Development of a Biomechanical Knowledge System to Identify Brain Injuries in Emergency Department

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Abstract—*Traumatic brain injury (TBI) has an annual incidence rate of over one million emergency department (ED) visits in the United States (U.S.). A patient subjected to trauma-induced alternation of mental status could have an TBI that may, or may not, involve any loss of consciousness. In clinical practice, diagnosis of TBI is very difficult because the presence of a head injury may be masked by a serious injury to another body part, subtle and changeable symptoms, or the delayed onset of symptoms. Many people with TBI do not receive medical care at the time of the injury and may complain to their physicians of their persistent symptoms for days, weeks, months, or even years after the injury. Currently, there is no reliable diagnostic tool to assist the ED physician when he, or she, sees a patient with TBI, especially mild traumatic brain injury (MTBI). Meanwhile, over forty years of injury mechanism study in the area of impact biomechanics proved to be effective in predicting brain injuries. To date, there is no diagnostic tool using impact biomechanics to quantify the risk factors of motor vehicle crash (MVC) occupants for MTBI in EDs. To the best of our knowledge, no one has explored how to prepare and model the knowledge of impact biomechanics into an information system for EDs. Our overall hypothesis was that an MVC scenario in association with the injury mechanism are important risk factors for MTBI. As part of our study series, this paper reports the development of a Web-based application system using the knowledge of impact biomechanics, based on MVC scenarios, in order to identify the patients, in EDs, at risk for MTBI and to stratify their risk levels. The system has been able to capture 94% of hypothetical MTBI patients at risk. The system could potentially assist the ED physicians in decision making for a proper referral pattern and clinical diagnosis of MTBI. The study also provides a novel approach to modeling the knowledge in impact biomechanics into a database, a shell for managing the knowledge rules, and a generic interface for editing the rules. The system shell could be easily adapted to other knowledge based systems to provide domain expertise from other fields for biomedical applications.*

Index Terms—*Traumatic Brain Injury, Mild Traumatic Brain Injury, Emergency Medicine, Knowledge System, Biomedical Information System, Expert System, Telemedicine*

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1. *INTRODUCTION*

Over the past few years, a large number of clinically useful tools and reference resources for ED physicians have become available, either as stand-alone software, or as resources available through the Internet. To the best of our knowledge, however, there is no such system providing expertise in impact biomechanics in EDs to help identify brain injury, which is a very prevalent disease in the U.S. Furthermore, how to model the knowledge in impact biomechanics has not yet been explored.

There are approximately 1 million ED visits annually for TBI in the U.S. [1]. The majority of them are MTBIs primarily resulting from MVCs and falls [1]. However, the consequences of MTBI are often not mild [2]. According to the definition of MTBI by the American Congress of Rehabilitation Medicine (ACRM) [3], "A patient with MTBI is a person who has had a traumatically induced physiological disruption of brain function, as manifested by at least one the following: 1) any period of loss of consciousness, 2) any loss of memory for events immediately before, or after, the accident, 3) any alternation in mental state at the time of the accident, and 4) focal neurological deficit(s).

Clinically, however, there is no reliable diagnostic tool to assist an ED physician when he, or she, sees a patient with TBI, especially MTBI. Reliance on patients to report risk factors can be highly unreliable due to the lack of the patient's knowledge about the importance of certain risk factors, or the patient may have amnesia from the event. It is very hard for healthcare providers to record, or for a patient to report, a brief loss of consciousness, or memory loss, caused by a blow to the head. These patients are often given a nebulous diagnosis of “brain concussion” and discharged home without any concrete follow-up plan or neuropsychological assessment. The mis-diagnosed and un-diagnosed rates range between 20%-50%.

