \leq z \leq z_b$$

$$M(z) = \frac{m_2}{L_0} \int_0^z \{ \ddot{x}_0 + (L_0 - z') \ddot{\theta}_2 \} (z - z') dz' - F_s(z - z_s) \quad (6)$$

$$(iii). \quad z_b \leq z \leq L_0$$

$$M(z) = \frac{m_2}{L_0} \int_0^z \{ \ddot{x}_0 + (L_0 - z') \ddot{\theta}_2 \} (z - z') dz' - F_s(z - z_s) - F_b(z - z_b) \quad (7)$$

The sum of the deformation of the impactor foam material and the deformation of the hood leading edge, bumper energy absorber, and spoiler energy absorber x_h , x_b , x_s is expressed as:

$$\begin{aligned} x_h &= x_0 - (z_h - L_0) \theta \\ x_b &= x_0 - (L_0 - z_b) \theta_2 \\ x_s &= x_0 - (L_0 - z_s) \theta_2 \end{aligned} \quad (8)$$

The forces of the energy absorber $F_h(x_h)$, $F_b(x_b)$ and $F_s(x_s)$ can be determined from the deformation based on the force-displacement characteristic of the energy absorbers.

Equation (1) of the rigid body model was solved numerically using the Runge-Kutta method. The FE analysis was also conducted using the TRL legform FE model and a simple energy absorber model. Figure 2 shows the tibia acceleration and the knee bending angle calculated from both models. The tibia acceleration has a maximum value around 10 ms, and knee bending angle has a maximum value at 20 ms. As shown in Figure 2, the tibia acceleration and knee bending angle from the rigid body model and the FE model are comparable. Consequently, it can be assumed that the assumption of this simple rigid body model is reasonable and this rigid body model can be used for examining the response of the TRL legform impactor. From the equations of motion of the rigid body model, physical parameters that can affect the injury measures can be determined.

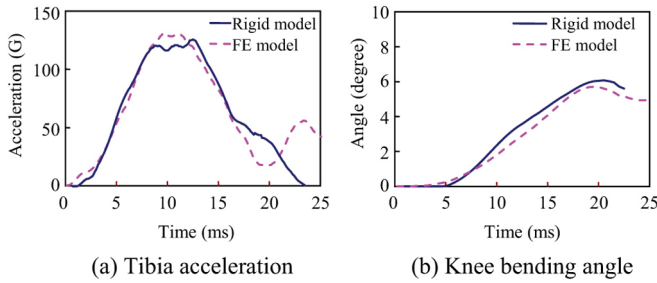


Figure 2. Numerical calculation of rigid body model

PREDOMINANT PARAMETERS

Based on the equations of motion of the rigid body model of the TRL legform impactor, the mechanical parameters that are dominant for injury measures such as tibia acceleration, tibia bending moment and knee bending angle, were investigated.

Tibia acceleration

The equation of motion of the tibia shaft is

$$m_2 \ddot{x}_2 = F_b + F_s - T \quad (9)$$

where T is shear force that is transmitted from the knee joint to the top edge of the tibia shaft. The tibia acceleration of the TRL impactor has a maximum value at the initial phase of impact, and at this time the acceleration of femur shaft is still small. Accordingly, it can be assumed that the shear force is negligible compared to the bumper force F_b , and the spoiler force F_s , and that angular acceleration of tibia is small ($\theta \approx 0$). From Eqs. (3) and (9), the tibia acceleration at the accelerometer is expressed as:

$$a_A \approx \ddot{x}_2 \approx (F_b + F_s) / m_2 \quad (10)$$

It is observed that the tibia acceleration is proportional to the sum of bumper and spoiler force $F_b + F_s$.

Tibia bending moment

Though the tibia bending moment is not measured in the TRL legform impactor, it is a significant injury measure used to evaluate the tibia fracture risk and therefore has been adopted in the Flex-PLI. Accordingly, the bending moment also was determined from the rigid body model. In the rigid body model as shown in Figure 3, the bending moment across the cross section of the tibia was calculated from the forces F_b and F_s and its distance z from the reference point (i.e., the lower edge of the tibia). Tibia bending moment has a maximal value at the time when the forces F_b and F_s are maximal. At this time, the knee bending moment is still small, and it was assumed that the knee bending moment can be neglected. Moreover, for simplicity, it was also assumed that the tibia inertial force that is distributed along the tibia

shaft is concentrated at the both edges of the tibia. The tibia bending moment $M(z)$ has a maximal value $M_{\max}$ at the location of the bumper energy absorber z_b , or the spoiler energy absorber z_s and can be expressed as:

$$\begin{aligned} M_{\max} &= \max \{ M(z_s), M(z_b) \} \\ M(z_s) &= \frac{F_b(L_0 - z_b) + F_s(L_0 - z_s)}{L_0} z_s \\ M(z_b) &= \frac{F_b z_b + F_s z_s}{L_0} (L_0 - z_b) \end{aligned} \quad (11)$$

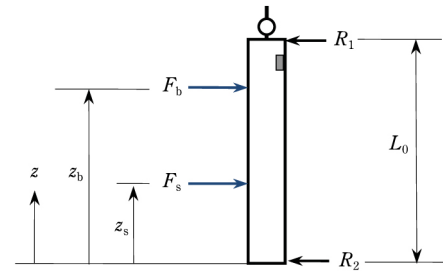


Figure 3. Simple model for calculating the bending moment in the tibia.

Knee bending angle

The equation of angular motion of the tibia with respect to the tibia shaft center of gravity is as follows.

$$I_2 \ddot{\theta}_2 = -F_b(z_b - L_2) + F_s(L_2 - z_s) + T(L_0 - L_2) + k(\theta_1 - \theta_2) \quad (12)$$

Assuming that $F_b, F_s \gg T$ and $\theta_2 \approx 0$, Eq. (12) then can be simplified as:

$$k(\theta_1 - \theta_2) = F_b(z_b - L_2) - F_s(L_2 - z_s) \quad (13)$$

Therefore, the knee bending angle $\theta = \theta_1 - \theta_2$ is related to the moment that is exerted around the center of gravity of the tibia shaft $F_b(z_b - L_2) - F_s(L_2 - z_s)$. It also can be pointed out that the knee bending angle is related to the tibia angle and that the tibia moves with vertical posture during the impact.

FE ANALYSIS

ANALYSIS MODEL

FE analyses were carried out for simulating impacts of the TRL legform, Flex-PLI, and human FE models against a car FE model; and injury measures were compared for three FE models for various vehicle parameters (energy absorber stiffness and dimensions). For these simulations the impact velocity was 40 km/h. According to specifications of the test method, the initial ground clearance of TRL legform was 25 mm, and that of Flex-PLI was 75 mm [6,7]. The external forces acting on the TRL legform and Flex-PLI impactors are