ASSESMENT OF THE INJURY SEVERITY OF THE PEDESTRIAN LOWER LIMBS AT THE COLLISION WITH A VEHICLE

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***Abstract*—**The purpose of the paper is to determine the severity of the injury that may appear at the collision of the frontal part of a vehicle with the pedestrian's lower limbs. In this study the bio-mechanic model of the lower limbs was constructed, in order to determine the bending moment of the tibia. The collision forces that were used as input data were collected from a simulation performed in a traffic accident reconstruction software. The developed multi-body simulation is considering all forces acting on the lower limb. The injury severity is estimated using the bending moment of the tibia.

***Keywords*—** Accident, collision, injury, leg, multi-body, pedestrian

I. Introduction

THE pedestrians are the most vulnerable road users [1]. Pedestrian protection is one of the most important topics regarding the safety measures taken during the accident [2]. When a vehicle collides with a pedestrian, in most of the cases, the lower limbs enter in contact with the front bumper. It was researched that the lower limbs fractures due to the impact with the front bumper, with a higher level than 2 on the AIS (Abbreviated Injury Scale), were distributed as follows: 55% of the fractures occurred in the tibia and fibula; 32% of the fractures were in the tibia; 10% of the fractures occurred at the knee ligaments [3]. These injuries require a long term hospitalization, and are interfering with the daily activities, thus the injury mechanism in the case of collision with the vehicles must be analyzed in order to reduce the number of fatalities.

After determining the injury mechanism, it is necessary to perform an accurate accident reconstruction. When this is performed, the injuries are considered the starting point of the reconstruction [4]. In case of real accidents, the injuries can give information regarding the impact velocity, but also the positions of the pedestrian and the vehicle in the moment of impact [5]-[7]. The position of the front bumper and the type of injury have to be determined in the reconstruction.

The most important parts of the lower limbs, where the forces appear during the impact are the femoral bone respectively tibia and fibula.

The femoral bone is the longest bone of the human body. It connects the pelvis with the fibula and tibia. Any lateral force upon the knee articulation acts like a bending moment upon the femoral bone. Any type of accidents where pedestrians are involved lead to a bending of the femoral bone [8].

The bending tolerances both static and dynamic of the tibia were given in previous studies. For example, Yamada (1970), presented the static bending moment of tibia [9], after the tests performed by Motoshima in 1960 with a medium tolerance of 184 (N·m), which indicate that the man have a resilience of 6 times higher than women. For dynamic bending, Nyquist et al. (1985) reported that the fractures that appear in the middle of tibia occur at moments of 280 (N·m) for women, and 320 (N·m) for men, independently of the impact direction [9].

The structure of the front bumper of the vehicle has a major importance in pedestrian safety. In this regard, using structures for absorbing energy were proved to be efficient. In order to reduce injuries that appear in the lower limbs, composite elements were used in the structure of the energy absorbers. In certain environmental conditions, the legform impactors used in EEVC (European Enhanced Vehicle-Safety Committee) tests were investigated [9].

There are two different types of legform impactors used in the tests regarding the pedestrian safety: TRL and Flex-Pli. TRL impactor is used in the European programme Euro NCAP (New Car Assessment Programme), while the impactor Flex-Pli is used in the tests performed in Japan, by JNCAP (Japan New Car Assessment) [10].

II. Biomechanical Model of the Leg

To study the severity of the injury that appears in the lower limbs due to the collision between a vehicle and a pedestrian, the bio-mechanical model of the leg was built. The model was created in the Matlab software package, using the Simmechanics and Simulink extensions. The model contains 3 parts, which are interconnected with a rotation joint. This joint has one degree of freedom, allowing one rotation.

The biomechanical model of the lower limb was constructed based on the following assumptions:

1) The elements of the leg are connected by ideal joints and all axis of rotation are parallel

2) The joints used are rotation joints, with one degree of freedom, while the leg of the pedestrian model used by PC-Crash is composed by joints with more than one degree of freedom.

3) The model is fixed to the base with a rotation joint in the upper part, and all the movement of the other elements of the model occur relative to the base, while in the simulation with PC-Crash, the hip of the pedestrian model has also a movement

From the traffic accident reconstruction software PC Crash, version 10.1, were obtained the values of the forces acting upon the leg, at the moment of impact. The collision was framed in the accident scenario. The accident is described in the following.

