INJURY BIOMECHANICS RESEARCH
Proceedings of the Thirty-Sixth International Workshop

Rib Failure Detection Using Time-frequency Analysis: A Feasibility Study

D. Subit, E. Ogam, F. Gabrielli, P. Guillemain, R. Kent, and C. Masson

ABSTRACT

Experimental testing is a major source of data to quantify the tolerance of the human body to impact and to develop protection strategies. In the field of vehicle safety, it has been demonstrated that chest injuries are a good predictor of an impact severity. Correlating the time of rib fractures with the kinematics of the occupant and the action of safety systems would provide valuable data for assessing safety systems and developing injury risk functions. However, there is currently no satisfying method to monitor rib fractures; time history analysis of strain gauges data is commonly used for this purpose, but this method is not very sensitive and requires instrumentation of the ribcage with more than 100 strain gauges. A new approach based on time-scale analysis of signals obtained from piezoelectric transducers (PZT) was investigated. A post-mortem human subject was instrumented with four PZT on ribs 3 and 7 on both sides and was laterally-impacted to the shoulder and the chest. The fractures were documented after each test, and a criterion was developed to process the PZT signals. The criterion consists in detecting in the PZT signal the onset of a high frequency transient generated by the fracture of a rib using the continuous wavelet transform. Two thresholds were successfully determined to detect fractures that occurred (1) on an instrumented rib, and (2) on the rib close to it. Further development of this method should allow the detection of all rib fractures using only a few PZT.

INTRODUCTION

A comprehensive understanding of injury mechanisms remains an important and elusive challenge for designers of vehicle safety countermeasures. Tests performed in impact biomechanics allow to reproduce in the laboratory impact conditions that are observed in real life accidents. In the field of car safety, the chest injuries are a good predictor of an impact severity because rib fractures compromise the ability of the chest to protect internal organs critical to life such as the lungs and the heart. Correlating the time of bone injury with other events such as the kinematics of the occupant and vehicle, the action of safety systems, and measured chest deformation would provide valuable, unbiased data for assessing safety systems and developing statistically based injury risk functions. Moreover, the capability to monitor rib fractures in the case of an impact to the chest would allow to run several none injurious impact tests on one given subject, either for multiple test conditions or various impact velocities. This would cancel the influence of inter-subject biological variability that alters their mechanical response for a given impact configuration. Performing a CT-scan after each test to assess the rib fractures does not provide the required level of accuracy. Indeed, the only reliable way to document rib injuries is to perform an in-depth necropsy (Kent et al., 2002), because non-displaced fractures cannot be seen on CT images. Non-displaced fractures are however, critical to document because they decrease the chest strength (Kuppa and Eppinger, 1998). Sensors to identify the timing and location of both displaced and non-displaced bone fractures in the chest during an impact have not been convincingly demonstrated. Strain gauges are commonly used to achieve this goal (Lebarbe et al., 2005, Kemper et al., 2008; Trosseille et al., 2008). At the time of fracture, strain is released and a brutal drop can be observed in the strain measurement. This drop in the strain time-history is used to determine if and when there was a rib fracture (Lebarbe et al., 2005). The limitation in this approach is to rely on the amplitude in the temporal domain; any attenuation in the signal challenges the ability to predict fracture. This limitation is due to the short detection range of the strain gauges. A fracture has to happen within about 50 mm of a strain gauge to be detected by this strain gauge (Lebarbe et al., 2005). As a workaround, 5 to 6 gauges per rib are commonly required to properly map the fracture timing of a chest. Installing more than 100 strain gauges per chest is an invasive procedure and requires the set-up of the same number of data acquisition channels. An alternative methodology based on time scale analysis is investigated in the present paper to overcome these limitations. Time-scale analysis (TSA) is a signal processing tool based on wavelet decomposition already used in mechanics to study transient and fast changing signals (Gaul and Hurlebaus, 1998; Meo et al., 2005; Guillemain and Kronland-Martinet, 1996; Cheng and Pellettiere, 2003; Knox, 2004). TSA has been used in biomedical analysis (Akay, 1998), for gait analysis (Verdini et al., 2000), or used to localize and identify impact location on a plate (Gaul and Hurlebaus, 1989; Meo et al., 2005), but it has never been used in impact biomechanics. Piezoelectric transducers (PZT) are used to measure rib deformation. PZT transform the mechanical deformation in any direction into a voltage. They are different from strain gauges that measure deformation in only one direction. The objective of this study is to determine how TSA can be used to detect rib fractures during an impact test performed on Post-Mortem Human Subjects (PMHS) instrumented with PZT. Six full-scale lateral impact tests were performed on one PMHS. Ribs 3 and 7 on each side were instrumented with a PZT. The rib fractures were assessed after each test. The fracture data were supplemented with the PZT data process. Two fracture thresholds derived from TSA were evaluated to correlate rib fracture occurrence with PZT signals.

MATERIALS and METHODS

Side impact

One PMHS (male, 47 kg, 173 cm, cause of death: lung cancer) was selected for this study, based on the absence of pre-existing fractures, lesions, and other bone pathology, as confirmed by pre-test computed tomography (CT) analysis. The cadaver was obtained and treated in accordance with the ethical guidelines established by the US National Highway Traffic Safety Administration (NHTSA), and all testing and handling procedures were reviewed and approved by an independent oversight committee at the University of Virginia. The subject was screened negative for infectious diseases and stored in a freezer (-15˚C) until it was removed and thawed at room temperature 48 to 72 hours prior to the pre-test preparation. Incisions were made at the level of the anterior left and right ribs 3 and 7 (Figure 1). The soft tissues and periosteum on the section of the rib where the PZT (see following section) were to be installed were removed to clear the rib bone. The rib bone was then dried with an isopropanol solution to remove grease. Next, the cleared rib bone was sprayed with a cyanocrylate activator (Loctite, #7455), and the surface of the PZT to be affixed to the bone was covered with cyanocrylate glue (Loctite, #382). Finally, the PZT was pressed against the bone for about 10 seconds, until the glue hardened.