Recently, in emergency care, the consideration of an injury scenario began to be appreciated in association with the risk factors for TBI. The EFNS (European Federation of Neurological Societies) Guideline on MTBI considers a high-energy MVC as an important risk factor associated with an increased risk of intracranial injuries [4]. Current advanced trauma life support system suggests the consideration of the injury mechanisms and vehicle occupant kinematics for identification of risk factors [5-7]. However, the identification and quantification of these risk factors is a unique piece of science called impact biomechanics which is the “basic science of injury causation” [8]. Without the analysis of an impact scenario and the mechanical load applied on a patient’s head/brain, the fast and accurate diagnosis of MTBI is a great challenge to the currently available clinical diagnosis and detection techniques.

Meanwhile, the lack of 24/7 available expertise in impact biomechanics is a considerable barrier for the biomechanical identification of brain injury in an ED. To the best of our knowledge, there is no diagnostic tool using impact biomechanics to quantify risk factors of MVC in ED settings for MTBI, nor has anyone explored how to prepare and model the knowledge of impact biomechanics into an information system for emergency medicine. Our overall hypothesis was that MVC scenarios in association with the injury mechanism are important risk factors for MTBI. This is also well supported by the current practice of EFNS guidelines on MTBI and ACSTC field triage criteria of trauma patients. As part of our systemic effort, our specific aims in this study were 1) to develop a Web-based system using the knowledge of impact biomechanics to identify the patients at risk for MTBI and to stratify their risk levels in EDs and 2) to investigate an approach to modeling the knowledge in impact biomechanics into an information system.

2. Materials and Methods

2.1 Development of Data Collection Instrument

To collect necessary MVC parameters, on scene, that contribute to the risk for MTBI, a data collection instrument (Figure 1) was developed, in a separate study, for EMTs to use. From Jan 2002 to May 2003, we collected 317 crash cases with an overall completion rate of 82%. Our results demonstrated that EMTs could collect the MVC data, on scene, without affecting their primary duties. The description of the instrument and justification of MVC parameters were narrated in the separate study. We include a brief summary here, however, for completeness.

The instrument included impact data forms and a digital camera (Figure 1). There were four sections to complete on the impact data form. The first section was general information. This was where information, such as the date of the accident, the type of information source, and patient’s information, such as gender, height, and weight was recorded. The second part dealt with the information about the vehicle involved in the accident, such as the year, make, model, seatbelt use, and airbag deployment. Next was the information involving the seat location and body position of the patient in the vehicle prior to impact. The last of the overall four sections was three photo entries that were taken by the data collector using the digital camera to identify impact depth and impact direction and location. When the impact data form was completed, it was placed into an envelope along with the memory card from the camera and given to the emergency medical technician (EMT) dispatcher.

There was no patient identification information, such as patient’s name, social security number, telephone number, home address, etc., on the data form. The only data collected were injury mechanism-related MVC information.

2.2 Justification of Crash Parameters

Among many MVC factors, the seatbelt use, airbag deployment, and vehicle make, year, and model are crucial factors to record in our data collection kit. It has been well recognized by the public and documented by the U.S. National Highway Traffic Safety Administration (NHTSA) that the occupant’s seatbelt use and the availability of an airbag can significantly reduce the death and disability during vehicle crash accidents [9]. Furthermore, considering the size, body weight, and design of vehicles, different vehicles also have different safety parameters (http://www.nhtsa.gov).

In addition, the vehicle occupant’s body height and weight signifies the possible interaction of the occupant’s head with vehicle interiors [10]. Furthermore, the occupant’s gender and age are also reported to be factors contributing to his or her vulnerability [11].

