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Automated Trauma Management Evaluation for Knowledge Acquisition Through Simulation

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Resumen

La lesión traumática es una de las principales causas de muerte en el mundo, siendo la principal causa de muerte para personas menores de 45 años; por lo tanto, aprender cómo manejar este tipo de lesiones es importante. En esta Tesis, se resaltan los aspectos principales a considerar antes de tratar a un paciente de trauma: entender la severidad de las lesiones; el país en el cual se aprende el manejo de estas lesiones, puesto que la exposición y los recursos disponibles pueden variar; y la respuesta fisiopatológica del cuerpo, en función del mecanismo y del tipo de lesión sufrida. La formación en trauma ha mejorado desde que se creó la primera formación específica en trauma en 1978, el Advanced Trauma Life Support (ATLS). Debido a la importancia de estas lesiones de trauma, se han llevado a cabo revisiones periódicas de esta formación y nuevas formaciones han surgido, centrándose en encontrar la mejor manera de formar a los clínicos.

La simulación clínica ha apoyado el aprendizaje del manejo del trauma a lo largo del tiempo, ofreciendo experiencias prácticas, lo que supone un método de aprendizaje más rápido, incluyéndose como complemento a las clases tradicionales. En esta Tesis, se lleva a cabo un análisis exhaustivo sobre el estado actual de las formaciones en trauma basadas en simulación. En este análisis se presentan las principales áreas de mejora detectadas.

Por lo tanto, se ha desarrollado una modalidad de simulación que pueda estar accesible para diferentes niveles de conocimiento y de experiencia. Esta modalidad, es un simulador de trauma web que permite incluir cualquier escenario de trauma así como cualquier acción que sea necesaria para estabilizar a un paciente con este tipo de lesión. Cuando una acción se lleva a cabo en el simulador, hay un impacto en las constantes vitales del paciente, dotando de realismo a la simulación. Además, todos los datos que se generan a lo largo de la simulación se guardan automáticamente en una base de datos y, nada más finalizar la simulación, un informe se genera también de forma automática. Finalmente, el simulador que se desarrolla en esta Tesis permite incorporar protocolos de manejo del trauma, lo que es clave para poder medir la adquisición de conocimiento.

Definir protocolos de manejo del trauma es todavía un reto pero, es una necesidad clara para poder mejorar la atención a los pacientes de trauma. Por lo tanto, en esta Tesis se presentan protocolos de manejo del trauma. Para elaborarlos, guías generales del manejo del trauma tales como los manuales del ATLS y del Prehospital Trauma Life Support (PHTLS) se han tenido en cuenta, junto con la experiencia de clínicos especialistas en trauma. De esta manera, se han elaborado protocolos de actuación basados en acciones, en los cuales, todas las acciones a llevar a cabo se detallan, también cuándo se deben hacer y el orden en el que se deben llevar a cabo. Debido a que los protocolos de trauma precisan de flexibilidad por las circunstancias imprevisibles que pudieran darse, se proponen diferentes alternativas para cada protocolo de trauma. Finalmente, se presentan protocolos de actuación para cuatro escenarios diferentes de trauma.

Incorporar los protocolos de trauma en el simulador web desarrollado es el paso siguiente en esta Tesis. Esto permite comparar cómo se ha realizado una simulación llevada a cabo por un alumno con respecto al protocolo de trauma correspondiente. Este es un aspecto importante para que sea posible construir un sistema de evaluación automático. Por otro lado, otro aspecto importante es, desarrollar unas métricas que permitan medir el nivel de cumplimiento con respecto al tratamiento que se debería dar a un paciente de trauma. Las métricas desarrolladas en esta Tesis tienen en cuenta todos los aspectos relevantes del manejo del trauma, lo que permite analizar cómo se ha llevado a cabo la simulación con respecto a las acciones que se deberían haber hecho en los primeros minutos del tratamiento, si las acciones mínimas que se deberían llevar a cabo se han hecho y cómo de bien se ha hecho todo el tratamiento completo con respecto al protocolo establecido.

Por lo tanto, nuevas métricas se han desarrollado. Algunas de estas métricas provienen de la matriz de confusión; dos de ellas, las puntuaciones de subsecuencias y diagonales, se han desarrollado específicamente en esta Tesis y un alineamiento global se ha creado basado en el algoritmo de Needleman-Wunsch. Este algoritmo se ha modificado teniendo en cuenta las necesidades específicas del manejo del trauma. Estas necesidades son muy importantes puesto que, el tiempo para estabilizar a un paciente con una lesión de trauma es muy poco y se tiene que responder muy rápidamente. Por lo tanto, llevar a cabo acciones o tratamientos que no son exactamente los que se deberían llevar a cabo consume tiempo, lo que no deja mucho para poder corregirlos y actuar de nuevo. Es por esto que nuevos parámetros se incluyen en este algoritmo, para premiar las acciones que se hacen bien o que son similares a las que se deberían llevar a cabo, o para penalizar las acciones que no son adecuadas en un determinado momento, o que tienen un impacto negativo en las contantes vitales del paciente o que, simplemente, no se hacen.

Finalmente, las métricas que se han desarrollado en esta Tesis se han usado en una prueba experimental con el simulador web desarrollado, obteniendo resultados satisfactorios. Estos resultados miden el nivel de aprendizaje adquirido usando el simulador web desarrollado, presentando una mejora en el manejo de casos de trauma tras dos semanas de entrenamiento. Los resultados que se han obtenido en esta Tesis confirman las hipótesis y los objetivos de investigación.

Abstract

Trauma is one of the leading causes of death in the world, being the main cause of death in people under 45 years old; therefore, learning how to manage traumatic injuries is of great importance. Within this Thesis, the main aspects to consider prior to trauma treatment are highlighted: understanding the severity of the lesions; the country in which a training takes places, as the exposure and resources available may be different; and the pathophysiology response of the body, due to the mechanism of the injury and the types of lesions suffered. The current trauma management training landscape has improved since the first ATLS training was created in 1978. Due to the importance of trauma injuries, continuous improvements are developed on how to better train clinicians.

Clinical simulation has supported trauma management learning along time, providing a hands-on experience which supports a faster knowledge acquisition method to incorporate in traditional lecture courses. Within this Thesis, a deep analysis on the current state of simulation-based trauma trainings is presented, in which the main gaps detected are addressed.

Therefore, a simulation modality that can be available to different levels of knowledge and expertise has been developed. This is a Web-based Trauma Simulator (WBTS) which allows to include any trauma scenario as well as all the necessary actions to stabilize the trauma patient. Once an action is accomplished, there is an impact on the vital signs of the patient, providing realism to the simulation. Additionally, all the data generated along the simulation is automatically gathered into a database and a report is automatically generated after the simulation. Finally, the simulator developed within this Thesis supports to incorporate trauma management protocols which is key to measure knowledge acquisition.

It is still a challenge to define trauma management protocols but, it is a clear need to provide a quality treatment to trauma patients. Therefore, trauma protocols are objectified in this Thesis. To develop them, general trauma management guidelines such as ATLS and PHTLS manuals are considered, together with the experience of trauma experts. This supports the translation from general guidelines to the local real clinical practice. Therefore, an action protocol is set, in which all the actions to accomplish, when are they done and the order in which they should be accomplished is designed. Due to the flexibility needed in trauma protocols considering the unpredictable circumstances that they may appear, several possibilities for each trauma protocol are envisioned. Finally, this is done for four different trauma scenarios.

Incorporating trauma protocols into the WBTS developed is the next step taken on this Thesis. This allows to compare how a trainee performed with respect to the trauma protocols set in an automated manner. This is an important aspect to be able to build an automated evaluation system. On the other hand, another essential part is to develop metrics that allow to measure the level of performance with respect to the treatment that should be provided to the simulated trauma patient. The metrics developed in this Thesis consider all trauma relevant aspects allowing to analyze how the performance was done with respect to the actions accomplished during the first minutes of treatment, whether the minimum actions to take along the treatment are done and how well the whole treatment compared to the trauma management protocol set was performed.

Therefore, new metrics have been developed. Some of these metrics come from the confusion matrix; two of them, the subsequences and the diagonal scores have been developed specifically within this Thesis and a global alignment has been created based on the Needleman-Wunsch algorithm. This algorithm was modified according to specific trauma management requirements. These requirements are very relevant, as the time to stabilize a trauma patient is short and quick actions need to be

taken. Therefore, to take actions that are not exactly the ones that should be accomplished will take time, which will not leave enough to counteract. Consequently, new parameters are included within this algorithm to reward actions that are correctly done or that are similar to the ones to accomplish, or to punish the actions that are not correctly performed or that have a negative impact on the vital signs of the patient or that are, simply, not done.

Finally, the developed metrics in this Thesis are used in an experimental test obtaining successful results. These results measure the knowledge acquired using the WBTS presented and show an improvement after a two weeks training period. The results obtained in this Thesis confirm the investigated research hypotheses and objectives.

To my Family

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En definitiva, a todos, ¡Gracias!

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Nomenclature

AIS Abbreviated Injury Scale

AP Anatomic Profile

API Application Programming Interface

ASCOT A Severity Characterization of Trauma

ATLS Advanced Trauma Life Support

BR Breathing Rate

CPR Cardiopulmonary Resuscitation

CR Capillary Refill

DBP Diastolic Blood Pressure

DOM Document Object Model

FK Foreign Key

FN False Negatives

FP False Positives

GCS Glasgow Coma Scale

HR Heart Rate

ISS Injury Severity Score

MVS Model-View-Controller

NISS New Injury Severity Score

NPM Node Package Manager

ORM Object-Relation Mapping

OSCE Objective Structured Clinical Examination

PHTLS Prehospital Trauma Life Support

PK Primary Key

RE Respiratory Effort

RR Respiratory Rate

RTS Revised Trauma Score

SBP Systolic Blood Pressure

SCI Spinal Cord Injury

TBI Traumatic Brain Injury

TEAM Team Evaluation and Management

TN True Negatives

TP True Positives

TRISS Trauma and Injury Severity Score

TS Trauma Score

WBTS Web-based Trauma Simulator

1 Introduction

1.1 Motivation and Problem statment

Trauma is one of the leading causes of death in the world, being the main cause of death in people under 45 years old (Coalition for National Trauma Research, 2021). Trauma deaths have followed a classical trimodal distribution (Trunkey and Lim, 1974), but the epidemiology of these deaths have changed since the year 2000 towards a bimodal distribution in which the third peak is no longer detected (Kleber et al., 2012; Pang et al., 2008; Evans et al., 2009). Whereas immediate deaths are still quite high, the second and the third peak merge, not showing differences, as deaths tend to constantly decline with time (Rauf et al., 2019; Lansink et al., 2013). Figure 1.1 shows the change in trauma deaths compared with the classical trimodal distribution proposed by Trunkey. Historically, trauma deaths had three peaks represented by the red curve in Figure 1.1, in which the first curve are immediate deaths, the second one, early deaths and the last one, late deaths. Nowadays, having a look at the time distribution of trauma deaths, two peaks can be differentiated. The first one considers the deaths that happen during the first hour and the second one, the deaths that occur after the first hour after the lesion.

Therefore, as immediate deaths are still an important number, trauma training remains to be a necessary task. The Advanced Trauma Life Support (ATLS) training was created in 1978 in the United States (Committee on Trauma of the American College of Surgeons, 2018) and since then, it has been disseminated all around the globe being the main trauma standard in approximately 44 countries (American College of Surgeons, 2020). Nevertheless, this training is only available for doctors and not for medical students. Due to this fact, medical students request more trauma specific training (Jouda and Finn, 2020; Mastoridis et al., 2011) and the American College of Surgeons have created an introductory trauma course named Trauma Evaluation and Management Team Evaluation and Management (TEAM) (American College of Surgeons, 2020). Moreover, the ATLS training is restricted to a number of students per year and therefore, there is a waiting list that depending on the country could vary from six months to two and a half years. Taking all this into account, other trauma training methods are arising (Wallin et al., 2007; Minor et al., 2019; Long et al., 2019; Harrington et al., 2018). Some of these trainings focus on prehospital trauma management (Mobrad et al., 2020; Häske et al., 2017; Ali et al., 1998; Requena et al., 2015; J. Campbell; International Trauma Life Support (ITLS), 2013), some others focus on specific technical skills (Kuhlenschmidt et al., 2020) and, additionally, trauma trainings are incorporating non-technical skills into their trainings as they improve the management of the trauma patient (Ziesmann et al., 2013; Gillman et al., 2016; Doumouras and Engels, 2017). Technical skills focus on training specific techniques and treatments whereas non-technical skills focus on managing the trauma scenario including communication, leadership and coordination with different clinical specialties.

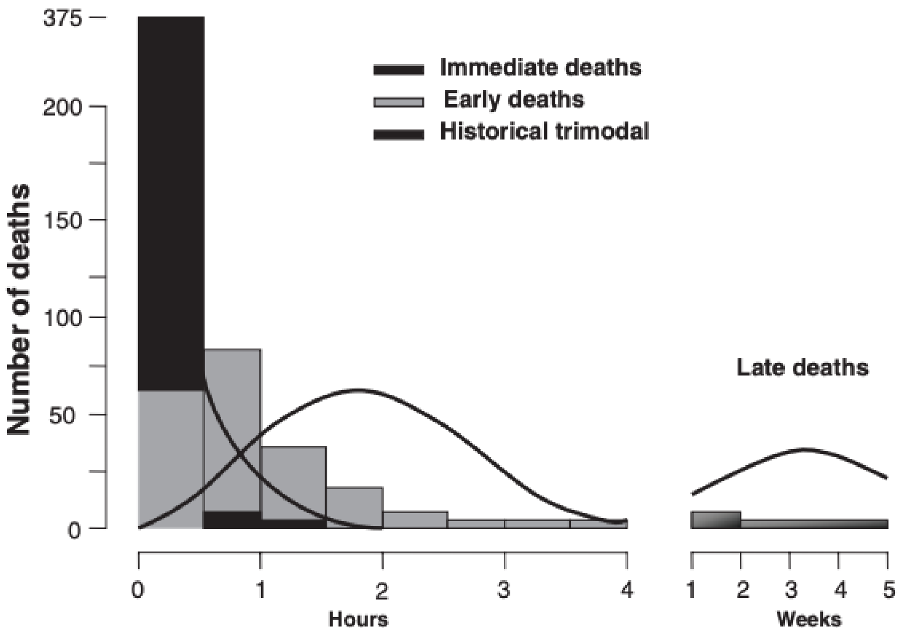


Figure 1.1: Trauma deaths distribution compared with the classical trimodal distribution (Gunst et al., 2010).

The role of simulation in clinical training is key as it allows to practice skills as many times as needed and without producing any harm to a patient (Abelsson et al., 2014; Murray et al., 2015; Dillen et al., 2016; Cuisinier et al., 2015). Nowadays, there are several simulation modalities and each of them has advantages and disadvantages (Quick, 2018; Borggreve et al., 2017). In general, clinical simulation is classified as low-fidelity, medium-fidelity and high-fidelity. The fidelity term refers to the degree of accuracy with which a simulator represents a real clinical situation. Low-fidelity simulation is used to train specific technical skills such as airway management or peripheral line placement. Medium-fidelity incorporates easy software modules to pyhisical simulators which allows to partially interact with the trainee. Finally, high-fidelity simulation considers complex mechanical and software modules and it is usually used to train non-technical skills, including a simulated patient in which the simulator is able to replicate a real clinical scenario.

In clinical training, different simulators are used from high-fidelity mannequins to standardized patients, skill stations or web-based simulation (Quick, 2018; Borggreve et al., 2017). Standardized patients are real people who are appropriately garbed to replicate a clinical scenario. They are able to interact with the trainee but some technical skills cannot be accomplished. Skill stations are usually used to train specific maneuvers or techniques, including low or medium-fidelity modules. Web-based simulation allows to provide an authentic learning environment to train experiences that could happen in the clinical practice. Moreover, it allows the possibility to train a high number of students simultaneously which is currently demanded in medical schools (Wise et al., 2016). Web-based simulators offer several possibilities providing flexibility to the trainings, allowing several profiles to access to the different trainings at the same time and it is more cost-effective than mannequin-based simulation. Moreover, it offers the possibility to objectively evaluate the simulation which is a key aspect considering that there is a lack of reliable objective evaluation tools (Murray et al., 2002).

When this lack of objective evaluation methods in simulation was detected, a panel of trauma experts was consulted. This panel was composed of 18 trauma clinicians and the aim of the enquiry was to evaluate simulated clinician performances in trauma scenarios performed by medical students and residents. These simulations included four different trauma scenarios to better understand the important aspects to consider when evaluating a trauma scenario. 151 simulations were created, performed and then, sent to the trauma experts for evaluation. They were requested to evaluate each simulation from 0 to 10. Being 0 the minimum score, which means that the simulation performed did not comply at all with the treatments that should be accomplished for a trauma patient, and 10 the maximum score, which means that the simulation reflected, perfectly, the treatment that should be provided to a trauma patient. The average results obtained for all the simulations are shown in Figure 1.2.

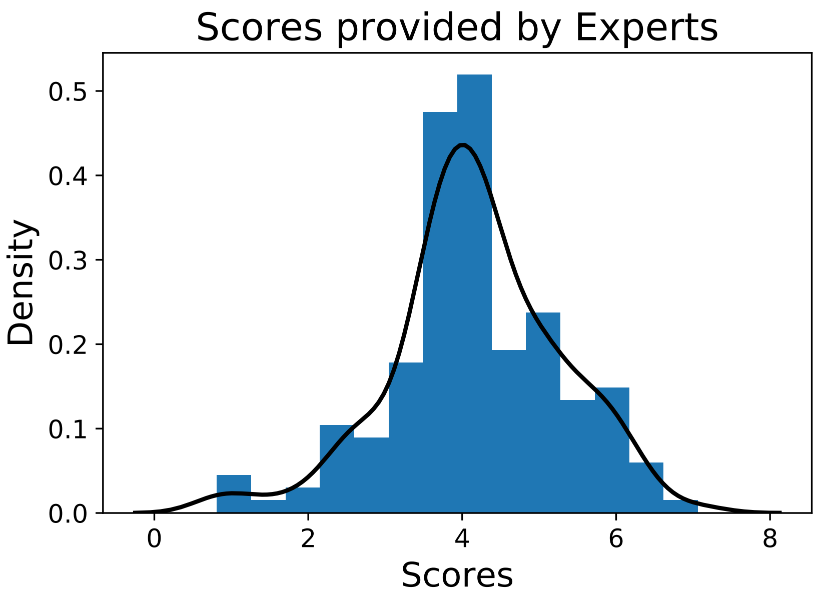


Figure 1.2: Histogram of all the average scores provided by the panel of experts to 151 simulations created.

It is perceived that an important number of simulations received an average score between 3.5 and 4.5, which means that they do not comply with what is expected to do when treating a trauma patient. In fact, the average value is 4.17 quite similar to the median value which is 4.16 and the mode is 3.80. Then, the first conclusion drawn from these data is that there is a need to train trauma management. Then, a deeper analysis is performed with respect to all the scores provided per trauma scenario. As previously mentioned, 151 simulations were created considering 4 different trauma scenarios and all the scores provided by the experts are shown in figures 1.3, 1.4, 1.5 and 1.6.

The results in Figure 1.3 show all the individual scores provided by the experts for the first trauma scenario. For the same trauma scenario, 43 different simulations were analyzed by the 18 experts obtaining a quite diverse response. Having a look at Figure 1.3, it is perceived that for some simulations, there are completely different evaluations. For example, in simulation 18, one expert provided a score of 1 and another expert provided a score of 9. This could be considered exceptional but, in general, an important dispersion on all the scores provided is perceived. The median value of the differences between the maximum and minimum scores provided for each simulation is 6, and the average is 5.71. In fact, only 6 simulations have a difference below 5, and the rest of them present a difference between 5 and 7 points on the scores provided. This means that, for the simulations of this trauma scenario, experts provided quite diverse responses.

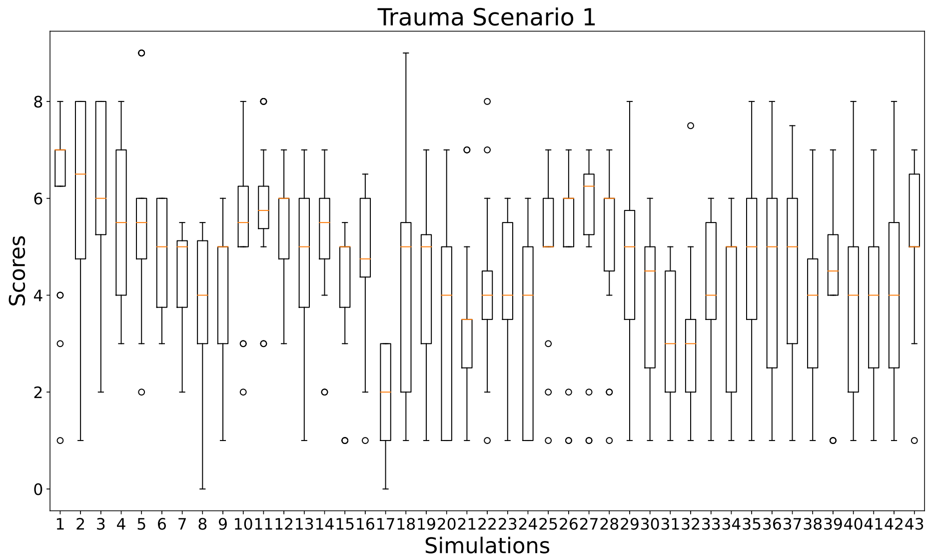


Figure 1.3: Scores provided by the panel of experts to all the simulations performed for the same trauma scenario, which is the trauma scenario 1.

In Figure 1.4 the scores provided by the experts to all the simulations created for the second trauma scenario are shown. In this case, 38 different simulations were evaluated by the experts and something similar is perceived. In fact, on the first 14 simulations, a similar dispersion of the values of the scores provided are shown, which vary from a minimum score of 1 or 2, to a maximum score between 6, 7 or even 8. Then, for the rest of the simulations the scores dispersion is also important even though there are some exceptions. For example, for simulation 32, the scores provided are not so different. With respect to the differences between maximum and minimum score values provided, the median value is 6 and the average value is 5.44 which is a little bit below the value obtained for the simulations of the first trauma scenario. In this case, 7 simulations show a difference below 5 whereas the rest of them have a difference on the scores provided higher than 5. Once again, an important diversity on the responses provided by the experts is perceived.

In Figure 1.5, the scores provided to all the simulations of the third trauma scenario are shown. For this trauma scenario, 35 different simulations were analyzed. Once again, there are simulations with an important dispersion on the score values provided by the experts, such as simulation 30 and 31. For simulation 30, a score of 1 was provided by one expert and a score of 8, by another one. For simulation 31, a minimum score of 0 was obtained whereas a maximum score of 7 was given by another expert. Once again, analyzing the differences between the maximum and minimum scores provided per simulation, the median value is 5.55 and the average value is 5.39. In this case, 8 simulations show a difference between maximum and minimum below 5; this is more than in the previous trauma scenarios but it only represents the 23% of all the simulations. Furthermore, 5 is a quite important difference in an evaluation score.

Finally in Figure 1.6, the scores provided to all the simulations of the last trauma scenario are shown. For this trauma scenario, another 35 different simulations were evaluated by the trauma experts. Once again, there are simulations with an important dispersion on the score values provided, such as simulation 31. For this simulation, a score of 1 is received by an expert and a score of 9 by another one. Additionally, the difference in this case, between the maximum and the minimum values for all the

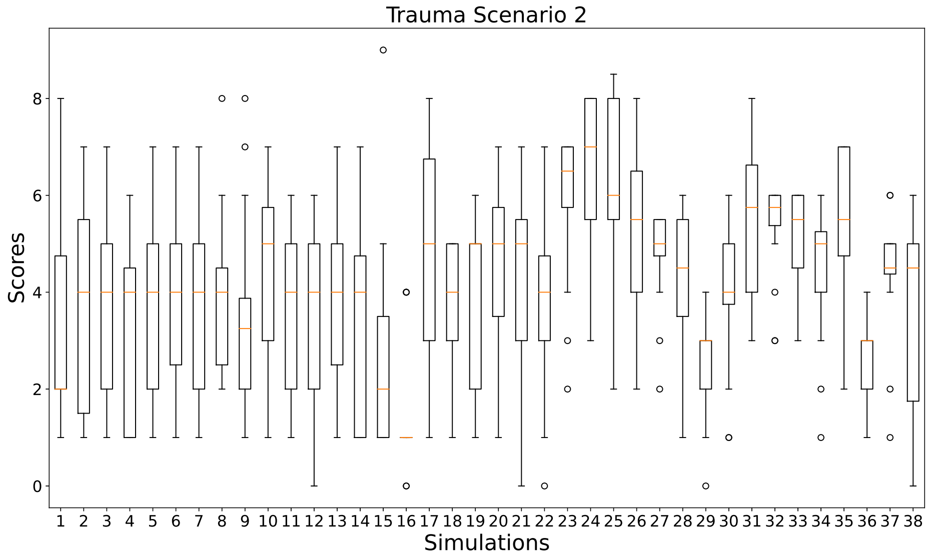


Figure 1.4: Scores provided by the panel of experts to all the simulations performed for the same trauma scenario, which is the trauma scenario 2.

simulations has a median value of 5.5 and an average value of 5.38; the lowest for all the trauma scenarios presented. As in the previous trauma scenario, 8 simulations show a difference below 5.

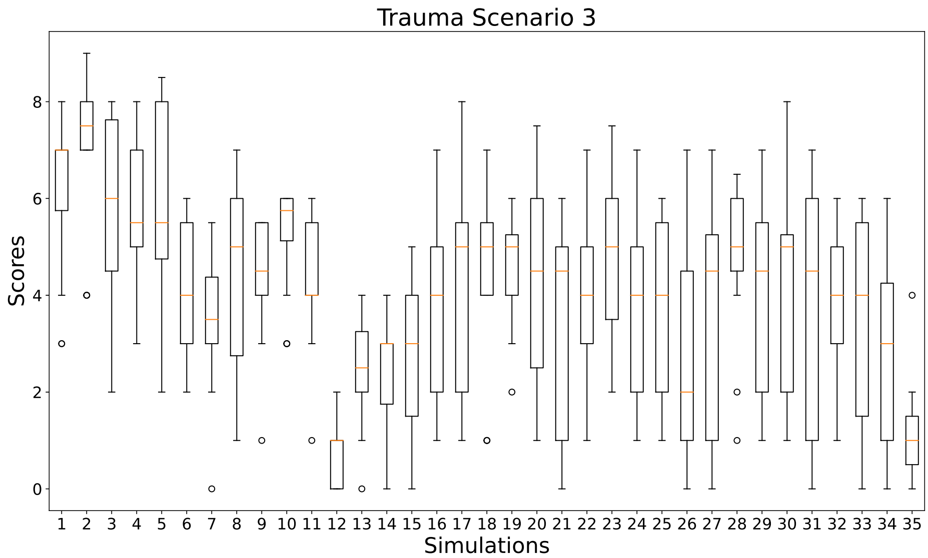


Figure 1.5: Scores provided by the panel of experts to all the simulations performed for the same trauma scenario, which is the trauma scenario 3.

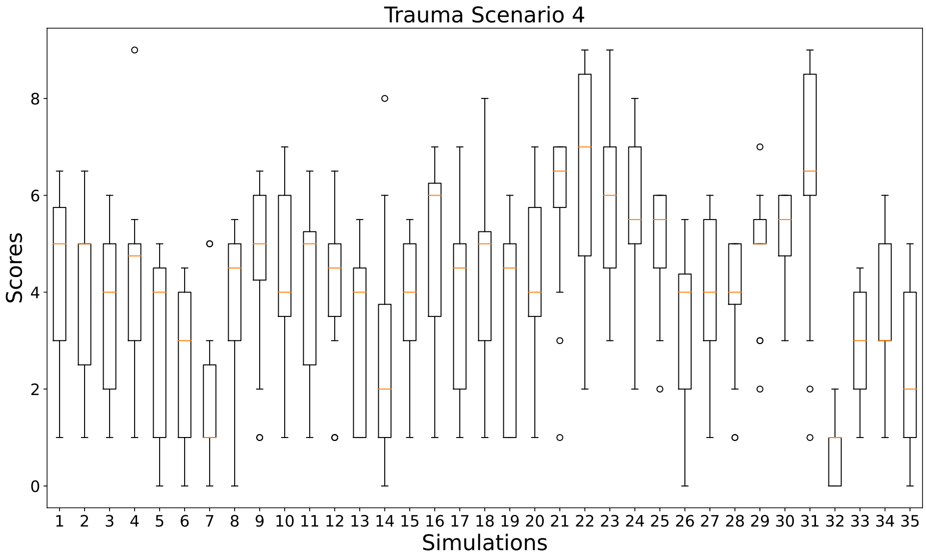


Figure 1.6: Scores provided by the panel of experts to all the simulations performed for the same trauma scenario, which is the trauma scenario 4.

Therefore, it is clear that different criteria are followed when evaluating a trauma management scenario. Consequently, another conclusion can be drawn, which is the need to develop an objetive evaluation system for trauma management. To do so, it is important to understand which are the main principles behind trauma management and the best way to learn and teach them. The number of actions to accomplish a trauma management scenario is large, and therefore, it is important to be able to prioritize actions and to do it fast. Moreover, understanding in detail what are the implications that each of the actions have on the vital signs of the patient is key. Additionally, identifying the actions to apply according to the trauma lesion suffered, is another key aspect to analyze in detail before developing an automated evaluation system.

In this Thesis, a solution to the aforementioned problems is proposed. Specifically, a simulator is proposed and developed in order to train trauma management, providing a tool that is easy to use, accesible and that includes all the relevant information needed to stabilized a patient with a traumatic lesion. Additionally, an objective evaluation system is proposed, in which all the relevant aspects to consider are included. To do so, trauma experts, as well as trauma guidelines and protocols currently in use such as the ATLS and Prehospital Trauma Life Support (PHTLS), are considered. Combining written standars with day to day practice allows to provide a comprehensive evaluation system.

1.2 Thesis aim

The aim of this Thesis is to develop an automated trauma management evaluation system to measure the knowledge acquired through simulation. The objective of the evaluation process is to provide an objective simulation score by considering all the relevant aspects on trauma management. Thanks to clinical simulation, relevant information is managed during simulations; nevertheless, not all this information is gathered and later on used with the purpose to analyze how well the simulation was done. Therefore, developing an evaluation system with different metrics, that are able to automatically measure how the simulation was performed, could provide an important and additional value to simulation. The aim of the metrics developed is to implement the flexibility needed in a trauma management learning process. As a trauma injury requires flexibility, due to the unpredictable circumstances that they may appear, this should be considered within the developement of this evaluation process. Therefore, the actions taken along a simulation has to be gathered and compared with a target solution. Then, with the evaluation system developed, an analysis on how this was done is accomplished. This analysis takes into account trauma management aspects such as the importance on the order on which actions are taken or how fast they were accomplished. Additionally, this is automatically done without having to make this analysis after the simulation. The current evaluation processes focus more on subjective information. By incorporating this evaluation system, trauma training evaluation will be enriched with real-time objective information gathered at the moment of decision. Moreover, this information is not only relevant for evaluation, but also for learning purposes. Integrating this evaluation system within clinical simulation will provide this information when training. Therefore, trainees could learn from their own experiences.

The proposed trauma management evaluation must satisfy the following features:

- *Objectivity:* it has to consider the real time and objective information generated during a trauma simulation. This evaluation system will gather all the relevant data directly from the simulation modality used in order to include real information at the time of performance. Therefore, objective data will not be lost and could be appropriately managed.

- *Automatic:* it must provide an evaluation of the simulation automatically. Once the simulation is finished, the evaluation is ready as all the data is gathered in real-time and directly processed to obtain an objective evaluation.

- *Flexibility:* it has to allow changes and they should be easy to implement. This is important, as trauma management protocols change and adapt to new practices. Therefore, the evaluation system should be prepared to be changed when needed.

- *Robustness:* it has to be able to work independently of any simulation modality. The only requirement is that the simulation modality used allows to gather the relevant data to evaluate the performance of a trauma management scenario.

- *Quick deployment:* this evaluation is quick to deploy and to incorporate into the simulation modality used once all relevant data are extracted.

1.3 Thesis structure

This Thesis is divided in three main parts which are preceded by the research hypotheses and objectives stated in Chapter 2. In Part I, the basic concpets of this Thesis are introduced to provide the reader with the necessary context to understand the problem stated and the proposed solution. Chapter 3 gives an introduction to trauma injuries. The epidemiology of trauma injuries, how to classify them and the different trauma injuries scores are presented. The clinical simulation modalities as well as its application in trauma management are described in Chapter 4.

In Part II, the proposed trauma management evaluation system for knowledge acquision is described. Chapter 5 presents current practices on teaching and learning protocols using simulation. From those current practices, important information is obtained with respect to how protocols are taught with the focus to build an evaluation system for trauma management. Chapter 6 proposes new metrics to evaluate trauma management protocols, considering all the information that is relevant in those protocols. Chapter 7 presents and develops a Web-based Trauma Simulator (WBTS) to train trauma management scenarios. At the end of Chapter 7, the trauma management evaluation system is presented. Chapter 8 combines the simulator developed on the previous chapter with the evaluation system developed, integrating it into the WBTS, presenting and summarizing the results obtained.