The subject was seated on a simplified seat designed to mimic a standard car seat. The impacts were applied using a pneumatic impactor. A catching system was used to prevent interactions with the ground and avoid any fractures that would be artifact. The impact velocity was 3 m/s. The subject was successively impacted at 3 levels (Figure 1): shoulder (S) with the arm along the chest, upper chest (U), and mid chest (M), both with the arm at 90˚ flexion.

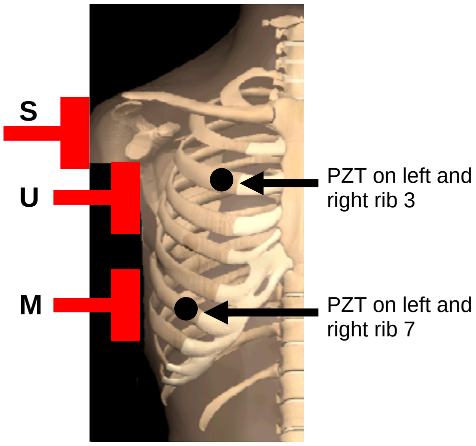


Figure 1: Position of the impactor for the shoulder, upper chest, and mid-chest impacts. The PZT were installed on ribs 3 and 7.

Table 1 shows the sequence of impacts on the two sides of the subject. After each test, the rib fractures were detected via palpation by a physician-researcher with extensive experience in thoracic biomechanics. A careful necropsy was performed after the tests series to document the rib fractures produced by all the 6 tests.

Table 1. Test matrix and impacted ribs for each impact level (Right and left are defined with respect to the subject). In the 3rd column, RR: right rib, LR: left rib.

Impact number	Impact location	Ribs impacted
1	Right Shoulder (RS)	RR1
2	Right Upper chest (RU)	RR3 to RR4
3	Right Mid chest (RM)	RR5 to RR8
4	Left Shoulder (LS)	LR1
5	Left Upper chest (LU)	LR3 to LR4
6	Left Mid chest (LM)	LR5 to LR8

Injury report

Each injury was described as displaced, non-displaced, mono-cortical, or bi-cortical (Table 2, Figure 2). Fractures were found for ribs 3 and below. No fracture was detected after the impact on shoulder. As expected, not all the fractures were detected by palpation. Seven out of the ten fractures were not displaced. The success rate to detect non-displaced rib fractures is unusually high because the subject was thin which facilitated the palpation.

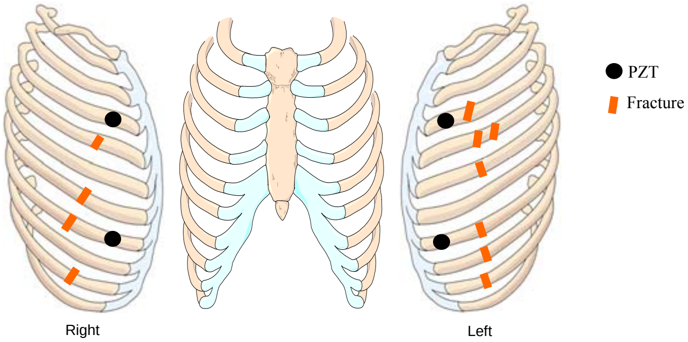


Figure 2: Injuries documented during the necropsy.

Table 2. Repartition of the injuries documented during the necropsy and by palpation after each test.

Impact test	Fracture detected by palpation & autopsy	Fracture missed during palpation and detected during autopsy
RS	None	Right rib 6 (non displaced) Right rib 9 (non displaced) Left rib 5 (non displaced)
RU	Right rib 4 (non displaced)	
RM	Right rib 7 (non displaced)	
LS	None	
LU	Left rib 3 (Bi cortical) Left rib 4 (Mono Cortical, fragments)	
LM	Left rib 7 (Bi cortical, displaced) Left rib 8 (Non displaced) Left rib 9 (Displaced)	

Piezoelectric Transducer (PZT)

PZT have the ability to generate an electric potential in response to applied mechanical stress. A useful PZT electrical model is a voltage source proportional to the applied strain in series with a capacitance *C*. Any resistive load *R* forms a divider network with a *RC* high-pass filter characteristic that determines the PZT resonance frequency. For frequencies below the resonance frequency, the PZT gives an output signal proportional to the rate of change of the strain (differentiator system). It is therefore an appropriate sensor to measure transient signals. The PZT for this study was chosen so that its resonant frequency was higher than the upper bound of the data acquisition system (DAS) frequency bandwidth. Figure 3 shows that the PZT was used in the optimum frequency range. The signals were sampling at 10 kHz with an Impax DSPT TRAQ-P 12 bit-resolution data acquisition system (DSP Technologies, Fremont, CA, USA). A low-pass anti-aliasing filter with a cut-off frequency *Fco* of 3.3 kHz was applied at the front end of the DAS. The 9.9 mm-diameter PZT with a resonant frequency of 7 kHz (model AB1070B, Projects Unlimited, Dayton, OH, USA) was found to be appropriate for this study because of its size (it fits on a rib bone) and its frequency response (Figure 3). No calibrating procedure was conducted prior to the impacts.