Another critical vehicle crash factor is the patient’s body posture for being out-of-position (OOP). OOP has been widely recognized by the

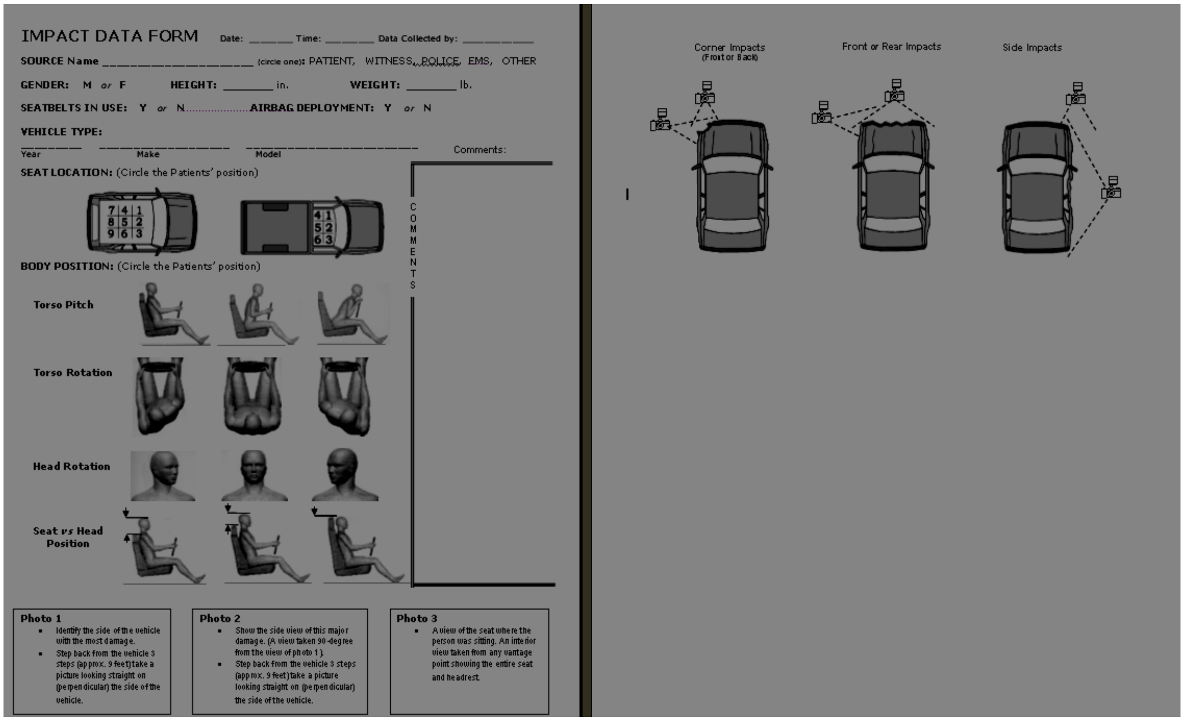


Figure 1. Data Collection Instrument.

U.S. NHTSA, the automotive industry, and the aerospace industry in injury causation analysis [12-16]. The term OOP refers to any patient who is not in the "normal seated position" (NSP) prior to impact. The NSP is defined as follows: the occupant's shoulder blades are pressed firmly into the seat back, and their head is close to the head restraint [17]. Full scale experimental tests on crash dummies and mathematical models of rear-end collisions have shown that only a small variation in occupant position can result in a large increase of impact forces [18-22]. In the 1990s, research on airbags recognized the need to address the problem of occupants being OOP with regard to airbag deployment in frontal collisions [12-16].

In summary, depending on the collision direction (frontal, rear, or side), the use of the seatbelt, the airbag deployment, the stiffness of the seat and the height of head restraint, OOP patients could develop risks for the injuries on their head, neck, and other parts of their body. An occupant not wearing a seatbelt could easily be OOP. In a frontal collision, especially with airbag deployment, an OOP occupant would be at high risk for developing head, neck, or chest injuries. In a lateral collision [23], especially an impact on the occupant's side, an OOP occupant will be more vulnerable than a normal seated patient for developing head/neck injuries. This is due to the greater inertial forces, or possible direct impact forces, regardless of the airbag deployment. In rear-end collisions, if the head restraint is lower than an occupant's head or even neck, the occupant would easily develop whiplash, or possible head injury. Moreover, the deeper the intrusion into the occupant's vehicle, the higher likelihood of injury by considering relative direction of impact versus the occupant's seating position.