A vehicle was driving on the right side of the road, while a pedestrian was walking towards the vehicle on the same side of the road. The vehicle braked, but the collision couldn't be avoided. The impact took place at a velocity of 20 (km/h). By simulating the impact, the software was able to compute the impact forces that act upon the leg of the pedestrian. The value of the force acting upon the tibia is presented in Fig. 1. The peak value of the force that acts upon the tibia is obtained after 0,060 (seconds), with a magnitude of 200,86 (N).

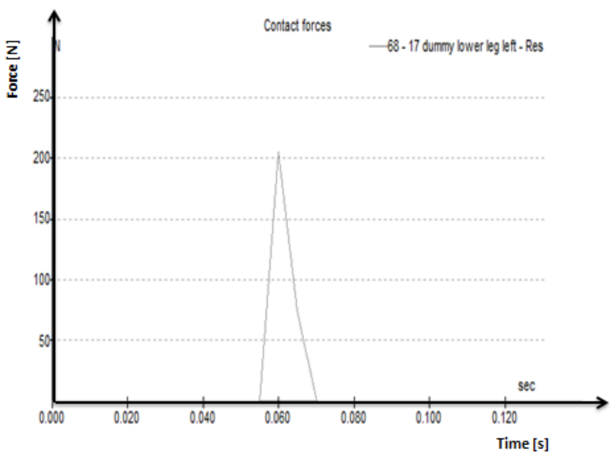

Fig. 1. Force diagram from PC-Crash

These values were used as input data in the biomechanical model of the leg. The scale for the model is 1:1. The length of each part of the model is similar to the dimensions of a Hybrid III 50th percentile male dummy. Also the pedestrian that PC-Crash is using has similar anthropometric characteristics as the dummy.

For realistic behavior of the leg model, it was necessary to consider also the values of the forces that act upon the femur and the foot at different time points.

In the figures below are shown the similarities between the behavior of the leg between the simulation and the proposed biomechanical model at different time points (Fig. 2, Fig. 3 and Fig. 4).

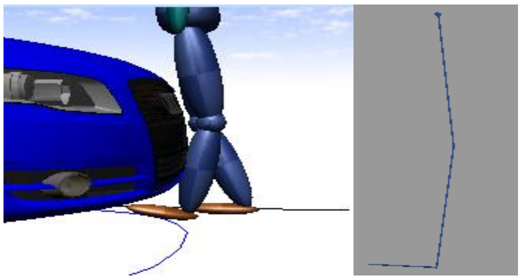

Fig. 2. The beginning of the impact

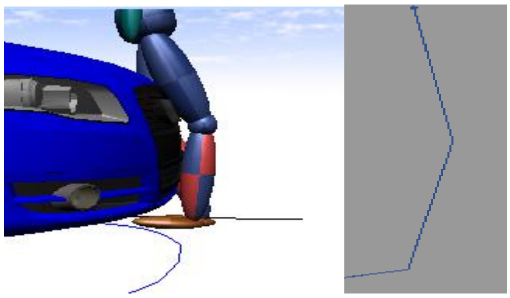

Fig. 3. The moment when the force is applied on the tibia

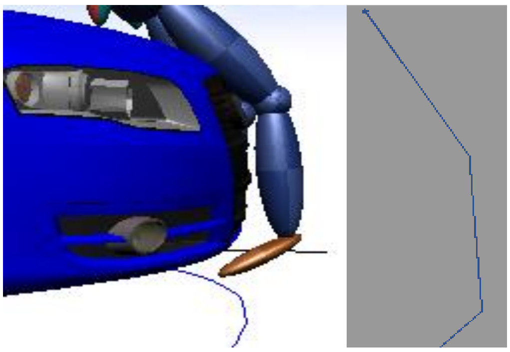

Fig. 4. The moment when the pedestrian leg is raised up from the ground

In the left side of Fig. 2 is presented in the PC-Crash software the beginning of the impact where the lower leg is bended by the force applied by the front bumper of the vehicle. On the right side of the picture it is presented the bending of the biomechanical model built in Simmechanics which is subjected to the same values of the force. At this time point, the force applied is upon the femoral bone.

The Fig. 3 presents the moment when the force is applied both on the tibia and the femoral bone, tibia having a higher value of force applied.

In the Fig. 4 on the left side is presented the last phase of the impact when the lower limb is raised up from the ground due to the moments of inertia generated by the forces applied. On the right side of the picture is shown the biomechanical model built in Simmechanics behaving similar with the pedestrian from the PC-Crash simulation, being subjected to the same values of the forces.