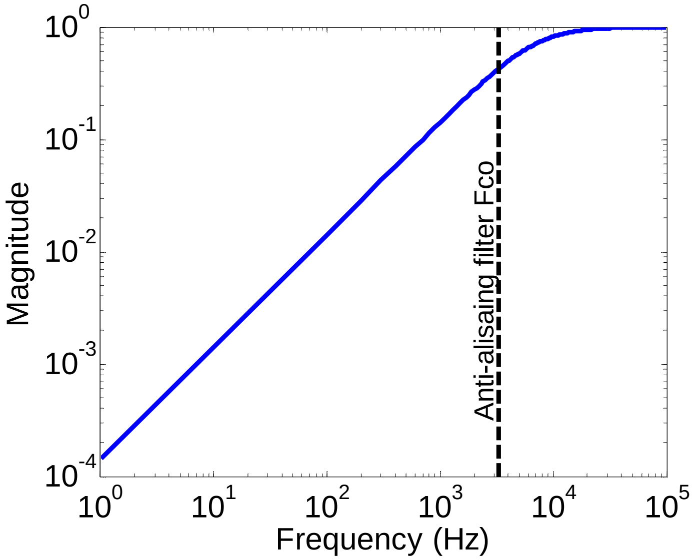


Figure 3: Frequency response of the PZT.

Time Scale Analysis (TSA)

In order to quantify the transient within the PZT signal we propose a method based on the Continuous Wavelet Transform (CWT). CWT is a technique of time-scale analysis. The continuous wavelet transform of a signal x(t) is defined by:

$CWT_x^{\Psi}(b,a) = \int_{-\infty}^{+\infty} x(t) \frac{1}{\sqrt{a}} \overline{\Psi}\left(\frac{t-b}{a}\right) dt$ where $\overline{\Psi}$ designs the complex conjugate of Ψ, and Ψ is the analyzing wavelet.

The wavelet transform is fundamentally a correlation between the signal x(t) and a wavelet function $\psi(t)$ translated by b and dilated by a. The chosen mother wavelet function $\psi(t)$, known as the Morlet wavelet, is a modulated Gaussian:

$$\Psi(t) = e^{-\frac{t^2}{2} + j2\pi f_0 t}$$

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 $\psi((t-b)/a)$ is localized around t = b and its Fourier transform around $f = f_0/a$. Hence |CWT(b,a)|, the magnitude of CWT, represents the power density of the signal x(t) around the time t = b and the frequency $f = f_0 / a$. The CWT was chosen for its ability to operate at every scale up to the defined maximum. In addition, as the wavelet analysis is smoothly done along the signal, it allows to localize any change in the frequency content or any transient (Guillemain and Kronland-Martinet, 1996). The CWT was applied to each PZT signals. Figure 4 shows a typical time-history response of a PZT. The output of the CWT analysis is called a scalogram, which is a three-dimensional representation where time is on the *x*-axis, scale (inversely proportional to the frequency) is on the *y*-axis, and magnitude is on the *z*-axis (Figure 5).

The evaluation of the strength of the transient is based on the fact that the shorter the transient in time, the richer its frequency content (Figure 5). The limit is the Dirac pulse, which has a zero length in time and an infinite frequency width. When a fracture occurs, strains in the material are relieved which generate a high frequency wave in the bone, leading to an increase in the signal frequency bandwidth. Therefore, the occurrence of a fracture can be detected by tracking the frequency bandwidth of the PZT signals as a function of time. A criterion was developed to determine the time of fracture by trying to correlate the changes in the frequency width with the fractures documented after each test.

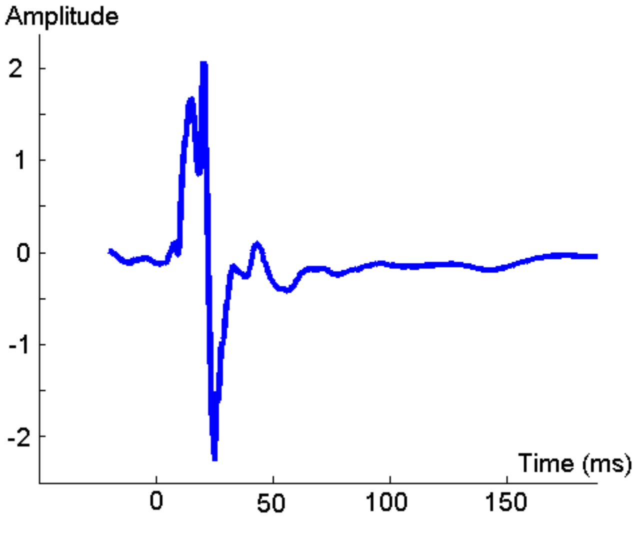


Figure 4: Example of time-history PZT response to chest impact.

