TIME SCALE ANALYSIS APPLIED TO LOWER LIMB IMPACT TEST

[1]Gabrielli F., [2]Guillemain P., [1]Masson C.

Laboratoire de Biomécanique Appliquée, UMRT 24 INRETS, 13916 Marseille Cedex 20, France
Laboratoire de Mécanique et d'Acoustique UPR CNRS 7051, 13402 Marseille Cedex 20, France

ABSTRACT

Pedestrian safety is a current issue and the lower limb being widely injured during vehicle-pedestrian crash, injury mechanisms of the lower limb are being investigated. Impact tests were conducted on isolated lower limb in order to reproduce pedestrian injuries such as ligament rupture and tibia fracture. Accelerometer signals were then processed using time scale analysis and a new injury criterion is defined, based on how transient the signal is. The criterion successfully discriminates ligament injuries from bone injuries and creates a way to get the chronology of the injury during an impact test on cadaveric specimen.

Keywords : BIOMECHANICS, INJURY CRITERIA, KNEES, DATA PROCESSING

IF PEDESTRIANS SUSTAIN multisystem injuries, head and lower extremities injuries are the most frequently injured body regions. Particularly, lower limbs are highly loaded during crash situations with joints damages and bones failures (Stutts 1999). To improve the understanding of the mechanisms and establish tolerance criteria for lower limb, coupled experimental and numerical studies were conducted. Experimental studies were performed to represent condition of pedestrian accident focusing on the lower limb (Kajzer 1993, Masson 2005, Masson 2006) and concluded that collateral tibial ligament and anterior cruciate ligament are mostly injured by shearing and bending effect of lower limb impact.. Results were confirmed by (Bose 2004)., Posterior cruciate ligament injuries, fibula, tibia and femur fractures can also be observed. Recent researches on pedestrian injury using PMHS focused on sustained injuries. They reported in details bone and ligament injuries, proposed injury criteria and gave only typical load or accelerometer responses of the lower limb (Kerrigan, 2003; Bose, 2004; Ivarsson, 2004).
Unfortunately those methods lack an injury identification technique. Indeed whereas autopsy is generally done after impact test, no clues are given concerning the timeline of injury. (Kajzer 1993) based its interpretation on a drop of the knee shearing force that can be more sudden in the case of bone fracture than in the case of ligament failure. (Kerrigan 2003) proposed to place Acoustic Emission sensor and set the occurrence of lesion as the first instant of apparition of fluctuation on the AE. More generally speaking, in the case of sub system impact test on lower limb with limited solicitation, injuries are considered to occur as there is a drop in the effort/displacement curve. It is clearly enough in the case of a single injury but (Bose 2004) concluded that it is difficult to identify the timing and threshold of multiple injuries. The present paper introduces a new methodology based on time scale analysis of the accelerometer signal that leads to an identification of the injury and its localisation in time.

MATERIALS AND METHODS

The experiment consisted in lateral impacting an isolated lower limb stood up straight. The impactor had a mass of 37kg including instrumentation. Impact experiments were conducted on 13 human lower limbs. The subjects are Post Mortem Human Subjects (PMHS) who have given voluntary before dying their body to the science. The joint range of physiological mobility, knee laxity and bone integrity were checked by an anatomist surgeon. Ages of subjects were 78±8 years.

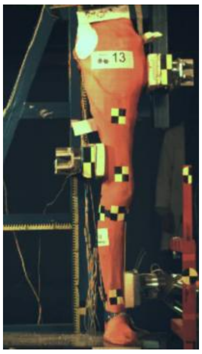

Figure 1 - Experimental set up for impact test #13, impact on lower leg

The thigh was blocked with 2 foam-padded plates: one was placed on the external face at femoral condylar level, the second on the internal face at pubic bone level. The foot was on a mobile plate to minimize ground friction and a mass of 40kg allowed preloading the lower limb (Figure 1). In order to reproduce the large spectrum of injuries, impacts were performed by loading the leg at three different heights: upper leg (right under the knee), mid leg and lower leg (right upper the ankle). The impact tests were performed at 5.2-6.5m/s. Limbs were instrumented with 4 3D accelerometers: upper femur, lower femur, upper tibia and lower tibia. Only lower femur and upper tibia accelerometer signals were processed in the present study in order to characterise knee injuries. Signals were sampled at 10kHz and impact time is set at 0.5s and therefore time will be referred to it as a time difference in millisecond (ms). Legs were then fully autopsied by an anatomist surgeon.

