Journal of the National Academy of Forensic Engineers®

http://www.nafe.org
ISSN: 2379-3252

Vol. XXIV No. 1 June 2007

Forensic BioMedical Engineering Experimentation and Modeling

by Laura Liptai, Ph.D. (NAFE C339)

Abstract

BioMedical Engineering applies engineering principles to biological systems, holistically utilizing knowledge in engineering, biology and medicine. The cross-disciplinary field integrates engineering (e.g. external force applied) with BioMedical sciences (e.g. tissue tolerance) and clinical input from Health Care Providers (e.g. medical diagnosis).

Written for those familiar with forensics, this introduces BioMedical Engineering by explaining how medicine and engineering are integrated. Scientific methodological approaches for the analysis of trauma causation and the specific applications to forensics are outlined. Common interactions or relationships with other forensic and medical disciplines illustrate how BioMedical Engineering uniquely contributes to forensics. The section on *design and proper use of experimentation* outlines applications of standardized automotive crash tests. In situations where the scale of the analysis does not allow for customized full scale testing and when the use of crash test databases is not appropriate, the proper design of engineering subsystem experimentation is introduced. Lastly, an alternative method for force quantification in trauma causation analysis, computerized mathematical modeling, is illustrated.

Objective and Introduction

Humans have developed refined mental activity and physical adeptness but have not evolved to withstand impact at high speeds.

In a high velocity incident, analysis of physical evidence on the human body may assist in identifying the cause of impact trauma. BioMedical Engineering integrates engineering, biological principles, and physical evidence for forensic analysis and can therefore provide useful input for the consideration of causation, in conjunction with accident reconstruction, forensic pathology, orthopaedic surgery and neuroradiology.

What is Forensic BioMedical Engineering?

Scientific methodological approaches for the analysis of trauma causation integrate medicine and engineering. Physical evidence on the body can be exam-

---

Laura Liptai, Ph.D., 1660 School St., #103, Moraga, CA and Orlando, FL

ined and interpreted relative to the physical interaction with the environment. The BioMedical Engineer applies engineering principles to better understand the effect that forces have on the body.

BioMedical Engineering may have first begun more than 3000 years ago with the oldest known limb prosthesis. In the year 2000, a 3,000 year-old mummy from Thebes bearing a wooden prosthetic tied to its foot, serving as a big toe, was uncovered by German archaeologists. Since then, BioMedical Engineering progressed through a series of publications. The first known published work was in 1848 by DuBois Reymond on the subject of electrophysiology entitled “Ueber die tierische Elektrizitaet” (Animal Electricity). Reymond’s colleague, Hermann von Helmholtz, later applied engineering principles to identify the resistance of muscle and nervous tissues to direct electrical current. In the 1950s, Sam Talbot of Johns Hopkins University petitioned the National Institutes of Health for teaching grants in conjunction with the University of Pennsylvania, the University of Rochester, and Drexel University. Other academic programs followed: Boston University in 1966; Case Western Reserve University in 1968; Northwestern University in 1969; and Carnegie Mellon, Duke University, Rensselaer, and Harvard/MIT in 1970.

Historically, the BioMedical Engineering programs focused on prosthetic design. In the last fifty years the field has also contributed to the study of injury mechanics relative to accident analysis. Today, there are more than 90 university programs in BioMedical Engineering. In forensics, the field focuses on kinematics and the mechanics of trauma.

BioMedical Engineering Methodological Approach to Trauma Causation

There is no single forensic formula to assess the causation of trauma. The approach is not uniform because the causes are not uniform. There are, however, proven foundations for the BioMedical Engineering analysis of trauma. This chapter will outline the generalized methodology.

No single element of the BioMedical Engineering collective analysis yields the solution. The engineer considers multiple variables to determine the probability of injury. These generally include: vehicular damage, change in velocity, pre-existing medical condition, the temporal relationship to the onset of diagnosis, and the expertise of medical doctors, surgeons and/or forensic pathologists to provide the specific diagnosis of trauma. Insights and analysis of the Accident Reconstructionist may also be utilized to further understand the mechanism of trauma. Because the BioMedical Engineering discipline involves training in biology and medicine, BioMedical Engineers are called upon to evaluate how external outputs, i.e. forces and accelerations on the body, will affect the internal structures, i.e. load capacity and failure modes.

There are three categories of analytical elements that serve as a foundation for study. These elements are integrated with the available investigative facts in order to evaluate the mechanisms of trauma, and/or determine if the trauma is consistent with the specific incident. The collective analysis is termed M.A.M: Mechanical, Analytical and Medical.