The conclusions and future works are collected in Part III with Chapter 9. Section 9.1 reviews the work done in the Thesis and discusses its main aspects. Section 9.2 suggests a list of proposals and improvements of the proposed evaluation system. Finally, a review of the author related contributions is summarized in Section 9.3.

2 Research hypotheses and objectives

2.1 Research hypotheses

The general hypothesis of this Thesis is defined as follows:

H1. An objective evaluation system can be designed and implemented to measure trauma management knowledge acquisition.

Trauma is one of the leading causes of death in the world. Considering that immediate deaths are still an important number, trauma training remains to be a necessary task. There are a number of trainings which focus on teaching and learning trauma management but there is an important gap with respect to objective evaluation tools of those trainings. Therefore, there is a need to offer the possibility to objectively evaluate knowledge acquisition after a trauma management training.

The core of this Thesis is to develop and implement an evaluation system that allows to measure how well a simulation is performed, considering all trauma management relevant aspects. As trauma patients may suffer unpredictable circumstances, this should be considered on the evaluation system defined. The main aspects to consider are:

- To define and develop an appropriate trauma protocol for different trauma scenarios.
- To analyze all the trauma relevant aspects to be able to evaluate how well a simulation is done.
- To perform an analysis using the evaluation system developed to prove that trauma management knowledge acquisition is properly measured.

H2. A clinical simulator modality that allows to incorporate trauma management protocols and the evaluation system defined can be developed. This simulator has to allow gathering all the relevant aspects to analyze how a trauma patient treatment has been done.

Clinical simulation has been used to provide real-patient experiences to clinicians to train and face clinical circumstances as if they were real. There are several clinical simulation modalities. From the clinical simulation landscape, most of the simulators try to interact as much as possible with the trainee in order to provide realism to the simulation. To achieve that realism, a simulator that allows implementing a real trauma scenario in which a patient suffers a trauma and the stabilization of the patient is performed, can be developed. There are already simulators that allow it but, there is a need to further investigate on a modality that can integrate those scenarios together with the option to train people simultaneously, independently of the location of the trainee. A reduced development cost would be another important aspect to consider. Additionally, a consistent database has to be present in the simulation, in order to gather all the relevant aspects of the simulation, such as the actions taken, when they were taken or the impact suffered on the vital signs of the patient. This allows to implement the evaluation system previously defined. This part of the research is centered on finding an adequate solution to this hypothesis.

H3. Trauma management protocols which combine general trauma management guidelines together with experts' experience can be defined. A step by step action protocol will make trainees to learn protocols more easily. Additionally, these protocols have to be flexible, to include, if necessary, any changes due to new procedures and/or techniques that may appear.

There is the a need to have protocols in place for trauma management. They support a faster and efficient treatment response to trauma patients. Considering the important number of immediate deaths within these patients, a quick and fast response is needed. To do so, important concepts need to be previously integrated and therefore, practical and detailed protocols need to be in place. The Advanced Trauma Life Support (ATLS) and Prehospital Trauma Life Support (PHTLS) provide general trauma management guidelines with the need to locally translate them to each healthcare facility. Additionally, these protocols have to be flexible in order to incorporate new techniques or procedures, if needed, and the current practices as per trauma experts' experience. Moreover, this flexibility has to consider different trainee profiles, as different clinical personnel are involved in trauma management. Therefore, these protocols can be taught in different levels of clinical education. Consequently, trauma protocols have to allow all these changes easily to be able to incorporate an updated clinical practice to protocols.

H4. A set of metrics can be designed and implemented to measure compliance with trauma management protocols. These metrics have to consider all trauma management relevant aspects.

To measure how well a trauma protocol is learnt, new metrics can be developed. First of all, all trauma management relevant aspects need to be considered. The actions taken during the first minutes of treatment are key due to the trauma death distribution. Therefore, analyzing how well the treatment starts has to be considered. Additionally, there are some actions which have to be always accomplished. If they are not, the patient suffers important consequences; therefore, some metrics have to analyze this relevant aspect. Moreover, the global performance of the whole simulation has to be deeply studied. In this study, the most important aspects are:

- The correct order of the actions.
- When the actions are accomplished.
- If the sequence of actions is similar to the protocol set.
- The number of correct subsequences of actions accomplished.

2.2 Objectives

The general objective of this Thesis is to develop an automated trauma management evaluation system to measure the knowledge acquired through simulation. The proposed evaluation system is validated by studying its application in four specific trauma management scenarios integrated in a simulation modality with the characteristics defined in the previous section. Therefore, the specific objectives are established as follows:

- To accomplish a deep analysis of the current simulation-based education landscape in trauma management. This analysis allows to understand the gaps and needs to build an appropriate simulation modality to achieve trauma management learning.
- To design and implement trauma management protocols for different trauma scenarios in which all trauma relevant aspects will be considered.
- To build and generate new trauma management evaluation metrics to measure trauma management protocol compliance.
- To design and develop a simulator that supports the integration of the trauma management protocols together with an evaluation module.
- To develop an evaluation system by integrating the relevant metrics previously defined.
- To perform experimental tests with the proposed automated trauma management evaluation system. These tests should consider different trauma management scenarios.

PART I

Background

3 Trauma

3.1 Introduction

Trauma injuries are one of the leading causes of death in the world, taking the lives of 4.4 million people each year, which represents approximately the 8% of all deaths (World Health Organization, 2021c). For people with ages comprised between 5 and 29 years old, three of the top five causes of death are injury-related. Moreover, trauma injuries represent the first cause of death being the 37% of deceases due to both, unintentional and intentional injuries, as shown in Figure 3.1.

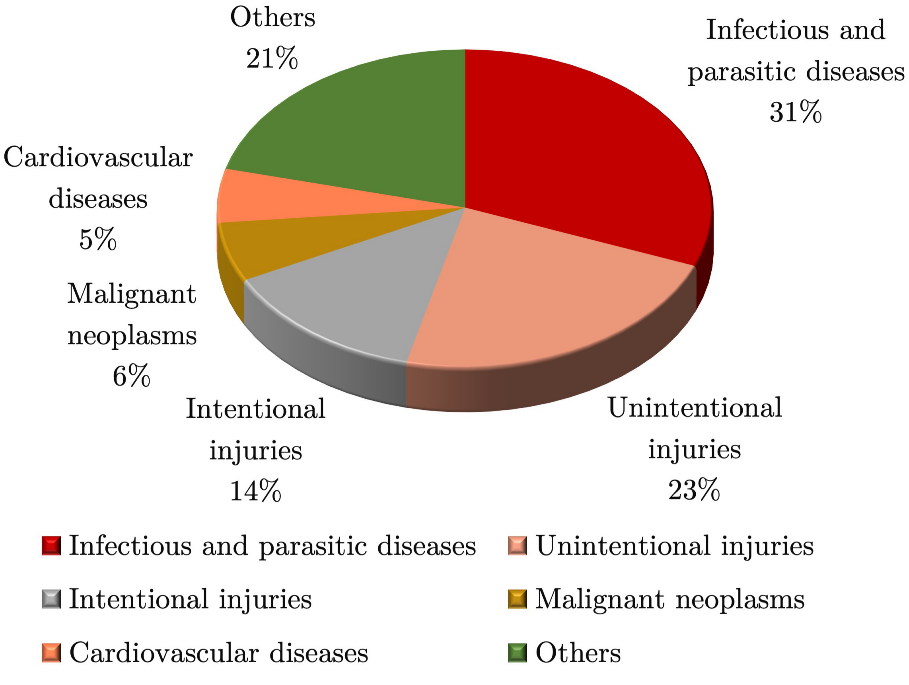


Figure 3.1: Global health estimates 2019, causes of death (World Health Organization, 2021a).

The most frequent trauma injuries come from traffic accidents, self-harm and falls as shown in Figure 3.2. Additionally, these injuries produce disabilities, being trauma injuries responsible for approximately 10% of all years lived with disability. These are the reasons why trauma injuries have an important impact on economies, as the healthcare costs might be extended in time due to those disabilities. Additionally, these injuries affect to active workers.

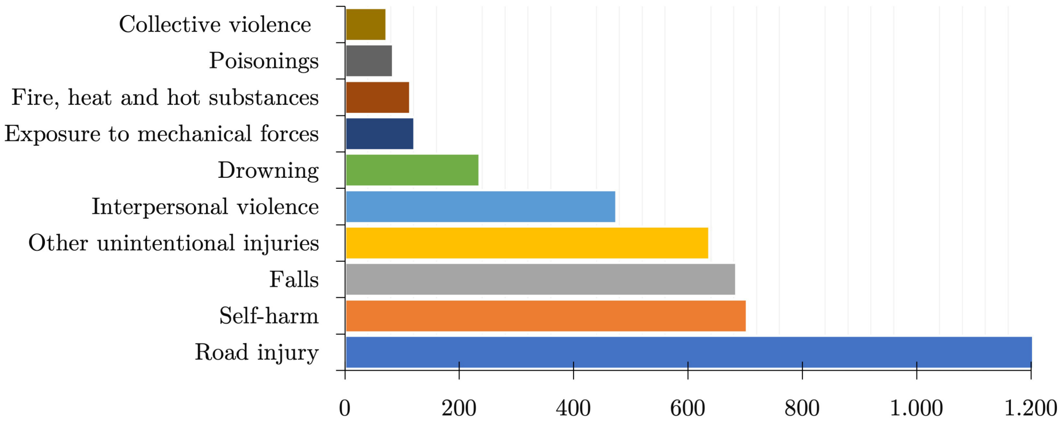


Figure 3.2: Global number of deaths per injury cause, data in millions (World Health Organization, 2021a).

Apart from the deceases caused by trauma injuries, tens of millions more people suffer injuries which are not fatal but require medical services and attention. This means that hospitalization is required, as well as treatments such as rehabilitation coming from the injury suffered or mental health support to cope with the consequences of the injuries. For these reasons, it is important to educate people on injury prevention. Depending on the country, the exposure to different injuries vary. In low and middle income countries, trauma injuries happen more often as the measures they have to prevent and reduce those injuries is reduced. Moreover, the resources to treat them are also limited. Injuries are the leading cause of death for people with ages between 5 and 49 years old in the following regions: the Region of the Americas (Amr) which comprises all the countries located in the American continent, the European Region (Eur) which includes all the countries located at the western and central part of Europe, the Eastern Mediterranean Region (Emr) and the Western Pacific Region (Wpr). Moreover, it is the second cause of death in the African Region (Afr) and the South-East Asia Region (Sear) in which the leading death cause is infectious and parasitic diseases. As previously mentioned, the distribution of the prevalence of injuries changes depending on countries characteristics. Considering the previous regions, unintentional injuries are more frequent in the South-East Asia Region followed by the Western Pacific Region and the African Region. The incidence in Europe, Eastern Europe and America is almost half of the one presented for the other regions as shown in Figure 3.3. Nevertheless, there are important differences when the injuries are intentional, being the American region the leading one followed by the South-East Asia region. The African and Western Pacific regions reduce the incidence to a half. The European Region together with the Eastern Mediterranean one maintain a similar incidence for both intentional and unintentional injuries as shown in Figure 3.3.

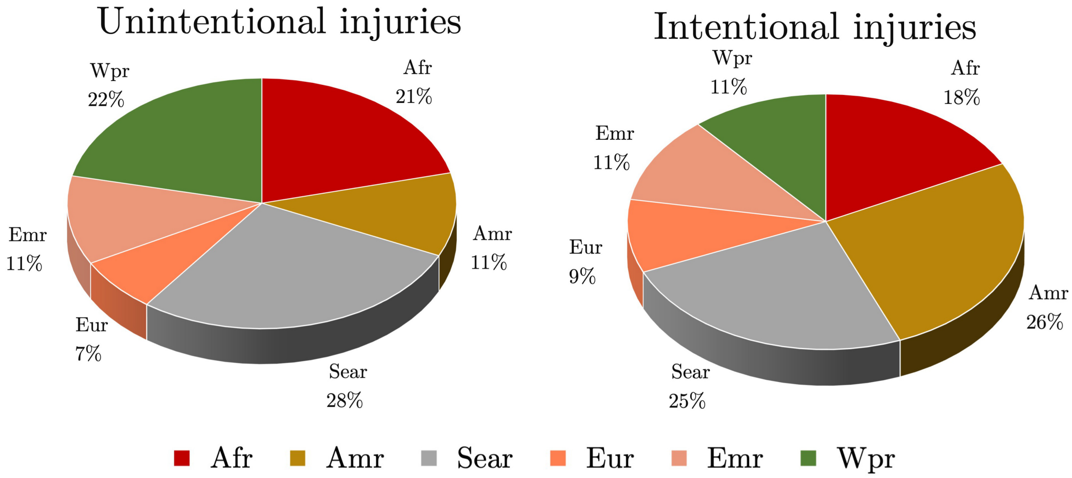


Figure 3.3: Prevalence of unintentional and intentional injuries per region (World Health Organization, 2021b).

3.2 Trauma injuries

Considering the importance of trauma injuries, severity scales have been developed in order to classify them. The main objective was to be able to predict the evolution of a patient taking into account the severity of the injuries suffered. The measurement of injury severity started 50 years ago. In 1969, a group of researches developed the Abbreviated Injury Scale (AIS) to grade individual injuries. Since then, new scores have arisen based on this AIS score (Fandino et al., 2000; Rapsang and Shyam, 2015; Boyd et al., 1987).

3.2.1 Trauma scales

The different injury severity scores can be classified as follows:

- **Anatomical scores**: These are scores based on the characterization of injuries anatomically. The main scores are:
  - *Abbreviated Injury Score (AIS)*: This score was created by the Committee on Medical Aspects of Automotive Safety of the American Medical Association in 1971. It rates the severity of injuries becoming a tool that enhanced trauma treatment to patients, that entailed a new way of sharing information about automotive crash and injury prevention. This score included a set of 73 non-penetrating injuries providing a severity level from 1 - minor severity injury to 6 - incompatible with life injury as shown in Table 3.1.

    This score has been updated along time, the last update has been released in 2015 which includes an improvement in brain injury coding, spinal cord impairment coding and enriches many code definitions incorporating updated medical terminologies. This score is often calculated in the initial assessment of patients in the emergency department. Additionally, this code is the basis for the Injury Severity Score (ISS) and identifies injuries according to nine AIS body regions: head, face, neck, thorax, abdomen, spine, upper extremity, lower extremity and external and other.

Score	Injury
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Incompatible with life

Table 3.1: Injuries ranked from 1 to 6 being 1 a minor injury and 6 an injury incompatible with life.

– *Injury Severity Score (ISS)*: This score was created to provide an overall severity score for patients with multiple injuries and it was introduced in 1974. To calculate the ISS, the body is divided into six ISS body regions:

1. Head or neck - including cervical spine
2. Face
3. Chest - including thoracic spine and diaphragm
4. Abdomen or pelvic contents
5. Extremities or pelvic girdle
6. External

Then, the ISS score is calculated as follows:

$$ISS = A^2 + B^2 + C^2 \tag{3.1}$$

where A, B and C are the highest AIS scores of the most severe injury of three different ISS body regions. The ISS score ranges from 3 to 75 because if any of the AIS scores is 6, the ISS is automatically set to 75 considering that 6 is an injury incompatible with life and therefore, the patient does not need any further treatments. When the ISS score obtained is higher than 16, it is considered that the patient suffers a polytrauma. Some studies consider this score to be a good predictor of prognosis whereas some others consider that this score has limitations and, therefore, should not been used for prognosis (Fandino et al., 2000; Rapsang and Shyam, 2015). Nevertheless, this scoring system has limitations such as it only considers three body regions and that it only considers one injury per body region. This has more impact on penetrating trauma, in which more than one lesion could appear in the same body region.

– *New Injury Severity Score (NISS)*: This score is similar to the ISS one but takes into account the three most severe injuries regardless of the body region in which they occur. Therefore, if there are three injuries in the abdomen, each of them would be considered whereas the ISS would only consider the abdomen once. This simple modification counteracts the limitations of the ISS score. The way this score is calculated is very similar to the ISS calculation; it takes into account the three most severe injuries of a patient regardless of the body region, squared them and then add them up.

- **Physiological scores**: These scores are based on physiological aspects.

  – *Glasgow Coma Scale (GCS)*: This is a clinical score to determine the consciousness of a patient after a trauma injury. It was developed in the Glasgow University in 1974 and it was the first scoring system to measure injuries on the brain (Restrepo-Álvarez et al., 2016; Rapsang and Shyam, 2015). Nowadays, this scale is worldwide used to measure the traumatic brain injury severity. Several studies show that there is an important correlation between this GCS and the neurological condition of a patient. This score is calculated as the sum of individual scores provided to the visual, verbal and motor response of a patient after an injury:

$$GCS = E + V + M \tag{3.2}$$

where E is the eye/visual response, V is the verbal response and M is the motor response which possible values are shown in Table 3.2.

Score	Best eye response (E)
1	No eye opening
2	Eye opening in response to pain
3	Eye opening in response to verbal commands
4	Spontaneous eye opening

Score	Best verbal response (V)
1	No verbal response
2	Incomprehensible sounds
3	Inappropriate words
4	Confused
5	Orientated

Score	Best motor response (M)
1	No motor response
2	Extension response to pain
3	Flexion response to pain
4	Withdrawal in response to pain
5	Localizing response to pain
6	Obeying commands

Table 3.2: Glasgow Coma Scale (GCS).

Obtaining a GCS higher or equal than 13, it means that the patient suffers a mild brain injury; if the score is between 9 and 12, it is considered a moderate injury whereas if the GCS is 8 or lower, it is considered that the patient suffers a severe brain injury.

– *Trauma Score (TS)*: The trauma score assesses the trauma severity of patients and it was introduced in 1981 (Champion et al., 1981; Rapsang and Shyam, 2015). This score considers five variables: the GCS, the Respiratory Rate (RR), the Systolic Blood Pressure (SBP), the Respiratory Effort (RE) and the Capillary Refill (CR). Each of the variables has a value assigned according to Table 3.3 and the score is calculated summing up all the individual scores:

$$TS = GCS + RR + SBP + RE + CR \tag{3.3}$$

The value of this score ranges from 1 to 16, being 16 the highest score in which a patient response is positive and therefore, the severity of the trauma injury is very low. However, the capillary refill and the respiratory effort are difficult parameters to assess and this score was hard to be computed.

Trauma Score	Value	Points
Glasgow Coma Scale (GCS)	14-15	5
	11-13	4
	8-10	3
	5-7	2
	3-4	1
Respiratory Rate (RR)	10-24	4
	25-35	3
	> 35	2
	< 10	1
	0	0
Systolic Blood Pressure (SBP)	> 90	4
	70-90	3
	50-69	2
	< 50	1
	0	0
Respiratory effort (RE)	Normal	1
	Shallow or retractive	0
Capillary Refill (CR)	Normal	2
	Delayed	1
	None	0

Table 3.3: Trauma Score (TS).

– *Revised Trauma Score (RTS)*: This score was introduced in 1989 coming from an evolution of the Trauma Score (TS) after analyzing more than 2,000 patients that were treated at the Central Hospital of Washington (Champion et al., 1989) and then it was validated with 26,000 patients from 51 different health care institutions. This revision considered less physiological variables than the TS as those variables were hard to asses. The RTS provides information about a patient taking into account the GCS, the SBP and the RR. The result of this RTS score is obtained using the following equation:

$$RTS = 0.9368 * GCS + 0.7326 * SBP + 0.2908 * RR \tag{3.4}$$

The constants that multiply each of the variables come from a logistic regression model for mortality data of patients included in the Major trauma outcome study (Champion et al., 1990b). This score is more complex to compute so it is hard to use it in the field but it has been proved to be successful in patient prognosis (Champion et al., 1989). To compute this score, values have been assigned to the three variables as stated in Table 3.4.

Then, taking into account the value of each of the three variables, they are included in the RTS formula obtaining the final score being 0 the worst one and 7.84 the best one in which the trauma injury of the patient is considered low. This score can be related with the survival probability of a patient by using the Equation 3.5 in which p is the survival probability. Additionally, this score is used as part of the Trauma and Injury Severity Score (TRISS) and A Severity Characterization of Trauma (ASCOT) that will be explained hereinafter.

GCS	SBP	RR	Value
3	0	0	0
4-5	< 50	< 5	1
6-8	50-75	5-9	2
9-12	76-90	> 30	3
13-15	> 90	10-30	4

Table 3.4: Revised Trauma Score (RTS).

$$p = \frac{1}{1 + e^{-}RTS + 3.5718} \tag{3.5}$$

- **Combined scores**: These scores combine both, anatomical and physiological characteristics of the injuries.
  - *Trauma and Injury Severity Score (TRISS)*: In 1987 Boyde et al (Boyd et al., 1987) presented the TRISS as a combination of the injury anatomical structure and the physiological response to such injuries. Therefore, it considers the ISS, the RTS and the age of the patient considering that the age had an impact on the survival of the patients, most likely due to the fact that the cardiovascular compromise is affected by the age of a patient. In Table 3.5, the different TRISS coefficients are presented:

Variable	Blunt trauma coefficients	Penetrating trauma coefficients
RTS	0.9544	1.1430
ISS	-0.0768	-0.1516
Age ≥ 55	-1.9052	-0.6029
Constant	-1.1270	-0.6029

Table 3.5: Trauma and Injury Severity Score (TRISS) coefficients.

To calculate the TRISS, the RTS and the ISS values should be used. With respect to the age, if the patient has 55 or more years old, the parameter age will be 1; if the patient's age is lower than 55 years old, then the age parameter will be 0. For blunt traumas, the TRISS will be calculated as follows:

$$TRISS = \frac{1}{(1 + e^{X})} \tag{3.6}$$

where,

$$X = 0.9544 * RTS + (-0.0768 * ISS) + (-1.9052 * age) + (-1.1270) \tag{3.7}$$

For penetrating traumas, the TRISS will be calculated following the same approach. The results obtained show the survival probability of a patient with the injuries that he or she suffered, considering also the age of the patient (Lefering, 2002; Champion et al., 1990b).

  - *A Severity Characterization of Trauma (ASCOT)*: This severity score was introduced in 1990 (Champion et al., 1990a) trying to find a better predictor for trauma patients. To that moment, TRISS was the most used score to calculate survival rates when a trauma injury was suffered but, the limitations of the ISS caused limitations also in TRISS. Therefore, this ISS was not considered and a new variable was defined, the Anatomic Profile (AP). This AP was introduced in 1990 to overcome some limitations of the ISS. The AP score is calculated as the square root of the sum of the squares of all the AIS scores in a region; therefore, multiple injuries in the same body region are taken into consideration. Additionally, the age of the patient was considered but not as a binary variable (0, 1) but as a continuous one (Champion, 2002; Champion et al., 1996). Therefore, the ASCOT considers the RTS, the AP and the age as shown in Table 3.6:

Variable	Blunt trauma coefficients	Penetrating trauma coefficients
GCS scores (according to RTS)	0.7705	1.0626
SBP scores (according to RTS)	0.6583	0.3638
RR scores (according to RTS)	0.2810	0.3332
Body region A	-0.3002	-0.3702
Body region B	-0.1961	-0.2053
Body region C	-0.2086	0.3188
Age scores	-0.6355	0.8365
Constant	-1.1570	-0.8365

Table 3.6: A Severity Characterisation of Trauma (ASCOT).

The value of the variable body region A is calculated considering the AIS of injuries on the head, brain and spinal cord; the variable body region B considers the AIS value of the thorax and neck and body region C takes into account all other body regions. With respect to the variable age score, it is calculated considering the age of the patient: if the age is lower than 54, the age score value is zero; if the age of the patient is between 55 and 64 years old, the age score is one; if the age is between 65 and 75 years old, the age score is two; if the age is between 75 and 84 years old, the score is three and if the age is higher or equal than 85 years old, the age is score is four. For blunt traumas, the ASCOT will be calculated as follows:

$$ASCOT = \frac{1}{(1 + e^Y)} \tag{3.8}$$

where,

$$\begin{aligned} Y = {} & Constant + (0.7705 * GCS) + (0.6583 * SBP) + (0.2810 * RR) \\ & - 0.3002 * APRegionA - 0.1961 * APRegionB - 0.2086 * APRegionC \\ & - 0.6355 * Age \end{aligned} \tag{3.9}$$

The ASCOT shows better results in predicting patient survival rate but being more complex to calculate than TRISS makes that this score is the most used when analyzing trauma patients (Champion, 2002).

3.2.2 Trauma classification

The condition of the patient is intimately related with the mechanism of the injury. In general, trauma injuries are grouped in two main categories: penetrating injuries and non-penetrating or blunt trauma injuries.

- **Penetrating trauma injuries**: these are injuries caused by violent situations such as gunshots or stabbings. They are called penetrating as an external object enters into the body causing damages and generating an open wound. This object may remain within the body of the patient, may go inside and outside of the body of the patient or may cross the body of the patient exiting from a different location.

  Penetrating trauma injuries may be serious as they could damage internal organs due to the external object entering into the body but the severity depends on the organs damaged. In these traumas, it is important to pay attention to the mass of the object that is causing the injury, but more importantly, the velocity it had when entering into the body. This is because the kinetic energy ($\frac{1}{2}mv^2$) that is absorbed by the body due to an external object is in function of the mass and the velocity but the velocity is squared, in the axis of penetration, whereas the mass is not.

- **Blunt trauma injuries**: these injuries as also known as non-penetrating trauma injuries. They are injuries caused by an external force impacting towards the body. They are usually produced in traffic accidents, falls or injuries during sports. Non-penetrating trauma injuries may result in contusions, bone fractures, internal damages and hemorrhages. They could be also severe, depending on the organs damaged during the accident. In these injuries, having information about the type of accident: car, motorcycle, pedestrian, fall from height or fall from ground, could provide some hints about the type of lesion suffered by a patient.

Moreover, depending on the part of the body affected, the trauma injuries could be classified as:

- **Thoraric Trauma**: the injuries that affect this body region correspond to the 20-25% of all traumas worldwide being the third cause of death after head and abdominal traumas (Demirhan et al., 2009; Lecky et al., 2010). The thorax is the body region that comprises between the neck and the abdomen as shown in Figure 3.4. This body region contains the lungs, heart as well as many muscles and several other internal structures. It is protected by the rib cage, spine and shoulder girdle.

  In thoracic trauma, blunt thoracic injuries are more common than penetrating ones, being traffic accidents the most common cause followed by falls (Wilson et al., 1977). Most of these blunt injuries are managed by chest tube drainage but surgery is needed in some cases in which the AIS and ISS are high (Kish et al., 1976). In those cases, patients are more likely to suffer a multi-organ failure (MOF). If the thoracic trauma is non-penetrating, less than 10% goes to surgery whereas if the thoracic trauma is penetrating, the percentage of patients that go into surgery increases, being between 15% and 30% (Edgecombe et al., 2021). Mortality and morbidity due to thoracic injuries are associated with the interruption of respiration, circulation or both. Problems with respiration could come from direct impact on the lungs or on the airway. Circulatory problems occurs when the blood loss is important or there is a direct cardiac injury.

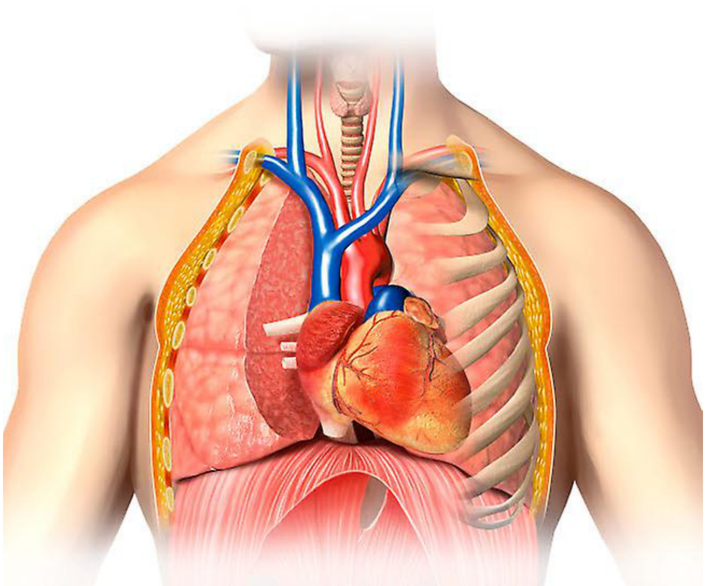


Figure 3.4: Image of a male thorax with the main organs and internal structures (Posterazzi, 2021).

- **Abdominal and Pelvic Trauma**: Approximately one third of all trauma injury patients suffer abdominal injuries (Ntundu et al., 2019) being responsible for 10% of the mortality due to trauma injuries (Aziz et al., 2014). Abdominal injuries is the second cause of death after head injuries (Lecky et al., 2010). This type of injuries require special attention and need early detection because approximately 25% of those injuries need surgery (Brooks, 2010; Ntundu et al., 2019).

  This body region comprises the abdominal and the pelvic cavity as shown in Figure 3.5.The abdominal cavity is a large part of the human body which is located under the thoracic body region and above the pelvic one. The main organs that are contained within the abdominal cavity are: the stomach, liver, gallbladder, spleen, pancreas, small intestine, kidneys, large intestines and adrenal glands. The pelvic cavity is bounded by all the bones that form the pelvis and it contains the reproductive organs, bladder, ureters, rectum and iliac vessels amongst others. Depending on the mechanism of the injury, the abdominopelvic injury could be blunt or penetrating, most of them are blunt and they come from traffic accidents, falls or industrial accidents whereas penetrating injuries are less common (Mohanty et al., 2013). It is really important an early identification of injuries in this body region as internal hemorrhages could appear. The external appearance of the patient may not be related to his/her actual state due to those internal damages. In fact, the major cause of mortality in polytrauma patients is hemorrhage, which is the main preventable cause of death within trauma injuries (Mohanty et al., 2013); therefore, early detection by analyzing the hemodynamic status of these patients is key.

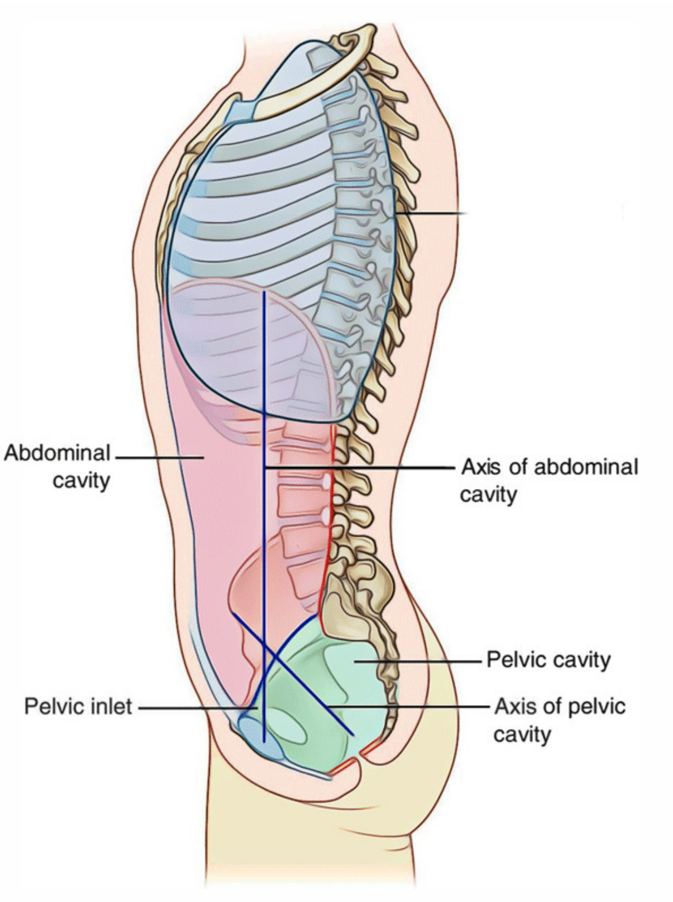


Figure 3.5: The Abdominal and Pelvic cavities that make up the abdominopelvic cavity (Earths Lab, 2021).

- **Head Trauma**: Head injuries are the most common types of trauma injuries and the leading cause of death amongst all trauma injuries (Lecky et al., 2010; Gean and Fischbein, 2010). Traumatic Brain Injury (TBI) due to head trauma is a common cause of death and disability and could be classified as mild, moderate or severe, depending on the Glasgow Coma Scale (GCS):

  - *Mild*: GCS between 13 and 15; it is also called concussion.
  - *Moderate*: GCS 9 to 12.
  - *Severe*: GCS 3 to 8.

  Worldwide, approximately 10 million people are affected annually by TBI and, in the United States, it is the leading cause of death in people younger than 44 years old. The impact of these injuries is really high as, apart from death, they cause important disabilities after the lesion. Between 70-80% of TBIs are mild in severity and the remaining ones are equally divided between moderate and severe injuries (Shaikh and Waseem, 2021). The mortality associated to each of the TBIs is as follows: mild injuries have a mortality rate lower tan 0.5%, moderate injuries have a mortality of approximately 15% whereas severe injuries have a mortality rate of almost 40% (Brommeland et al., 2018; Portaro et al., 2018; Salehpour et al., 2018). Head injuries usually result from blunt or penetrating injuries. The majority of these injuries come from falls and accidents and, although penetrating injuries are less common than blunt injuries, they are more fatal (Santiago et al., 2012). Penetrating injuries differ from blunt injuries in the fact that an object fractures the cranium and penetrates it.