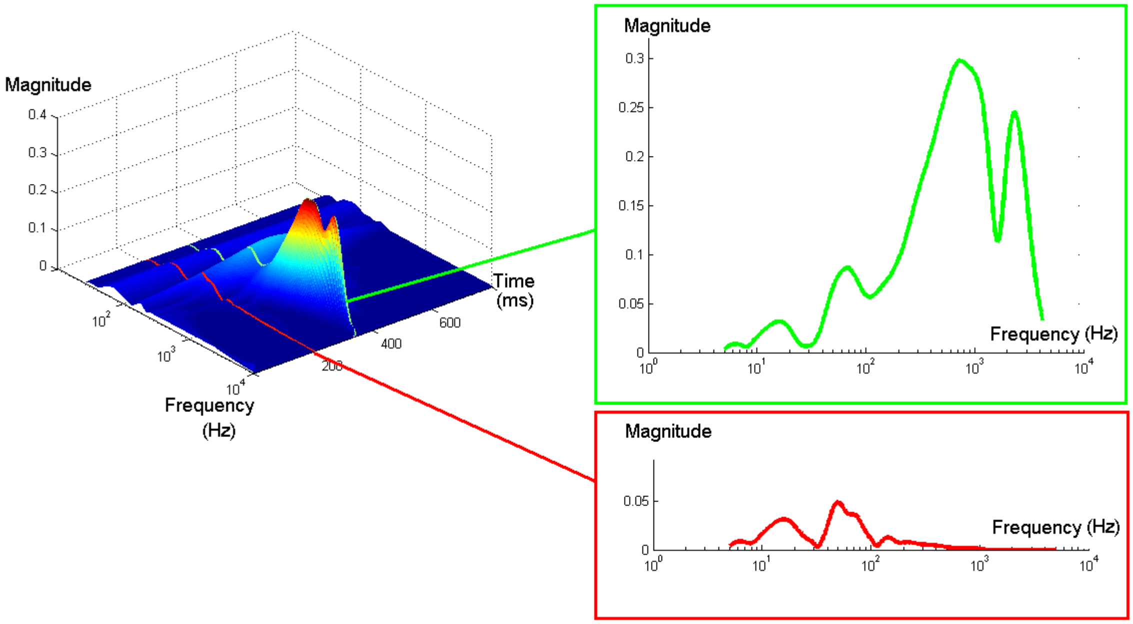


Figure 5: Scalogram selection at two separate instants with different upper frequency spectrum.

The methodology consists in looking for a wide band of energy at a given time. It is adapted from a methodology proposed by Antoine et al. (1997) and Kang and Birtwhistle (2003). The strength of a transient is defined as the integral of the module of the CWT from a given scale a_0 up to the finest scale, determined for the bandwidth of the DAS (3.3 kHz here):

$$\delta(b)=\int_{a_0}^{a_{\max}}\left|CWT_x(a,b)\right|da$$

The resulting criterion reflects both the instantaneous bandwidth and the signal power. The higher the criterion is, the greater the energy in the upper part of the spectrum and the more transient the signal. The more transient the signal is, the more likely it is to reflect the occurrence a fracture. Indeed, transient signals depend on the structure; when a rib brakes, there is a sudden change in the length of the structure to which the PZT is affixed. After fracture, the PZT remains on a smaller structure, and the energy released by the fracture generates a highly oscillatory signal. The phenomenon was analyzed by plotting the function δ for all the PZT for each impact test as a function of the translation integer *b*, which is the translation of the wavelet and consequently is equivalent to time.

Thresholds were defined for the criterion δ by correlating its value with the rib fracture occurrences (Table 2). Anytime the criterion overruns the threshold level T, a fracture has to occur nearby. The values of the threshold T and the parameter a_0 which delimits the low and high frequencies were determined so that the value of δ(b) was greater that T when a fracture was detected.

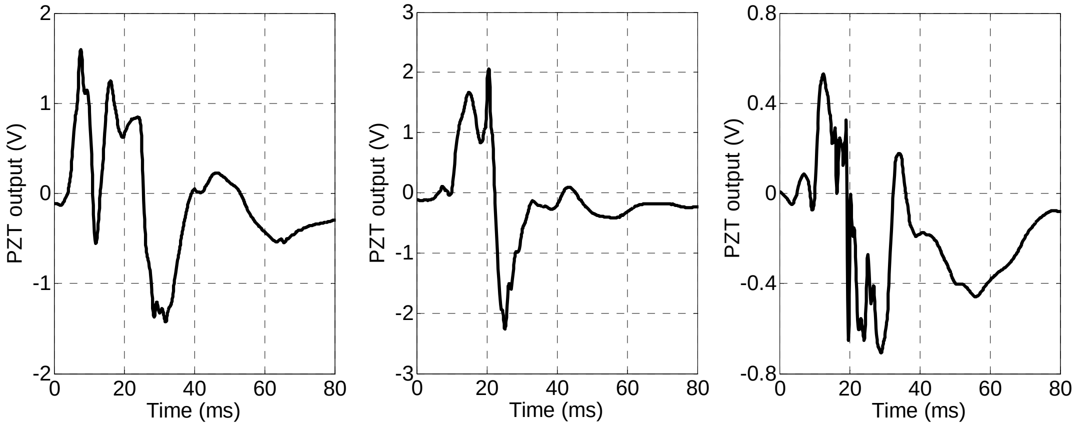
RESULTS

PZT signals

It was noted during the autopsy that the PZT LR3 was loose after the test series. It was not possible to determine when it occurred. The LR3 signal was, therefore, removed from the analysis.

Examples of PZT signals are shown Figure 6. These signals were recorded by the PZT on Right Rib 3 during the tests 1, 2, and 3. Fracture of right rib 4 was documented after Right Upper chest impact (Fig. 6(b)) and fracture of right rib 7 was documented after Right Mid chest impact (Fig. 6(c)). There is, however, no measurable differences in the PZT time-history signals between Figure 6(a) on the one hand, and Figure

6(b) and (c) on the other hand, to discriminate fracture occurrences. Therefore, the signals were analyzed using CWT.



(a) (b) (c)

Figure 6: No significant differences can be found between time-history of PZT signals (Right rib 3 PZT signals for tests (a) Shoulder, (b) Upper chest, and (c) Mid chest).

Transient criterion

Figure 7 shows the resulting criterion for the right mid chest impact (test 3). For this test, a fracture was detected by the PZT RR7. The criterion exhibits a large peak for RR7 and two smaller and delayed peaks for the PZT further away from the broken rib (LR7 and RR3). It shows that two thresholds for the criterion value can be determined to discriminate fractures that occurred on the rib to which the PZT is attached or on another rib. When the criterion reaches the first threshold level, referred to as close rib level or CRL, the corresponding sensors detected a fracture that occurred on a close rib. When the criterion reaches the second level, referred to as the very rib level or VRL, the very rib supporting the sensor fractured.