2.3 Modeling and Stratifying of the Risk Factors

Based on our research experience in forensic investigation, experimental reconstruction and computer simulation of MVCs, and our search of published literature, we developed a knowledge base to quantify the risk factors and at-risk scenarios of MVCs. A risk factor for MTBI could be a significant MVC parameter, e.g. non-use of seatbelt, or a combination of several MVC parameters to form a crash scenario. Each risk factor is empirically assigned a level of risk for MTBI from low, moderate, to high. Three low level risks are equivalent to a moderate level risk; three moderate risks are equivalent to a high level risk; and the overall risk level of a patient is the summation of all risk factors.

By structuralizing the knowledge information and considering the potential interactions of knowledge, we developed a set of rules to represent this knowledge base. For the ease of modeling into a database, we further structuralized this rule set. Each rule has six parts:

1) The rule name.
2) The IF conditions to make the rule fire, which is the logical combinations of crash variables.
3) The weight of each rule in contribution to a patient at risk.
4) The rule status: valid or invalid. (This will be discussed in the Rule Management section.)
5) Rule description, which is to be displayed on the result page as explanatory information about the risk factors of this rule if the rule is fired.

6) Reference information, which is the published biomechanical data in support of this rule definition.

By structuralizing the rules, we could easily model the rules into a database by storing each part of a rule as a data entry. One rule was a data record. In the evaluation of a case, the software queries rule set from the database, evaluated the true, or false of an IF conditions. Once the evaluation was true, this rule's specific weight for a risk factor was counted; and the description regarding its risk factors and the reference information about this rule was also compiled into an evaluation result page to display for end users.

2.4 System Design

We designed the system in a three-tier architecture model using the currently most popular LAMP technology (Figure 2): Linux operating system, Apache Web server software, MySQL relational database, and PHP script language for server programming. All of these technologies were open source software without a license charge.

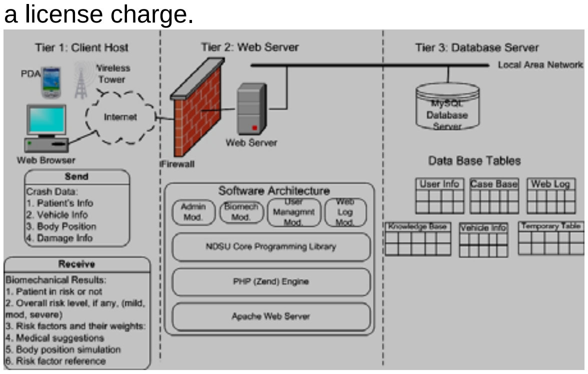


Figure 2. System Architecture.

At tier 1, the ER users could use the Web browser either in desktop/laptop personal computer (PC), or in personal digital assistance (PDA) to send MVC data in an HTTP request to the web server at tier 2. The PHP script program on the Web server processed the hypothetical case information, stored the case data, queried the vehicle information from the database located at tier 3, evaluated the risk factors of the hypothetical patient, and stratified the risk level of that patient. Both the Web server and database server were located within the North Dakota State University (NDSU) campus firewall to protect against hacking.

Two versions of the system were developed: one was for the desktop PC using a regular Web browser and the other was for a PDA. The PDA version could only evaluate the risk factors of the hypothetical patient and retrieve previous cases. There was no administrative function for PDA version.

A typical process of a hypothetical patient case evaluation consisted of three steps:

a.) An emergency staff user logged into their account in our system (URL: http://www.ndsu.edu/biomech).

b.) The user entered the impact MVC data on the Web, which included the general information of the hypothetical patient, vehicle information, patient's body position, and vehicle damage information.

c.) The user waited for 2-5 seconds to allow the system to evaluate the case and return the results. The result page consisted of the following information shown in Figure 3 as a sample page:

1) Patient at risk, or not.
2) Overall risk level, if any.
3) Detailed risk factors, if any.
4) Medical suggestions based on risk level, if patient was at risk.
5) Illustration of patient's body position prior to moment of crash.
6) Published reference data in support of risk factors involved for patient.