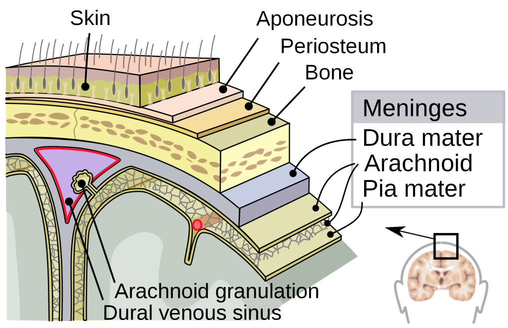


Figure 3.6: The meninges that cover the brain: the dura mater, the arachnoid and the pia mater (Wikimedia Commons, 2021).

Figure 3.6 show the brain cover. The skull is the bone structure that contains the brain, it is irregular and the brain moves during a traumatic event within the skull. The skull is divided in three regions:

1. Anterior fossa: in which the frontal lobes are located.
2. Middle fossa: in which the temporal lobes could be found.
3. Posterior fossa: in which the lower brain stem and cerebellum are located.

Then, the meninges cover the brain and they are three layers as shown in Figure 3.6. The dura mater is a tough membrane that is attached to the skull, then the arachnoid is a thing and transparent layer which is not directly attached to the dura mater but there is a distancia between them and finally, the pia mater is the layer that is attached to the surface of the brain. The cerebrospinal fluid (CSF) fills the space between the dura mater and the arachnoid. Finally the brain consist of the cerebrum, the brainstem and the cerebellum.

- **Spine and Spinal Cord Trauma**: The overall incidence of Spinal Cord Injury (SCI) is of 3.7% of all trauma patients (Milby et al., 2008). Additionally, SCI is considered to be a severe traumatic injury after TBI with respect to morbidity and disability (Bárbara-Bataller et al., 2018; den Berg et al., 2011). More than 90% of spinal cord injuries are due to traumatic events mainly traffic accidents (39.2%), falls (28.3%), violence or gunshot (14.6%) and sports related (8.2%) (Alizadeh et al., 2019; Zhang et al., 2021; National Spinal Cord Injury Statistical Center, 2020). An important factor is alcohol, which plays an important role in approximately 25% of all SCIs (Zhang et al., 2021). SCI is defined as a damage to the spinal cord; as previously highlighted, most of them are due to traumatic events and the minority to non-traumatic events such as chronic diseases, tumors, infections or degenerative disc diseases. This injuries cause an important physical, psychological, social and financial sequelae that affect not only to the patients but also to their families and to the society.

  SCI usually results from a sudden traumatic impact on the spine that fractures or dislocates the vertebrae. The first event that produces an external force to the spinal cord at the time of the injury is called the Primary Injury. Not all the injuries damage completely the spinal cord (Tator and Fehlings, 1991), that is the reason why the outcome of SCI depends on the severity and location of the injury, as it may produce partial or complete loss of sensory and/or motor function below the level of injury.

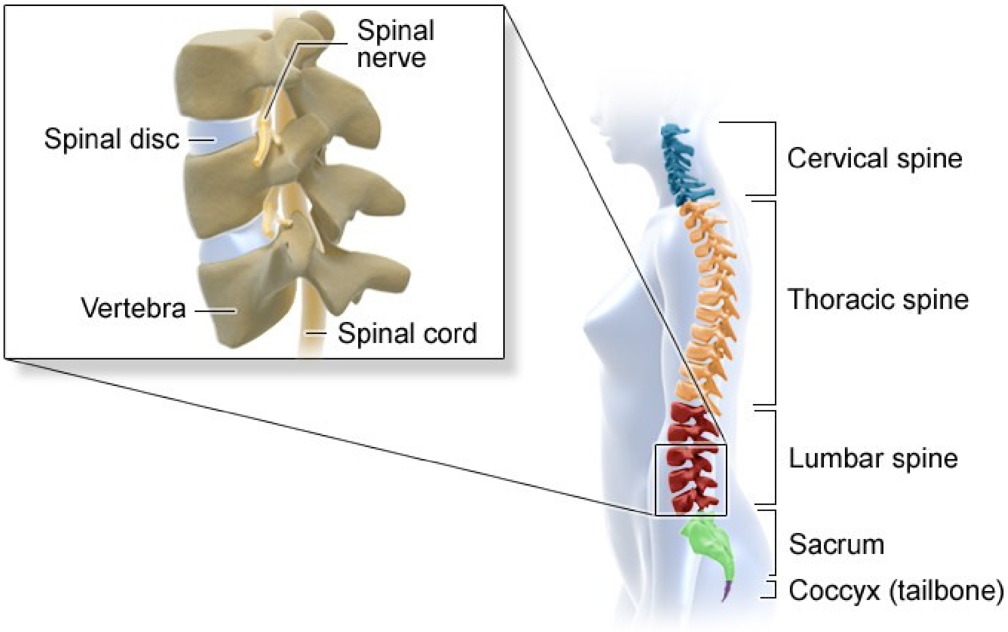


Figure 3.7: Parts of the spine (Institute for Quality and Efficiency in Health Care, 2021).

The spine average length is 71 cm in men and 61 cm in women; the bones that conform the spine are called vertebrae and there are 33 of them in total. In the spine there are four natural curves as shown in Figure 3.7: the cervical, the thoracic, the lumbar and the sacrum spines having at the end the coccyx. These vertebrae also protects the spinal cord which crosses the whole spine from the beginning until the end. Although the spine is made of bones, the vertebrae, it is also flexible thanks to ligaments and spinal disks. The spinal nerves are in charge of carrying electrical signals from the brain to the muscles and internal organs thanks to the spinal cord. Then, also the information received through senses it is sent to the brain thanks to this spinal nerves and the spinal cord.

Lesions at lower thoracic level could cause paraplegia whereas lesions in the cervical area could result in quadriplegia (Wilson et al., 2012). SCI affects more the cervical area being 50% of the SCI lesions; the thoracic area is affected in 35% of the cases and the lumbar area in 11% of the SCI injuries (Hachem et al., 2017).

Independently of the primary injury, the forces that cause an SCI impacts directly the pathways in the spinal cord, disrupting blood vessels and cell membranes (Rowland et al., 2008; Figley et al., 2014) and causing several damages that should be treated with an early surgical decompression of the spinal cord. The most used scoring system for SCI is the ASIA system developed in 1984 by the American SCI Association. The first step is to identify the neurological level of injury and then, both sensory and motor functions are scored as shown in Table 3.7. Then, with the motor and sensory functions scores and taking into account the neurological level of the injury, an ASIA classification is provided to the injuries as shown in Table 3.8.

Grade	Description
Motor Function	
0	Total paralysis
1	Palpable or visible contraction
2	Active movement, full range of motion (ROM) with gravity eliminated
3	Active movement, full ROM against gravity
4	Active movement, full ROM against gravity and moderate resistance in a muscle specific position
5	Normal active movement
Sensory Function	
0	Absent
1	Altered, either decreased/impaired sensation or hypersensitivity
2	Normal

Table 3.7: Scores of the motor and sensory functions (ASIA American Spinal Injury Association, 2021).

Neurological injury severity	Clinical description
Complete ASIA A	No sensory or motor function below neurological level
Incomplete ASIA B	Sensory but no motor function below neurological level
Incomplete ASIA C	Less than grade 3 motor function below neurological level
Incomplete ASIA D	Grade 3 or more motor function below neurological level
Incomplete ASIA E	Neurologically intact

Table 3.8: ASIA Impairment Scale (Kirshblum et al., 2011).

- **Musculoskeletal Trauma**: Injuries to the musculoskeletal system occurs in 85% of blunt traumas (Alsheikhly, 2019), being the two more common causes of these injuries traffic accidents and falls from below two meters (Middlebrook et al., 2021; Cook et al., 2018; Kehoe et al., 2015). Penetrating injuries are more unlikely to happen and in case they appear in the extremities, injuries could derive in major arterial vascular injuries. Moreover, musculoskeletal injuries (MSI) are a major cause of morbidity and mortality across the world that affects mainly to low and middle income countries which lack of trained healthcare services to treat these injuries (Mattson et al., 2019; Hoy et al., 2014; Agarwal-Harding et al., 2016).

  The severity of the injuries depend on the injury suffered and, even though they may not be a life threatening situation, if not treated appropriately, life or limb may be at risk (Alsheikhly, 2019). The injuries caused by blunt traumas usually result in extremity fractures or joints dislocations and if they are close to an artery, they could also disrupt the artery and cause a significant hemorrhage. This is the reason why open fractures and hemorrhages should be treated as soon as possible. The musculoskeletal system, also known as the locomotor system, is a multiple organ system composed by bones, muscles, tendons, ligaments, intervertebral disks and their corresponding nerves and blood vessels (Alsheikhly, 2019). In Figure 3.8, the main bones and muscles are presented. This system provides support, stability and flexibility protecting vital organs.

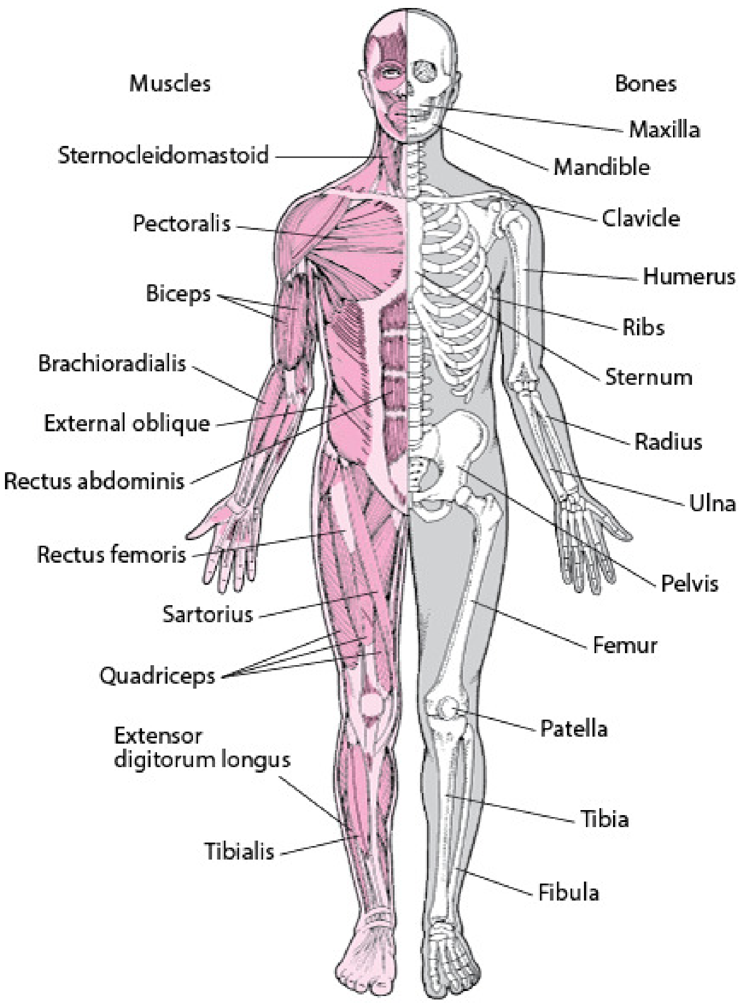


Figure 3.8: Musculoskeletal system in which the main bones and muscles are shown (MSD Manual Consumer Version, 2021).

3.3 Trauma management

3.3.1 Origins of Trauma Management

Trauma management origins go back to the Baron Dominique-Jean Larrey (1766-1842), who served as the Chief Surgeon of the Army of Italy under the command of Napoleon Bonaparte. Dominique organized the transport of injured patients on the battles to field hospitals by means of what he called *ambulance horses*. Therefore, he was the first one to develop ambulance services and dedicated his career to improve the healthcare service to soldiers on the field. Additionally, Dominque also introduced the concept of triage in order to prioritize the most urgent patients and to attend the most critical patients first (Remba et al., 2010).

Years later, during the Crimean war (1853-1856), a nurse called Florence Nightingale introduced a new concept in patient treatment on the battlefield. She realized that most of the soldiers were dying because of communicable and infectious diseases and therefore, she worked on improving patient's conditions. She provided a clean environment to patients and a personal treatment to each patient which improved their diet and rest; the mortality rate decreased dramatically (Karimi and Alavi, 2015).

Then, during the American Civil War (1861-1865), the nurse Clara Barton introduced a new transport system of injured soldiers to the field hospitals minimizing the time spent of the transport. Nevertheless, the biggest change that she introduced was that she did not prioritize the treatment depending on the soldiers' side. She was the founder of the American Red Cross (Strickler, 2018). Improvements on injured patients' treatment were basically done during war periods and therefore; during the two World wars, a lot of injured patients appeared in a very short time period improving a lot their treatment (Barr and S., 2020). After World War I, the occupational therapy increased and was professionalized but the intensity of the World War II created a good environment for medical and surgical innovation in the Unites States. The story of the penicillin is one the most successful developments, which comes from the integrated relationship between the government and medical research in the Unites States that was originated during World War II.

During the Korean War (1950-1983), the helicopter is introduced as a means of transport of injured soldiers (Barr and Montgomery, 2019) and some years later, in the Vietnam War (1955-1975), an important improvement in concepts such as emerging surgery, vascular reconstruction and anesthesiology were achieved (The United States of America Vietnam War Commemoration, 2021). Notwithstanding, the mortality rates of injured patients around the globe continued increasing.

In the early 1970s, R. Adam Cowley, an American military surgeon, popularized the term *Golden Hour* as he observed that a great number of deaths happen during the first hours after the injury. Therefore, this concept is defined as the time in which if the patients are correctly treated and transported to trauma specialized centers, they have more probability to survive (Dharap et al., 2017; Lerner and Moscati, 2001; Rogers et al., 2015). During the same period, Donald Trunkey proposed to include the prehospital care as part of trauma treatment and management (Dharap et al., 2017; Trunkey, 1985). Nevertheless, the great improvement in trauma management came together with the Doctor James Styner plane crash accident in 1976. The unprepared medical response received in this event made Dr. Styner to take action and created a course entitled Advanced Trauma Life Support (ATLS) which was held for the first time in 1980 (Committee on Trauma of the American College of Surgeons, 2018). This course is based on the systematic evaluation of a trauma patient using the ABCDE approach, acronym for Airway, Breathing, Circulation, Disability, and Exposure, which was previously developed to attend all clinical emergencies and which benefits immediate assessment and treatment of injured patients of all age categories (Thim et al., 2012; Maconochie et al., 2015; Linders et al., 2021). The ATLS course is owned by the American College of Surgeons and in parallel with this course, the Prehospital Trauma Life Support (PHTLS) course was created (**?**). This course is sponsored by the National Association of Emergency Medical Technicians and it is developed in cooperation with the American College of Surgeons based on the concepts of the ATLS program.

3.3.2 Advanced Trauma Life Support (ATLS)

The ATLS course was developed in 1976 and it was nationally imparted in the United States under the American College of Surgeons for the first time in January 1980. Since that year, international expansion of this course started and the program has increased in participants and in number of trainings since then. The main concept behind the ATLS was simple. Up to that moment in time, trauma injury patients were treated as any other patient and this treatment consisted of having a complete medical history of the patient, making a complete physical examination and getting to a final diagnosis providing the patient with a treatment. This process worked well for patients in general but, for patients that suffer a sudden and intense accident, it was too slow and needed to change. This is why the ATLS course was born and the three underlying concepts of this training are:

1. Treat the most dangerous injury that risks the life of the patient first.

2. Apply an indicated treatment even though there is not a definitive diagnosis yet.

3. A detailed medical history of the patient is not essential to evaluate the patient.

Until 2018, the ATLS course has trained more than 1.5 million participants in more than 75,000 courses around the world. Every year, an average of 50,000 clinicians are trained in approximately 3,000 courses. Nevertheless, the greatest improvement nowadays is the international expansion of this course, being more than half of the ATLS training activity outside the United States frontiers. At the time the 10th edition of the ATLS Student Manual was published, 78 countries were providing ATLS training programs. To provide this training, a surgical organization recognized by the American College of Surgeons should request it to the ATLS Program Office. The text of the course is revised every four years approximately in order to incorporate new methods, treatments that are adopted by the community of doctors that treat trauma patients. These revisions are done together with different doctor communities including surgeons, emergency physicians, anesthesiologists, course instructors, educators and participants. Other courses have been developed with similar concepts and with the aim to support trauma management training to the clinical community such as the Advanced Trauma Care for Nurses.

The result of ATLS is to apply the ABCDE approach to trauma which evaluates and treats the most dangerous injuries first providing an order in the interventions:

- **Airway** with restriction of cervical spine motion.
- **Breathing**.
- **Circulation**, stop the bleeding.
- **Disability** or neurologic status.
- **Exposure** undress and **Environment** temperature control.

When treating trauma injury patients, time is crucial and therefore, a systematic approach could benefit a fast treatment. That is why having a sequential process with steps to take in those moments may provide support to clinicians when they face those situations. This approach is called the “initial assessment” which includes the following steps:

- **Preparation**: preparation for trauma treatment occurs in two different places at the same time: in the place in which the injured patient is located and in the hospital. When prehospital personnel gets to the place in which the injured patient is located, an immediate treatment should start as well as a coordination from the very beginning with the hospital that will receive the patient. The prehospital treatment will focus on airway maintenance, control of external bleeding, immobilization of the patient and transport as fast as possible to a hospital. The coordination from the beginning with the hospital is important so that when the patient gets there, all the necessary medical providers and resources would be ready to treat the patient. It is also important that the prehospital personnel gathers all the necessary information to properly triage the patient at the hospital, including information with respect to the time of injury, the mechanism of the injury and patient history. More details with respect to the prehospital trauma management will be provided in Section 3.3.3. The transfer of a patient between prehospital and hospital personnel should be smooth. That is why it is important that communication happens from the very beginning. The main aspects that should be ready to treat the patient are:
  - A resuscitation area may be prepared and ready to attend a trauma patient.
  - Airway equipment is ready to use and organized so that it is easily accesible.

– Warm liquids such as crystalloids solutions are available for infusion and monitoring devices are ready to use.
– A clear protocol is in place to call for assistance as well as to ensure fast laboratory and radiology responses.
– Transport agreements must be in place with hospital specialized in trauma management.

All trauma team members should be appropriately prepared to receive a trauma injured patients wearing face mask, eye protection, water-impervious gown and gloves as shown in Figure 3.9 just in case they get in contact with body fluids and they should be ready once the patient reaches the hospital facility.

Figure 3.9: Trauma team members use the following precautions (Federal, 2021).

- **Triage**: as previously mentioned, this concept was introduced by Dominique-Jean Larrey during the 18th century. It basically refers to prioritize medical care depending on the condition of the patients, when several patients are injured at the same time. The order of treatment is based on the ABC priorities (airway with restriction of cervical spine motion, breathing, and circulation with hemorrhage control). Even though other factors are also considered such as the mechanism of the injury or the available resources. During this process, also the selection of the medical facility to which the patient will be transferred is determined. Prehospital trauma scoring is helpful for taking this decision based on the scores explained in Section 3.2.1. Situations in which triage is used are classified as:

  – *Multiple casualties*: these are situations in which several patients are injured but the number of patients and the severity of the injuries do not exceed the capabilities of the facility that will take care of the patient. In these situations, patients with serious and severe lesions are treated first.
  – *Mass casualties*: in these situations, several patients are also affected but the number of patients and the severity of the injuries exceed the capabilities of the facility that will take care of the patients. In these

circumstances, the patients that have more options to survive are treated first.

- **Primary survey (ABCDE) with immediate resuscitation if needed**: Once patients have been assessed, management should start. This should be done in a fast and organized manner. Therefore, this management is based on a fast primary survey with immediate resuscitation if needed, a secondary survey which is a more exhaustive patient examination and the final care to the patient. The primary survey is focused on a quick ABCDE exploration, identifying life-threatening conditions. This should be done in a 10-seconds assessment in which the patient is asked basic questions such as his name and what happened. If a proper answer is provided, this means that the airway is not compromised and that breathing is also not compromised. This due to the fact that if the patient is talking, the movement of air to allow speech is working and; additionally, the level of consciousness has not been severely affected. Nevertheless, if there is no answer to these basic questions, a problem may be happening in A, B, C or D. Therefore, during this primary survey, the most dangerous injuries of the patient are identified and teated by following the prioritized ABCDE sequence.

  – *Airway with restriction of cervical spine motion*: the first evaluation of a trauma patient is the airway, in order to check if there are any obstructions such as foreign bodies, facial, mandibular or any other fractures that could block the airway, blood or any other fluids that could also obstruct the airway. While actions to clear the airway are taken, the cervical spine motion should be restricted.

    As already mentioned, if the patient is able to speak, the airway is not compromised but this should be reassessed to be cautious. Patients with a GCS of 8 or lower usually need to place a definitive airway management by placing a secured tube to accomplish a patency airway. Initially, the chin-lift or jaw-thrust maneuver shown in Figure 3.10 is usually enough as a first measure.

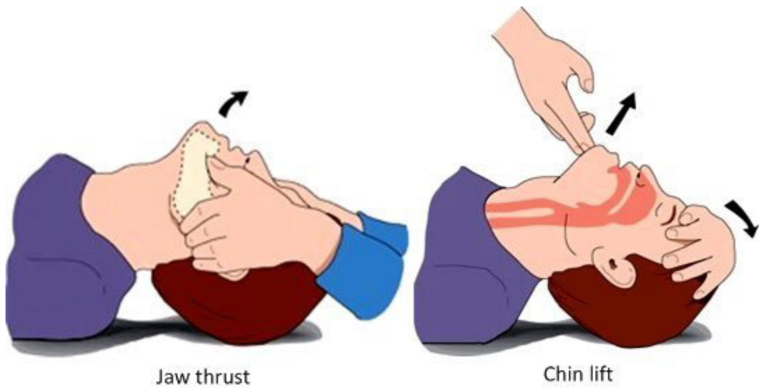


Figure 3.10: Head jaw-thrust and chin lift maneuvers (Tests, 2021).

    In any case, to establish a definitive airway is a must if it is not clear that the patient is able to have its airway permeable. When managing the airway, the cervical spine must be taken into consideration as, in any trauma injury, the first assumption is that the patient may suffer a spinal injury. Therefore, the spine must be protected from mobility by using a cervical collar.

  – *Breathing*: a clear airway does not guarantee a correct ventilation but adequate gas exchange may happen. Breathing and ventilation needs

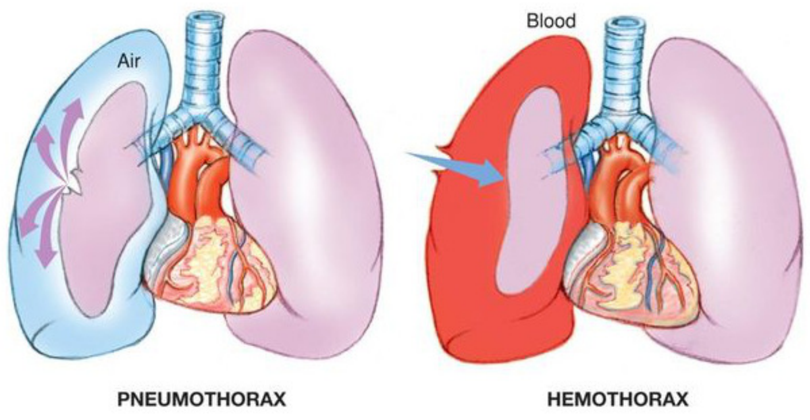


Figure 3.11: An air penetration within the pleural cavity is a pneumothorax and a blood penetration is called a hemothorax (Care, 2021).

that the lungs, the chest wall and the diaphragm work appropriately. Therefore, during this step, these organs must be examined and evaluated. To assess problems in ventilation, auscultations should be performed in order to check if the gas flow in the lungs is correctly circulating. Then palpation and visual check of the chest wall should be done to detect possible injuries. The typical injuries that cause ventilation problems are: tension pneumothorax, massive hemothorax, open pneumothorax and tracheal or bronchial injuries. The difference between a pneumothorax and a hemothorax is that in the first case air is within the pleural cavity and in the second one, blood is within the pleural cavity as shown in Figure 3.11. The pneumothorax could be produced from different injury events and it could be an open pneumothorax or a tension pneumothorax. An open penumothorax occurs if there is an open wound that is compromising the lungs and allowing the entrance and the release of air in the pleural cavity. A tension pneumothorax, the air enters into the pleural cavity but can not leave it producing a high pressure in this cavity.

These injuries should be identified during the primary survey, as they require immediate attention. They should also be treated immediately, to assure a correct ventilation of the patient. It is important to consider that every trauma injury patient should receive oxygen by a mask reservoir device or similar, and that a pulse oximeter should be used to monitor oxygen saturation.

– *Circulation, stop the bleeding*: problems in the circulatory system of a patient that suffers a trauma injury may be due to different causes. The blood volumen, cardiac output and bleeding are the most important aspects to consider within this primary evaluation. Hemorrhage, as previously discussed, is the main preventable cause of death within trauma injuries. Therefore, identifying and controlling hemorrhages is key. Nonetheless, to assess the hemodynamic status of the patient is essential during this primary survey. The elements that need to be checked and managed are: the level of consciousness, the skin perfusion and the pulse. The level of consciousness is important because when the blood circulating within the body is not enough, cerebral perfusion is affected and therefore, consciousness is affected. The skin perfusion is important to identify patients with hypovolemia, which is the reduction of the circulating volume of blood or any other liquids within the cardiovascular system. Patients with a gray or ashen facial skin and pale extremities may reflect this hypovolemic state. Finally, the pulse is another indicator of hypovolemia, specially if the pulse is weak and fast. If there is no pulse at all and there is no external factors causing this absence of pulse, immediate resuscitation has to be accomplished.

After this evaluation, if there is any bleeding, it should be controlled. The bleeding could happen due to external or internal damages. External hemorrhages should be quickly identified and controlled during this primary survey. They are usually managed, applying manual pressure on the wound but, if this is not enough, a tourniquet may be applied in order to stop the bleeding. Internal hemorrhages are harder to identify and it is usually done by physical examination and using imaging techniques such as x-rays. The most dangerous ones are hemorrhages happening in the pelvis, long bones, chest, abdomen and retroperitoneum areas and immediate action should be also taken such as a pelvic binder to stabilize the pelvis. In these cases, surgical intervention may be required.

Bleeding control is essential together with an appropriate replacement of intravascular volume by administering fluids, plasma and blood. To do that, two peripheral venous catheters may be placed and blood samples should be taken to check blood type for possible transfusions.

- *Disability or neurologic status*: a fast neurologic evaluation should be performed determining the level of consciousness of the patient as well as the pupillary size and reaction. This determines the SCI in case there is any and the presence of lateralizing signs which are helpful to localize the damage on the brain. The Glasgow Coma Scale if a fast, simple and objective method to evaluate the neurological status of the patient. a Low level of consciousness may be due to problem in perfusion or oxygenation of the brain or due to a direct injury suffered in this part of the body. Considering that damages in the brain may not be present at the beginning of the primary survey but they may appear later on, it is crucial to repeat this neurological status evaluation. Patients with brain damages should be treated in medical facilities that are prepared to do so, if not, a transfer should be organized as soon as possible.
- *Exposure and Environment temperature control*: it is important to undress the patient during the primary survey so that physical examination is easier. Once this is done, the patient should be covered with warm blankets to prevent hypothermia. Additionally warm fluids could be provided intravenously as hypothermia can be present in trauma patients and this could be a potentially lethal complication in patients with important injuries.

- **Additional actions to the primary survey and resuscitation**: additional actions may be taken, as some aspects may have been perceived during the primary survey but there was no time to accomplish them directly. These actions may be: continuous electrocardiography, carbon dioxide monitoring using capnography, assessment of the ventilatory rate and arterial blood gas analysis. Additionally, urinary or gastric catheters may be used, x-rays examinations may be needed or any other imaging test. It is important to constantly monitor the vital signs of the patient in order to see if the measures taken are stabilizing the patient.
- **Transfer of the patient if needed**: During the primary survey with resuscitation, enough information about the state of the patient and the health care needed is obtained. Therefore, it is also at this point in time that, if the patient needs to be transferred to a different healthcare facility for definitive care, he or she should be transferred with no delay.
- **Secondary survey which includes a complete examination of the patient considering also the medical history**: the secondary survey is

initiated once the primary survey has been completed, the patient has been resuscitated if needed and, an improvement of the vital signs of the patient has been observed. This secondary survey is a complete and exhaustive physical evaluation of the patient including also the medical history of the patient; therefore, all the regions of the body are carefully examined.

- *History*: a complete history information from a trauma patient is, frequently, hard to obtain. Therefore, information should be provided by families and prehospital personnel, obtaining information about allergies, medications currently used, past illnesses, pregnancy, last meal and events related to the injury. Some injuries can be predicted taking into account the mechanism of injury shown in Table 3.9.
- *Physical examination*: during the secondary survey, a comprehensive physical examination of the patient is done according to the following order: head, maxillofacial structures, cervical spine and neck, chest, abdomen and pelvis, perineum/rectum/vagina, musculoskeletal system, and neurological system.

- **Additional actions to the secondary survey**: specific diagnostic tests and checks may be done during the secondary survey in order to identify any injury that the traumatic patient may suffer. These tests include addition x-ray examinations, CT scans, contrast urographies and angiographies, ultrasounds and any other diagnostic procedure that may be required to treat the patient.

- **Continuous tracking and monitoring of the patient**: trauma patients must be constantly reevaluated to ensure that anything is not overlooked and to treat any problem that may arise as a consequence of the injuries suffered in the trauma event. A continuous monitoring of the oxygen saturation, vital signs and urinary output is essential. Also, it is important to treat the pain that the trauma patients suffer; therefore, an appropriate analgesia should be provided and tracked considering the evolution of the patient.

- **Definitive care**: this point is important in the case that the patient may be transferred to a different healthcare facility for specific and definitive care. This happens when the resources of the current healthcare are not enough or a more specialized care must be provided. Therefore, a healthcare center with the resources and expertise to treat each patient should be the one in charge of the definitive care.

Mechanism of Injury	Suspected Injury Patterns	Mechanism of Injury	Suspected Injury Patterns
	Blunt Injury		
Frontal impact, automobile collision ∗ Bent steering wheel ∗ Knee imprint, dashboard ∗ Bull's-eye fracture, windscreen	∗ Cervical spine fracture ∗ Anterior flail chest ∗ Myocardial contusion ∗ Pneumothorax ∗ Traumatic aortic disruption ∗ Fractured spleen or liver ∗ Posterior fracture or dislocation of hip and/or knee ∗ Head injury ∗ Facial fractures	**Rear impact**, automobile collision	∗ Cervical spine injury ∗ Head injury ∗ Soft tissue injury to neck
		Ejection from vehicle	∗ Ejection from the vehicle precludes meaningful prediction of injury patterns, but places patient at greater risk for virtually all injury mechanisms.
Side impact, automobile collision	∗ Contralateral neck sprain ∗ Head injury ∗ Cervical spine fracture ∗ Lateral flail chest ∗ Pneumothorax ∗ Traumatic aortic disruption ∗ Diaphragmatic rupture ∗ Fractured spleen or liver and or kidney ∗ Fractured pelvis or acetabulum	**Motor vehicle impact with pedestrian**	∗ Head injury ∗ Traumatic aortic disruption ∗ Abdominal visceral injuries ∗ Fractured lower extremities/pelvis
		Fall from height	∗ Head injury ∗ Axial spine injury ∗ Abdominal visceral injuries ∗ Fractured pelvis or acetabulum ∗ Bilateral lower extremity fractures (including calcaneal fractures)
Penetrating Injury		***Thermal Injury***	
Stab wounds ∗ Anterior chest ∗ Left thoracoabdominal ∗ Abdomen	∗ Cardian tamponade if within "box" ∗ Hemothorax ∗ Pneumothorax ∗ Hemopneumothorax ∗ Left diaphragm injury or spleen injury or hemopneumothorax ∗ Abdominal visceral injury possible if peritoneal penetration	**Thermal burns**	∗ Circumferential eschar on extremity or chest ∗ Occult trauma (mechanism of burn/means of escape)
		Electrical burns	∗ Cardiac arrhythmias ∗ Myonecrosis/compartment syndrome
		Inhalational burns	∗ Carbon monoxide poisoning ∗ Upper airway swelling ∗ Pulmonary edema
Gunshot wounds (GSW) ∗ Truncal	∗ High likelihood of injury ∗ Trajectory from GSW/retained projectiles help predict injury		
∗ Extremity	∗ Neurovascular injury ∗ Fractures ∗ Caompartment syndrome		

Table 3.9: Mechanisms of injury and suspected injury patterns (Committee on Trauma of the American College of Surgeons, 2018).

3.3.3 Prehospital Trauma Life Support (PHTLS)

The Prehospital Trauma Life Support (PHTLS) training started in 1981, just right after the release of the ATLS training. As the ATLS is revised every four or five years, the changes that apply to the ATLS are transferred to the PHTLS. Even though the PHTLS follows the same principles of the ATLS, this training is specifically designed for the prehospital environment and personnel. This training focuses on the principles of the prehospital attention which are called the Golden Principles of Prehospital Trauma Care and are listed below:

1. Ensure the safety of the prehospital care providers and the patient.
2. Assess the scene situation to determine the need for additional resources.
3. Recognize the kinematics that produced the injuries.
4. Use the primary assessment to identify life-threatening conditions.
5. Provide appropriate airway management while maintaining cervical spine stabilization as indicated.
6. Support ventilation and deliver oxygen to maintain an SpO_2 greater than 94%.
7. Control any significant external hemorrhage.
8. Provide basic shock therapy, including appropriately splinting musculoskeletal injuries and restoring and maintaining normal body temperature.
9. Maintain manual spinal stabilization until the patient is immobilized.
10. For critically injured trauma patients, initiate transport to the closest appropriate facility as soon as possible after the emergency services arrival.
11. Initiate warmed intravenous fluid replacement en route to the receiving facility.
12. Ascertain the patient's medical history and perform a secondary assessment when life-threatening problems have been satisfactorily managed or have been ruled out.
13. Provide adequate pain relief.
14. Provide thorough and accurate communication regarding the patient and the circumstances of the injury to the receiving facility.