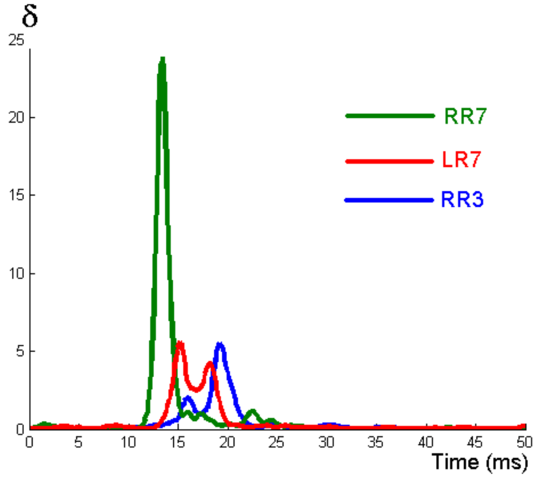


Figure 7: Values of the criterion for the impact to the right mid-chest calculated for the PZT signals on RR7, where a fracture was documented, RR3 and LR7 (a_0 = 120, corresponding to a frequency of 1 000 Hz).

A parametric study to assess how much the value of the criterion is sensitive to the value of a_0 was performed. The minimum criterion values for the PZT attached to a rib that broke, and the maximum values for the PZT attached to a rib close to a rib that broke were calculated for a_0 varying from 339 Hz to 2578 HZ (Figure 8).

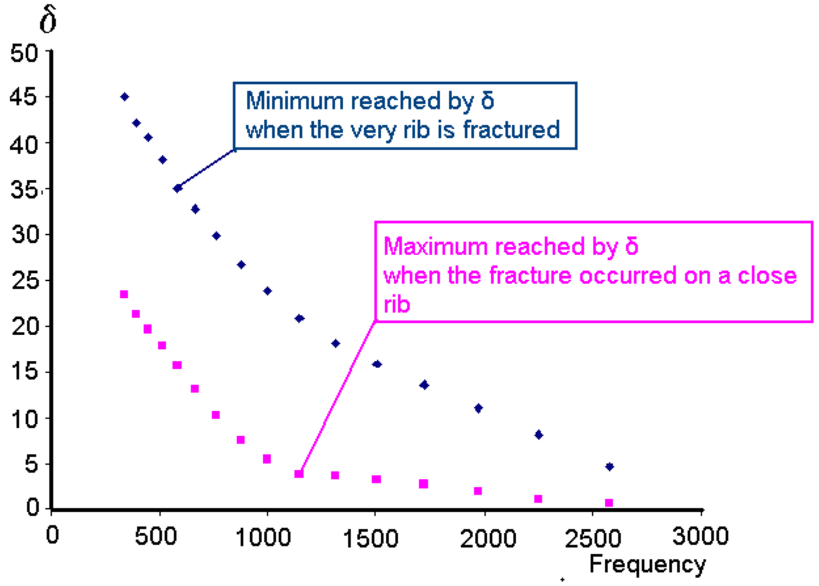


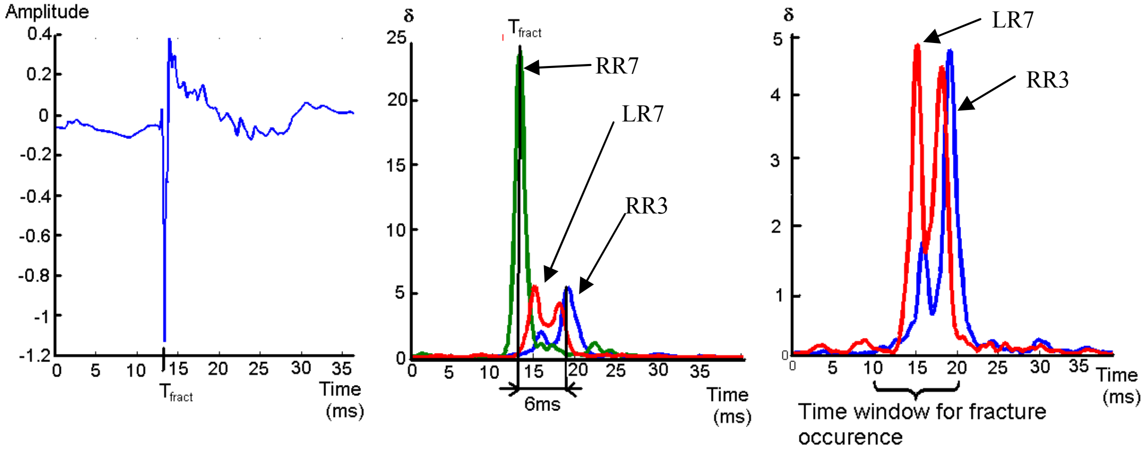
Figure 8: Variation of the criterion levels as a function of a_0.

As expected, the criterion value decreases with the frequency: the criterion is indeed the integration from the cut off frequency defined by a_0 up to the upper limit of the bandwidth, therefore the wider the integration domain, the higher the criterion. For the range of tested cut-off frequencies a_0, the criterion is able to discriminate a fracture occurring on a close rib from that occurring on the very rib. Very Rib Level and Close Rib Level were further investigated for a scale value a_0 of 110 corresponding to a frequency of 1145 Hz (Table 3). The Right Rib 3 PZT detected a fracture on a close rib for all the impacts except for the shoulder impacts. The Right Rib 7 PZT detected a fracture on its very rib during the right mid chest impact. Finally, the Left Rib 7 PZT detected a fracture on a close rib during the left upper chest impact and a fracture on its very rib on the left mid chest impact. Once a PZT had reached the VRL threshold for a test, it was removed from the analysis for the subsequent tests.

Table 3. Successful fracture detection using $a_0 = 110$ (f = 1145Hz) and VRL = 10 and CRL = 1.