Accelerometer signals are then processed. When an injury occurs, strains in the material are relieved, which generates a high frequency wave in the bone, leading to an increase in the signal frequency bandwidth. We made the hypothesis that transient signal depends on the injury: a bone fracture would generate a more transient signal than a ligament failure. In order to quantify the transient within the accelerometer signal we propose a method based on the Continuous Wavelet Transform (CWT). The continuous wavelet transform of a signal x(t) is defined by:

$$CWT_x^{\Psi}(b,a)=\int_{-\infty}^{+\infty} x(t)\frac{1}{\sqrt{a}}\,\overline{\Psi}\left(\frac{t-b}{a}\right)dt$$

with Ψ (t), a modulated Gaussian (Morlet wavelet): $\Psi(t)=e^{-\frac{t^2}{2}+j2\pi f_0 t}$

The Morlet wavelet is localized around time t = 0 and its Fourier transform is centered on frequency f_0. It is easily understood that the function Ψ ((t-b)/a) is localized around t = b and its Fourier transform around f = f_0/a. Hence |CWT(b,a)|, the magnitude of CWT, represents the square root of the power density of the signal x(t) around the time t = b and the frequency f = f_0 / a. The CWT was applied to each accelerometer signal. The output of the CWT analysis is called a scalogram, which is a three-dimensional representation where time is on the x-axis, frequency (related to scale) is on the y-axis, and magnitude is on the z-axis (Figure 2).

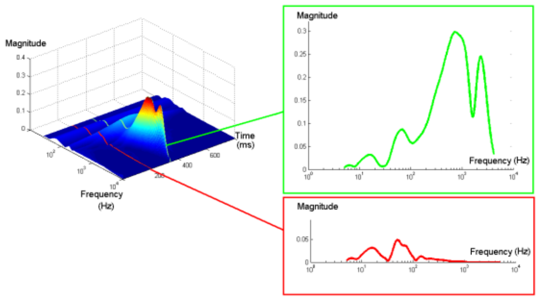

Figure 2 - Scalogram selection at two separate instants with different upper frequency spectrum

A criterion was developed to determine the time of injury by correlating the frequency bandwidth with the injuries documented form the autopsy. The methodology consists of seeking a wide band of energy at a given time. It is adapted from a methodology proposed by (Kang 2003). The strength of a transient is defined as the integral of the module of the CWT from the finest scale (corresponding to the maximum frequency and set to 1) up to a cut off scale a_c (corresponding to a cut off frequency f_c) :

$$\delta(b) = \int_{a_{\min}}^{a_c} \left|CWT_x(a,b)\right| da$$

The resulting criterion reflects both the instantaneous bandwidth and the signal power. The greater the magnitude of the criterion, the greater the energy in the upper section of the spectrum and the more transient the signal (Figure 2). The phenomenon was analyzed by plotting the maximum of the function δ for all the three directions of each accelerometer for each impact test as a function of the translation integer b. Thresholds were defined for the criterion δ by correlating its value with the results of the autopsy: impact test leading to ligament injury only or bone injury only gave the corresponding thresholds. Based on those thresholds, more complex impact tests were analyzed in order to confirm the autopsy in the case of multiple injuries.

RESULTS

Table 1 shows the injuries listed after full autopsy of the 13 legs and the peaks reached by the transient criterion. Injury legend includes: Nothing to report (N.T.R.), Anterior cruciate ligament (ACL), Collateral Tibial ligament (CTL), Posterior cruciate ligament (PCL), and leg #3 revealed a bone tissue affected by adipose and osteoporose. From table 1 two thresholds were successfully determined that discriminate a ligament injury from a bone injury, based on how transient the signals are. When the criterion reaches the first threshold level, referred to as ligament level or LL and set to 300, the corresponding sensor detects a lesion at a ligament. When the criterion reaches the second level, referred to as the bone level or BL and set to 1200, the corresponding sensor detects a lesion linked to a bone material. The cut off frequency that maximizes the difference between the criterion level of a fracture and the criterion level of a ligament rupture is set at 2250Hz, corresponding to a_c=3.77.

Table 1. Transient criterion fits with injuries reported by autopsy

Impact	Injuries reported by autopsy	Transient criterion reached
1,2,9,11,13	N.T.R.	120
3	Tibial fracture, adipose	800+1800
4	Fibula head fracture	1400
5	ACL rupture	500
6,7,8,12	CTL rupture	600
10	CTL,ACL,PCL rupture, tibial diaphyse fracture	650+3800

Figure 3 shows the accelerometer resultant for the femur sensor and the tibia sensor and the resulting criterion for the impact test #10. For this test, the autopsy showed rupture of CTL, ACL, and PCL and a fracture of the tibial diaphyse. The transient criterion successfully discriminated two ligament ruptures around 30ms from a bone injury at 110ms where accelerometer resultant is unable to differentiate efficiently the two injury types.