To determine the injury of the tibia, the values necessary to calculate Revised Tibia Index were computed. Tibia Index is a criterion regarding the injury tolerance of the tibia, using for calculation bending moments and axial compressive loads. Tibia Index is used in some tests regarding pedestrian safety. It has been developed to evaluate tibia and fibula fractures. This criterion does not include the injury severity of the foot or ankle. It has been developed by performing tests on PMHS (Post Mortem Human Subjects) [11].

Later was observed that the values for critical bending moment and critical compression force are not realistic, therefore new values were determined, giving a Revised Tibia Index (RTI).

The maximum bending moment determined with the biomechanical model was 25,2 (N·m). This value was used to determine Revised Tibia Index. The diagram of the tibia bending moment is presented in Fig. 5.

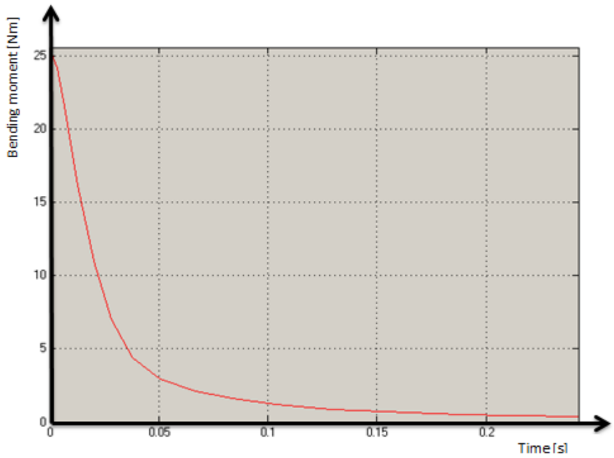

Fig. 5. Tibia bending moment diagram

In Fig. 6 is shown the scheme of the model built in Simulink.

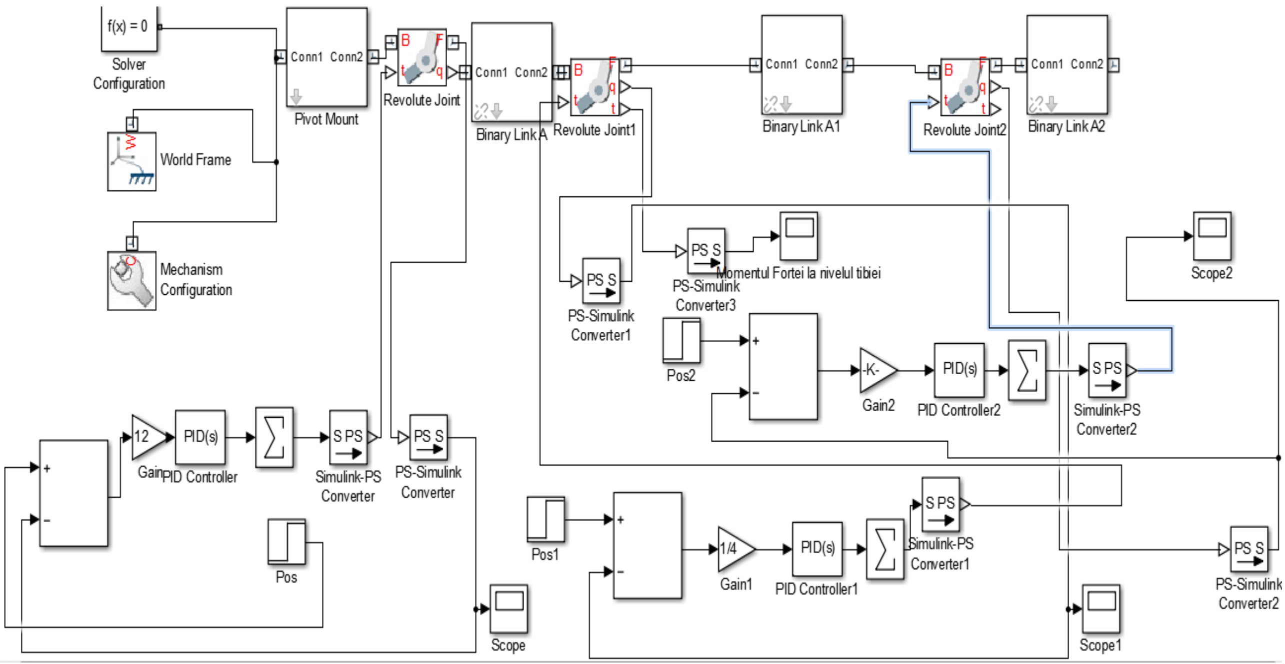

Fig. 6. Scheme of the model built in Simulink

The differences on the time scales between the model and the simulation is due to the position of the pedestrian used in PC-Crash in the collision configuration. The simulation started before the contact between the vehicle and the pedestrian took place.