- Mechanical Input – consideration of the static and dynamic forces acting on the body
  - Impetus for the trauma / Accident reconstruction
  - Trauma characteristics
  - Kinematics – the study of the positions, angles, velocities, and accelerations of body segments and joints during motion
  - Pre-impact position
- Analytical Engineering – examination of available evidence in conjunction with accepted scientific principles
  - Tissue tolerances and susceptibilities
  - Testing
  - Computerized Mathematical Modeling Analysis
  - Crash Recorder or GPS Datum
- Medical Facts and Findings
  - Radiological findings
  - Clinical facts and findings
    - History
    - Diagnosis
    - Contact Trauma (bruising, contusions, etc.)
  - Surgical findings

The findings of the BioMedical Engineer are dependent upon the quantity and quality of available evidence and data. The analysis simplifies to a net result when all of the elements point clearly to the same causal factor. If the results do not fit consistently toward a single cause, then both consistent and inconsistent findings are identified and/or additional work is recommended.

The Application of BioMedical Engineering to Forensic Disciplines

BioMedical Engineering can be applied to a large variety of forensic analyses. Here we will focus on vehicular forensics, for example: occupant restraint usage, pedestrian analysis (contact specifics and injury causation), trauma causation, repetitive stress in the automobile environment and product defect. A few examples of the types of issues that can be analyzed follow.

Occupant Restraint

The physical evidence of the seat belt condition, the occupant kinematics and trauma, and the vehicle interior may determine whether the occupants were likely restrained, and restrained properly. From this information, other elements can be determined, such as: 1) the proportion of the trauma due to the lack of a seatbelt verses the vehicle's excessive speed, or 2) likely trauma sustained had the two year old been properly restrained in a child's car seat compared to seated in his mother's lap.

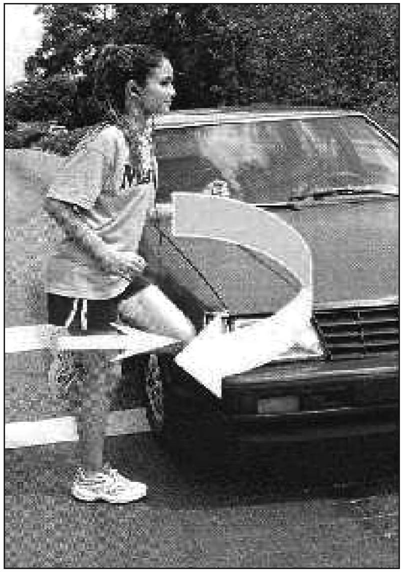

Figure 1
Pedestrian Direction of Travel
Prior to Impact

Pedestrian Analysis

Pedestrian analysis may reveal multifaceted data about the incident. For example: 1) the direction the pedestrian was traveling prior to impact (Figure 1), 2) whether the brain injury occurred from the initial impact or from the subsequent impact, 3) if the brain trauma would/would not be less severe if the vehicle was traveling at the speed limit, 4) at the time of impact, whether the boy was on his bike or walking next to his bike in the crosswalk. Had the boy been wearing a helmet, what trauma would likely have been sustained?

Trauma Causation

BioMedical Engineering analysis can be utilized to determine if the mechanics are present or if sufficient force is present to cause the trauma diagnosed by the Medical Doctor. For example: 1) the statistical likelihood that a brain injury would be sustained by the average person in the incident, 2) the mechanics for shoulder impingement are or are not present in the impact, 3) the boy's arm was amputated during ejection, or inside the vehicle

Figure 2
Before and After Elbow Implant Failure:
Due to frontal impact or roller blade fall?

prior to ejection, 4) the front seat occupant's trauma traced to no seat belt use or the kinematics of the unrestrained rear occupants, 5) using the principals of fracture mechanics, the elbow implant most likely failed from the unrestrained frontal impact or the same day's fall on roller blades. (Figure 2)

Repetitive Stress in the Automotive Environment/Product Analysis

An example is: the lateral femoral cutaneous nerve damage present in 52 Highway Patrol officers can or cannot be casually traced to a change in holster design that compresses the hip over the lateral femoral cutaneous nerve. (Figure 3)