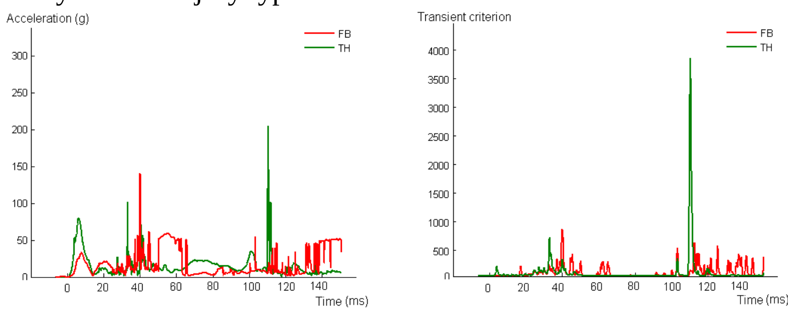

Figure 3 - Acceleration resultant and transient criterion for impact test #10

DISCUSSION AND CONCLUSION

Several lower limbs were impacted in order to induce ligament and bone injuries that mimic pedestrian injuries. The results of the present study showed that a methodology based on time scale representation is promising for discriminating ligament from bone lesion and determining the time window of the lesion occurrence. A direct application is a better understanding of the timing of injuries that could be a useful tool for full-scale car crash reconstruction: it may allow to associate a specific source to a specific injury or to leave less space to hypothesis based on final autopsy. One major improvement compare to AE analysis (Kerrigan 2004) is the ability to discriminate ligament rupture from bone fracture from processing of the accelerometer signal only. There is no need to add extra sensors or to increase sampling frequency. In addition, the injury detection criteria is not based on a external sensors that measure a shearing or bending effort and thus is not influenced by the thickness of soft tissue. More generally, a commonly accepted criterion for injury occurrence is a drop in the effort-displacement curve: in the case of full scale experimentation, such a signal is not available and therefore one must rely on internal sensors only. Table 1 shows that a ligament failure would induce a peak in the transient criterion for sensors placed on bones that are linked to the ligament. Both cruciate and lateral ligament failures are visible from sensors on femur and tibia. This could lead to a reduction of the number of sensors for a given impact test. A side application would be cross comparison with timing of injury proposed by finite element models (Arnoux 2002, Beillas 2001). FEM gives access to internal injuries as they reproduce full anatomy and their accuracy to predict ligament injury could be confirmed by application of the transient criterion to impact test that can be completed both experimentally and numerically. A limitation to the study is that it is not yet possible to differentiate the bone fracture of a bone affected by adipose from a ligament failure (Table 1): both lesions generate a transient criterion of the same magnitude. Further work is being done to remove that issue and define a more precise signature of a fracture of a bone affected by adipose.
To conclude, a new application of CWT was developed for impact biomechanics. CWT allowed to characterize a transient within a signal that is the image of an injury in order to localize it in time.

ACKNOWLEDGMENTS

The authors want to thank Max Py and Christophe Reigner for their exceptional work on the experimental part of the study.

REFERENCES

Arnoux, PJ, Knee ligament failure under dynamic loadings, International Journal of Crashworthiness,7:3, 2002, 255 — 268
Beillas, P., Lower Limb: Advanced FE Model and New Experimental Data, Stapp Car Crash Journal, 2001, pp. 469-494,.
Bose D., Response of the knee joint to the pedestrian impact loading environment, SAE World Congress, 2004., SAE paper no. 2004-01-1608.
Ivarsson J,. ”Dynamic Response Corridors and Injury Thresholds of the Pedestrian Lower Extremities. IRCOBI 2004
Kajzer, J., Response of the knee joint in lateral impact: Effect of bending moment, International Conference on the Biomechanics of Impacts (IRCOBI), 1993.
Kang P.,.Characterisation of vibration signals using continuous wavelet transform for condition assessment of on-load tap-changers, Mechanical Systems and Signal Processing,17(3), 2003, 561–577
Kerrigan, J. R., Tolerance of the human leg and thigh in dynamic latero-medial bending, International Journal of Crashworthiness,9:6, 2004, 607-623
Masson C.Pedestrian injury mechanisms & criteria .A coupled experimental and finite element approach. 19th International Technical Conference on the ESV, 2005
Masson C.. The influence of the impact point on pedestrian lower limb injury and criteria. Journal of Biomechanics, Vol. 39 (1), 535, WCB2006
Stutts J. C, Motor Vehicle and Roadway Factors in Pedestrian and Bicyclist Injuries: an Examination Based on Emergency Department Data. *Accident Analysis and Prevention.* Vol. 31, 1999. P. 505-514