PHTLS provides an understanding of the anatomy and physiology, the pathophysiology of trauma and the assessment and healthcare of the trauma patient using the ABCDE approach. The last version of the PHTLS introduces a new approach which is called XABCDE in which the hemorrhage, X, is recognized as a potentially irreversible cause of death and therefore, an immediate threat to take care of. Therefore, having the X prior to the ABCDE approach sets the necessity to take care, immediately, of any external hemorrhage, just right after ensuring safety of prehospital personnel and the patient and before assessing the airway.

A severe hemorrhage, in particular the arterial bleeding, has the potential to cause a complete loss of the blood volume in a relatively short time. Depending on the bleeding, this could happen in only some minutes. As in the prehospital setting, is not possible to transfuse blood, it is extremely important that the hemorrhage is controlled and that this blood loss does not happen before getting to the healthcare facility.

4 Clinical Simulation

Clinical simulation is a technique used to provide real-patient experiences to clinicians so that they can train and face situations as if they were real and before they have to face them providing a hands-on training experience. From its origins, clinical simulation started to support clinical training taking into account patient safety (Hammond, 2004; Aggarwal et al., 2010; Datta et al., 2012; Borggreve et al., 2017). It also offers some other benefits, such as the opportunity to repeat a simulation as many times as needed, to face uncommon medical situations or to train a great variety of technical and non-technical skills (Abelsson et al., 2014; Murray et al., 2015; Dillen et al., 2016; Cuisinier et al., 2015; Berkenstadt et al., 2013). There is evidence that practicing technical skills with a clinical simulator improves the technique learning curve (Datta et al., 2012; Abelsson et al., 2014). Nevertheless, there is still limited evidence on the impact of simulation-based training on the performance in trauma management (Aggarwal et al., 2010; Borggreve et al., 2017) and on the long-term knowledge retention of such trainings (Borggreve et al., 2017; Lewis and Vealé, 2010). The Advanced Trauma Life Support (ATLS) and Prehospital Trauma Life Support (PHTLS) trainings use a variety of simulation modalities combined with classroom sessions. These simulation modalities include skill development workstations and trauma patient simulations (Kim et al., 2020; Häske et al., 2017).

4.1 Clinical simulation modalities

There are several clinical simulation modalities as different technologies have allowed to explore new clinical simulation methods. The choice of the modality to use in a clinical simulation scenario is based on the desired outcome which is usually divided between training technical or non-technical skills (Quick, 2018). The technical skills refer to the application of a correct triage, primary and secondary surveys including the techniques and treatments needed to do that. The non-technical skills focus on communication, leadership, management of the situation and decision-making. Even though, both types of skills are intrinsically related; some trainings focus only on technical skills, others in non-technical skills and others on both of them. The different clinical simulation modalities are highlighted below:

- **Standardized patients**: these are actors, either volunteer or paid, that play de role of a real patient during simulation exercises. Participants in the simulation cases assess and manage the patient appropriately interacting with the patient which will answer and provide challenges according to the clinical case scenario that he or she is representing. The use of standardized patients in medical education can be tracked back to the 1960s and are widely used (Datta et al., 2012; Quick, 2018; Berkenstadt et al., 2013). These patients can be additionally garbed with some simulation modules such as a bleeding module to simulate hemorrhages or be dressed and moulage appropriately to simulate injuries as shown in Figure 4.1.

Figure 4.1: Moulage is applied to a standardized patient's face to simulate a facial injury (University, 2021).

Standardized patients provide interaction to the trainee and real-time feedback which allow to practice communication competencies, clinical reasoning and diagnosis depending on the patient conditions and immediate responses. This clinical simulation modality is more appropriately used to practice non-technical skills and it could be used for individual and team training.

- **Low-fidelity and high-fidelity simulators**: fidelity is a common term in simulation which refers to the degree of realism and technical complexity of a model which tries to simulate real-life experiences. This realism could go from low to high depending on the training needs. Low-fidelity simulators are usually more artificial, less complex and less realistic, but on the other hand they are not so expensive and can be easily developed. High-fidelity simulators include mannequins which are complex with physiological responses to provide real-time feedback to trainees, pupils response, peripheral pulses and blood pressure amongst others. These simulators are quite expensive, need specific maintenance and are more complex to develop. Therefore, depending on the training needs, low or high-fidelity simulators would be more appropriate. To practice specific technical skills, low-fidelity simulators may be more appropriate such as a cricothyroidotomy simulators or intubation simulators as shown in Figure 4.2. These simulators allow to practice a specific skill as many times as needed until the skill is acquired and can be extremely effective and are usually used in skill stations to evaluate specific tasks.

  On the other hand, high-fidelity simulators allow to train and practice a clinical scenario considering several aspects at the same simulation. This allows to practice both technical and non-technical skills and also individual and team trainings. Nevertheless, the cost of such simulators are quite high as well as the maintenance they require. Therefore, high-fidelity simulators are not always the response, as it depends on the goals needed to achieve with the simulation. In Figure 4.3, a high-fidelity simulator in which a team is taking care of a patient is shown. Additionally, high-fidelity simulators could be placed in a real environment such as a surgical room or an intensive care unit, in which a more realistic training case could be provided to trainees.

- **Virtual reality**: it is a simulation modality in which the trainee is offered with an immersive experience. Usually the trainee wears eye googles which allow

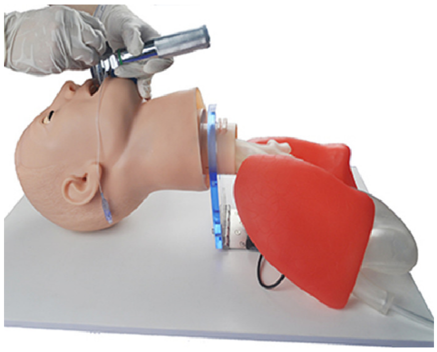


Figure 4.2: Endotracheal intubation simulator (TSE, 2021).

Figure 4.3: SimMan 3G simulator (Laerdal, 2021).

to have a visual and 3D experience as if they were in the simulated scenario. This scenario is computer controlled and sometimes it is possible to incorporate physical interaction by means of haptic feedback. Virtual reality training has shown to be an effective tool with some advantages such as the possibility to connect multiple users at different locations and low cost (Berkenstadt et al., 2013; Quick, 2018; Datta et al., 2012). In Figure 4.4 a full immersive 3D experience is shown in which a surgical environment is programmed and a trainee is placing a device on the patient to fix the knee.

- **Web-based training**: this simulation modality is useful to provide the trainee with a different and user-friendly tool that will support to learn theoretical aspects such as action protocols or medication administering. They allow to train an important number of trainees simultaneously and the development cost is reduced. The scenarios provided in web-based trainings can be easily customized per training goals and they can be used remotely, independently of the location.

Each simulation modality has advantages and disadvantages as highlighted in Table 4.1; therefore, it is important to consider which simulation method to use depending on the goals and the resources.

Figure 4.4: 3D Virtual reality simulator used in a surgical environment (MedicalDesign, 2021).

Simulation Modality	Cost	Technical skills	Non-Technical skills	Team training
Standardized patients	Medium	Low	Medium	Low
Low-fidelity simulators	Low	High	Low	No
High-fidelity simulators	High	Medium	Medium	High
Virtual reality	Medium	Low	Medium	Low
Web-based training	Low	Medium	Low	No

Table 4.1: The strength of each simulation modality from low to high.

4.2 Scoping review on the simulation-based education landscape in trauma management

A scoping review has been performed with the purpose to analyze the current practice in teaching trauma management using simulation with the aim of summarizing it, identifying gaps and providing a critical overview on what has been already achieved in terms of trauma training.

In April 2021, a search was done in the Web of Science website accessing to the following databases: Web of Science Core Collection, BIOSIS Citation Index, BIOSIS Previews, Current Contents Connect, Derwent Innovations Index, KCI-Korean Journal Database, MEDLINE, Russian Science Citation Index and SciELO Citation Index. The search was done using the topic searching field. This topic field includes title, the abstract and/or the keywords and the terms used in the search were the following: simulation OR web simulation OR patient simulation OR mannequin OR interactive AND trauma AND training OR education.

This initial search provided 1.617 publications in which 7 of them were duplicates. Then, titles of the 1.610 articles were screened removing those which were not the scope of this review. Therefore, the ones which focus on children, adolescents, post-traumatic stress disorder (PTSD), obstetrics, and other specialties which do not relate to traumatic injuries were excluded. Moreover, articles published from 2010 until 2021 were selected, obtaining 120 articles. Subsequently, the 120 articles were reviewed, including their titles and abstracts finding that 55 articles were in fact, out of scope, according to the same logic already used but not detected on the title. Therefore, 65 articles were reviewed and analyzed. From these 65 articles, 17 were review articles and 13 were still out of scope as they either focused on a very specific technique or they considered simulation in a different field with no focus on trauma. Therefore, 35 articles really focused on trauma training and provided studies on how different simulation training techniques could impact trauma management training. The process followed is shown in Figure 4.5 following the PRISMA Flow Diagram (PRISMA, 2021).

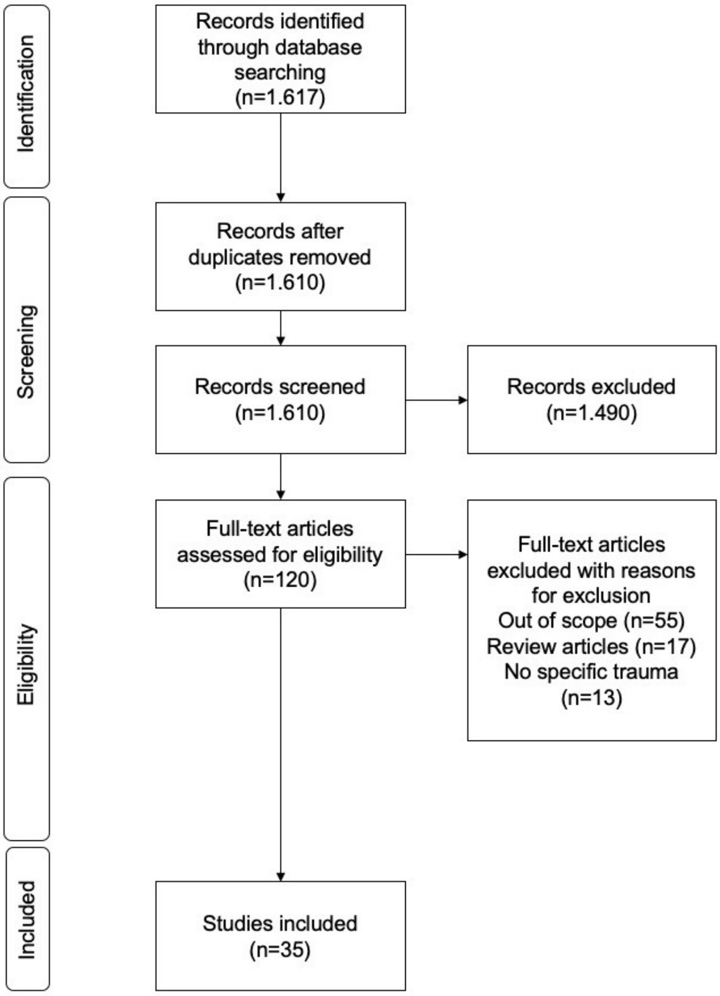


Figure 4.5: PRISMA Flow Diagram to show the study selection process.

The 35 studies included in this review were analyzed. The main characteristics of the 35 articles are included in Table 4.2. in which NS: not stated, VR: virtual reality, SP: standardized patients, L: lectures, HF: high-fidelity mannequin, LW: low-fidelity mannequin, SS: skill stations, PS: porcine simulation, CC: casualty cards, CS: case scenarios, T: technical skills, NT: non-technical skills, WE: written evaluations or checklists, SB: subjective evaluation, PH: pre-hospital and IH: in-hospital.

Manuscript	Population of training	Simulation method	Skills trained	Evaluation type	Context
(Ali et al., 2010)	Surgical residents	HF	T	SB & WE	IH
(Bredmose et al., 2010)	Helicopter emergency medical service doctors and paramedics	HF	NS	SB	PH
(Jacobs et al., 2010)	Surgeons	PS	T & NT	WE	IH
(Knudson et al., 2010)	Residents	L & HF	T & NT	WE	IH
(Ruesseler et al., 2010)	Final year medical students	HF	T	SB & WE	PH & IH
(Taylor et al., 2011)	Paramedics and different roles involved in emergency medicine	VR	NS	NS	PH & IH
(Fernandez et al., 2012)	Residents	HF & LF	T	WE	IH
(Cohen et al., 2013a)	Pre-hospital clinicians and emergency medicine consultants	VR	T	WE	PH & IH
(Cohen et al., 2013b)	Ambulance HART practitioners, surgical residents and emergency consultants	VR	T & NT	SB & WE	PH & IH
(Jawaid et al., 2013)	Final year medical students, interns and consultants	L, SS & CS	T	WE	IH
(Montán et al., 2013)	Physicians, nurses, paramedics, military doctors, administrator	CC	T & NT	SB	PH & IH
(Pringle et al., 2013)	Attending and senior resident physicians	SP	T & NT	WE	IH
(Springer et al., 2013)	Residents	HF	NS	WE	IH
(Kaban et al., 2014)	Residents	NS	T	WE	IH
(Aekka et al., 2015)	Non doctor first responders	HF	T	SB & WE	PH
(Cuisinier et al., 2015)	Medical students	HF	T	WE	IH
(Murray et al., 2015)	Emergency medicine, surgery and anesthesia residents	HF	T	WE	IH
(Amiel et al., 2016)	Physicians and nurses	SS & HF	T & NT	WE	IH
(Farahmand et al., 2016)	Interns	L, CS, SS	T	SN & WE	IH
(Figueroa et al., 2016)	Interns	L, SS & HF	NS	WE	IH
(Walker et al., 2016)	Residents	SP	T & NT	SB & WE	IH
(Alsaad et al., 2017)	Residents	HF & SP	T	WE	IH
(Doumouras and Engels, 2017)	Residents	HF	NT	WE	IH
(Gräff et al., 2017)	Doctors	HF	T & NT	SB & WE	IH
(Campbell et al., 2018)	Paramedics	HF	NS	SB & WE	PH
(Cecilio-Fernandes et al., 2018)	Medical students	HF & SS	T	SB & WE	IH
(Courteille et al., 2018)	Medical students and residents	L & VR	T	WE	IH
(Fleiszer et al., 2018)	Undergraduate medical students	VR	T	SB	NS
(Harrington et al., 2018)	ATLS trainees	VR	T	WE	IH
(Hayden et al., 2018)	Nurses, radiology technicians, attending and trainee physicians	HF	T	NS	IH
(Mills et al., 2018)	Paramedical students	SP	NS	SB & WE	PH
(Sullivan et al., 2018)	Residents and emergency nurses	HF	NT	WE	IH
(Park et al., 2019)	Residents	NS	T	NS	IH
(Kuhlenschmidt et al., 2020)	Residents	SS	T	WE	IH
(Patel et al., 2020)	Residents	CineVR	NS	SB	IH

Table 4.2: Main characteristics of the 35 articles included in the scoping review

4.2.1 Results of the scoping review

- **Target audience of the trainings**: Out of the 35 studies, only seven of them focused on medical students (see Figure 4.6 (a)). From these seven studies in which the target audience were medical students, one of them focused on paramedic's students and another training focused on both medical students and doctors altogether. This shows that only 20% of the studies presented a simulation-based trauma training delivered specifically for medical students during their undergraduate academic training. The rest of the studies presented simulation-based trainings for either consultants, residents in a similar proportion and just three of them had as a target audience paramedics.

- **Simulation methods used**: With respect to the simulation methods used , 18 of them (51.4% of the trainings) used high fidelity mannequins during the trainings as shown in Figure 4.6 (b) whereas the rest used other methods. Regarding the other methods used, one of them presented simulation cards as the training method used; three of them used standardized patients trained for that purpose; another three studies used skill stations to practice several skills during the trauma management training and seven of them used virtual reality training as the simulation method. The remaining studies did not specify the simulation method used.

- **Skills trained**: Regarding the skills trained, 18 of them (51.4% of the trainings) focused on training technical skills considering the application of correct protocols to attend trauma patients as well as specific treatments and techniques for trauma treatment. Only two of the studies included in this scoping review focused on non-technical skills and 8 of them focused on both technical and non-technical skills training (see Figure 4.6 (c)).

- **Evaluation methods used**: Taking into consideration the evaluation methods, only two of the studies provided an automated evaluation of the training delivered as shown in Figure 4.6 (d). An automated evaluation of the training is considered automated when the simulation method used provides an assessment just right after the simulation taking into account the performance. To do so, the simulation methods should be prepared to gather all the necessary information for such evaluation. The rest of the studies provided a manual evaluation. With respect to the evaluation methods used on the different trauma management trainings, a more comprehensive analysis has been performed. From the different methods presented in the 35 articles, 18 of them use either checklists or evaluation forms that have been previously prepared, providing different options to the trainees. Then, there are four studies which used subjective evaluation methods which included interviews, written comments or direct observation. Ten of the studies used both checklists and subjective evaluation methods and finally, three studies do not state the evaluation method used as shown in Figure 4.6 (e).

- **Context of the simulation**: With respect to the context in which the simulation took place, four of them focused on extra-hospital training, presenting trauma management trainings in which the personnel and the resources are different from the ones in the hospital. 25 studies focused on the hospital trauma management whereas five of them, as shown in Figure 4.6 (f), provided a trauma management training with focus in both, extra and in-hospital scenarios.

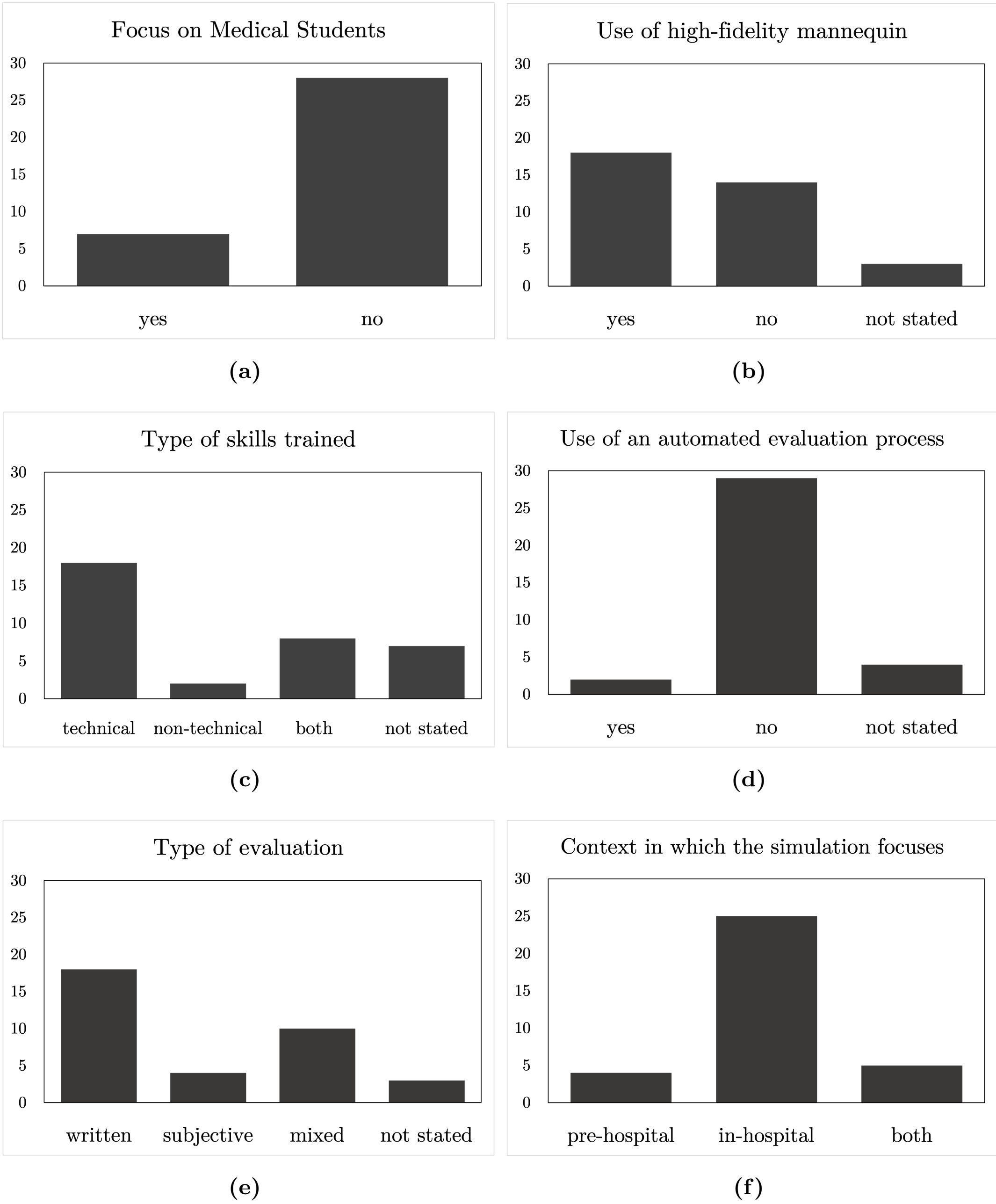


Figure 4.6: Results of the different aspects highlighted in this scoping review.

4.2.2 Discussion on the scoping review

Results show that there is scarcity on trauma management trainings for medical students. Moreover, according to (Borggreve et al., 2017; Jouda and Finn, 2020) the best simulation method and procedure to teach trauma management to medical students has not yet been established. This is a field that needs further development as medical students should be trained on trauma management skills taking into account that they will soon be residents; therefore, having a specific trauma training before this happens will provide a better treatment to patients (Cuisinier et al., 2015; Cecilio-

Fernandes et al., 2018; Ruesseler et al., 2010). Additionally, it is important to gain clinical reasoning during medical school, as it will be key for the clinical practice, and this could be obtained with a trauma management training in which clinical reasoning is key (Fleiszer et al., 2018). According to (Ashcroft et al., 2021), none of the 29 articles included in the review were capable of demonstrating significant objective impact on mortality and morbidity of trauma patients; therefore, there is still more research needed on this field. Nonetheless, several studies (Cecilio-Fernandes et al., 2018; Alsaad et al., 2017; Barleycorn and Lee, 2018) support and present statistical improvement in trauma management performance after simulation training. They confirm that, if the correct simulation modality is used, the expected outcome could be more easily predicted (Quick, 2018). Therefore, it is important to know the different simulation modalities and how they should be implemented within a trauma management training. In (Quick, 2018), it is stated that trauma training uses both low and high-fidelity training modalities. Low-fidelity allows to reproduce and practice technical skills such as airway management whereas high-fidelity offers the possibility to train both technical and non-technical skills. Additionally, standardized patients could be also used to train non-technical skills and, if properly garbed and with the appropriate modules, also some technical skills could be practiced. Moreover, virtual reality is currently increasing its presence as it allows to connect multiple users at multiple locations increasing the availability to centers with limited resources. This simulation modality offers the possibility to immerse learners into authentic clinical scenarios at low cost.

With respect to the simulation methods used, traditional simulation methods try to imitate a real patient simulation; that is the reason why high-fidelity mannequins or actors have been widely used (Abelsson et al., 2014; Knudson et al., 2010). Nevertheless, technology allows the development of other simulation methods that offer a solution to the limitations that actors and mannequins have. The simulation with actors has limitations as some techniques cannot be applied and high-fidelity mannequins are expensive models that require specific technical requirements and resources. Virtual reality offers a solution to these limitations, as it allows the trainee to immerse in the situation and to accomplish different trauma scenarios without compromising the patient (Patel et al., 2020; Cohen et al., 2013b; Fleiszer et al., 2018; Taylor et al., 2011). Nevertheless, each simulation method has its advantages and disadvantages and, therefore, a further reflection is needed with respect to the simulation method selection as stated in (Quick, 2018; Borggreve et al., 2017). It is also important to consider, for the selection of the simulation method, which are the skills to train. Taking into account the results obtained for the skills trained, there is still a majority of simulation-based trainings with focus on technical skills as one of the goals of the simulation is to teach complex and specific skills (Kuhlenschmidt et al., 2020). Moreover, the number of trainings that consider non-technical skills is increasing (Ziesmann et al., 2013; Gillman et al., 2016; Doumouras and Engels, 2017). That is the reason why the number of simulation-based trainings that consider both types of skills are also higher. It is important to highlight that, the articles included in this scoping review focus on individual training; therefore, it makes sense that more articles focus on training technical skills, as the majority of the trainings that focus on non-technical skills prefer training in groups or teams.

As previously highlighted, depending on the skills to train, low-fidelity simulators would be better to train technical skills and high-fidelity simulators or medium-fidelity simulator including virtual reality would be better to train non-technical skills. According to (Datta et al., 2012), skills training should be adapted to the level and the type of education. Therefore, it focuses on undergraduate teaching, postgraduate teaching, continuing medical education, disaster management and military trauma management. Whereas according to (Quick, 2018), the type of skills to train should be classified into either task-oriented or non-technical skills, independently on the type of education of the trainee. Hence, the focus is on the type of simulation method and the possibility it offers with respect to those types of skills. Independently of the name provided to the focus of the training, it is clear that the trend is to incorporate non-technical skills within the trainings, in order to make a comprehensive trauma program. Therefore, high-fidelity mannequins seem to be the best option but, incorporating virtual reality together with low fidelity mannequins could be another

alternative with some advantages such as the cost of the simulation method used. For trauma trainings, both types of skills need to be trained and therefore, simulation methods that combine low, medium and high-fidelity should be used making the trainings customized.
Regarding the evaluation methods currently used in simulation-based trainings, only two of them considered the option of having an automated evaluation method (Harrington et al., 2018; Walker et al., 2016) but, either this was only partially considered or the details on how automation was achieved were not explained. Therefore, the majority of the trainings analyzed in this scoping review did not offer an automated evaluation method, showing an important gap. It is true that there is an important discussion about how the evaluation of a simulation-based training must be done (Murray et al., 2015; Cuisinier et al., 2015; Fleiszer et al., 2018; Knudson et al., 2010; Walker et al., 2016; Fernandez et al., 2012; Montán et al., 2013; Jawaid et al., 2013; Figueroa et al., 2016) but it is surprising that the majority did not even consider the option to include an automated option. Additionally, this is also unforeseen as the advantage of having high fidelity mannequins or other simulation methods is that they allow the possibility to gather objective information directly from them. That information would be extremely valuable, as it is entirely objective and fits with the purpose to use simulations to provide a more objective evaluation method (Ali et al., 2010; Wallenstein et al., 2010). Moreover, the objective information gathered by the simulation methods has a positive impact on trainees, as having high-quality feedback, allowing them to see the impact of their actions during the simulation, supporting skills learning and performance (Cohen et al., 2013a; Dausey et al., 2007; Issenberg et al., 2005).
Because the majority of the trainings did not use an automated evaluation method, an analysis on the methods used was done. The majority of the trainings used written evaluation forms or checklists which have been previously agreed before the trauma training starts as stated in (Murray et al., 2015; Knudson et al., 2010; Amiel et al., 2016; Pringle et al., 2013; Springer et al., 2013). This made the evaluation process more objective but not entirely, as the trainees' answers to the questionnaires or checklists comprised his or her opinion on how the simulation occurred. That opinion is valid and necessary after a simulation-based training but, evaluating the performance of the training only with this information should not be the case. Just a few trainings, four of them, used purely subjective evaluation methods that consisted of either personal interviews, written comments or evaluation by direct observation of video performances. Finally, most of the articles analyzed in this scoping review focused on training, either technical or non-technical skills, for traumas that took place in a hospital environment but, the presence of pre-hospital training is increasing (Abelsson et al., 2014). This situation highlights the importance to train all the professionals involved in a trauma scenario in any of the environments in which the patient could be located, taking into account the resources and personnel available in each of the settings.

Therefore, as conclusions, this scoping review has shown that there is an important gap with respect to the current evaluation methods and medical students training on trauma management. There are currently discussions on how to better evaluate simulations, but none of them discusses the benefits of including pure objective information. Therefore, including this type of evaluation together with others currently in use, could provide a more solid evaluation process. Moreover, including trauma training in medical students has important benefits as already highlighted, which should encourage medical schools in developing trauma training programs within their medical degrees.

It is important to highlight that there is a great variety of simulation methods which offer to train a great number of skills, being able to use different simulation modalities depending on the focus of the training. From low cost to more expensive solutions are available in clinical simulation; therefore, this should be further investigated to be able to set the modalities to use depending on the skills to train and the budget available. Additionally, prehospital settings should be included in the trauma trainings, as doctors should be able to attend a trauma patient as soon as possible, with the knowledge of the available resources depending on the environment in which they need to support the patient. This is currently increasing but more trainings should focus on both environments.

PART II

Trauma protocols: a new training paradigm

5 Trauma Management Protocols through Simulation

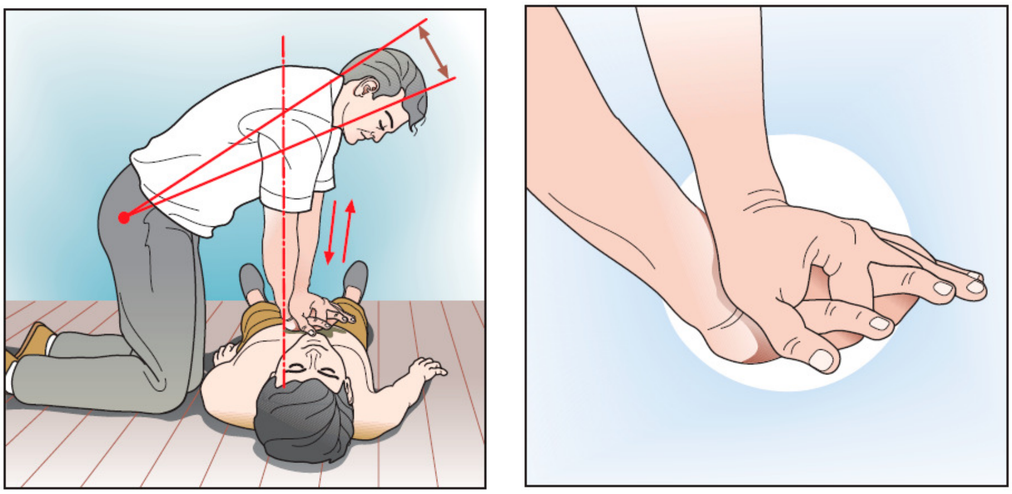
5.1 Trauma Management Protocols

Trauma injuries are unpredictable medical emergencies that need a quick and fast response. It is still a challenge to reduce medical treatment time to decrease the number of preventable deaths that occur during the first peak of death in traumas (Kleber et al., 2012; Evans et al., 2009). To provide this medical treatment, trauma experts must respond immediately and without hesitations; therefore, a proper training is needed (Bernhard et al., 2007; Hilbert et al., 2007). As highlighted in (Wurmb et al., 2008), patients who suffer severe injuries are the ones that require a medical treatment which avoids, to the maximum, preventable errors as they have a direct impact in mortality and morbidity. Therefore, a standardized training program for these patients is mandatory. The Advanced Trauma Life Support (ATLS) training developed by the American College of Surgeons Committee on Trauma is worldwide known and applied (Committee on Trauma of the American College of Surgeons, 2018). Additionally, there is evidence that this training provides techniques and skills to treat trauma patients fast and efficiently, but its principles need to be translated to local conditions (Olden et al., 2004a,b). There is a discussion whether guidelines and protocols for trauma management are adequate due to the unpredictable circumstances that may appear (Spain et al., 2008; Pritts et al., 2009); nevertheless, there are studies that show clear improvements on trauma management after following trauma guidelines, clinical pathways or protocols (Curtis et al., 2016; Carrie et al., 2018; Todd et al., 2006; Nyland et al., 2016; Sahr et al., 2013; Menditto et al., 2012; Morrison et al., 2009; Frederickson et al., 2012). These are three levels of standard procedures which go from more general, guidelines, to more precise which are first, clinical pathways and then, protocols (Dunham et al., 2001; Jacobs et al., 2003; Wilson et al., 2001b). Clinical guidelines are defined as statements that provide recommendations with the focus to optimize patient care which are supported by a review of evidence and an assessment of the benefits. A clinical pathway is defined as an optimal sequence of actions in which the time of intervention is important and includes all the clinical professionals needed to treat a specific injury or illness. Finally, a protocol considers all the details to better describe each of the actions presented in a clinical pathway, and may consider only a medical specialty or a predefined action. However, these procedures do not discuss the need to develop an evaluation system. This may allow to study the deviation from the protocols defined in order to improve training, to incorporate flexibility in the protocols and to constantly evaluate whether changes might be considered in the analyzed protocol (Baker et al., 2020; Unsworth et al., 2015; Kourouche et al., 2018; Roberts, 2004; Kwan, 2004; Vanhaecht et al., 2009; Evans-Lacko et al., 2010; Hipp et al., 2016). Since the ATLS course was developed, a general framework was provided with respect to how to manage trauma injuries. Nevertheless, attrition and low compliance rate with that framework are important issues even in major trauma facilities (Ali et al., 2002; Tsang et al., 2013). The attrition rate is affected by several aspects such as the time from the trauma training and the volume of trauma patients treated regularly. Therefore, trauma trainings need to be repeated specially if the volume of trauma patients treated regularly is not high; if not, the attrition rate diminishes. The studies that investigate this aspect, evaluate the trauma adherence to protocols by using exams and practical skills stations by the Objective Structured Clinical Examination (OSCE) performance. These skills stations are evaluated by trainers using a checklist which could be improved by incorporating objective information directly from the simulation modality used within the skill station. However, the low compliance rate is not deeply investigated and only a few number of studies focus on this aspect (Santora et al., 1996; Spanjersberg et al., 2009; Rein et al., 2018). In these studies, the main source of evaluation is video-taping trauma performance whereas in others, patient data after trauma management is analyzed. Nevertheless, in general, the analysis performed are considered of poor quality (Rein et al., 2018). Therefore, it is important to teach, learn and evaluate those protocols in the most efficient manner. Since the ATLS, new management protocols have been developed to treat trauma patients such as traumatic brain injuries, hemorrhagic trauma injuries and general trauma management (Chesnut et al., 2020; Baksaas-Aasen et al., 2020; Kinoshita et al., 2019). Nonetheless, there is still a gap between the general instructions to follow when treating a severe trauma injury and how they should be integrated into a practical management protocol. That is why trauma management protocols have been taught using different simulation modalities as the ones mentioned in Chapter 4. By doing this, protocols are more real and practical, being able not only to learn the process but also, to practice the techniques needed to manage the traumatic scenario and to evaluate deviations from protocols. Nevertheless, there are improvements that are necessary to introduce in some simulation modalities to allow a better trauma management learning. These improvements consider, not only real-time feedback, but also the possibility to objectively evaluate simulations. To better understand how teaching and learning protocols are currently done, some protocols which use simulation have been analyzed.