Figure 3. A sample result page.

2.5 System Development

The system development process was performed in a software engineering paradigm using the Object-Oriented approach. The system was designed in a layered architecture in order to guarantee reusability, portability, and easy maintenance. There were three layers: the interface layer, the business layer, and the data access layer.

The interface layer was responsible for the user interaction with the system. The business layer was responsible for the system's logic and was comprised of the objects inherent to the application domain. The data access layer was responsible for accessing the data storage medium. It contained classes that actually implemented the interface for a specific storage medium and database table. We used the NDSU Core Programming Library to implement the data access layer, as shown in Figure 2. The library is a repository of class objects developed, NDSU's Information Technology Services (ITS), in an

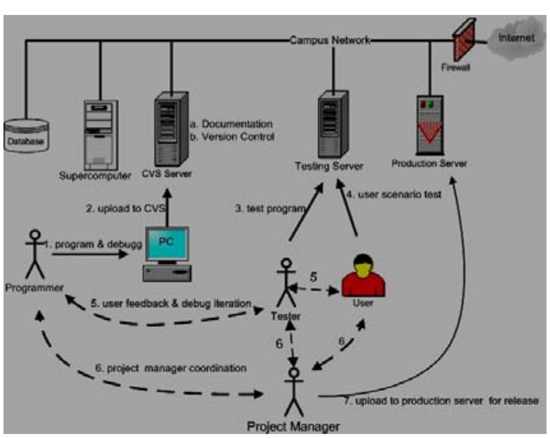
Object Oriented Programming paradigm. It provided commonly used components for the development of web database systems, and was tailored to the specific configuration of the information infrastructure at NDSU.

The implementation process, as shown in figure 4, mainly consisted of the following interweaving steps:

1. Programmers wrote and debugged programs on their local machines.
2. Programmers submitted their code to the Concurrent Versions System (CVS) server, which kept track of the version evolution and documentation; and submitted the inline and implementation documentation when the debugging work was done.
3. The testers copied the code to a testing server for software; and provided feedback to the programmers.
4. The users worked with the system testers to evaluate the user interface, use cases, capacity requirements, etc.
5. Based on the testing results and users' comments, the testers interacted with programmers to provide feedback for debugging iteration. All of the testing reports were documented in the CVS server associated with each version.
6. The project manager coordinated with programmers, testers, and users for the software development iteration during the entire process.
7. Once the software passed the testing, the project manager released the software system by uploading it onto the production server which was NDSU's campus web server for end user field evaluation.

Based on our experience on project development, we set up a NetOffice environment for project management. It was an open source web-based virtual working environment for project management, where the project team members had different access privileges: the manager generated a work task, the testers reported bugs, programmers generated documents, users initiated new requirement and any member could initiate a discussion. All of the project activities were recorded and generated as report files. The project team members received email as a reminder of any activity.

Figure 4. System Development Process.



2.6 A Shell for Knowledge Rule Management

In the design and maintenance of a rule-based knowledge system, one of the difficulties is to manage the knowledge rules. Potential problems such as adding new rules, deleting old rules, testing of the rules and checking conflict of the rules must be addressed [24]. An administrative module was developed to provide an interface for rule management by an administrative user. By querying the rules stored into database tables, the module allowed the administrative user to perform the following functions:

a) Adding a new rule(s): A generic rule editing interface was designed to allow the expert in biomechanics add a new rule even without any knowledge of information systems. The interface will be discussed in the next section.
b) Testing rule(s): The administrative user could select any subset of the rules and input an MVC case to evaluate the functions of this rule set. During the testing process, the system could trace which specific rule had been fired under what condition, which was extremely useful to test the compatibility of the rule set and find potential conflict of rule(s).
c) Deleting rule(s): Any subset of the rules could be deleted by the administrative user.
d) Updating rule(s): In the current rule base, there were two possible status of each rule: Valid or Invalid. A valid rule meant it was active in the production machine and would be fired if the condition for this rule was met, and an invalid rule meant the rule was hibernating and was used only for testing purposes by the system administrator. The rule status could be changed by our administrative user. The reason for this feature was that during the long-time maintenance of the rule set, a domain expert could be unsure of some rule(s) and want to test it further rather than adding it directly into, or deleting it from, the rule base. It was determined that it would be better to let the unsure rule(s) hibernate.

2.7 A Generic Interface for Rule Editing

Compatible with the structuralized rule set, a generic user-friendly interface was developed for rule editing. A domain expert, who is even a novice in information system, could easily edit new rule(s) into the knowledge base. As shown in figure 5, all of the potential MVC variables to be considered in the rule base, e.g. gender, passenger seating position, crash position and depth, were incorporated into pull down menus in the interface. All of the potential relationships of these variables, e.g. =, >=, <=, were also provided in pull down menus as well. The parentheses potentially used in the logic combinations of these variables were also provided. The IF condition for a new rule could be designed by taking any combinations of these variables. For example, if a rule said "if the vehicle occupant is a female no less than 65 years old, and the damage depth is over 6 inches, of the female had direct head impact onto the vehicle interior, she could be at moderate risk," the logic expression for the IF condition would be:

((Patient Age >=65)AND(Patient Gender==F)AND((Impact Depth>=6inches)OR(Head Strike==Y)))

as shown in Figure 5.

The MVC variables were also defined as programming variables in the server script program. To determine if a specific rule's condition was met, the system retrieved this rule from the database and evaluated the true, or false, of the logic expressions stored in the IF condition entry.

The risk factors, rule name, rule status, brief description of the rule, reference source of the rule and a brief digest from the reference regarding this rule were also provided in the interface along with the IF conditions (Figure 5).

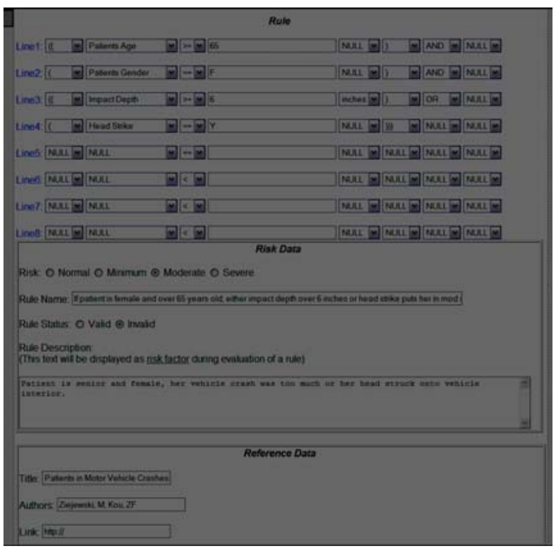


Figure 5. An Interface for Rule Editing.

3. RESULTS

The validation results of the knowledge base were encouraging. We used 29 hypothetical cases (n=29) to validate the system. Based on detailed biomechanical analysis, in conjunction with human brain tolerances, 16 were affirmative MTBI cases (n1=16) and 13 were non-MTBI cases (n2=13). The system identified 22 of the total 29 cases at risk. Among these 22 at-risk hypothetical cases, 15 were affirmative MTBIs, which takes 94% of the 16 affirmative MTBI cases and results in the system sensitivity of 94%. By stratifying the at-risk cases into different risk levels, the results show that the hypothetical patients' risk levels signified their frequency of MTBI. Two out of 6 cases (33%) at low risk level were affirmative MTBI, 7 out of 10 cases (70%) at moderate risk level were affirmative MTBIs and all 16 cases (100%) at high risk level were affirmative MTBIs. A logistic regression analysis also confirmed that patient risk level was significant in predicting their injury probabilities (Wald Chi-Square test value 8.073, p=0.0045).