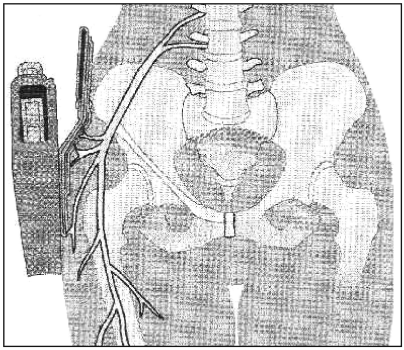

Figure 3
Holster Over the Pelvis and Neuronal Structures Illustrating Compression of the Lateral Femoral Cutaneous Nerve

Product Analysis

Examples include: 1) the seat anchor failure did or did not cause the trauma, 2) the injuries were or were not caused by either the ejection or the initial impact itself, 3) the roof should or should not have withstood the force as the commercial truck rolled onto it's roof, mechanically asphyxiating the occupant (Figure 4), 4) the globe (eyeball) rupture was, or was not, caused by the air bag rather than the occupant's diamond wedding ring, 5) the small stature female's cervical and facial fractures are or are not caused by the airbag rather than the non-use of seat belts.

Figure 4
Should the Roof Have Withstood the Weight of the Commercial Truck?

The Design and Proper Use of BioMedical Engineering Experiments

The previous section outlines how BioMedical Engineering is applied to Forensics. This section describes the added value of well executed experiments to scientifically determine the likely causal factors.

A means of determining causation is to experimentally analyze the issue by isolating variables. These experiments can make use of variants in the environment to compare results. Common questions that experiments may help to answer are:

- Would a seat belt have prevented specific trauma?
- If the vehicle were traveling the speed limit, what trauma would most likely be sustained?
- Which of the ejected decedents was driving?
- What is the statistical probability for brain injury in the subject incident if a seat belt is worn correctly?
- Was the bilateral locked cervical spine facet trauma caused by the first or second impact?

Engineering experimentation can be called upon to assess the BioMedical Engineering elements of vehicular accidents through two principal methods:

1) Interpolation: Using existing experiments to "bookend" a specific incident, and/or
2) Custom Experimentation: Designing a custom experiment to answer a specific question.

Utilizing Existing Experiments

Exhausting the sources of existing experiments is recommended as a first step, even if eventually custom experiments are required. If the subject incident falls into a category of standardized crash tests, i.e. in the U.S. an example is the New Car Assessment Program's frontal impact at 35 mph, existing experiments may be sufficient and more cost/time effective. If not, customized experiments may be necessary. Internationally, there are additional sources for crash tests and experimental results. In the United States the most common include:

National Highway Safety Administration (N.H.T.S.A.)

Insurance Institute for Highway Safety (I.I.H.S.)

Society of Automotive Engineers (S.A.E.)

American Association for Automotive Medicine (A.A.A.M.)

Other State or National Agencies

Automotive Manufacturers

The Application of Standardized Crash Tests: Interpolation

The key here is how the standardized experimental results may be properly applied to a specific problem by *interpolation, not extrapolation*. Interpolation of engineering experiments means to explain the expected result or trend between data points. Take the example of two crash tests, one at 10 mph and one at 15 mph. If substantially similar vehicles, crashes, and occupants are analyzed, the results of a 12.5 mph crash tests could potentially be interpolated as between the two experimental bookends of 10 mph and 15 mph. Conversely, it may be inappropriate to quantitatively extrapolate, or go outside the data bookends, to project 30 mph results from tests at 10 mph and 15 mph; however, sometimes nominal data can be derived from tests outside of the research bookends, if conducted correctly. For example, an appropriate extrapolation about the 30 mph analysis relative to the 15 mph test is that the forces and accelerations would be expected to be higher. The nominate data may prove informative in the absence of quantitative data. How much higher may not be reliably projected without data to interpolate the trend.

BioMedical Engineering Experimental Design

The second most common categorical use of BioMedical engineering forensic experiments is the development of customized experiments to investigate specific issues in a specific incident. If the analysis undertaken doesn't fit into common categories, such as the side, rear, or frontal impacts, if there is no similar test, then custom test directions may provide insight. Test alternatives include full-scale vehicle testing, deceleration sled testing, and/or simplified subsystem testing. Subsystem refers to a system in which variables are isolated.

Computerized Mathematical Modeling Analysis

Mathematical modeling allows a scientist to analyze the motion of a human and quantify the forces sustained in an injurious event without exposing human subjects to potential harm. The human body is represented by a number of rigid bodies linked together by springs and dashpots that represent the characteristics of human joints and collectively, the human body. Due to the body's numerous degrees of freedom, the occupant's motions during a collision can be complex. Mathematically the human body, modeled by connected rigid bodies, can interact with the environment via system inputs or external accelerations. External accelerations include impacts with surfaces, interaction with restraint systems and/or airbags, for example. Simple systems such as inverted pendulums can be modeled as well as complex systems such as an unrestrained occupant hitting a complex surface at impact. Note that simulation is different from animation since simulation mathematically defines kinematics and kinetics. In contrast, animation is simply the visualization of motion that may or may not be defined by the simulation or mathematical results. Animation relies upon the quality and validity of the simulation to determine the accuracy of the result.