5.2 Cardiopulmonary Resuscitation Protocols

Cardiopulmonary Resuscitation (CPR) protocols were born in 1960 when the CPR maneuver was created (Kouwenhoven et al., 1960; Safar, 1965). These protocols have been worldwide standardized through the directives of organizations such as the American Heart Association, the European Resuscitation Council and the Spanish Cardiopulmonary Resuscitation Council (Abella, 2016). Even though, the CPR maneuver is not part of a trauma resuscitation protocol; in any clinical emergency, it is key to check the patient's condition and, if necessary, to perform the CPR maneuver. Additionally, trauma management protocols emerged following the example of CPR protocols that have been successfully implemented worldwide. Therefore, looking into the current landscape of simulation modalities to teach CPR protocols would give us information with respect to what should be considered for trauma management protocols.

The cardiopulmonary resuscitation is defined as a combination of maneuvers which aim is to revert the cardiorespiratory arrest that occurs suddenly on a patient. If correctly performed, it is possible to restore the breathing and the spontaneous blood circulation of the patient (Yan et al., 2020). The CPR is composed of chest compressions and ventilations known as rescue breaths. Chest compressions are applied on the middle of the chest in which the sternum is located. The aim is that blood circulation is restored, whereas the aim of the rescue breaths is to send blood to the lungs to receive oxygen (Olasveengen et al., 2021). During chest compressions, the person performing the CPR should be placed on his/her knees next to the person who suffered the cardiac arrest as shown in Figure 5.1 (a). Then, the sternum should be pressed with the heel of one hand placing the other hand on top and weaving them together, see Figure 5.1 (b). Both arms should be stretched along the whole time the chest compressions are applied and they should be totally vertical with respect to the patient.



(a) (b)

Figure 5.1: Position of the rescuer and the hands on the rescuer for a correct CPR maneuver (Campus, 2022).

To measure the efficiency of the chest compressions, three parameters need to be considered: the rate of compressions per minute, the depth of each compression and the total decompression of the thorax. To measure the efficiency of rescue breaths, two parameters are considered: the frequency of the rescue breaths and the volume of air insufflated to the patient. Therefore, a high quality CPR must fulfill the following criteria (Meaney et al., 2013):

- Interruptions during the CPR maneuver have to be minimized, guaranteeing a minimum rate of 80% along the total assistance time.
- The frequency of chest compressions have to be between 100 to 120 compressions per minute.
- The depths of the compressions have to be higher than 5 cm and lower than 6 cm. Compressions higher than 6 cm increase the possibility to cause costal fractures, myocardium hematoma or lesions in visceral organs. The survival rate improves when the chest compressions are deep but without exceeding the 6cm which implies a relation dose-effect between the depth of the compressions and the effect they have on the survival rate of the patient.
- The patient must be on a firm and even surface to optimize the mechanics of the chest compressions.
- The thorax decompression has to be guaranteed after each chest compression without detaching the hands from the thorax of the patient.
- Rescue breaths must provide a volume of air between $5 - 8\,ml/Kg$ and they should have a frequency below 12 respirations per minute considering that the thorax expansion must be minimum.

A high quality CPR can double, or even triple the survival rate of the patient (Association, 2022). If possible, the assistance personnel treat a patient who suffers a cardiac arrest in teams, rotating in period no longer than 2 minutes. In this way, the fatigue of the rescuers does not interfere on the maneuver (Pechaksorn and Vattanavanit, 2020). Therefore, the population in general, clinicians and bystanders, should acquire and learn how to perform a high quality CPR. Of course, clinicians should acquire more specific skills considering different tools and equipments that would support, for example, a proper airway management if needed. This need led to create a basic and an advanced life support training. The difference between these two trainings is the target population, being bystanders for the basic one and clinicians for the advanced. Additionally, in Spain, medical students are evaluated on their CPR skills using a skill station designed for that purpose (García-Puig et al., 2018). In general, the mannequins used in CPR trainings and in the skill stations for the examination of medical students, are basic mannequins that do not provide real-time information. This does not allow to objectively evaluate the maneuver and all the characteristics that, according to the protocols, must be fulfilled. In the current simulation landscape for CPR, there are high-fidelity mannequins that provide real-time information but they are not usually used due to the important cost they have. Therefore, a low cost high-fidelity simulator has been developed to verify how CPR protocols are trained.

5.2.1 Design and development of a CPR simulator

To design and develop the low cost CPR simulator with real-time feedback, the following tasks have been performed:

- Include, in a low fidelity CPR mannequin, a distance and a flow sensor to capture the parameters of the CPR maneuver.
- Process the data captured by the sensors to obtain information about the parameters that characterize a high quality CPR.
- Develop a database that would allow all data gathering along the simulation.
- Design and develop a web interface for the simulator.
- Perform a clinical validation of the simulator to measure how CPR protocols are accomplished.

The low cost simulator used is the Prestan CPR mannequin shown in Figure 5.2. This mannequin has a sound device called clicker that sends out a sound when the depth of the compressions is higher than $5\,cm$. Additionally, this mannequin has a block that does not allow to compress more than $6\,cm$. This mannequin was chosen as it is low cost and allows the possibility to change its structure, making possible to incorporate the distance and flow sensors needed.

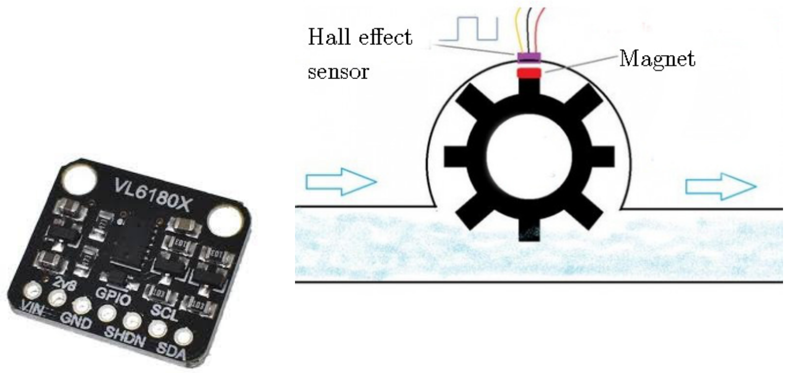
The distance sensor allows to measure the frequency and the depth of the chest compressions and how the decompression is done. The sensor used is the VL6180X shown in Figure 5.3 (a) (Prototyping, 2022). This sensor is composed of a laser that emits a beam of light perpendicular to the object which distance wants to be measured. The object needs to be encountered within the range of measure of the sensor and the beam of light rebounds from the object to the emitting device in which a detector is found. In this way, the distance sensor measures the flight time to obtain the distance of the object. The distance is calculated according to Equation 5.1.

$$D = \frac{V * t}{2} \tag{5.1}$$

being V the velocity of the light, $3 * 10^8\,m/s$ and t the time in seconds that it takes the beam of light to travel to the object and then back to the detector.

The flow sensor used is the model YF-201 which is a turbine type flowmeter that measures the flow of air that goes trough a turbine per unit of time (Mechatronics, 2022). The components of the sensor are: a turbine, a magnet placed in one of the turbine blades and a hall effect sensor as shown in Figure 5.3 (b). The hall effect sensor detects the magnetic field from the magnet, according to the movement of the turbine. Then, the sensor sends output pulses, and the frequency of those pulses is proportional to the frequency of the flow to measure. To calculate the flow of air

Figure 5.2: Low fidelity CPR Prestan mannequin without monitor (Warehouse, 2022).



(a) (b)

Figure 5.3: Sensors used: (a) distance sensor VL6180X (Prototyping, 2022), (b) components of the YF-201 flow sensor: turbine, magnet and hall effect sensor (Mechatronics, 2022).

that passes through the sensor, the Equation 5.2 is used following the manufacturer datasheet (Mechatronics, 2022). This sensor is located within the mannequin thanks to a plastic tube which is fixed, on one side with the mouth of the mannequin and, on the other side with the flow sensor. Then, the air insufflated to the mannequin passes through the flow sensor.

$$D = \frac{P}{k} \tag{5.2}$$

being P the frequency in Hz of the output pulses and k, a constant which value is 7.5 for this sensor.

Both sensors are managed with a microcontroller Atmel SAM3X8E ARM Cortex-M3. This allows to gather and process all the relevant information from the mannequin in order to evaluate if a proper CPR has been performed. To do so, the distance sensor provides information with respect to the frequency of the chest compressions and the depth of the compressions and the decompressions. The first one, the frequency of the chest compressions, is calculated processing the data obtained from the distance sensor. Then, the depth of the compressions and decompressions is automatically obtained by the sensor. With respect to the flow sensor, the information that it provides is the flow of the air that has been insufflated to the patient. Nevertheless, the information that is needed to evaluate the performance of the rescue breaths is the volume of air insufflated. As the flow is the modification of a volume in time, the volume of air insufflated is obtained. Additionally, to locate the sensors and to allow the Prestan mannequin to accomplish chest compressions with a broader range, the block that did not allow to accomplish chest compressions higher than 6 cm was removed and additional pieces were designed and 3D printed to incorporate them into the mannequin.

Once all the data from the sensors are obtained, it has to be gathered in a database which will be placed in a server. Additionally, this server will host the web interface of the simulator. To accomplish these two objectives, a Raspberry Pi 4 model B has been used. A LAMP web server has been configured on the Raspberry Pi, which includes Linux as operating system, Apache as the web server, MariaDB for the database management and PHP as the programming language. This PHP language generates an HTML which is directly sent to the user. This infrastructure is shown in Figure 5.4 and is suitable for dynamic web interfaces as the one to create for this CPR simulator. Additionally JavaScript, CSS and HTML were used to program the web interface. The web interface is developed in two modes: a training mode and an evaluation mode. As our focus is to evaluate how well CPR protocols are followed, the evaluation mode is explained. First of all, a trainer will create a clinical case that will be assigned to a specific trainee. The first thing to do by the trainee is to log in into the simulator and then, a panel appears with actions that should be taken prior to start the CPR. Once they are accomplished, the simulation with the mannequin starts and information about both, chest compressions and rescue breaths are shown in real-time is shown to the trainer. Additionally, once the simulation has been finished, a pdf document is generated with all the relevant information. This allows to objectively evaluate the quality of the CPR maneuver.

5.2.2 Pilot study

The CPR simulator developed was tested in a pilot study. This was done at Hospital Universitario La Paz with residents that attended a basic life support training that took place on September 2021. Along the course, the residents were trained in several techniques, and one of them was related to CPR compressions. Therefore, a skill station included our simulator to train and prove how the chest compressions were delivered. Therefore, from the six criteria to fulfill for a high-quality CPR, this pilot study focused in all of them except for the rescue breaths which were not part of the basic life support training. The number of trainees that attended the courses was 84 and all of them performed the chest compressions. For all the simulations, the trainees verified that the simulator was on a firm and even surface. Additionally, all of them performed the maneuver without any pause; guaranteeing the minimum assistance rate of 80%. Nevertheless, with respect to the depth of the chest compressions, the median value was 6.15 cm which is above the maximum depth of 6 cm as shown in Figure 5.5. With respect to the thorax decompression, this is reached when the thorax decompression reaches the value of 10.85 cm. As shown in Figure 5.5, the median value accomplished along all simulations is 10 cm which means that the trainees did not totally decompress the thorax of the simulator. Finally, with respect to the frequency of the chest compressions, even though there are exceptions as shown in Figure 5.5, the median value of 115 compressions per minute reached falls within the

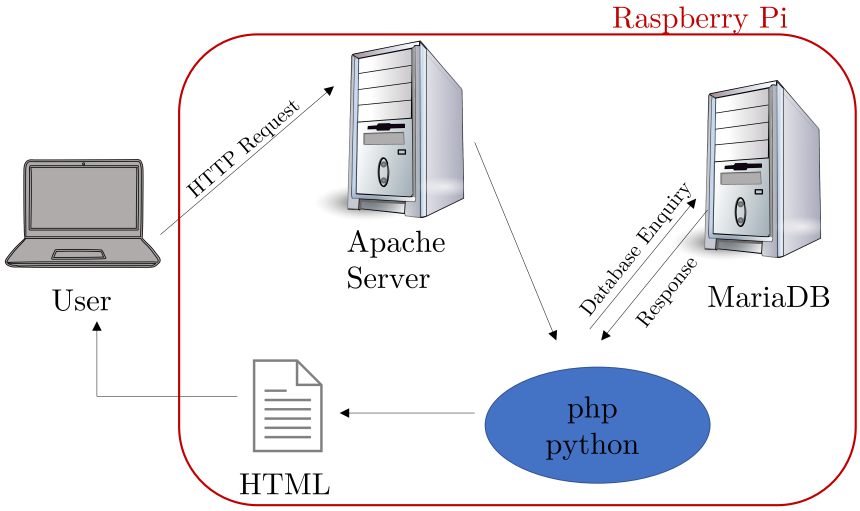


Figure 5.4: Infrastructure LAMP implemented in the Raspberry Pi to develop the web interface and the database.

range that should be achieved, from 100 to 120 compressions per minute. Therefore, by performing this pilot study it is confirmed that the CPR maneuver protocol for chest compressions is not correctly followed and that further training is needed.

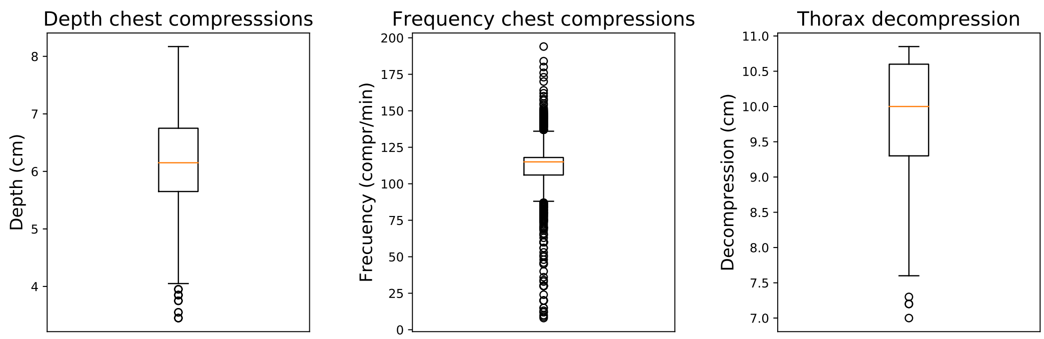


Figure 5.5: Depth of the chest compressions, frequency of the chest compressions and the thorax decompression performed during the 84 simulations.

Therefore, according to the evaluation of the CPR protocols performed and, even though CPR protocols have been integrated in medical education for a long time, there is still room for improvement on how to teach and learn them.

5.3 Hemorrhagic Trauma Protocols

Continuing with the analysis on how current protocols are trained, hemorrhagic trauma protocols are analyzed, as it is key to control and manage hemorrhages as soon as possible in a trauma scenario. Within the traumatic injuries, the hemorrhagic shock is the main preventable cause of death (Johansson et al., 2010). Therefore, detecting hemorrhages as soon as possible and learning different strategies to control them is really important. Traumatic injuries occur initially in a prehospital environment and, depending on the country, the treatment of how to deal with a hemorrhagic scenario may vary (Rau et al., 2010; Kragh, 2010; Doyle and Taillac, 2008). In the military environment, protocols on how to deal with hemorrhages are more spread out. Therefore, some of the actions used in this military environment can be adopted in the civilian environment, especially after the events that promoted the Hartford consensus which highlights that everyone could save a life (Doyle and Taillac, 2008). In this way, actions like the campaign “Stop the Bleed” (Ezeibe et al., 2019; Goolsby et al., 2018; Lei et al., 2019; Inaba et al., 2015) take momentum, approaching training to laypersons so they could learn how to identify different types of hemorrhages and how to control them. Massive hemorrhage may lead to hemodynamic instability, decreased tissue perfusion, organ damage, and death (Weil, 2005). The main goals of resuscitation are two: restoring circulating blood volume and stopping the source of the hemorrhage (Gutierrez et al., 2004). In order to decrease the number of deaths, clinicians must be able to rapidly identify and manage hemorrhages. Recognizing the type of bleeding is needed to apply the appropriate hemorrhage control technique. Moreover, if the type of bleeding is recognized, the risks associated with it could be understood and the blood loss could be estimated (Rossaint et al., 2010). Depending on the lesion suffered, three types of hemorrhages can be distinguished:

- **Arterial**: The arterial bleeding presents a bright red blood due to the fact that it carries hemoglobin, blood rich in oxygen. Moreover, the bleeding happens in a pulsating way showing the intermittent heart rate.

- **Venous**: The venous bleeding presents a dark red color as the blood has a low amount of oxygen. The venous flow blood is slower than the arterial one and it is homogeneous.

- **Capillary**: These vessels are smaller than venous or arteries. Therefore, the blood loss will happen slower than for venous or for arterial bleeding. It is the most common bleeding and the least dangerous.

The bleeding depends on its localization. When some of these vessels are bleeding, it may be appreciated outside of the body, known as external bleeding. However, in other situations, it may occur inside some cavity of the organism, known as internal bleeding (Cannon, 2018). Moreover, a classification of hemorrhages could be made taking into account the amount of blood lost. Therefore, it is possible to make a differentiation between the degrees of the shock according to the amount of blood loss as shown in Table 5.1. Additionally, the speed at which blood loss occurs worsens the situation (Kauvar et al., 2006).

When there are hemorrhages with high intensity, the human body reacts generating a pathophysiological response which is shown in different ways: pale and cold skin, sticky sweating, tachypnea, yawning, thirst, fast and soft pulse (Weil, 2005). Due to the loss of blood pressure, dizziness and even disturbances of consciousness can occur. Therefore, it is necessary to learn how to control hemorrhages. To measure and check how this is accomplished, a hemorrhagic trauma simulador for lower limbs has been also developed.

Parameters	Level 1	Level 2	Level 3	Level 4
Blood loss (mL)	750	750-1500	1500-2000	>2000
Blood loss (%)	15%	15-30%	30-40%	>40%
Pulse rate (beats/minute)	<100	100-120	120-140	>140
Blood pressure	Normal	Decreased	Decreased	Decreased
Respiration rate (breaths/min)	14-20	20-30	30-35	35-40
Urine output	>30	20-30	5-15	Negligible
Mental status	Normal	Anxious	Confused	Lethargic

Table 5.1: Levels of hemorrhagic shock (Gutierrez et al., 2004).

5.3.1 Design and development of a hemorrhagic trauma simulator

To develop the lower limb trauma simulator, four main components have been designed:

- **The bone**: One of the main functions of the bones is to support the soft tissues, and the fulcrum of most skeletal muscles. Superficially, the bone is formed by a compact, smooth and very hard outer layer. Nevertheless, the bones internally are not completely solid, as they have many spaces. They have a porous structure formed by trabeculae. The femur is the main bone in the thigh, and it is the largest bone in the human body. It is the base of the simulator and therefore, it must be resistant enough to support the actions that will be performed on the simulator without deforming.

- **The muscles**: They are between 35% and 45% of the total weight of the body. The mechanical behavior of the muscles can be described through a basic model that involves elastic and contractile elements. In addition, they have a protective function of the bones. They are in charge of defining the shape of the simulator and to generate a firm structure.

- **The blood vessels**: The blood vessels are in charge of supporting the pressure exerted by the blood when it travels through them. They are in charge of conducting the blood in order to reproduce the different bleeding scenarios. There are many vessels in the thigh but only the main veins and arteries will be considered in this simulator: the deep and superficial femoral artery, the femoral vein and the greater saphenous vein. Moreover, they must be located in the precise place in the thigh to create a correct simulation.

- **The skin**: It is the largest organ of the human body with a dimension from $1.5\,m^2$ to $2\,m^2$ and a weight from $3\,Kg$ to $4\,Kg$. Its structure is made of multiple layers, which makes its deformation behavior complex. The main functions of the skin are protection, reparation and adaptation. It has three superimposed layers: the epidermis, the dermis and the hypodermis. The epidermis is the most superficial and thin layer of the skin. It is joined to the following layer, the dermis, through a basement membrane to which it is firmly attached, and which provides the smooth appearance and texture of the skin. The dermis provides resistance and elasticity to the skin. It is the thickest layer of the skin and it is like a soft netting. Finally, the hypodermis layer is placed behind the dermis. All of them can be seen in Figure 5.6. Creating a skin as real as possible has been one of the main goals in the mechanical design. It is the superficial layer of the emulator and the real appearance of this layer is an important aspect, as clinicians are in direct contact with it. For this reason, the touch should be very similar to the real skin.

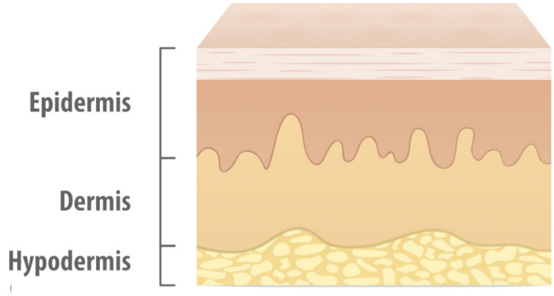


Figure 5.6: Layers of the skin (Shutterstock, 2020).

The materials chosen to simulate each of the biological components are the following:

- **Polymer**: As previously mentioned, the bone is in charge of providing support as it is the main structure of the simulator. Therefore, the chosen material must have the functionality to be resistant enough. The material used is a biodegradable polymer derived from lactic acid, called polylactic acid or PLA, whose mechanical characteristics are appropriate to achieve the required functionality. On the one hand, this polymer has a glass transition temperature of 60 °C. This temperature allows to have a wide range of working temperatures in which the material maintains its stiffness. Moreover, PLA is a biodegradable thermoplastic derived from renewable resources, which makes it a more environmentally friendly solution than other petrochemicalbased plastics. In this way, bone made from PLA fulfills the required structural support function.

- **Silicone**: The muscles and the skin have been manufactured using platinum silicones: PlatSil Gel-25 and PlatSil Gel-0030. The main advantages of silicone-based models are related to the broad range of properties that can be simulated: easy manipulation, non-toxicity during and after preparation and long-term stability. Besides, models manufactured using silicones are durable and can be molded to obtain various shapes, from simple geometries to anatomical shapes. On the one hand, PlatSil Gel-25 has been chosen to simulate muscles because it is a silicone with appropriate hardness. Taking into account that the muscles in this simulator have the goal to support the skin, it is a good option. In addition, it cures quickly, only within 4 hours, which allows to work with it quite fast. On the other hand, PlatSil Gel-0030 has been chosen to simulate the skin taking into account that its properties need to be similar to the human skin. Moreover, the study in [30] shows an experiment in which silicones with the same properties as PlatSil Gel-0030 offer similar mechanical characteristics as the skin. The skin has three different layers, and they have different densities. Slacker is a tactile modifier which allows modifying the densities of the silicones to be able to manufacture different layers as simulating the skin. For this reason, PlatSil Gel-0030 has been mixed with Slacker to reproduce the look, feel and touch of the living tissue.

- **Plastic tubes**: The blood vessels will be represented by intravenous lines used in hospitals. These are flexible plastic tubes with an internal diameter of 3.5 mm and an external diameter of 5 mm which allow fluids to be transported through them.

Finally, the manufacturing process followed to build and shape all the parts of the simulator will be presented hereafter:

- **3D printing**: The manufacturing of the bone with polylactic acid polymer is done by 3D printing. For this purpose, a Prusa i3 MK3S printer was used. This manufacturing system has provided the bone with the desired morphology.

- **Molding**: The soft parts made using silicones will be shaped using different molds. This technique will allow to create different complex morphologies. The use of molds to create silicone objects is one of the modern manufacturing techniques to construct parts that are used directly as finished products in which the post-processing is not necessary. The system is low-cost as specific machines are not required and moreover, the molds can be reused. The molds used have been made of paperboard but, in this process a wide range of materials could be used such as plastic, wood, or cork among others (Dabrowska et al., 2015).

Taking into account the manufacturing process explained, the 3D printing of the femur has been done first. Then, the different silicones have been used to implement the muscles and the skin. For the skin, three different layers have been built to simulate the epidermis, the dermis and the hypodermis by mixing silicones with different densities thanks to the Slacker. In order to mix the components appropriately, the dimensions and the properties of the layers of the skin have to be considered. In Table 5.2, the different mixtures of Slacker and silicone are presented showing different results. The desired effect for the dermis layer would be very tacky and therefore, the proportion used to mix the silicone with the Slacker has been the second option shown in Table 5.2. In this way, the touch of the skin obtained is really similar to the real touch of the skin.

Mixture	**Results**
33.3% Part A silicone + 33.3% Part B silicone+ 33.3% Slacker	Tacky
25% Part A silicone + 25% Part B silicone+ 50% Slacker	Very Tacky
20% Part A silicone + 20% Part B silicone+ 60% Slacker	Extremely Tacky
16.6% Part A silicone + 16.6% Part B silicone+ 66.6% Slacker	Super Soft Tacky Silicon Gel

Table 5.2: Different mixtures of Slacker with silicones in order to obtain different results. Part A and part B corresponds to an equal amount of product (Dargahi, 2017).

Additionally, to simulate the different blood vessels that irrigate the lower limb, endovenous tracts have been incorporated in different areas of the lower limb taking into account the real location of the blood vessels. After the design of all these parts, they are implemented altogether in the prototype shown in Figure 5.7.

Then, two water-resistant hydraulic pumps are used to simulate the different hemorrhages depending on the hemorrhagic scenario to train. Each pump is immersed in either arterial or venous blood depending on the corresponding blood vessel to simulate. This blood is stored in two different tanks and it is simulated with dyeing water. Finally, pressure sensors (Electronics, 2020) are included in the prototype to measure the actions taken in the simulator to control the hemorrhage. Then, all the components are electronically controlled by a microcontroller Atmel SAM3X8E ARM Cortex-M3, providing automation to the simulator. The microcontroller provides an

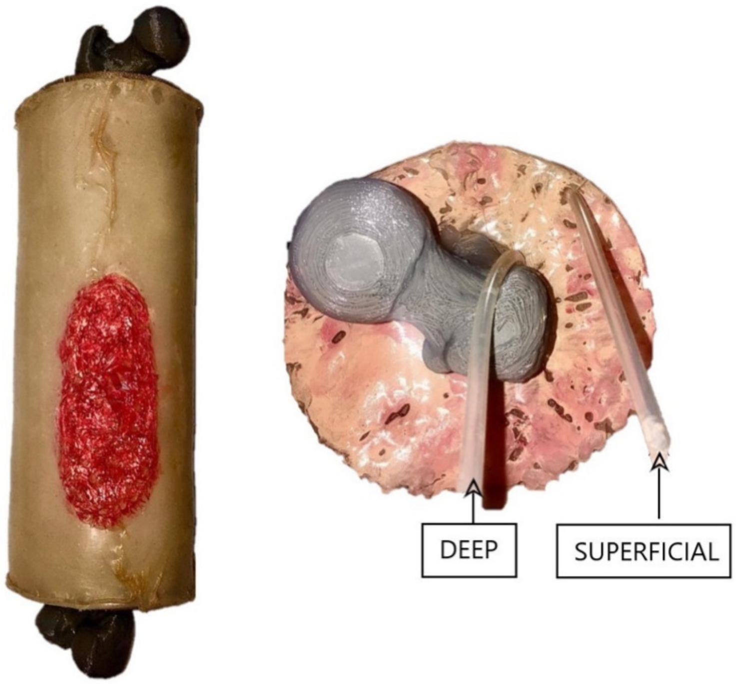


Figure 5.7: Prototype of the lower limb design and implementation in which the femur, the muscles and the skin are shown. In the left image, the simulator is shown with a lesion in the inferior part of the leg and in the right image, an axial section of the simulator is presented in which the location of different blood vessels is shown.

output signal which activates the hydraulic pumps and then, the bleeding scenario to train starts. Then, once the trainee is managing the bleeding scenario, the microcontroller received an input signal coming from the force sensors. All the data obtained during the simulation are gathered and stored in a database, allowing an objective analysis of the simulation performed.

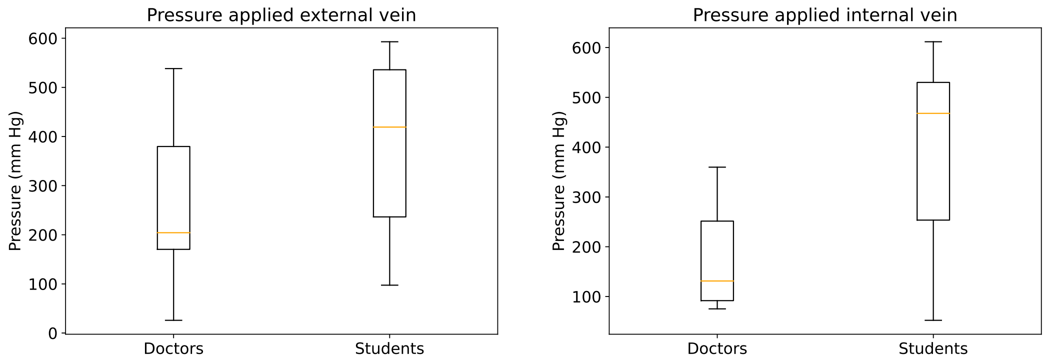
5.3.2 Pilot study

Four different hemorrhagic trauma scenarios have been designed in the lower limb simulator to allow testing how the hemorrhage is managed. The technique to train is the application of manual pressure on the simulated wound to stop the bleeding. The trauma scenarios are shown in Table 5.3 and they correspond with hemorrhages as a consequence of a lesion in the femoral vein, in the external saphenous vein, in the internal femoral artery and in the external femoral artery. These blood vessels have been chosen as they represent hemorrhagic trauma scenarios that could happen when the lower limb is affected and that could compromise the life of the patient. The trainer selects the hemorrhagic scenario to train which could correspond with an internal or with an external blood vessel injury. This selection is always done as the pressure to stop the bleeding is not only dependent on the type of blood vessel, artery or vein, but also on the location of the vessel on the lower limb, internal or external. Therefore, the type of blood vessel and the location are the two main aspects that the trainer needs to set before the bleeding scenario starts and the trainee needs to identify it. As the hemorrhages are different, the pressures to control them are also different as shown in Table 5.3.

Scenario	Blood Vessel	Location of Blood Vessel	Pressure Exerted to Stop Bleeding (mmHg)
1	Femoral vein	Internal	115
2	External saphenous vein	External	35
3	Internal femoral artery	Internal	200
4	External femoral artery	External	120

Table 5.3: Scenarios in which the lesion could happen classifying the blood vessel depending on the type, vein or artery and on the location of the blood vessel, internal or external. Additionally, the needed pressure to stop the bleeding is stated in mmHg.