4. DISCUSSION

By stratifying patients into different levels of risk, different probabilities of brain injury could be determined, and appropriate measures and referral patterns could be taken by emergency physicians to confirm the presence of MTBI and to manage the patients timely. Our system demonstrated the low risk level a 37% probability of brain injury in the hypothetical patients; moderate risk level at a 75% probability; and high risk level at a 94% probability. This system could potentially assist ED physicians in identifying a patient at risk for MTBI in order for a proper referral pattern to occur and for clinical decision making for further neuroclinical examinations. Given the different MTBI probabilities at different risk levels of patients, measures to be considered and referral patterns could be, but no limited to, clinical evaluation for brain injury, education of patients and patients' significant others, neuropsychological consultation, and follow-up phone calls within the next 1-2 days.

One-third of the nation's population lives in "rural" America and a disproportionate number of deaths due to MVCs (56.9%) occur in rural areas [25]. Telemedicine could bridge the gap between biomechanics research of head injury and its day-to-day clinical applications. Our system proved effective in identifying MTBIs in hypothetical patients. The system could be used in rural areas, especially in mid west states like North Dakota to help ED physicians identify biomechanical risk factors and to stratify patients into different risk levels for the appropriate referral pattern and management in a timely manner.

Currently no generally accepted standards exist for the treatment and management of MTBI, appropriate diagnosis, referral, and patient and family education are critical for helping MTBI patients achieve optimal recovery and to reduce, or avoid, significant sequelae [26]. Diagnosing MTBI, however, can be challenging because symptoms often are common to other medical problems, and onset of symptoms may occur days to even months after the initial injury [26,27]. The primary goal of initial management in MTBI is to identify the patients at risk of intracranial abnormalities. In view of the difficulties for evidence-based medicine to provide definitive strategies, additional knowledge of the injury risk factors can be beneficial in an evaluation process.

The American College of Surgeons [28] includes injury mechanism in its life trauma support protocol. Over 40 years of extensive research in the aerospace and automotive industries in the area of impact biomechanics has accumulated a large amount of data and corresponding theories in national databases, as well as biomedical and biomechanical publications [29-33]. Due to non-availability of this knowledge in ED settings, however, ED physicians have rarely benefited before now from the achievements in this field. Due to the urgent nature of emergency medicine, computerized systems could ideally provide instant assistance to ER physicians on the basis of 24 hours a day and 7 days a week.

The system shell proved to be very effective in managing the rules. The function of testing rules can be especially effective in identifying the potential conflict of the rules by tracing which rules fire under what specific conditions. The generic interface for adding new rules proved to be easy to use by experts in biomechanics who had no training. The system could handle multi-users concurrently. By placing the system inside the firewall of the NDSU campus server and reusing the NDSU Core Programming Library, we saved up to 60% of the maintenance effort and 30% of developing time.

5. *CONCLUSIONS*

We developed a Web-based application system to help identify the potential brain injury patient, in EDs. who have been involved in MVCs. The system proved to be effective in identifying 94% hypothetical brain injury patients by stratifying the patients in different risk levels for MTBI. This system could potentially assist the ED physicians in identifying a patient at risk for MTB, that could lead to a proper referral pattern and clinical decision making for further neuroclinical examinations. This would be particularly useful in rural areas that lack an advanced trauma care system. Furthermore, by modeling the knowledge in impact biomechanics into a database, the system provides a novel approach to handling the structural knowledge and checking the potential conflicts of the knowledge base. The system shell could be easily adapted to other knowledge based systems to provide domain expertise from other fields for biomedical applications.

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