	RS	RU	RM	LS	LU	LM
Test #	1	2	3	4	5	6
RR3	-	Close rib	Close rib	-	Close rib	Close rib
RR7	-	-	Very rib	-	-	-
LR7	-	-	Close rib	-	Close rib	Very rib
Palpated Fractures		Right rib 4	Right rib 7		Left rib 3, 4	Left rib 7,8 9
Fractures not detected during palpation	Right rib 6 (non displaced) Right rib 9 (non displaced) Left rib 5 (non displaced)					

If luckily a PZT is placed nearby the fracture location, the instant of fracture can be determined from the raw PZT time-history signal (Right mid chest impact, Figure 9(a)), without requiring any processing (it is, however, often not possible; see Figure 6). The results of the impact to the right mid chest were used to determine if there is any time delay in the fracture detection. Both the raw PZT signals and the corresponding value of the criterion show that the right rib 7 fracture occurred at time 13 ms (Figure 9 a and b). The RR3 and LR7 PZT saw this fracture too. The time differences in the peaks provide an estimate for the time of flight of the transient; LR7 detected the fracture after 2 ms, and RR3 after 6 ms. The further the PZT from the fracture location, the greater the time delay. Increasing the number of PZT would improve the accuracy of the fracture time prediction.



(a) (b) (c)

Figure 9: Right mid chest impact (a) PZT signal of RR7 with time of fracture at 13 ms. (b) Criterion for RR7 (green), LR7 (red) and RR3 (blue) with a delay of +6 ms. (c) Criterion for RR3 (blue) and LR7 (red) illustrating the time window of fracture occurrence.

DISCUSSION

Fracture detection

The injury report from the necropsy shows that a physician can easily miss non-displaced fracture during palpation and that it is therefore critical to have a tool that has a high success in fracture rib detection. The results of the present study showed that a methodology using PZT and time scale representation can be utilized to determine the time window of the fracture occurrence. A major improvement compare to the gauge-based method is the ability to detect a fracture even if it occurred on a non instrumented rib. Indeed the gauge needs to be on the broken rib and moreover, very close to the fracture location. Therefore, 20 PZT at most would be enough to lessen the risk of missing a fracture whereas more than 100 gauges are necessary to reach the same goal (Kemper et al., 2008; Trosseille et al., 2008). Ongoing work is being conducted to determine how to reduce the number of PZT while detecting all the fractures.

PZT location

For the subject used in this study, the fractures occurred on the anterior section of the rib, posterior to the PZT location. After fracture, the PZT remained attached to the short rib segment connected to the sternum. From Table 3, one could notice that once an instrumented rib is broken the PZT attached to it loses the ability to detect a fracture on an adjacent rib. Two explanations are proposed to explain this behavior. First, once the fracture has occurred, the stiffness of the rib is greatly reduced. Therefore, its ability to transmit high frequency waves decreases. Second, it is suggested that the transient signal generated by the fracture travels through the posterior rib and the spine, and not through the sternum. Indeed, the sternum is mainly made of cartilage that is a damping material compared to bone and could act as a low pass filter. On the contrary, the spine, especially on an erected subject, provides a stiffer structure than the sternum for wave propagation: the i^{th} rib attaches to the i^{th} and $i+1^{th}$ vertebra through the superior and inferior costal facet. Besides, the facet joints have very little cartilage. Consequently it is recommended to affix the PZT to the most posterior part of the rib. In this way, PZT should maintain their ability to detect fracture on a close rib after fracture of the rib they are fixed on.

Sensitivity to the parameter a_0

Results showed that a scale level a_0 could be found that separates high frequency from low frequency and that could detect a transient phenomenon in the signal, image of a fracture. The very rib level was straightforward to determine: the criterion always reached a very high level when the rib to which it was attached fractured. The challenge was more on the fine tuning of a_0 and CRL. Transient propagation within biological environment implies damping of soft tissues and joint connection between bony structures. High frequency composition of a transient is likely to be attenuated as the transient propagates through many biological structures. Thus, for a_0 that is too low, the band of frequencies considered as high would be very thin. It would make the PZT too restrictive and would deny it the capability of seeing a fracture occurring on a close rib.

Determination of fracture time

In the current analysis, the time of fracture was defined as the time when the criterion reaches a maximum. As a maximum in the criteria reflect an instant of high speed variation in the signal, the assumption that it is the instant of fracture is rather acceptable. A more acceptable assumption is that the fracture occurs within the time the criterion is above the threshold, leaving a window thin enough to narrow the origin of the fracture (Figure 10). In addition to that assumption several parameters have to be considered that widen the window of apparition of a fracture. One is the time of flight of the transient information if the PZT is on a close. A second parameter is the width of the Gaussian windows of the CWT. It decreases with the scaling parameter a. Thus, a lower a_0 would widen the peak of the criterion.

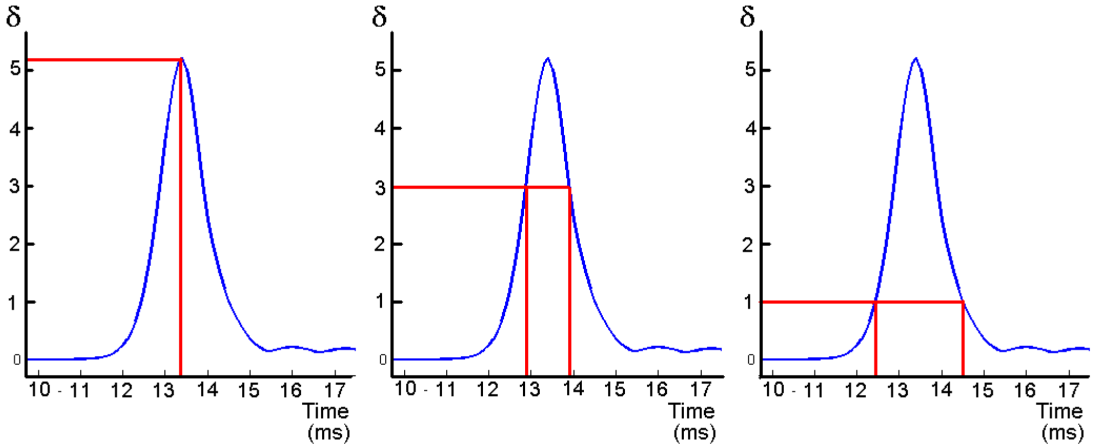


Figure 10: The window width depends of threshold.