As an example of this methodology, here we will review a model of a motor vehicle occupant subjected to a same side impact. The occupant is restrained, and the goal is to study the dynamics of the head. Therefore, the lumbar spine, pelvis and lower extremities are simplified. This is separately determined to be appropriate in this case because the lower body is restrained by the seat belt. The body is modeled in four segments representing the head, neck, thorax, and lumbar spine/pelvis.

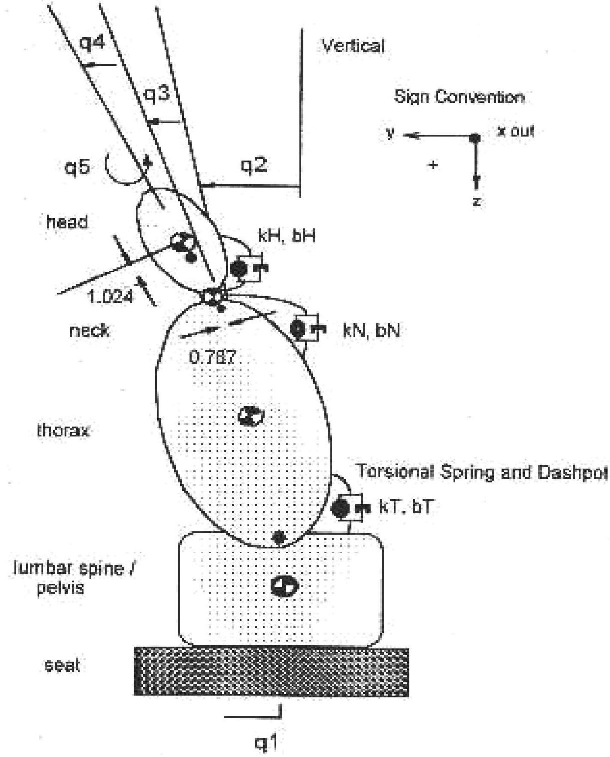

Figure 5
Five Degree of Freedom Occupant Side Impact Model

The human side impact (restrained) model with five degrees of freedom is illustrated in Figure 5. The model can be utilized in its two or three dimensional (3D) form.

The Variables are defined as follows:

q_1 Pelvic Translation

q_2 Rotation between the thorax and lumbar spine/pelvis (torsional spring and dashpot kT, bT)

q_3 Rotation between the neck and thorax (torsional spring and dashpot kN, bN)

q_4 Rotation between the head and the neck (torsional spring and dashpot kH, bH)

q_5 Head Axial Rotation

Once the model is developed and verified, it can be utilized within those parameters of verification. Examples of model verification include human subjects, cadaver, and anthropometric dummy experiments at impacts that bookend the subject incident (experiments at higher and lower exposure than the subject incident). The new variables should be within the validated parameters.

Properly validated computer mathematical modeling can be an effective BioMedical Engineering method to quantify the kinematics and kinetics of the impact incident. The correct use of the validated model is interpolation within the experimentally validated parameters. For example, if a model is validated at fall heights of 20 and 25 feet, the model might be used between that range, especially if it is known if the relationship is linear or predictably non-linear and no additional governing variables apply.

Mathematical modeling can also be utilized when the input variables change within the validated parameters. This is especially helpful, for example, when more information becomes available to the accident reconstructionist that alters the known vehicle's change in velocity. The model could be then used to re-analyze the result cost effectively as long as the new variables are within the validated parameters.

Conclusion

Written for those familiar with forensics, this introduces BioMedical Engineering by explaining how medicine and engineering are integrated. Scientific methodological approaches for the analysis of trauma causation and the specific applications to forensics are outlined. Common interactions or relationships with other forensic and medical disciplines illustrate how BioMedical Engineering uniquely contributes to forensics. The section on *design and proper use of experimentation* outlines applications of standardized automotive crash tests. In situations where the scale of the analysis does not allow for customized full scale testing and when the use of crash test databases is not appropriate, the proper design of engineering subsystem experimentation is illustrated. Lastly, an alternative method for force quantification in trauma causation analysis, computerized mathematical modeling, is illustrated.