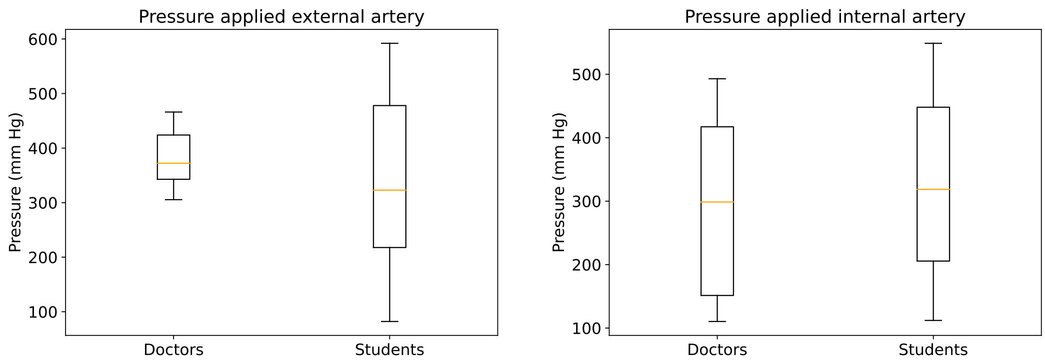
This simulator allows to visually distinguish the scenarios as the arterial bleeding will be pulsatile and the venous one will be continuous; additionally, the color of the blood will be also different. Moreover, the simulator will allow to measure the actions performed so that trainees could practice the pressure to apply to stop the bleeding by knowing the real pressure they are applying along the simulation and the impact that it has on the hemorrhage, depending on the scenario performed. Then, the evaluation of the technique could be done in an objective manner, analyzing all the data stored during the simulation. This pilot study took place in the Hospital La Paz Institute for Health Research, IdiPAZ, gathering data from 32 simulations of final year medical students and 22 simulations from doctors. The simulator was introduced during trauma seminars for medical students, residents and doctors and the people that finally participated in the pilot study did it voluntarily after those seminars. The data was gathered during two weeks in November 2020. The pilot study started with an introduction in which the simulator was shown to all the participants with a brief 15 min explanation before the first scenario starts. It is explained that the simulation scenarios present a lesion on the lower limb, that a hemorrhage will appear and that they would need to act accordingly. Reference to the trauma seminar is made to refresh some of the concepts on hemorrhagic trauma management provided. Then, the four different scenarios are accomplished sequentially providing a one-minute break between them. Once the four scenarios are finalized, the data about the pressure exerted to stop the bleeding was analyzed for both groups, medical students and doctors. As results, all the participants successfully completed all the scenarios presented with the exception of one of the participants that could only accomplish two of the four scenarios. This participant corresponds with one of the doctors that took part in this pilot study. The data analyzed were the pressure exerted to stop the bleeding and if the hemorrhage was controlled or not. With respect to the control of the hemorrhages, in all the simulated scenarios the hemorrhage was controlled. With respect to the pressure exerted, in the hemorrhagic trauma scenario in which the external saphenous vein is compromised, scenario 2 according to Table 5.3, the medical students apply a much higher pressure than the doctors. The median of the pressure exerted by the students is of 407 mmHg whereas the median of the pressure applied by the doctors is of 203 mmHg. Figure 5.8 (a) shows the wide range of values obtained depending on the doctor or student that performed the pressure to stop the bleeding. With respect to the femoral vein, scenario 1, as presented in Table 5.3, represents a hemorrhagic trauma scenario of an internal vein. The results obtained are shown in Figure 5.8 (b), in which a clear difference between the pressure applied by the students and by the doctors can be perceived. The range of pressures exerted by the doctors is smaller and the median is also much lower than the one exerted by the medical students to control this bleeding scenario. In this case, the difference is statistically significant, being the median pressure exerted by the students 468 mmHg and the one exerted by the doctors 131 mmHg.



(a) (b)

Figure 5.8: Pressure exerted to stop the bleeding by medical students and doctors if a venous bleeding occurs in the lower limb. (a) Pressure exerted to stop an external venous hemorrhage; (b) Pressure exerted to stop an internal venous hemorrhage.

With respect to the external femoral artery, scenario 4 according to Table 5.3, in Figure 5.9 (a) the pressure values exerted to stop these hemorrhages are shown. Also in this case, as in the previous ones, the doctors act more homogeneously, although in this case they apply a higher pressure than the medical students. In the previous scenarios, venous hemorrhages, the pressure exerted by the students has been always higher than the one exerted by the doctors. This may be due to the fact that doctors are more familiar with the fact that venous hemorrhages need a lower pressure to stop the bleeding than arterial hemorrhages. The median value of the pressure exerted for an external artery by the doctors is of 386 mmHg whereas in the case of the medical students, the median value is of 315 mmHg. In Figure 5.9 (b), the results obtained for a bleeding scenario of an injury of the internal femoral artery, scenario 3 as per Table 5.3, are shown. In this case, both groups apply a similar pressure. The median of the pressure exerted by the students is of 321 mmHg whereas the pressure exerted by the doctors is of 303 mmHg.



(a) (b)

Figure 5.9: Pressure exerted to stop the bleeding by medical students and doctors if an arterial bleeding occurs in the lower limb. (a) Pressure exerted to stop an external arterial hemorrhage; (b) Pressure exerted to stop an internal arterial hemorrhage.

Having a look at the results obtained, doctors apply a higher pressure to stop arterial hemorrhages whereas medical students apply a higher force in average to stop venous hemorrhages. Additionally, the applied pressure to stop internal hemorrhages has to be higher than the one needed to stop external hemorrhages (EN. Marieb and KN. Hoehn, 2013); in such cases, medical students apply a higher force for internal injuries whereas doctors apply similar pressure for both internal and external or even lower to stop an internal hemorrhage. This shows a clear need to improve trainings on how to better control hemorrhages as protocols are not clearly followed.

Therefore, CPR protocols have been set and taught for a long time and it has been perceived that there is still a need to further improve how to train those protocols. From the high quality CPR criteria, not all of them are fulfilled considering that the protocols were already explained and learnt by all the participants. From the experimental test performed, the trainees highlighted the importance of the information provided by the CPR developed. The main difference with respect to the simulators previously used by the trainees was that the information was provided in real-time. This supports and makes the learning process faster and more efficient as trainees can see, at every moment, what they are doing, making prossible to modify errors while integrating the technique. Additionally, having a look at the protocols to control and manage hemorrhagic trauma scenarios, a similar experience was obtained. These hemorrhage control protocols have been already in place and trained as stated in initiatives such as “Stop the Bleed” and it has been tested that they are not fully embraced by the trainees who participated in the experimental test with the lower limb simulator. Once again, providing real-time information was perceived as the main advantage compared to other hemorrhagic trauma simulators. Analyzing these experiences on how protocols are taught and trained, provided us with a valuable information to be able to build and develop an automated evaluation system to measure trauma management protocol compliance.

6 Trauma Management Evaluation Metrics

6.1 Introduction

There are a number of studies discussing on how to develop and implement standardized protocols (Michalowski et al., 2006; Tulu et al., 2013; Huang et al., 2014; Bahou et al., 2017; Othman et al., 2016; Joranger et al., 2014) but only a few which focuses on evaluating them, being considered a key aspect that needs to be addressed (Wilson et al., 2001a; Sesperez et al., 2001; Moore et al., 2015; Craig et al., 2013; OCathain et al., 2019; Boyko, 2013; Aspland et al., 2021). Considering that trauma management trainings include simulation as an important part of the training, incorporating an objective evaluation system to simulation is a clear need. Using simulators to learn and more specifically practice trauma standard procedures is already a reality, as shown in Chapter 5; therefore, evaluating the performance must be turned into a reality too. The current evaluation modalities available within simulation are, mainly, written evaluation checklists in which the information from the simulation is not automatically linked. Thus, the aim of this Chapter is to present an objective evaluation system that could be incorporated into a simulator in order to obtain real-time objective information about how a simulation was performed.

With this objective in mind, a panel of trauma experts was consulted. This panel was composed of 18 trauma experts and the discussion was to better understand how trauma management protocols are implemented, considering an action per action analysis. As trauma management protocols include all the actions needed to treat a trauma patient; this can be easily compared with the actions performed by trainees. Additionally, it is important to have in mind the Advanced Trauma Life Support (ATLS) guidelines and the experience of experts. Sometimes, protocols lack of updated information available from experts, which are the ones that interact with protocols day to day. That is why our purpose is to combine both, trauma protocols with experts' experience. In Figure 6.1, an example of a trauma management protocol for a pelvic trauma is shown. It is seen that, there are more than one option available as the order of some actions could be changed and the impact on the patient's vital signs is similar. Therefore, performing airway inspection before circulation and hemorrhage control is proposed by the experts to be as equally valid as performing circulation and hemorrhage control first. Basically, this depends on the vital signs of the patient when treating him/her. If there is any sign of an internal hemorrhage, circulation and hemorrhage control should be performed first and airway inspection should follow. If not, airway inspection should be accomplished first as explained in Section 3.3.2.

The advantage to develop a treatment protocol based on actions, is that it allows to analyze its performance considering how well a sequence is performed with respect to a target, which in this case is the solution proposed by both, the ATLS guidelines and the panel of experts. As we are comparing actions with target actions, distance metrics could be used. This would allow to analyze, on one side, the number of correct and incorrect actions but, on the other side, the order in which the different

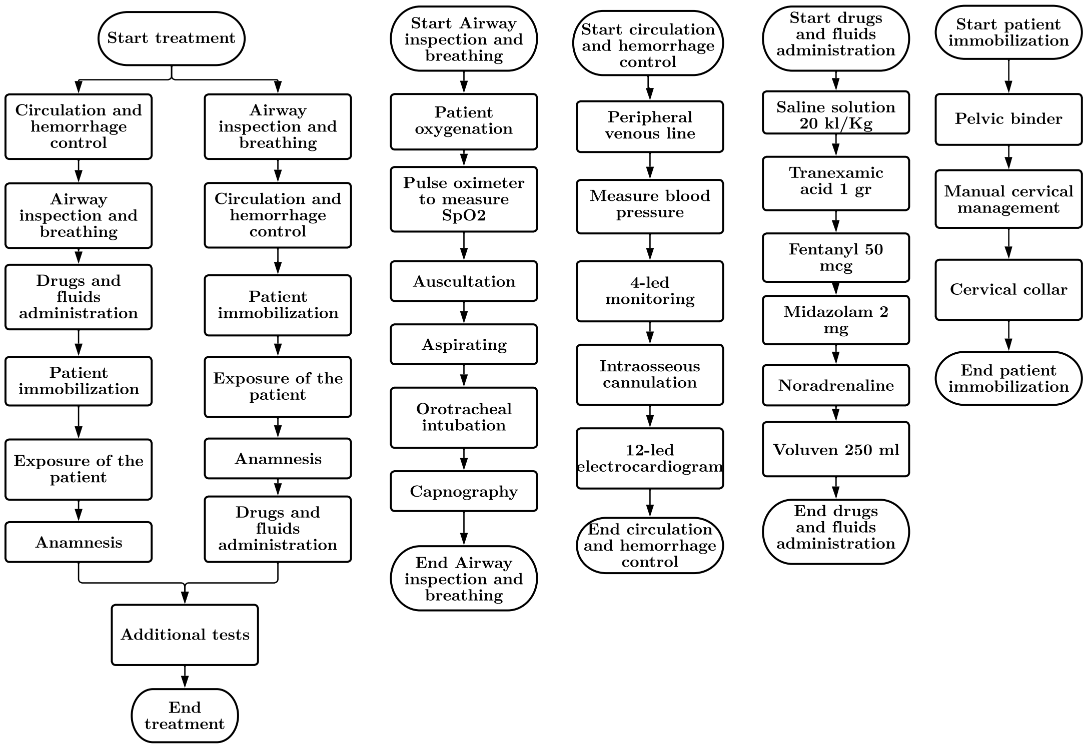


Figure 6.1: Trauma management protocol for a pelvic scenario in which the most important actions to stabilize a patient are considered.

actions are accomplished, which is a key aspect in trauma management. Let's make an example: having a look at Figure 6.2, one possible target solution is to perform actions to treat circulation and hemorrhage control, for example, actions 5 and 7 are two actions accomplished to comply with this first part of the treatment and they could be to insert a peripheral venous line, action 5, and to measure blood pressure, action 7. Then, another two actions are done to inspect the airway and breathing of the patients: auscultation, action 8, and oxygenation, action 6. After that, some drugs are administered: a saline solution, action 3, and tranexamic acid, action 2. Once this is done, a pelvic binder and a cervical collar are placed, actions 4 and 1, and then a thermal blanket is used to maintain the body temperature of the patient, action 9 which is an action related to the exposure of the patient. After all this, the patient is once again, oxygenated, action 6. Finally no additional tests are performed and the initial stabilization of the patient is achieved. Therefore, one target solution following the example presented, is to perform the following actions which have been converted into numbers: "5 7 8 6 3 2 4 1 9 6".

This allows to easily compare it to another sequence of numbers which will be the one taken from a simulation performed by a trainee. To do this, the first thing to do is to analyze, from the possible solutions, which is the one that matches the most with the trauma scenario performed by the trainee as, like in Figure 6.1, sometimes there is more than one target solution. Later on, a distance analysis between those two sequences is performed. There are several distance metrics: edit, token based and sequence based distances (Aspland et al., 2021). Edit distances compare two strings by counting the minimum number of operations needed to transform one string into another. Token based distances compare two strings by looking at units, tokens, of the string. Sequence based distances compare two strings by looking at different subsequences of the strings (Aspland et al., 2021). From those metrics, it was decided

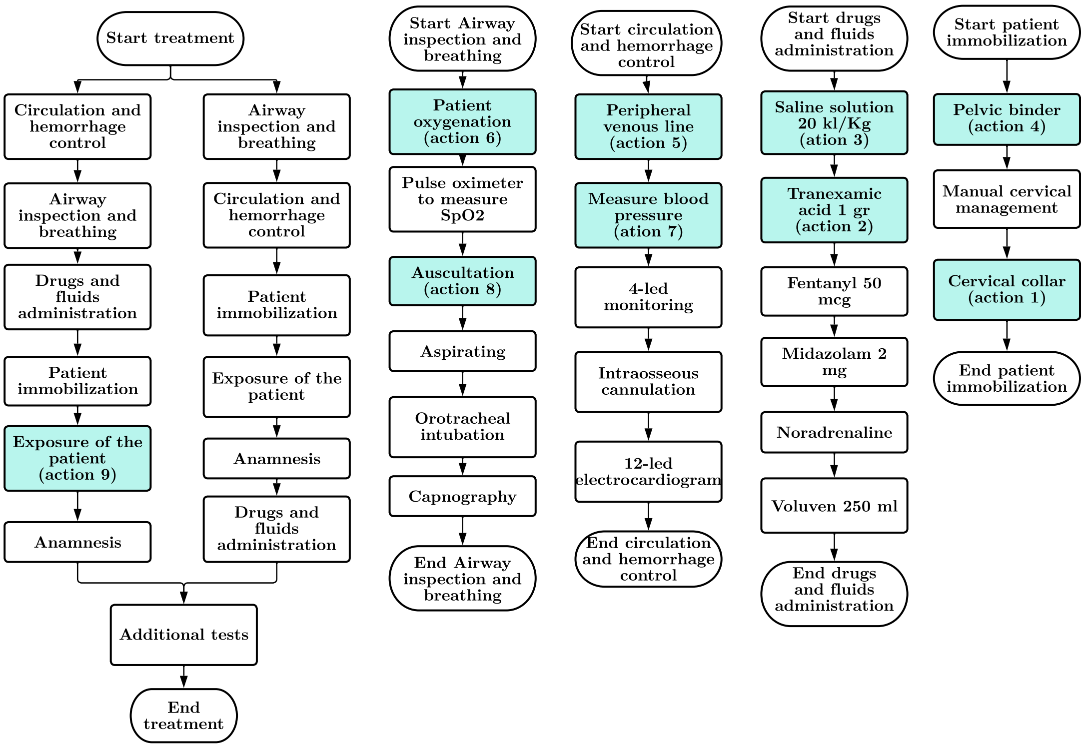


Figure 6.2: Example of a target solution in which the actions to be performed are highlighted in blue and the number of each action is provided.

to focus on the Needleman-Wunsch algorithm as it is an edit distance algorithm that allows to consider differently if there is a match between two sequences, a mismatch or a gap. This allows flexibility making the algorithm suitable for comparing two trauma management sequences. Additionally, two other metrics were created: one provides information with respect to the correct order of the actions, Diagonal Score, and the other provides information with respect to the number of correct subsequences of actions that are taken along the simulation, Subsequence Score.

6.2 Modified Meedleman-Wunsch algorithm

In origin, the Needleman-Wunsch algorithm appeared as a dynamic programming algorithm that would allow to provide a global solution to the problem of comparing two amino acid sequences (Needleman and Wunsch, 1970). This global alignment would allow to measure the distance between the two sequences. This algorithm consists of three steps: the first one is the initialization of the score matrix, the second one is the calculation of the scores in order to build the traceback matrix and, finally, the third step is deducing the best alignment from the traceback matrix as shown in Algorithm 1.

Algorithm 1 Needleman-Wunsch algorithm.

```
Steps of the Needleman-Wunsch algorithm
for i ← 0, len(A) do                                    ▷ Initialization score matrix
    D[i][0] = i ∗ S_g
end for
for j ← 0, len(A) do
    D[0][j] = j ∗ S_g
end for
for i ← 0, len(A) do                                    ▷ Fill traceback matrix
    for j ← 0, len(B) do
        if A[i] == A[j] then
            X = D[i − 1][j − 1]+S_match
        else
            X = D[i − 1][j − 1]+S_mismatch
        end if
        Y = D[i − 1][j]+S_g
        Z = D[i][j − 1]+S_g
        D[i][j] = max(X, Y, Z)
    end for
end for
Start from the bottom right term of the traceback matrix    ▷ Best alignment
for i ← len(A), 0 do
    for j ← len(B), 0 do
        Check the value of the diagonal, upper and left matriz value
        Select the maximum value and move to that term
    end for
end for
```

Following this algorithm, a modification has been included considering that some actions could have the same impact on the vital signs of the patient, some others could have a similar impact, some others could be completely opposite, and some others could be just different. All these possibilities are included within the algorithm in order to build the traceback matrix that would allow, afterwards, to find the best alignment. The way in which the scores are calculated to obtain the traceback matrix, $D(i, j)$, is as follows:

$$\text{D (i, j)=max}\begin{cases} D(i,j) + s(x_i, y_i) & \text{(6.1a)} \\ D(i-1,j) + S_g & \text{(6.1b)} \\ D(i,j-1) + S_g & \text{(6.1c)} \end{cases}$$

being $s(x_i, y_i)$ a different score considering four different possibilities: actions that match, S_{match}, actions that are equivalent and therefore could be swapped, S_{swap}, actions that are opposed or actions that are just different, $S_{contrary}$, and, therefore, they are considered a mismatch, $S_{mismatch}$. The score provided to a gap is S_g. Considering that the sequence of actions to accomplish is the following one: “5 7 8 6 3 2 4 1 9 6” and that a trainee performed the following sequence: “7 4 1 3 2 8 6 9” as shown in Figure 6.3; the traceback matrix is built given the values of the scores mentioned above and the best alignment is obtained as shown in Figure 6.4.

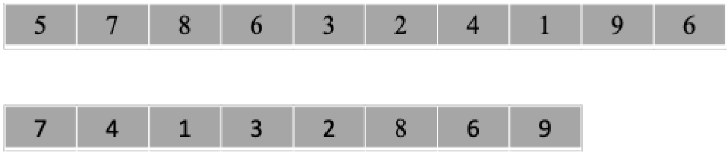


Figure 6.3: Example of the sequence to accomplish: "5 7 8 6 3 2 4 1 9 6" and the sequence of actions performed by the trainee "7 4 1 3 2 8 6 9".

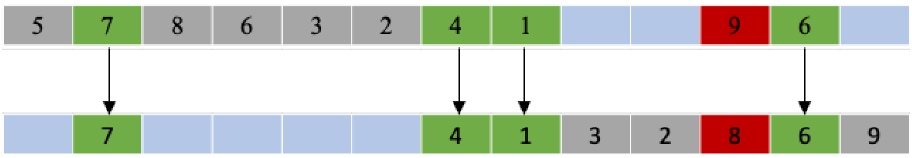


Figure 6.4: Best sequence alignment obtained after applying the modified Needleman-Wunsch algorithm for two sequences: "5 7 8 6 3 2 4 1 9 6" , the ideal one and "7 4 1 3 2 8 6 9", the one performed by the trainee.

The blue color in Figure 6.4, means that a gap has been introduced in a sequence which means that nothing has been done or should not be done to better fulfill with the sequence of actions that the trainee should have accomplished. The green color in Figure 6.4, means that actions between the two sequences match and the dark red color indicates that there is a mismatch. In the Best Alignment path shown in Figure 6.5, any vertical arrow means that a gap is introduced in the sequence at the top of the matrix, the diagonal arrows mean that there is a math or mismatch and the horizontal arrows mean that a gap is introduced in the sequence at the left side of the matrix. Then, in this example, the best sequence alignment has four matches, one mismatch and eight gaps. All scores set to fulfill the traceback matrix shown in Figure 6.5 follow the criteria: $S_{match} > S_{swap} > S_{gap} > S_{contrary} > S_{swap}$. The maximum score is provided to a match and then, to a swap. Later on, if there is a gap, the score provided is higher than the one for a mismatch and the one for a contrary action. In trauma management, it is worse to do something that should not be done than not doing anything. Finally, the worst case scenario is to accomplish an action which impact is the opposite to the one that the patient should have.

To define the four categories of actions previously mentioned: actions that match, actions that can be swapped, contrary actions and mismatches; 18 trauma experts were asked. As an example, actions that are considered equivalents are "to oxygenate the patient with an oxygen mask", "to oxygenate with a self-inflating bag" and "to insert an oropharyngeal airway". The equivalent actions are the one that have a similar impact on the vital signs of the patient. Therefore, these actions could be swapped and the impact on the patient is almost the same. Then, once the traceback matrix is built and the best alignment sequence is obtained, a score is provided to that alignment. This score is called the global alignment (GA) score and is calculated in Equation 6.2:

$$GA = n_{match}S_{match} + n_{swap}S_{swap} + n_{gap}S_{gap} + n_{mismatch}S_{mismatch} + n_{contrary}S_{contrary} \quad (6.2)$$

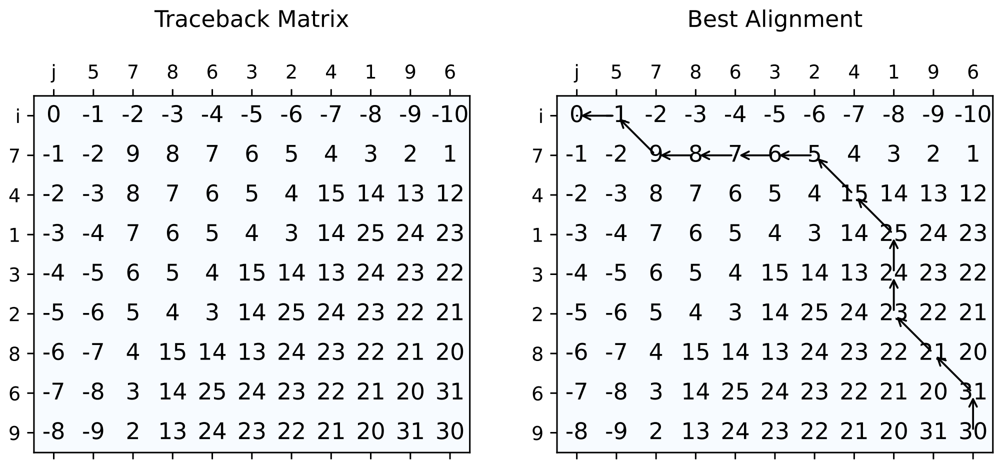


Figure 6.5: Example of the traceback matrix calculation and the best alignment obtained for two sequences: “5 7 8 6 3 2 4 1 9 6” which is the sequence that should be done and “7 4 1 3 2 8 6 9” which is the sequence of actions performed by the trainee.

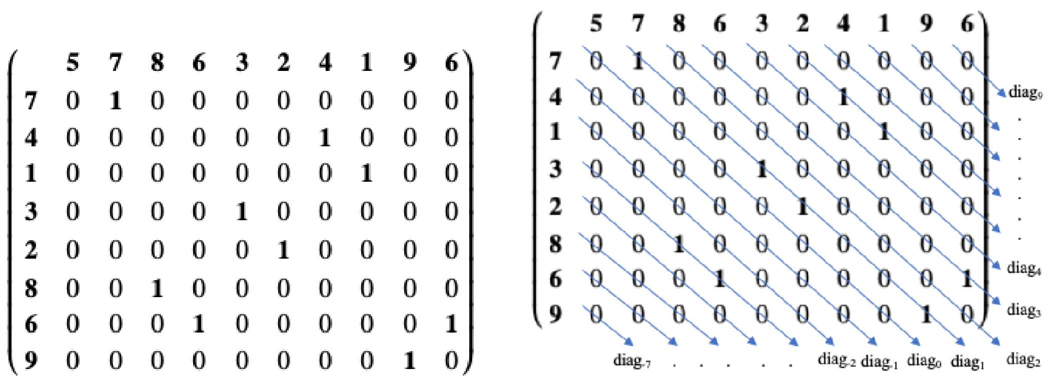
being n_{match}, n_{swap}, n_{gap}, $n_{mismatch}$ and $n_{contrary}$ the number of matches, swaps, gaps, mismatches and contrary actions that exist within the best alignment. Considering the maximum and the minimum possible punctuations, this score is normalized being $GA \in [-1, 1]$. The negative values of this score mean that the two sequences are different and positive values mean that they are alike; the higher the value the more different or the more alike are the two sequences. Therefore, this score will give us information about how the trainee performed the simulation, bearing in mind all the possibilities previously mentioned.

6.3 Diagonal Score

This score has been built in order to provide information with respect to the correct actions accomplished along the simulation considering that, if they are done at the correct timing, the score will be higher than if they are done in a different moment in time along the simulation. Therefore, a score matrix, $S(i, j)$, is built introducing the sequence performed by the trainee as the rows and the one that should have been performed as the columns. Then, when two actions match a score of one is introduced within the matrix and if not, a zero is included as shown in Equations 6.3.

$$\text{S (i, j)=max}\begin{cases} 1 & \textit{when } seq1(i) = seq2(j) \quad (6.3a) \\ 0 & \textit{when } seq1(i) \neq seq2(j) \quad (6.3b) \end{cases}$$

being $seq1$ the sequence performed by the trainee and $seq2$ the sequence that should have been performed. Figure 6.6 (a) shows an example of how the score matrix is built, being the sequence "7 4 1 3 2 8 6 9" the one performed by the trainee and the sequence "5 7 8 6 3 2 4 1 9 6" the ideal one.



(a) (b)

Figure 6.6: (a) Example of a score matrix for two sequences: "5 7 8 6 3 2 4 1 9 6" and "7 4 1 3 2 8 6 9" in which $S(i, j)$ is 1 when the two sequences are identical and 0 when they are not; (b) Diagonals used to sum the individual values of the score matrix, $S(i, j)$, for two sequences: "5 7 8 6 3 2 4 1 9 6" and "7 4 1 3 2 8 6 9".

To calculate the diagonal score, the values within the score matrix, called individual scores, are summed according to the diagonals of the matrix, $diag_i$, being i the number of the diagonals. Following the same example, in Figure 6.6 (b), the different diagonals are shown and their values are: $diag_{-7}$= 0, $diag_{-6}$= 0, $diag_{-5}$= 0, $diag_{-4}$= 0, $diag_{-3}$= 2, $diag_{-2}$= 0, $diag_{-1}$= 0, $diag_0$= 0, $diag_1$= 3, $diag_2$= 0, $diag_3$= 1, $diag_4$ = 0, $diag_5$= 2, $diag_6$= 0, $diag_7$= 0, $diag_8$= 0 $diag_9$= 0.

Then, they are all squared and summed up together according to Equation 6.4 to obtain de Diagonal Score (DS):

$$DS = \sum_{i=0}^{n} diag_i^2 \tag{6.4}$$

being i the number of diagonals from 0 to n. Considering that the maximum diagonal score is obtained when the sequences are identical, this score is normalized. Therefore,

$DS \in [0, 1]$. As the values provided are always positive, the maximum value obtained when two sequences are identical is 1 and the value 0 means that they are completely different.

6.4 Subsequences Score

This score has the focus to identify the correct subsequences performed by the trainee as well as the length of each of the subsequences. As previously explained for the diagonal score, a matrix $S(i, j)$ is built with both sequences including a one when two actions matches and a zero when they do not match. This subsequence score will identify the number of actions that are performed in order and join them together until an action that should not be done is found. This is done by comparing the value of $S(i, j)$ and the value of $S(i + 1, j + 1)$ according to Equations 6.5.

$$\begin{cases} if\ S(i,j) = 1\ and\ S(i+1,j+1) = 1 \rightarrow\ seq1(i) = seq2(j)\ and\ seq1(i+1) = seq2(j+1) & \text{(6.5a)} \\ if\ S(i,j) = 1\ and\ S(i+1,j+1) = 0 \rightarrow\ seq1(i) = seq2(j)\ and\ seq1(i+1) \neq seq2(j+1) & \text{(6.5b)} \end{cases}$$

The actions that fulfill the first condition condition are included into a subsequence vector until the value of $S(i + 1, j + 1)$ =0, which means that the values of two sequences are not the same anymore. When this happens, the subsequence finishes, and the algorithm will try to find other subsequences that may appear. Applying this algorithm to the example presented, the subsequences identified are: [4,1], [3,2] and [8,6]. Therefore, there are three subsequences with a length of two, as shown in Figure 6.7.

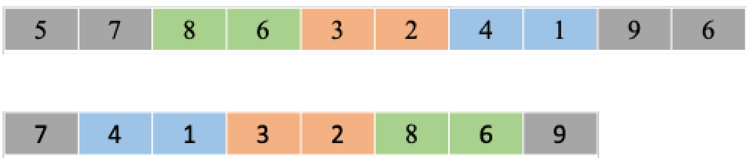


Figure 6.7: Diagonals used to sum the individual values of the score matrix, $S(i, j)$, for two sequences: “5 7 8 6 3 2 4 1 9 6” and “7 4 1 3 2 8 6 9”.

Then, the Subsequence Score (SS) is calculated as follows:

$$SS = \frac{\sum_{i=0}^{n} lengthofindividualsubsequences}{lengthofthetotalsequences} \cdot \frac{1}{n} \tag{6.6}$$

6.5 Metrics provided by the confusion matrix

Additionally to the scores presented above, the scores provided by the confusion matrix are used to obtain more information about how well a simulation was done. To do so, the following scores are used (Faes et al., 2020): precision, recall, specificity, accuracy and F1. The precision score provides information about the actions performed correctly from the ones the trainee accomplished. The recall score provides details with respect to the actions that the trainee, from the actions that he or she might have done, accomplished correctly. The specificity score gives details about the actions that should not be done and the trainee did not perform. The accuracy score provides details about the predictions correctly done, both positive and negative cases. Finally, the F1 score combines both the precision and recall scores within a unique value. To obtain the scores presented, the following terms need to be calculated:

- True Positives (TP): these are the number of common actions between the target sequence and the one accomplished by the trainee.
- True Negatives (TN): these are the number of actions that should not be performed and that the trainee did not take along the simulation.
- False Positives (FP): these are the number of actions that should not be performed and that the trainee did take along the simulation.
- False Negatives (FN): these are the number of actions that should be performed according to the target sequence but have not been performed by the trainee.

Then, the scores are calculated as follows:

$$
\begin{aligned}
Precision &= \frac{TP}{TP+FP} \\
Recall &= \frac{TP}{TP+FN} \\
Specificity &= \frac{TN}{TN+FP} \\
Accuracy &= \frac{TP+TN}{TP+TN+FP+FN} \\
F1 &= 2 \cdot \frac{Precision * Recall}{Precision + Recall}
\end{aligned}
\tag{6.7}
$$

Therefore, in the example presented in Figure 6.3, the ideal sequence to accomplish is “5 7 8 6 3 2 4 1 9 6” and the one performed by the trainee is “7 4 1 3 2 8 6 9”. Considering that the actions that should not be taken, as an example, are 0 and 10; all the information to calculate the different scores could be done. The TP value is eight as all the actions that the trainee performed are contained in the target solution. The TN value is two as there are two actions that should not be performed and the trainee did not take. Then, the FP value is zero as from the two actions that the trainee should not perform, the trainee took none along the simulation. Finally, the FN value is two as the action number 5 is the only one that should have been performed but the trainee did not take along the simulation and the action 6 was not repeated. Then, the following scores are obtained: $Precision = 1$, $Recall = 0.8$, $Specificity = 1$, $Accuracy = 0.8333$ and $F1 = 0.8888$.

With the scores developed in Section 6.2, Section 6.3, Section 6.4 and Section 6.5, all important information to evaluate a trauma management performance is considered. Not only the number of correct and incorrect actions is analyzed but also the order in which the actions are taken, if the actions taken by a trainee are similar to the ones that should be taken, or different or with an effect which is contrary to the one that should be expected. Additionally, if some actions are taken in order, this is taken into account as well as if the actions are done in the right moment that they should be applied. Therefore, this set of metrics comply with all the trauma management requirements to objectively evaluate the performance of a trainee.

7 Automated Trauma Management Evaluation

The aim of an automated evaluation system is not only focused on a pure examination objective of adherence to protocols; additionally, it provides important information that improves trauma management protocols learning process. The experiences with the pilot studies presented in Chapter 5 show that, there is still an improvement needed to make better the outcomes obtained using simulation. New technologies allow to incorporate new simulation modalities being the current simulation landscape quite varied as presented in Chapter 4. Therefore, different simulation modalities would allow to learn and practice different medical aspects (Abelsson et al., 2015; Knudson et al., 2010; Patel et al., 2020; Cohen et al., 2013b; Fleiszer et al., 2018; Taylor et al., 2011). An online trauma simulator shows flexibility and a good option to implement standard procedures that can be practiced by an important number of trainees simultaneously, and that would allow to incorporate an objective evaluation system which is a clear need in simulation (Wise et al., 2016; Murray et al., 2002). Therefore, a web-based trauma simulator is developed and tested incorporating a comprehensive trauma management evaluation.