III. CALCULATION OF REVISED TIBIA INDEX (RTI)

According to Tim Wehner et. al., the value of axial compression force of the tibia can reach up to 1,5 BW (Body Weight) [11]. In the given case, the pedestrian is in the "Foot Flat" phase from the gait cycle in the moment of impact, therefore, all the body weight it is transferred on the leg which is positioned on the ground. Consequently, the value of the axial compression force in the tibia is 1 (BW). The weight of the pedestrian used in the simulation is 80 (kg), while the height is 1,79 (m).

RTI is calculated with the following equations:

$$F_Z = m_{ped} \cdot g = 80 \cdot 9{,}81 = 0{,}78 \text{ (kN)}, \quad (1)$$

$$M_x = 0, \quad (2)$$

$$M_R = M_y = 25{,}2 \text{ (N·m)}, \quad (3)$$

$$RTI = \frac{M_R}{240} + \frac{F_z}{12} = 0{,}17 \quad (4)$$

where:

F_Z – Axial compression in Z- direction (kN);
m_{ped} – Mass of the pedestrian (kg);
g – gravitational acceleration (m/s^2);
M_R – Maximum bending moment (N·m);
M_x – Bending moment on the x axis (N·m);
M_y – Bending moment on the y axis (N·m).

According to Shashi Kuppa et. al the probability of an injury higher than AIS 2 with respect to Revised Tibia Index is very low, at the RTI value of 0,17. The diagram is presented in Fig. 7.

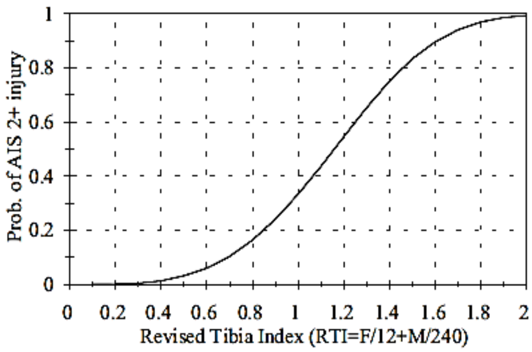

Fig. 7. Probability of an injury higher than AIS 2 with respect to RTI [12]

The severity of the injury of the lower leg was determined with the AIS scale. Abbreviated Injury Scale it is an anatomic assessment system regarding the severity of the injuries, introduced for the first time in 1969. Since then, the system was revised and updated constantly, therefore currently represents an accurate solution regarding the assessment of injury severity. The AIS system is developed and monitored by Association for the Advancement of Automotive Medicine (AAAM). The current edition, AIS-2005, updated in 2008, represents the result of a revision which lasted 5 years, involving hundreds of people from USA, Australia, Canada, New Zeeland and other European countries[13].

AIS is classified on a scale from 1 to 6, where the digit 1 represents minor individual injuries, while the digit 6 represent life threatening injury. Code 6 doesn't mean the person will die, but means an injury with a high lethality. AIS categorize and describe specific individual injury severity in a coded system and the basis of evaluation models of multiple injuries and assessment of cumulative effects of multiple injuries [13].

The classification of the AIS code is presented in the table I [14].

TABLE I
CLASSIFICATION OF THE AIS

AIS Code	Severity
0	No injury
1	Minor
2	Moderate
3 *4* *5* *6* *9*	Serious Severe Critical Fatal No additional information

IV. CONCLUSIONS

The obtained biomechanical model is capable of reproducing the behavior of the human leg during the impact by introducing values of the impact forces. The magnitude of the tibia bending moment obtained with the biomechanical model is plausible, and it can be stated that the obtained value of RTI is real.

From RTI value was determined that the probability of tibia injury higher than AIS 2 in the case of the collision of a vehicle driving with 20 (km/h) with a pedestrian is close to 0. The injuries that have a code 0 or 1 on AIS don't require long hospitalization time.

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