Finally, the physics of the event - onset of a crack, propagation and maybe complete fracture – has not been taken into account yet. The frequency response of the fracture process certainly varies as the crack propagates in the bone. This needs to be studied to describe the characteristics of the transient itself and how the value of the criterion relates to the fracture process.

Limitations

The major limitation in the analysis presented in this paper is the use of most of the fractures; three fractures documented during the necropsy were not detected during the tests (Table 2). These factures altered the sensor data, but it is not possible to know for which test. As stated in the introduction, there is presently no method to detect fracture in a not too invasive way. The only way to surely document the fractures would have been to run this experiment on a denuded and eviscerated rib cage. The approach was, however, put aside because of the suppression of the soft tissue effects. The PZT measures the propagation of a transient signal, which depends on the structure. It was consequently crucial to maintain the integrity of the soft tissues. Now that the concept has been proven, and in particular, that it is possible to detect fracture of the rib instrumented with a PZT, similar tests with each rib instrumented need to be performed to obtain an exhaustive injury report after each test. The new data set should be used to determine the minimum number of PZT required to detect all the fractures. Indeed, the time delay observed between the signals from the PZT attached to the rib that was broken and from the other instrumented ribs could be seen as a 'time of flight' of the transient information (Figure 9). Such a piece of information could be further investigated in order to cartography the path of the transient through the several structures of the rib cage.

A second limitation to the study is that the criterion could be subject-specific. The energy measured at time of the fracture depends not only on the position of the sensors on the rib (a sensitivity analysis is required to estimate the influence of the PZT location on the measured signal), but also on the mechanical properties of the rib material and surrounding soft tissues - properties that are subject-dependent. Thus, the two thresholds that were determined from our methodology might be subject-dependent. Further analysis of the fracture process is required to better describe the link between the physics of the fracture process and the signal measured by the PZT.

CONCLUSION

This study introduces a novel methodology to determine rib fracture time in impact biomechanics testing (Gabrielli, 2009). Contrary to the common method that relies on time-history analysis of strain-gauge data, the proposed method uses an in-depth analysis of the sensor signal frequency content based on time-scale analysis. This new method which requires fewer sensors than the strain gauge-based method shows promising results by its capability to detect fracture even though it did not happen on an instrumented rib. The parameter a_0, introduced to delimit low and high frequencies, needs to be adjusted. Likewise, the phenomena that actually happen at time of fracture and generate the wave measured by the PZT need to be better understood to determine if the thresholds, VRL and CRL, are subject-specific. The proposed method demonstrates the capability of time scale signal processing to characterize a transient signal within a time signal and thus a way to detect rib fractures with a small number of sensors.

This study has been submitted to the Journal of Biomechanical Engineering: Gabrielli, F., Subit, D, Ogam, E., Guillemain, Ph., Kent, R.W., Masson, C., Time-frequency analysis to detect bone fracture in impact biomechanics. Application to the thorax.

ACKNOWLEDGEMENTS

The authors wish to thank Hervé Guillemot (University of Virginia, Virginia, USA, and Université de Valenciennes et du Hainaut Cambrésis, Valenciennes, France, for his contribution in the subject instrumentation and injury documentation, Sonia Duprey (Laboratoire de Biomécanique et Mécanique des Chocs, Lyon, France), and Sabrina Lau (University of Virginia, Virginia, USA) for their help with testing.

REFERENCES

AKAY, M. (1998). Time Frequency and Wavelets in Biomedical Signal Processing. IEEE Press Series on Biomedical Engineering.

ANTOINE, J-P., BARACHEA, D., CESAR, R.M. JR., and DA FONTOURA COSTA, L. (1997). Shape characterization with the wavelet transform. Signal Processing, 62, 265-290.

CHENG, Z. and PELLETTIERE, J. (2003). Correlation analysis of automobile crash responses based on wavelet decompositions. Mechanical systems and signal processing, 17(6), 1237-1257.

CRANDALL, J., KENT, R., PATRIE, J., FERTILE, J., and MARTIN, J. (2000). Rib fracture patterns and radiologic detection–a restraint-based comparison. Annual proceedings of the Association for the Advancement of Automotive Medicine, 235–59.

GABRIELLI, F. (2009). Apport des méthodes temps-fréquence de traitement des signaux non stationnaires à l'analyse du comportement humain au choc (in English : Time-frequency methods for the analysis of non-stationary signals in impact biomechanics), Ph.D. thesis, Université de la Méditerranée – INRETS (French National Institute for Transport and Safety Research), in preparation.

GAUL, L. and HURLEBAUS, S. (1998). Identification of the impact location on a plate using wavelets. Mechanical Systems and Signal Processing, 12(6), 783-795.

GUILLEMAIN, P. H. and KRONLAND-MARTINET, R. (1996). Characterization of acoustic signals through continuous linear time-frequency representations. Proceedings of the IEEE, special issue on Wavelets, 84 (4), 561-585.