7.1 Web-based Trauma Simulator

The Web-based Trauma Simulator (WBTS) developed has as objective to train and support clinicians in the trauma management treatment and therefore, to learn trauma protocols. This tool emulates a virtual patient who suffers a specific traumatic lesion which will be called, the trauma scenario. This trauma scenario is previously created by a trainer who will be in charge of defining all the details of the trauma scenario to train. Once the trauma scenario is created, it is assigned to a trainee who will be in charge of treating and managing the virtual patient. The main page of the WBTS is composed by three components: the virtual patient, the vital signs of the patient and the actions to accomplish to treat the patient as shown in Figure 7.1. Additionally, along the simulation, all the actions accomplished as well as the impact that those actions have on the vital signs of the patient and the timing in which those actions are done are recorded. This allows to issue a report automatically, once the simulation is finished, in which all this information is shown. This helps the trainee to analyze the simulation in detail and the trainer to objectively evaluate the performance of the trauma scenario. To develop this WBTS, the application created has been designed taking into account three parts:

- **Frontend**: this is the visual part of the simulator and the one that the user sees and interacts with. This frontend is based on React, a JavaScript library that supports the development of interactive web interfaces.
- **Backend**: this is the logic part of the simulator. It is based on a server created on Express which is a Node.js framework customized for this web-based simulator and its Application Programming Interface (API)s.

- **Database**: this database collects all the data generated along a simulation. It is based on MySQL which is a an open-source relational database management system.

Figure 7.1: Web-based simulator in which the virtual patient is shown together with his vital signs and some of the actions that could be accomplished.

The technologies used to develop this web-based simulator are based on the Model-View-Controller (MVS) pattern. This pattern is a software architecture based on separating the logic of the application from the visual one. To do so, it distinguishes three components (Kalelkar et al., 2014):

- **Model**: shows and storage all the data which, in this case, the model is supported by a MySQL database.
- **View**: it is the component in charge of visualizing all the data from the model to the end-user.
- **Controller**:it is in charge of the interaction and the communication from the model and the view. The controller arrange all the data so that they can fit with the model and the view.

In Figure 7.2, the MVS pattern is shown. The user launches a request to the server by means of the controller which is in charge of managing the request. Then, this request may include data storage in the model or, it could demand data from the model. That is why the arrow within the model and the controller goes in both directions. Once the request is managed, the response will be shown in the view that can be accessed by the client. To develop this pattern, the JavaScript language together with some other environments will be used:

- **JavaScript**: it is a programming language to create dynamic web interfaces. It does not need a compiler as it is the browser the one that compiles the code. It is used to develop the frontend and the backend of the simulator and it is the ideal complement to HTML and CSS to create web pages.

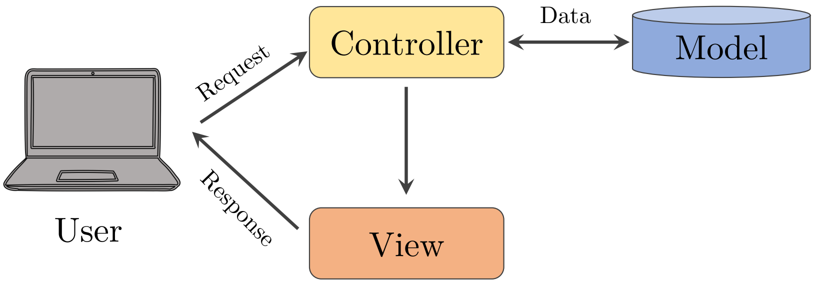


Figure 7.2: Model-view-controller pattern.

- *HTML*: (HyperText Markup Language) it is a language that allows to create and structure the elements of a web interface. HTML allows, through labels to organize the content of a web page such as sections, paragraphs or headings.
- *CSS*: (Cascading Style Sheets) it is a style language used to show the HTML documents created. CSS determines how each element should be rendered and structured in the web interface.

JavaScript has some functions that allow to create applications for mobile phones, computers, laptops and hybrids. The libraries and environments that are in charge of these functions are React from the client side o Express framework from the server side; both of them are included in the Node.js environment.

- **React**: it is a JavaScript library which is used to develop web interfaces through components and, it is used in this simulator to develop the frontend. This development is done in order and more efficiently thanks to the fact that its programming is done through components and its virtual Document Object Model (DOM). The components of React are the different pieces that create a web page. React builds a view by unifying all the simplified components are per programmer requirements. Those components receive and returns data with the information to show in the web page. Additionally, they gather the data internally, refreshing the view only when there is a change. Moreover, a component could be based on one or more components and, even other ones could be reused. React generates a virtual DOM anytime a change happens on the interface. Before refreshing the real DOM, Reacts compares the virtual and re real DOM trying to find the ideal path to make those changes. React has been chosen to develop the simulator due to its ability to divide the page in components which makes the design of this web-based simulator easier. Additionally, other libraries such as Bootstrap or Reactstrap are used to provide style of the different components.
- **Node.js**: it is a JavaScript environment from the server side, asynchronous and event oriented. This means that, when the client launches a request to the server, Node works with a single thread collecting events that come from client requests. These events are asynchronously executed to allow independence which allows a server to maintain several connections. Node uses libraries and resources that can be installed thanks to the package manager Node Package Manager (NPM) such as React, used for the fronted or Express which is used for the backend.

- **Express**: it is a Node.js environment used to implement the MVS architecture. Express can automatically generate a directory infrastructure in which all the contents of the application are stored:
  - *Server*: the server loads the App.js module which has all the information of the application developed as well as the http module which is the server of the application.
  - *Controller*: in Express, a middleware concept appears in the controller. This middleware is a function that receives an input, an output and an URL is assigned in which those two attributes are accesible. Therefore, this part has been used to create the Application Programming Interface (API). An API is a group of functions in charge of accomplishing one or more tasks and that it can be used by a different software.
  - *Model*: the information from the database is gathered in the model as well as the connection to it. The simulator will use the Sequelize package to connect and create the different tables of the database.
  - *View*: the development of the visual part in Express is done by using HTML.

  Therefore, Express has been used to create the APIs in charge of providing the data from the model to its corresponding view or to treat the data that are sent back from the views through HTTP requests.

By using these technologies, it is explained how the frontend, the backend and the database are developed:

- **Frontend**: the visual part of the fronted follows the pathways shown in Figure 7.3. Node.js need to be installed to create a React application. Therefore, using the package manager NPM and installing a module called create-react-app, the application in React is created. After running this module, some files and folders, the ones that create the structure of the application appear:
  - *node_modules*: it is a directory in which all the libraries to use as well as any needed dependencies are installed.
  - *public*: within this folder, the most important file is located. This file is the index.html in which all the components of the simulator will be rendered. Additionally, local files that could be used by the components could be found in this folder.
  - *src*: this directory includes all the components designed for the different views of the simulator.
  - *REAME.md*: short user manual with information about the application.
  - *package.json*: this file contains all the Node project in which all the information of the application is managed. It contains the name of all the installed dependencies so that, when the application is configured, it is automatically installed.
  - *yarn.lock*: this file is similar to the previous one with the difference that it only holds the information of the modules installed within the application.

  All these components create the different views that are shown in Figure 7.3. Finally, an international environment is included in order to be able to translate the content of the application to any language by means of a file in which all the translations are stored. This is the I18next environment which is written in JavaScript.

- **Backend**: this is the logic part of the simulator and will send and receive the data from the frontend, to the React application created. To create a server based on Express, a package.json is created through the package manager

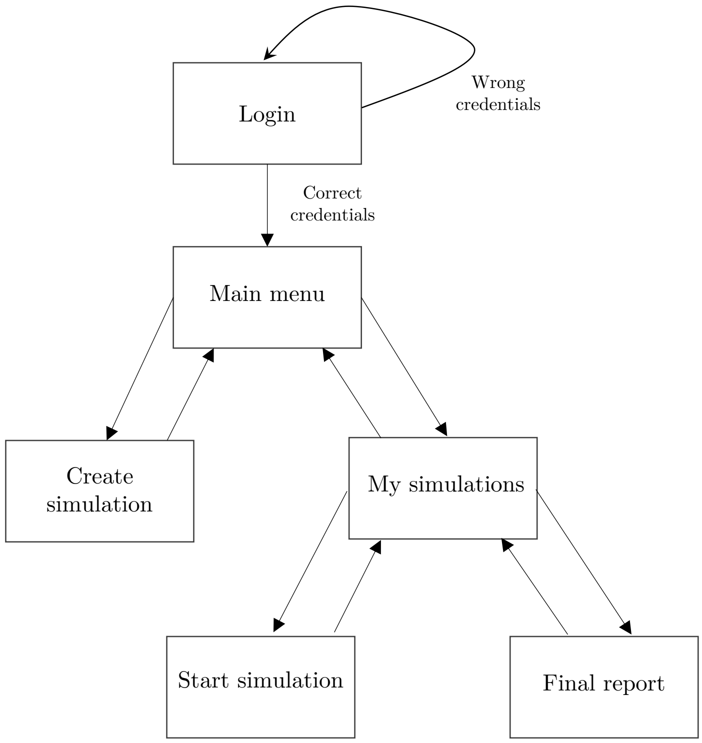


Figure 7.3: Navigation flowchart of the application developed for the simulator.

NPM and including all the information from the application as well as all the dependencies installed. Express allows to create the structure of the server by installing the package express-generator. Nevertheless, as React will be used to develop the visual part, the following structure has been developed:

- *node_modules*: directory in which all the libraries to use as well as any needed dependencies are installed, such as Express.
- *model*: it is where the model is located included all the data of the simulator and it is also where the connection to the database is done.
- *routes*: all the paths of the APIs create are written in this directory. This way, they could be called from the frontend.
- *controlers*: this is a directory in which all the files with the logic of the APIs are located.
- *App.js*: this is the most important file. In this file, the Express application which will create all the APIs is defined and run. In this file some configurations of the application such as the port TCP/IP is specified.

- **Database**:one important requirement of the simulator is to gather and storage all the data generated by the application developed. First of all, the data of the users that interact with the application is gathered, being specially important the role that the user has within the simulation as it will provide different access to resources. Secondly, it is key to storage all the information with respect to the vital signs of the virtual patient and all the actions taken along the simulation as well as their impact. To accomplish all this, MySQL has been used to manage and storage all that information.

- *MySQL*: it is a relational database management system, open source, using a client-server model that allows to create and manage databases. A database is a group of data stored and organized in a structured manner. The relational term refers to the fact that all the data are stored in different tables which are interconnected with each other. As MySQL is open source, it is free and available to anyone that could use it and even modify it. As the model used is a client-server one, the MySQL will be installed on the clients and when they need to access the data, they communicate with the server by a request, and the server will send the data as shown in Figure 7.4. These requests are done through Structured Query Language (SQL).

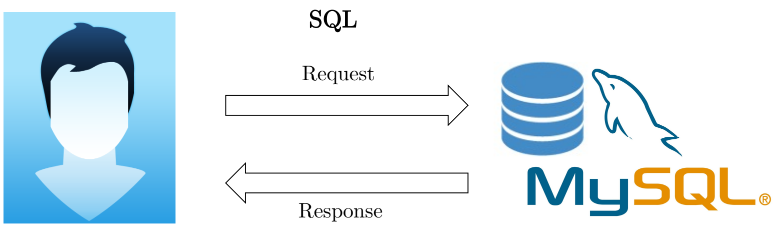


Figure 7.4: Client-server architecture in MySQL.

- *SQL*: SQL gets often confused with MySQL, but they are different. MySQL is a software in charge of creating the relational database whereas SQL is the language that both, client and server, use to communicate. Therefore, by using SQL a client can access the database information, modify the data by adding or deleting information, provide specific properties to the data as well as protect data restricting access to data if necessary.

- *Sequelize*: apart from the database creation, it is important to synchronize it with the backend. This is done thanks to an Object-Relation Mapping (ORM) which is an object oriented programming model that allows to map the tables of a relational database through an entity; that is, transform data into objects so that they can be used by the application. Additionally, it allows to leave aside the manual queries through the SQL language, using part of the ORM with its own language to do this. Sequelize is an ORM for Node.js that allows JavaScript functions to interact and manage SQL databases, MySQL among others, without the need to introduce SQL queries as they are already implicit in these JavaScript functions. Sequelize can be installed thanks to the package manager NPM and it perfectly adapts to the Express environment of the backend.

- *Design*: to create the database by using Sequelize, a configuration file is written. In this file, the name of the database to create is included as well as the management system which is MySQL and the credentials to access to it. Then, four different tables are created in which all the data as well as the type of the data are defined. As it is a relational database, the tables are related to each other by a Primary Key (PK) which is one of the attributes included within a table of the database. This PK will also appear as Foreign Key (FK) in a second table. Therefore, when two tables want to be related, the PK of one table will appear as the FK in the other table as shown in Figure 7.5. The table roles contain the definition of the different roles to have within the simulator. This table is related with another two tables which are trainer and trainee. Each of them contains the same information but they are fulfilled depending on the role defined. Then, the table simulation is created in which all the relevant information with respect to the clinical scenario managed during the simulation is stored. This table is related to the trainer and trainee tables thanks to the TranierId and TraineeId keys, as shown in Figure 7.5.

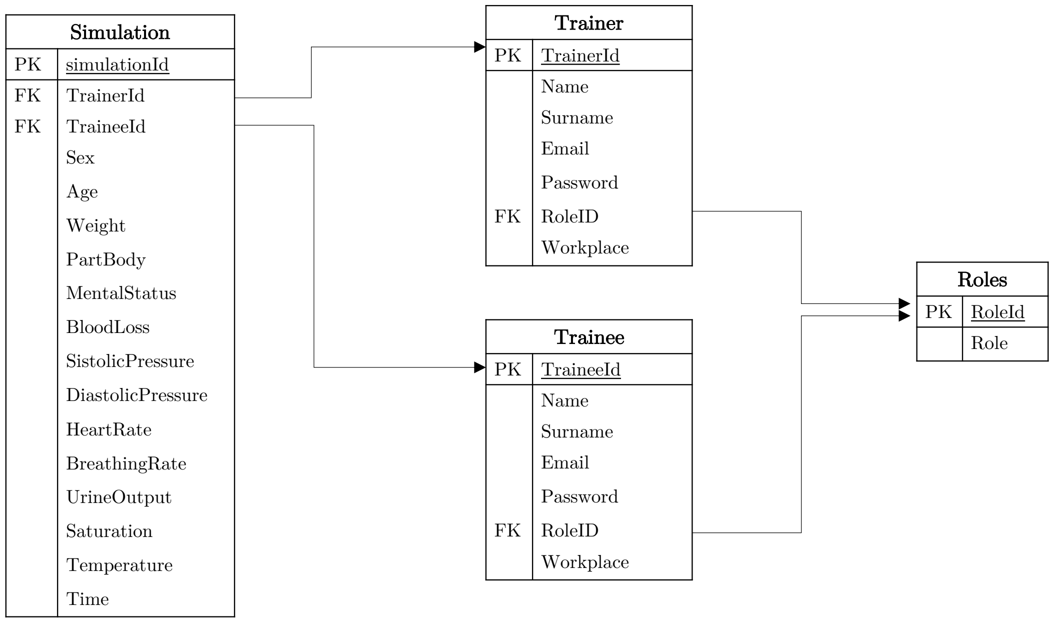


Figure 7.5: Relational database model of the web-based simulator.

The deployment of this web-base simulator is done in Docker (Arsys, 2019)[1]. Docker is a virtual software platform that allows to create containers that are isolated from one another and bundle their own software, libraries and dependencies. Docker offers the possibility to execute the application in any environment independently of the operating system. The two main concepts are: virtual platform and containers:

- **Virtual platform**: it creates a virtual version of a technological resource creating an abstraction layer between the hardware of the physical machine and the operating system of the virtual one. This layer is knows as hypervisor. The hypervisor hides the characteristics of the physical hardware to instal the virtual operating system in an upper layer, as shown in Figure 7.6. To create virtual machines usually uses a lot of resources of a physical machine as any virtual machine isolates the operating system installed in the physical machine. Nevertheless, Docker is a virtual software platform at operating system level. Therefore, Docker works directly with the operating system of the physical machine in which a container is executed. Then, the containers will share resources with the physical operating system isolating applications as shown in Figure 7.6.

- **Containers**: it has the same purpose as a commercial container. Its function is to storage objects and the transport them to a different place. In Docker,

[1]The source code is available at: https://github.com/Robolabo/trauma-simulator

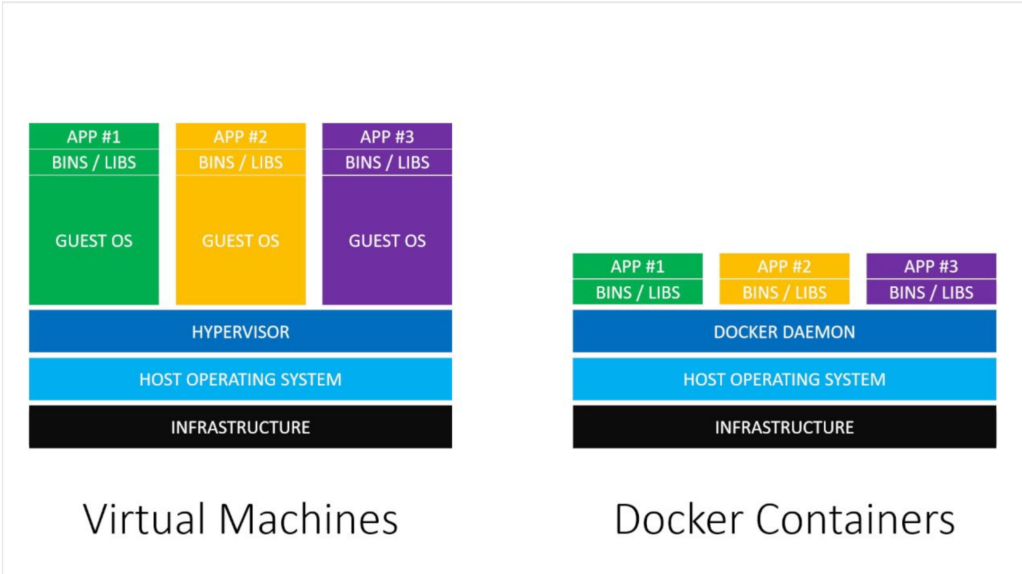


Figure 7.6: Differences between virtual machines and Docker containers (ManuFosela, 2018).

a container storages all the libraries and dependencies needed to execute an applications and, thanks to this storage characteristic, it is possible to run the application in any environment.

Containers are always linked to Docker images; in fact, an image is used to create a container. In that image all the code and configurations of the service to provide and that will be executed with the container. Images are immutable and they are made of reading layers (Envatotuts, 2020). This means that, after an image is created, no changes are allowed. On the contrary, containers can be modified. When an image creates a container, a reading-writing layer is added to the reading layers of the image. Then, all the changes made on the container will be gathered in that layer and will be recovered each time the container is started. Therefore, the same image can create identical containers but, once they are modified launching the container, they will not be identical anymore. There are already available images in the public register *Docker Hub* but, if a new image wants to be created, a configuration Dockerfile has to be written. Then once images and containers are created, there is the option to execute containers individually or in groups. To do it in groups, the *Compose* tool needs to be used as it allows to launch Docker images from different containers. Therefore, the file *docker-compose.yml* is created. As the simulator has three main parts: frontend, backend and database, three images will be created and therefore, three containers will include all the data that will be launched together by using the docker-compose tool. For the proper functioning of the visual part of the simulator, it is needed to have access to the different APIs that manage de simulation data. Therefore, it is a requirement that the database is connected to the backend. Due to this fact, when all the containers are launched, it is needed to maintain an order: the database container needs to be launched first, then the backend and, finally, the frontend. This is possible by including the *wait-for-it.sh* script within the different images created.

By using all these technologies, trauma scenarios can be programmed and included into the simulator which can be available by any computer. An example of these scenarios is shown in Figure 7.7. The clinical scenarios consist on a virtual patient that suffers a trauma and therefore, a natural evolution curve of the patient if nothing is done is implemented. Once this is set, the possible actions to accomplish are defined considering that there are actions that have an impact on the vital signs, such as patient oxygenation and actions that do not have an impact on the vital signs, such as anamnesis. The vital signs considered are: SpO_2, $BreathingRate(BR)$, $HeartRate(HR)$, $SystolicBloodPressure(SBP)$ and $DiastolicBloodPressure(DBP)$.

CLINICAL SCENARIO	Medicalized advanced life support unit. A call is received to treat a male who is 25 years old. He was in his car, stopped at a traffic light when another car crashed with his car. When emergency services arrive, he is conscious and oriented in a supine position. The patient complains about a strong pain on the groin level.

NATURAL EVOLUTION CURVE OF THE PATIENT IF NO TREATMENTS ARE TAKEN

	>>>>>>>>>>>>>>>	>>>>>>>>>>>>>>>>>>>	>>>>>>>>>>>>>>>>>>>>	>>>>>>>>>>>>>>>>>>	**END: 30 minutes**
	Minute 0	**Minute 5**	**Minute 15**	**Minute 22**	**Minute 30**
SpO2%	98%	96%	90%	85%	81%
BR	26	30	41	15	9
HR	110	120	135	121	63
SBP	141	133	110	75	61
DBP	89	81	65	52	42

AREA	QUESTION	MESSAGE
ANAMNESIS	What is your name?	Antonio.
	How old are you?	25 years old.
	Do you suffer any allergy?	To the skin of the peach.
	Do you have any important illness?	No
	Do you take any medicine regularly?	Paracetamol from time to time.
	Do you know where you are?	Yes, at the street.
	Do you know what happened?	I was waiting for the traffic light to turn Green when I felt a strong hit and suddenly, I was on the pavement of the street.
	Do you have any pain?	My groin hurst a lot. Anytime I try to move my leg, it hurts a lot.
	Can you breathe normally?	Yes, I can.
	Can you move your legs? Do you feel if I touch your leg?	Yes, I feel it. I can move both legs a little bit.

Figure 7.7: Clinical scenario in which a patient suffers a trauma including its natural evolution curve and the circumstances of the clinical scenario.

To incorporate into the simulator the actions that have an impact on the vital signs, different types of actions are defined considering the different impacts they may have into the vital signs of the virtual patient:

- **Type 1**: these are actions that increase or decrease the value of a vital sign in a certain period of time and after that, the evolution of the patient follows its natural evolution. In Table 7.1, all the type 1 actions included are shown together with the vital sign that is affected and the time that the action lasts. It is after that time that the patient evolution goes back to its natural curve.

Action	Vital sign	Duration($s.$)
Aspirating	SpO_2	0
Nasal cannula oxygenation	BR	120
Reservoir mask oxygenation	BR	30
Midazolam 2 mg IV	SpO_2	60
SSF 20 mg/kg	SBP/DBP	1200
Voluven	SBP & DBP	780
Massive transfusion protocol	SBP/DBP	300

Table 7.1: Type 1 actions with information with respect to the vital signs that they impact and the duration of the impact they have

- **Type 2**: there are actions that increase or decrease the value of a vital sign to a specific value and then, this value is maintained. The duration of all the type 2 actions goes from the moment they are taken until the end of the simulation. Therefore, the time included in Table 7.2, is the time that it takes a vital sign to change its value from the initial one, to the final one.

Action	Vital sign	Duration($s.$)
Reservoir mask oxygenation	SpO_2	30
Airway mask bag unit	SpO_2	40
Mechanical ventilation	BR & SpO_2	30
Noradrenaline	SBP & DBP	20

Table 7.2: Type 2 actions with information with respect to the vital signs that they impact and the duration it takes to get to the specific value that should be obtained.

- **Type 3**: these are actions that, when performed, they maintain the value of a vital sign and after a period of time, that value is modified until the end of the treatment. As type 2 actions, they time duration goes from the moment they are taken, until the end of the simulation. The time shown in Table 7.3 is the one that needs to wait until the vital sign affected is modified.

Action	Vital sign	Duration($s.$)
Tourniquet	SBP & DBP	300
Manual pressure on hemorrhagic injury	SBP & DBP	180
Hemostatic agent	SBP & DBP	180

Table 7.3: Type 3 actions with information with respect to the vital signs that they impact and the duration it takes to get modify the vital sign affected.

- **Type 4**: these are actions that increase or decrease the value of a vital sign until another action is accomplished. The time duration of these actions depends on the moment that the other actions is taken. Therefore, the total duration of the simulation is the limit. Considering the action shown in Table 7.4, the other action that should be accomplished is applying an airway mask bag unit.

Action	Vital sign
Medication for rapid sequence intubation	SpO_2

Table 7.4: Type 4 actions with information with respect to the vital signs that they impact.

- **Type 5**: these are actions That accelerate or decelerate the evolution of a vital sign by multiplying or dividing the value of that vital sign. The duration of these actions go from the moment they are applied until the end of the simulation. In Table 7.5 the pelvic binder is included within this type.

Action	Vital sign
Pelvic binder	SBP & DBP

Table 7.5: Type 5 actions with information with respect to the vital signs that they impact.

- **Type 6**: these are actions that increase or decrease the value of a vital sign in a certain period of time and then, the value of the vital sign is maintained. The duration shown in Table 7.6 is the one that it takes to the vital sign to get to its final value, the value that is maintained until the end of the simulation.

Action	Vital sign	Duration($s.$)
Nasal cannula oxygenation	SpO_2	120

Table 7.6: Type 6 actions with information with respect to the vital signs that they impact and the time it takes, to the vital sign, to get to the value that is maintained.

Then, another important aspect to consider is that, when an action is taken in a real situation, the impact of those actions does not happen automatically. Therefore, a latency time has been implemented in which this aspect is considered. Therefore, all the times previously shown do not take affect until the latency time defined passes by. Finally, an important aspect to consider is what happens when two or more actions temporarily overlap. In this case and, after consulting with trauma experts, a priority order is set as shown below:

1. First, the type 3 actions.
2. Secondly, the type 2 and type 6 actions.
3. Thirdly, the type 1 and type 4 actions.
4. Finally, the type 5 actions.

Once all the actions and their impacts are set; the simulation scenario is programmed and a trainee could use the web-based trauma simulator to stabilize a patient that suffers a trauma. All the data produced along the simulation is gathered into the datase. From one side, this allows the trainee to use this tool as a training tool, having access to what has happened during the simulation. On the other side, this allows the trainer to objectively evaluate the performance of a trainee. Therefore, this web-based simulator seems to be appropriate to use it for trauma management learning and for incorporating an evaluation system by integrating the metrics developed in Chapter 6. To test the appropriateness of this simulator, an experimental test is accomplished.

7.2 Expertimental test

The Advanced Trauma Life Support (ATLS) separates the assessment of a trauma patient care in two parts, a primary and a secondary survey as explained in Section 3.3.2. In the primary survey, life-threatening injuries are managed whereas other injuries are diagnosed and treated in the secondary survey. Therefore, this test focuses on the primary survey of a pelvic trauma scenario. A pelvic trauma scenario has been included in which no other injury is suffered by the patient. The experimental test was conducted at IdiPAZ – Hospital La Paz Institute for Health Research in Madrid, Spain. A pelvic trauma scenario was defined in which the trainer defined the characteristics of the trauma case that the trainee will manage. Therefore, the sex of the patient, age, part of the body affected together with the vital signs of the patient at the time of the trauma scenario will be provided as shown in Figure 7.8, in which all the details that the trainer sets are shown. Moreover, the remaining lifetime of the patient, if no specific action is taken, is provided. This creates a more realistic scenario in which a fast and efficient response should be provided under stressful circumstances.

The data analyzed are the actions taken to treat the trauma patient, the evolution of the vital signs of the patient, the timing spent on deciding which action to take, when each action was performed and the consequence that it had on the patient. This data is studied to obtain information about which actions were performed during the simulation, if those actions were performed following the ATLS guidelines and if the timing in which the actions were done was the right one for the patient.

Taking into account the set of actions defined that could be accomplished in the pelvic trauma scenario together with the ATLS guidelines, 432 different sequences of actions could be accomplished to treat the virtual patient and will be taken as references. These different sequences are defined taking into account the different actions to execute and the evolution of the virtual patient. There are a number of sequences that could be applied to treat the trauma patient, and each of them could have the same or a different number of actions as shown in Table 7.7. Therefore, as an example, 12 different scenarios have 8 actions which means that, taking into account the actions included in the simulator, 12 different possible scenarios could be performed to treat the patient carrying out 8 different actions. These are the scenarios that were possible to accomplish when treating a trauma patient. Each of the participants applied a different procedure, performing a different sequence of actions from all these options. These data were gathered and analyzed.

Number of scenarios	12	48	96	120	96	48	12
Number of actions	8	9	10	11	12	13	14

Table 7.7: Number of scenarios and the number of actions included in each scenario

The participants of this test were final-year medical students and doctors with an average experience of 12.36 ± 7.45 years were invited to participate. An explanation

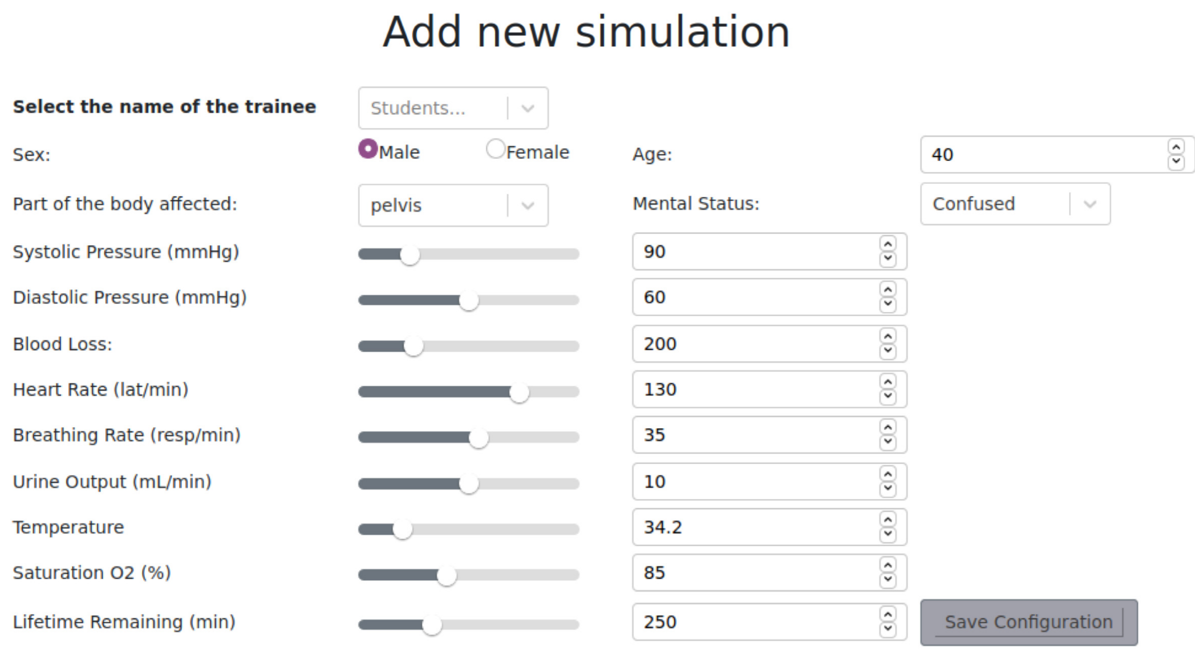


Figure 7.8: Trauma scenario definition screen. This section is only available for trainers in which the trauma scenario together with the trainee will be defined and selected.

on the WBTS was provided together with the instructions they must follow during the simulation. All participants received a 15 min explanation on the WBTS together with a first trial to get familiar with the simulation set-up. Once the trauma scenario was finished, a post-simulation questionnaire was distributed in order to gather information about the user experience. In total, 28 simulations from final-year medical students and 13 from doctors were analyzed. The data analyzed are the actions taken to treat the trauma patient, the evolution of the vital signs of the patient, the timing spent on deciding which action to take, when each action was performed and the consequence that it had on the patient. This data is studied to obtain information about which actions were performed during the simulation, if those actions were performed following the ATLS guidelines and if the timing in which the actions were done was the right one for the patient. Moreover, this analysis is done comparing two different groups of participants: final-year medical students and doctors and the Wilcoxon rank-sum test has been used to compare the two samples. Statistical significance is obtained if the p-value is lower than 0.05. The WBTS was tested with the pelvic trauma case explained. All the participants completed successfully the trial and a comparison analysis between the performance of the final-year medical students and doctors was done. From all the data gathered, several parameters were analyzed as shown in Table 7.8.

Some of the parameters show no difference between the groups. For example, the timing spent on the treatment in both groups is around 230 min. Both groups perform a mean of seven correct actions along the treatment. Taking into account the 432 different sequences of treatment, these results show that in some cases (14% of them) seven actions are close to the number of actions needed to treat the patient as shown in Table 7.8. However, in most of the cases (86%) they are not enough. Additionally, the correct sequence of actions taken to treat the patient as per ATLS guidelines is analyzed. Moreover, the mean of correct sequential actions as per ATLS is three actions for students whereas four for doctors, showing no significant differences.