KANG, P. and BIRTWHISTLE, D. (2003). Characterisation of vibration signals using continuous wavelet transform for condition assessment of on-load tap-changers. Mechanical Systems and Signal Processing, 17(3), 561–577.

KEMPER, A.R., MCNALLY, C, KENNEDY, E.A., MANOOGIAN, S.J., and DUMA, S.M. (2008). The influence of arm position on thoracic response in side impacts. Stapp Car Crash Journal, 52, 379-420.

KENT, R. W., CRANDALL, J., PATRIE, J., and FERTILE, J. (2002). Radiographic detection of rib fractures: a restraint-based study of occupants in car crashes. Traffic Injury Prevention, 3, 49–57.

KNOX, T. (2004). Validation of earplug accelerometers as a means of measuring head motion, SAE technical paper series, Proceedings of the SAE Motorsports Engineering Conference and Exhibition.

KUPPA, S. and EPPINGER, R. (1998). Development of an improved thoracic injury criterion. Stapp Car Crash Journal, 42, paper 983153.

LEBARBE, M., POTIER, P., BAUDRIT, P., PETIT, P., TROSSEILLE, X., and VALLANCIEN G. (2005). Thoracic injury investigation using PMHS in frontal airbag out-of-position situations. Stapp Car Crash Journal, 49, 323-342.

MEO, M., ZUMPANO, G., PIGGOTT, M., and MARENGO, G. (2005). Impact identification on a sandwich plate from wave propagation responses. Composite Structures, 71(3-4), 302-306.

TROSSEILLE, X., BAUDRIT, P., LEPORT, T., and VALLANCIEN, G. (2008). Rib cage strain pattern as a function of chest loading configuration, Stapp Car Crash Journal, 52, 205-231.

DISCUSSION

PAPER: **Rib Failure Detection Using Time-frequency Analysis: A Feasibility Study**

PRESENTER: ***Damien Subit, University of Virginia, Center for Applied Biomechanics***

QUESTION: *Erik Takhounts, NHTSA*
I was wondering that your fantastic glass analogy will allow [you] to answer a very important scientific question and that is: How many drinks of beer a 50th percentile male can have after workshop presentation before he breaks the glass? [laughter] I guess it depends on who is buying, right?

ANSWER: Exactly! And give me a few hours to figure it out!

Q: *James Funk, BRC*
Nice presentation. I was wondering: I did something like this for the breaking legs several years ago and I didn't get nearly this fancy. I just took the simplest approach, which was when the signal reached a certain amplitude, I could separate fracture or no fracture based on that and just took that time as the time of fracture. Does that not work on the ribs? Or, is that why you needed to go to the frequency domain?

A: I think that's what you do. You were actually using a microphone. Is that right?

Q: Right. I was using an acoustic sensor, which is a little different.

A: Well, it's actually a very low frequency. We use a sample at 10 kilowatts so we could be measuring the deformation and not any sounds that propagate.

Q: I'm just wondering if you see enough deformation from the signal to indicate fracture or if the amplitude—Is the amplitude just the same whether it fractures or not? You're looking at the frequency of your signal. I was wondering: Is the amplitude of your signal not enough?

A: Okay. The answer is no. We looked at the amplitude and it's not straight-forward. There is one reason for that. These are very cheap sensors. They're, like, a dollar each and they are not calibrated. So depending—For the same inputs, you won't get that same voltage. That's one thing. And, the other thing is that because there's a lot of dampening with all of the sub-tissues involved and things like that, that's why we saw that it was more interesting to actually measure what propagates in the bone itself rather than measuring the sounds or the noise made when it breaks.

Q: Okay. Well, interesting stuff.

A: Thank you.

Q: *Guy Nusholtz, Daimler Chrysler*
This sort of follows up on the other question. I'm not sure why you have to switch into the frequency domain. You're using the moving window, which will have the problem of leakage and a number of other contaminations associated with the numerical procedure. You didn't see any way you could test that in the time domain? And if there was no way, what is the advantage [testing?] in the frequency domain over in the time domain? Because you do have to decompose it into what would be sort of a modified gaber function where you have time, frequency, and I guess your color is the magnitude. And, that loses a certain resolution because of the way you have to move the window and the way you create the window.

A: That's correct.

Q: So, it would seem that there should be something in the time domain which would give you at least a little more precision in time than going into the frequency domain.

A: I'm not sure. It's pretty hard to see here. If you look at the time history in this case—So what you're telling me is that you would rather see a drop like that, as on the blue curve, rather than the oscillation on the purple curve. Right?

Q: If I look at the pink curve, and I can see it in fairly good detail, it has a very sharp rise close to where the blue curve falls off. So in the time domain, I would think that I could come up with an algorithm which would give me better resolution than time than if I switched into the frequency domain.

A: So the interest in the frequency domain—So when you look at the time history, the phenomenon on the closing frequency that you cannot detect, it's always very hard finding some strain gage data to see if a fracture occurs or if it's just because of the global kinematics. Or, is it because of a fracture further west? What I think is we know that when it breaks, there is energy, which is released, and it's in a certain frequency range that you can surely detect. That scenario we cannot do with time history.

Q: So that has to do with other data that's not here; because if I look at this time history, it looks pretty clear when it fractured.

A: You're totally right. The goal of this test was to compare the strain gage that we saw commonly used to determine time of fracture in this competence test. What I want you to do is to use similar techniques but for a full-scale test. The major issue with these strain gages is that many of them, because they have a short—they can see only in a small area around them, so you need maybe five or that number. The idea is that the frequency response that you need one and you can monitor it all with that. Because even though there is lots of dampening, or even if the amplitude is actually decreased because of interaction with soft tissue or dissipation of energy joint or things like that, you can still get the frequency response, even if the amplitude is low.

Q: Okay. Thank you.