However, some other variables are observed to report important differences between the groups.

Parameter	Medical students	Doctors
Teatment time	237 ± 68 $(mean \pm SD)$	228 ± 62 $(mean \pm SD)$
Number of actions performed	10 ± 2 $(mean \pm SD)$	10 ± 2 $(mean \pm SD)$
Number of correct actions performed	7 ± 6 $(mean \pm SD)$	7 ± 4 $(mean \pm SD)$
Number of sequential actions performed	3 ± 2 $(mean \pm SD)$	4 ± 3 $(mean \pm SD)$
Airway inspection	71 % (20/28)	85 % (11/13)
Patient oxygenation	96 % (20/28)	100 % (11/13)
Patient intubation	68 % (20/28)	54 % (11/13)
Pelvic binder placement	71 % (20/28)	77 % (11/13)
Blood transfusion	86 % (20/28)	92 % (11/13)
Crystalloids administration	71 % (20/28)	85 % (11/13)
Thermal blanket	43 % (20/28)	15 % (11/13)
Hot loquids administration	21 % (20/28)	62 % (11/13)

Table 7.8: Parameters analyzed during the simulations and comparison between medical students and doctors

Once this analysis is performed, another one is done following the primary survey steps as per ATLS recommendations and as stated in Section 3.3.2:

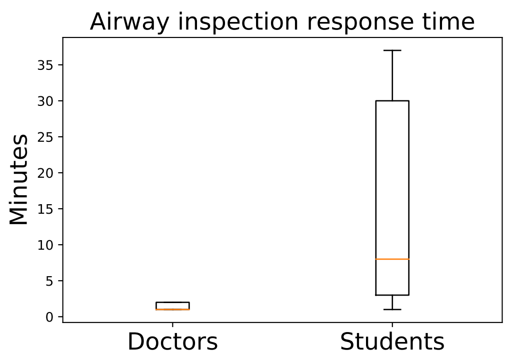
- **Airway assessment**: The first step to accomplish during the primary survey of a trauma patient is the airway assessment. 71% of the students takes this first step whereas only 84% of the doctors does it. From the students that inspect the airway, they do it from the third minute of treatment onward whereas the doctors start to inspect the airway during the first two minutes, showing significance (p-value = 0.0020) between the two groups analyzed as shown in Figure 7.9 (a).

- **Breathing**: Breathing is the second item to accomplish during the primary survey. For the trauma scenarios created, there are no pneumothorax, hemothorax or contusions, the clinical problems that may arise with respect to assure a correct breathing of the patient could be treated with measures such as ventilation or intubation. Actually, 96% of the students oxygenate the virtual patient and all the doctors also do it. The difference between the two groups is the moment in time in which they oxygenate the patient but not statistical significance is obtained (p-value = 0.5129). Students oxygenate in a wider range and in moments in time that are quite late such as 150 or 166 min after the arrival of the patient to the medical facility. All the doctors do it more or less in a similar time range with a median value of 8 minutes as shown in Figure 7.9 (b).

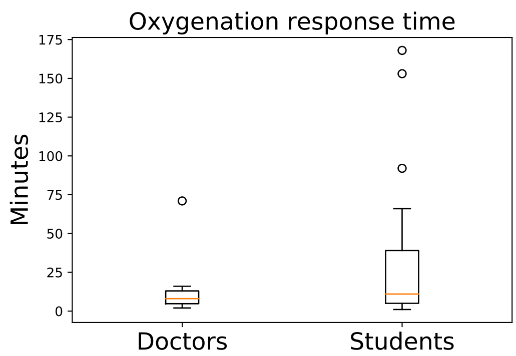
- **Circulation and hemorrhage control**: Circulation is the third priority during the primary survey. Notice that the main cause of problems in circulation are hemorrhages. Because the virtual patient suffers a pelvic trauma, a pelvic binder should be placed as soon as possible, in order to decrease blood loss. Then, liquids should be provided in order to reinstate a normal blood volume as soon as possible. 71% of the students place a pelvic binder on the patient and 77% of the doctors does it. Nevertheless, the response in time of the location of this device is done late in both groups as shown in Figure 7.9 (c) and statistical significance is obtained (p-value = 0.0165). The median response time of the students is 72 min and for the doctors it is 157 min. Therefore, in both cases, a scarcity in trauma training is clearly perceived. Moreover, 86% of the students infuse liquids to regain a normal blood volume and 92% of the doctors does it too, to support the blood circulation restoration.

- **Disability**: Disability should be assessed as the fourth task to accomplish during the primary survey. None of the participants made this assessment, nor the students nor the doctors.

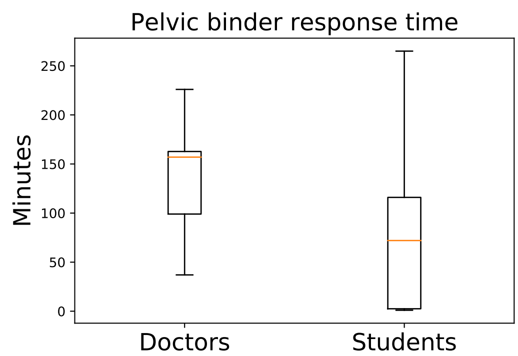
- **Exposure**: The last step of the primary survey considers the exposure of the patient such as hypothermia, burns or possible exposure to chemicals. In the cases in which the body temperature of the patient is below or equal to 35 °C, 64% of the students provided the patient with hot liquids or with a thermal to increase the temperature of the patient. 77% of doctors take those measures in order to increase the body temperature of the patients. There have been no important differences between both groups with respect to when the trainees, students or doctors, apply a treatment to the virtual patient to avoid hypothermia. The patient of this trauma scenario does not suffer any burns or exposure to chemicals.



(a)



(b)



(c)

Figure 7.9: Airway inspection, oxygenation and pelvic binder response times performed by doctors and by medical students.

The experimental test accomplished demonstrated that the WBTS is suitable to train and evaluate trauma management. The simulator allows to interact with a virtual patient as the treatments applied have an impact on the patient. Moreover, all the treatments are recorded as well as the impact on the vital signs of the patient which allows the trainee to use this simulator as a learning tool and it allows the trainer to objectively evaluate the performance of the trainee. Additionally, this study has highlighted the scarcity trauma training, specially in the medical students' community as highlighted in Section 4.2. Nevertheless, also doctors may need trauma management refreshing courses according to the results obtained (Borggreve et al., 2017; Lewis and Vealé, 2010). Therefore, a WBTS could be implemented to learn and refresh trauma management protocols. Consequently, this WBTS presents an alternative tool to continue improving trauma management protocols learning process.

7.3 Trauma Management Evaluation System

Once the experimental test was accomplished, the metrics presented in Chapter 6 were created for each simulation and included into the WBTS database. Considering that the target trauma management solution was set; by comparing it with the treatment performed by the trainee, all the scores can be calculated applying the equations presented in Chapter 6. All the scores were automatically created and incorporated into the web-based simulator database. To define a trauma management evaluation system, it is important to consider all the important aspects avoiding redundancies. Therefore, a correlation analysis between all the scores created is performed as shown in Figure 7.10. The specificity and the precision scores have a correlation score of 0.78; therefore, only one of them should be considered. Moreover, the recall, accuracy and F1 score are correlated as shown in Figure 7.10; then, only one of them would be chosen for the evaluation system. The rest of the scores in Figure 7.10 have a correlation value below 0.75 and therefore, all of them provide different information. Consequently, the set of scores to create a trauma management evaluation system is composed of: the precision, the F1, the GA, the DS and the SS scores.

After this analysis, the panel of trauma experts previously mentioned was consulted. The objective of this enquiry was to obtain information about the importance that each of the scores chosen should have when evaluating a trauma management simulation. To do so, experts were requested to provide to each of the scores a punctuation from 1 to 10, being 1 not important and 10 very important to consider when evaluating a trauma management simulation. All of them are considered important as the average value is above seven in all cases; nevertheless, the distributions are different as shown in Figure 7.11. The precision score which provides information about the actions performed correctly from the ones the trainee accomplished seems to be the least important from all the scores created in average but, the lowest score provided is six which means that all the experts considered this aspect relevant. The $F1$ score which combines both the precision and recall scores, is the one that in average is considered the most important when evaluating a trauma simulation. In our case, the $F1$ score is more related to the recall values considering the values obtained in all the simulations; therefore, details with respect to the actions that the trainee, from the actions that he or she might have done, accomplished correctly are considered key. Nevertheless, it is important to highlight that one expert provided a value of four to this score. The GA importance is also highlighted in Figure 7.11 in which all the experts provide a score above 7 except one expert that considers that this global alignment score is not important, providing a score of two. The DS score is also considered important but, there is more dispersed values than in the other scores. Finally, the SS score is considered very important with a lowest value of six and having an important number of experts providing a 9 or 10 to this aspect as shown in Figure 7.11.

Therefore, in average, the order in which these aspects should be considered is the following: F1 score, subsequences score, global alignment score, diagonal score and precision score.

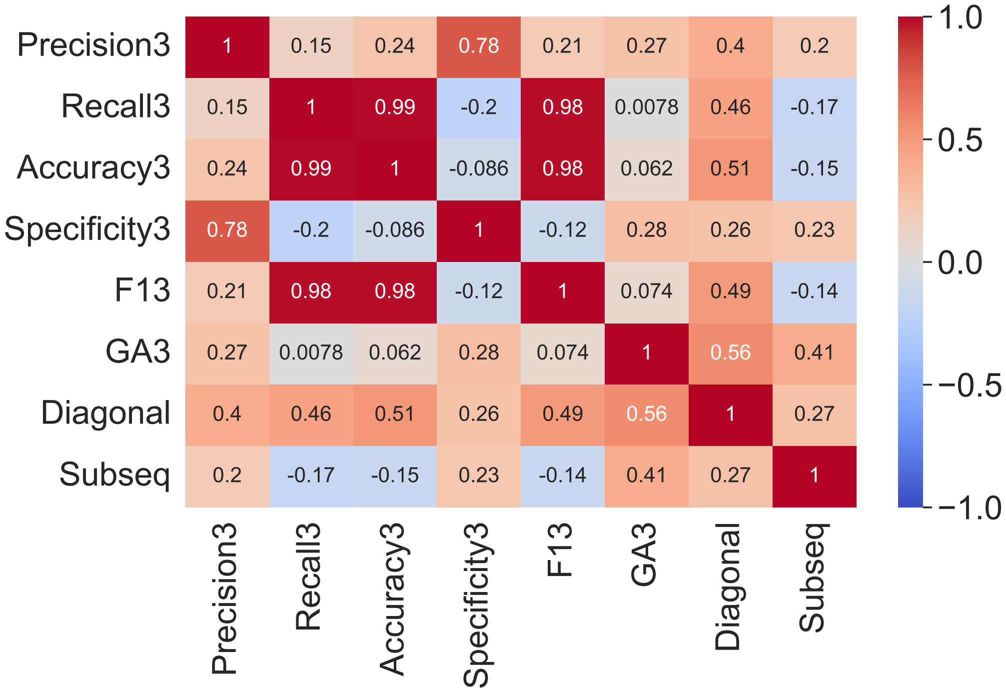


Figure 7.10: Correlation matrix of all the scores calculated for all the simulations performed.

Consequently, the trauma management evaluation system proposed will provide a score as per Equation 7.1, in which the weights assigned to each score have been calculated considering the punctuation provided by the experts and how much each score, in average, contributes to the total score provided.

$$\boxed{Score = 0.2189\ F1 + 0.2132\ SS + 0.2017\ GA + 0.1903\ DS + 0.176\ Precision} \tag{7.1}$$

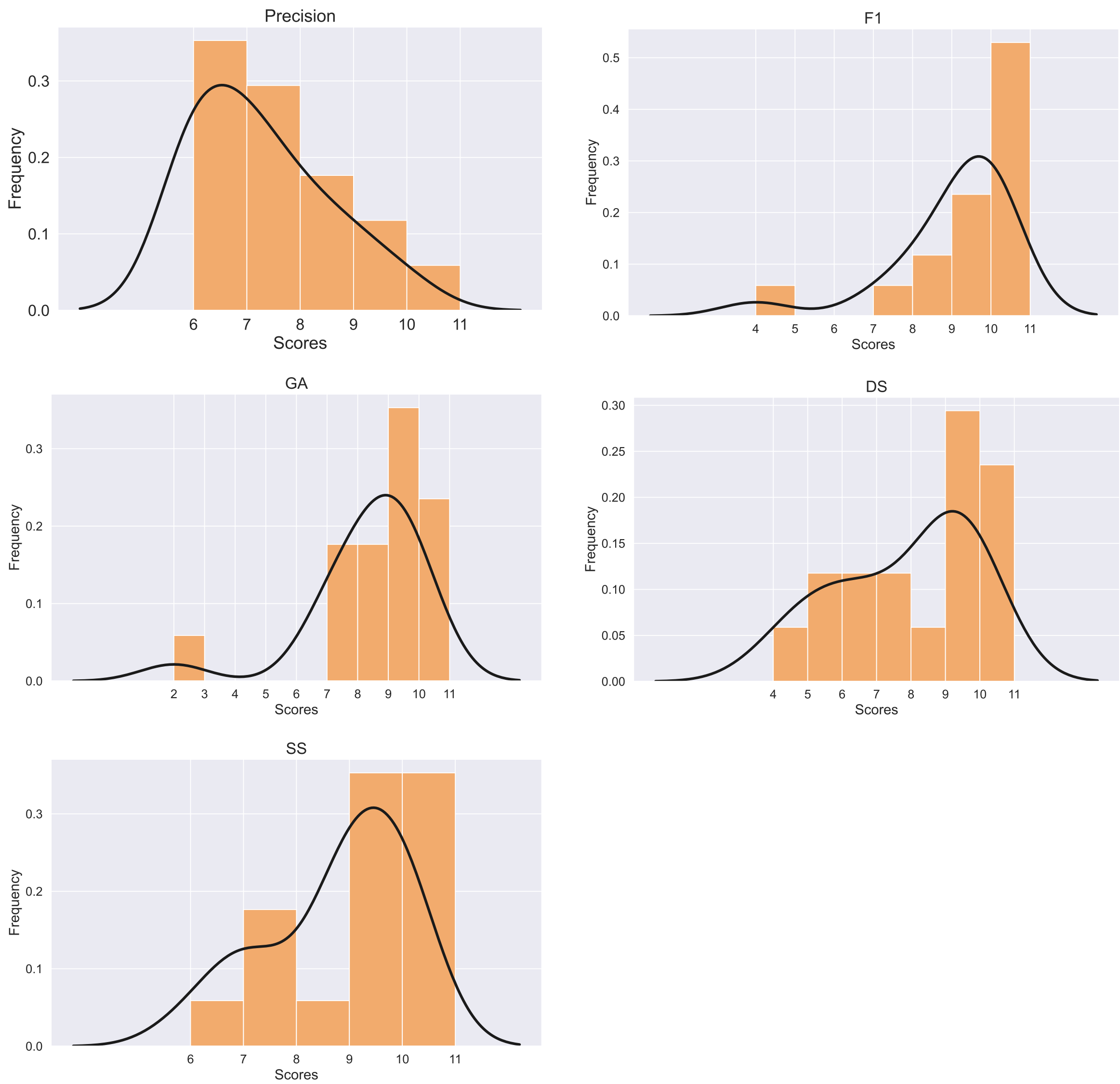


Figure 7.11: Score distribution provided by the panel of trauma experts in which 1 means that the score is not important when evaluating a trauma simulation and 10 means that the score is key when evaluating a trauma simulation.

8 Results and Discussion

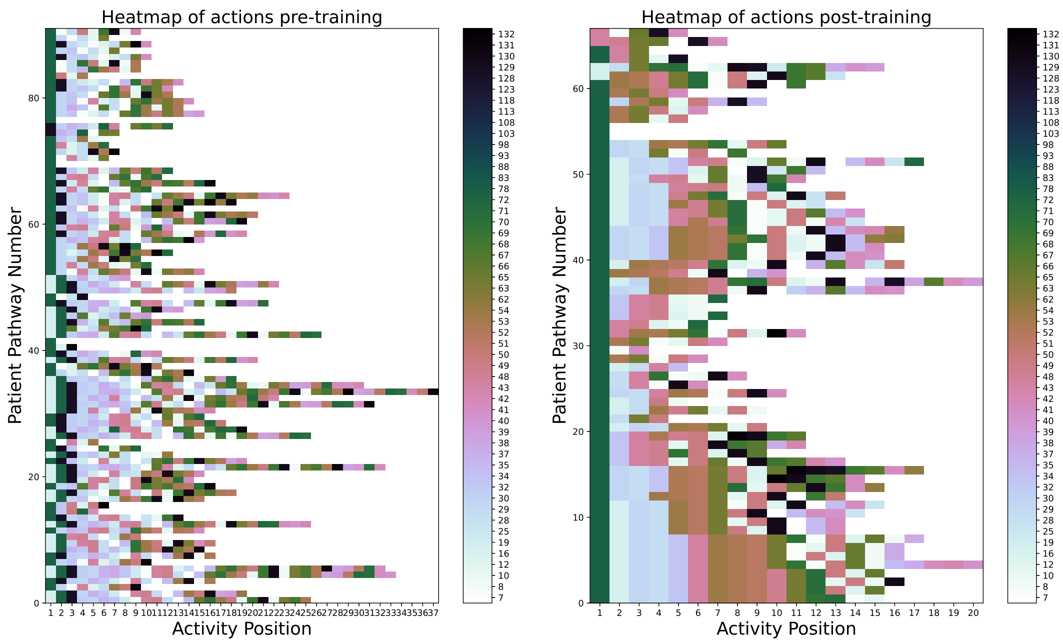
Using the Web-based Trauma Simulator (WBTS) presented in Chapter 7 and all the scores developed in Chapter 6, a deep analysis on the impact that the use of this simulator has on the learning process of trauma management, using the new scores developed, was performed. To do so, sixteen different trauma scenarios were created based on two different trauma injuries: pelvic and lower limb lesions. Both types of traumas could occur either on a hospital or on a prehospital setting; therefore, four different scenarios are trained: a prehospital pelvic trauma, a hospital pelvic trauma, a prehospital lower limb trauma and a hospital lower limb trauma. Depending on the setting in which the trauma is treated, different actions are shown. To analyze the new scores developed to evaluate trauma management performance, the sequence performed by the trainee is compared with the target sequence of actions defined by the trauma experts for each scenario. Therefore, once the simulation was performed, these new scores were automatically created and added into the web-based simulator database which allows to perform an automated analysis. To test this, a training test was performed for two weeks and it was organized as follows: first of all, all the trainees accomplished the four different trauma scenarios, gathering all the relevant information to analyze how the simulation was performed and incorporating the new scores developed. Then, for two weeks, trainees practiced with the other trauma injuries scenarios created. Finally, once the two-weeks training was accomplished, the same four trauma injuries scenarios as the ones performed the first day were done. Hereinafter, an analysis on these trauma management scenarios was done using the scores presented on 6 and comparing the results obtained pre- and post-training.

8.1 Participants

Medical students from the Universidad Autónoma de Madrid and residents from Hospital Universitario La Paz were invited to participate in this study. A user manual together with a demo video with instructions on how to use the simulator were provided to the participants[1]. Within the instructions, a calendar was provided stating that the first day the trainee should manage the first four different scenarios mentioned. Then, the rest of the days for two weeks, they should train with the simulator with at least one simulation per day. Once the training was completed, the simulator would allow trainees to access again the first four trauma cases. In total, 91 simulations accessed for the first time and 66 simulations repeated after the training were analyzed. This was due to the fact that not all the trainees finished the training sessions as requested. Once the complete test was performed, all the data was gathered and analyzed. First of all, information about the sequences of actions accomplished were gathered on a heatmap to show the actions performed on the pre-training simulations and on the post-training simulations. Figure 8.1 shows

[1] Available at: https://github.com/Robolabo/trauma-simulator

information about all the simulations, (a) before and (b) after training. The complete sequence of actions accomplished per simulation is shown. Each action is represented by a number and all of them are detailed in Annex A. It is observed that there is an important variety of responses when managing a trauma scenario. However, after training, there is an increase on homogeneity on the response provided to the trauma scenario. For example, the first action on dark green in both Figures 8.1, (a) and (b), which is the question "what is your name?" considered within the anamnesis category (action 78 as shown in Annex A), in pre-training it was accomplished in 63% of the simulations whereas in post-training it was accomplished in 94% of the simulations. Additionally, the number of actions performed decreased in post-training, being 20 the maximum number of actions accomplished to manage the trauma scenario whereas in pre-training, this number goes up to the value of 37 actions. This number of actions in post-training (20) is closer in average to the number of actions included within the possible solutions provided by the panel of experts which ranges from 16 to 24 actions. All the possible solutions provided by the trauma experts are found in Annex B.



(a) (b)

Figure 8.1: Heatmap with the sequence of actions taken in all the simulations: (a) the whole sequence of actions are shown for all the pre-training simulations and (b) the whole sequence of actions are shown for the post-training simulation.

The analysis performed on trauma management was done according to three categories:

- First of all, the actions that should have been accomplished during the first four minutes of trauma management. This is key following the panel of experts advice and considering that trauma patients should be treated as soon as possible (Hall et al., 2019).
- Secondly, the minimum actions that should have been accomplished for each of the trauma scenarios as there are some actions that need to be always accomplished.
- Finally, the complete sequence of actions taken along the simulation.

These three categories analysis was done for the four trauma management scenarios trained: a prehospital pelvic trauma, a hospital pelvic trauma, a prehospital lower limb trauma and a hospital lower limb trauma.

8.2 Results

8.2.1 Prehospital Pelvic Trauma Management

As previously mentioned, the actions taken on the first four minutes of trauma treatment are analyzed. In Figure 8.2, all the scores obtained in pre- and post-training are shown. The pre-training simulations scores are in blue and the post-training simulation scores are in orange. For the actions taken on the first four minutes, it can be seen that all the scores improve showing statistical significance on the recall and the F1 score in which the median values increase from 0.333 to 0.666 for the recall score with a p-values of 0.025, and from 0.5 to 0.8 for the F1 score with a p-value of 0.036. With respect to the minimum actions that should have been accomplished for this pelvic trauma management scenario, the difference between pre- and post-training simulation is small, as shown in Figure 8.2 (b), showing no significance between simulations. In fact, the precision and specificity scores are the same whereas the small differences are perceived for the recall, accuracy and F1 scores. Figure 8.2 (c) shows the analysis of all the actions taken along the simulation based on the scores provided by the confusion matrix. In all cases, except for the precision and specificity scores, significance is obtained. The median values changes from 0.25 to 0.437 for the recall score, from 0.31 to 0.5 for the accuracy score and from 0.4 to 0.61 for the F1 score, obtaining p-values of 0.0089, 0.0129 and 0.009 respectively. This shows a clear improvement on the post-training simulation with respect to the pre-training simulation. With respect to the global alignment score, pre- and post-training remains practically the same with a median value of zero as shown in Figure 8.2 (d). The diagonal score evolution shows an improvement on the post-training simulations with a higher median value, from 0.047 to 0.025, but no statistical significance is obtained. Finally, for the subsequences score, it can be seen, in Figure 8.2 (f), that the median value improves from zero in the pre-training simulations to 0.125 in the post-training simulations. However, in some simulations, the subsequences score values are better in the pre-training simulations.

Once all the individual scores are calculated, the overall score as per Equation 7.1 was calculated. For the prehospital pelvic trauma management, the average scores shown in Table 8.1 improve in post-training, which shows an overall improvement on managing this trauma scenario by using the WBTS developed.

	Mean	**Standar Deviation**
Pre-training	2.97	0.67
Post-training	3.14	0.75

Table 8.1: Trauma management overall score obtained in pre-training and post-training simulations.

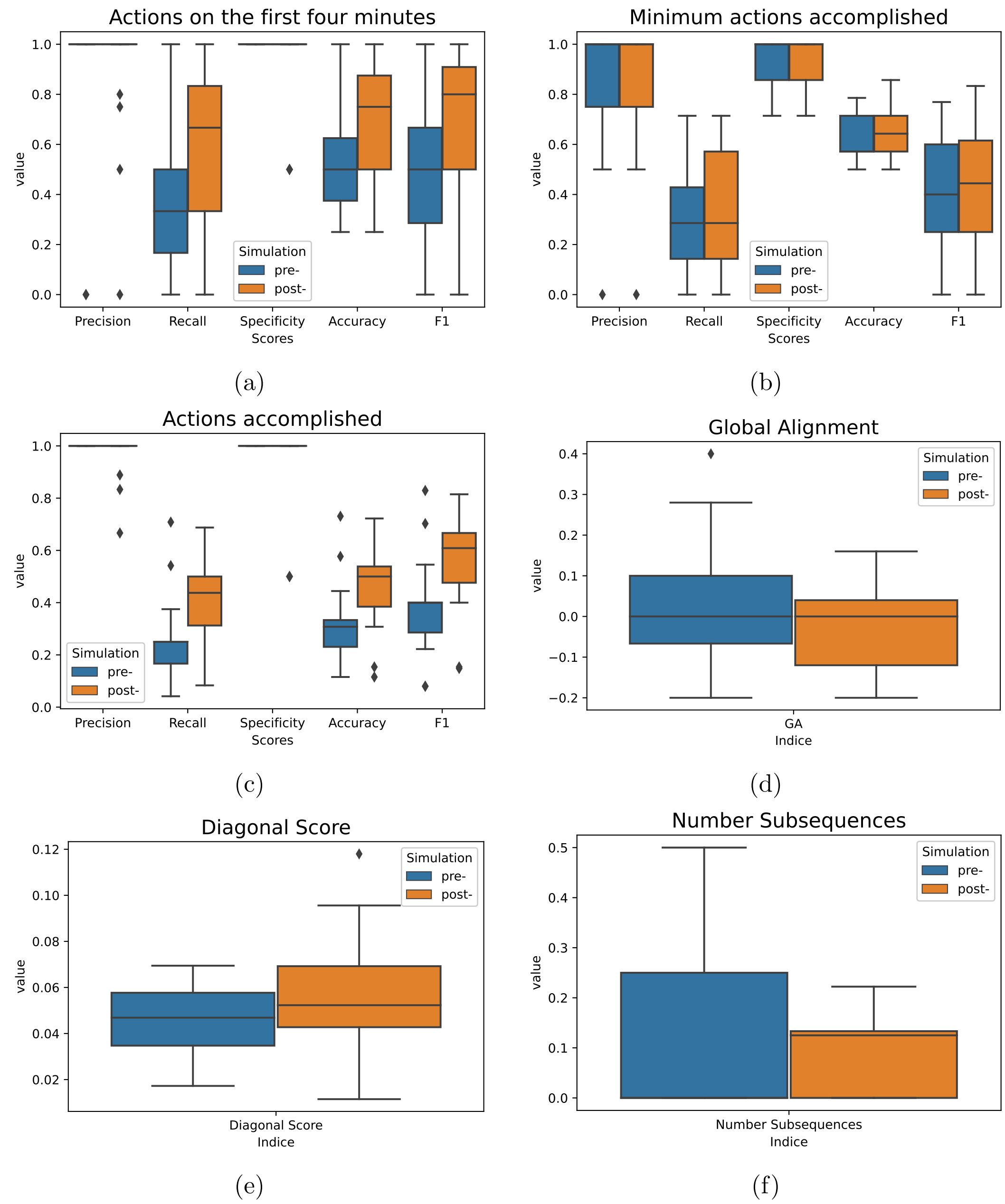
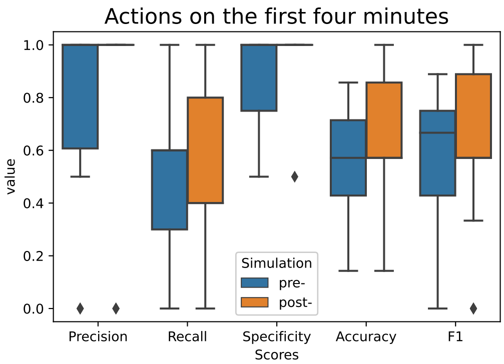


Figure 8.2: Scores obtained from the pre- and post-training simulations: (a) shows the analysis on the actions that should have been performed during the first four minutes; (b) the minimum actions that should have been taken along the simulations; (c) analysis of all the actions taken along the whole simulation; (d) the global alignment scores; (e) the diagonal score and; (f) the subsequences score.

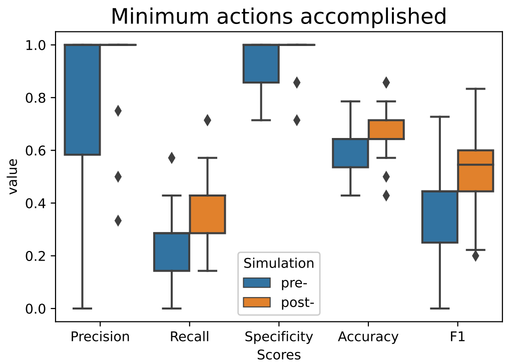
8.2.2 Hospital Pelvic Trauma Management

When the pelvic trauma is treated within a hospital facility, the actions to take may be different, as resources differ from the ones at prehospital. For example, it is possible to take an X-rays whereas in the prehospital setting, this option was not available.

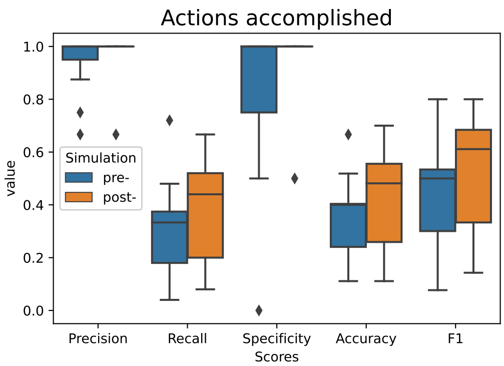
In this scenario, the improvement obtained on the actions taken during the first four minutes is perceived but significance is not shown, see Figure 8.3 (a). However, with respect to the minimum actions that should have been accomplished in the hospital setting, a clear improvement is obtained in medians for the recall, accuracy and F1 scores but significance is obtained only for the accuracy score. The median recall score improves from 0.286 to 0.428; the median accuracy score remains the same, which value is 0.643 but, as it can bee perceived in Figure 8.3 (b), significance is obtained and the p-value obtained is of 0.045. Finally, the F1 score improves from 0.444 to 0.545. With respect to all the actions performed along the simulation, Figure 8.3 (c) shows an improvement on the post training simulation, but no statistical significance is obtained between both simulations for any of the scores of the confusion matrix. The precision and the specificity scores do not show any change in medians but, the data dispersion is low in the post-training simulations. For the rest of the scores, the median values vary from 0.333 to 0.44 for the recall value, from 0.4 to 0.482 for the accuracy score and from 0.5 to 0.611 for the F1 score; being the highest increase related to the recall median value. With respect to the global alignment score which considers the complete sequence of actions accomplished, its median value is better pre-training than post-training even though, in both cases, their score is a negative value; pre-training is -0.028 and pos-training is -0.12. Nevertheless, with respect to the diagonal score, Figure 8.3 (e) shows an improvement in median of its value, from 0.048 to 0.052. Finally, the subsequences score also improves in median, from 0 on the pre-training simulations to 0.125 on the post-training; even though no statistical significance is obtained.



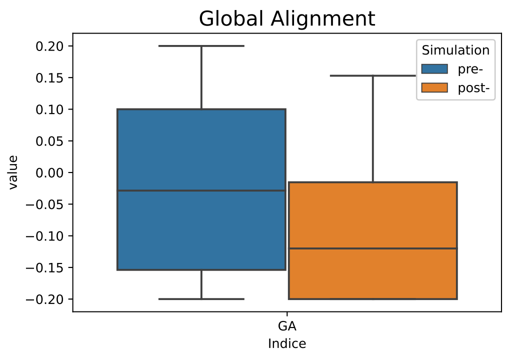
(a)



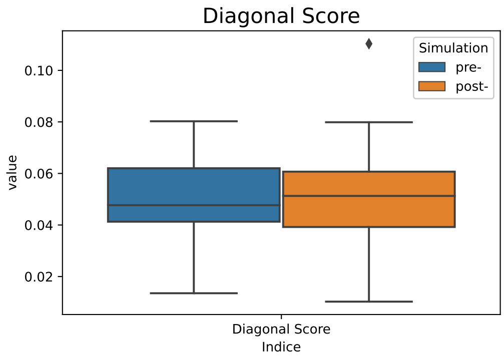
(b)



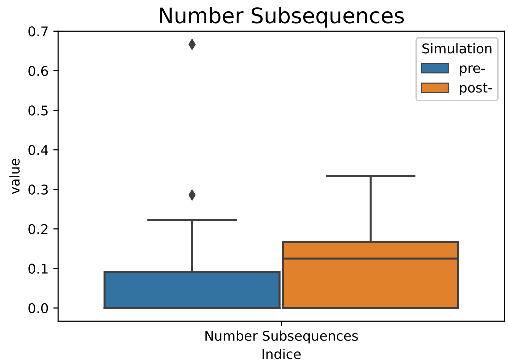
(c)



(d)



(e)



(f)

Figure 8.3: Scores obtained from the pre- and post-training simulations: (a) shows the analysis on the actions that should have been performed during the first four minutes; (b) the minimum actions that should have been taken along the simulations; (c) analysis of all the actions taken along the whole simulation; (d) the global alignment scores; (e) the diagonal score and; (f) the subsequences score.

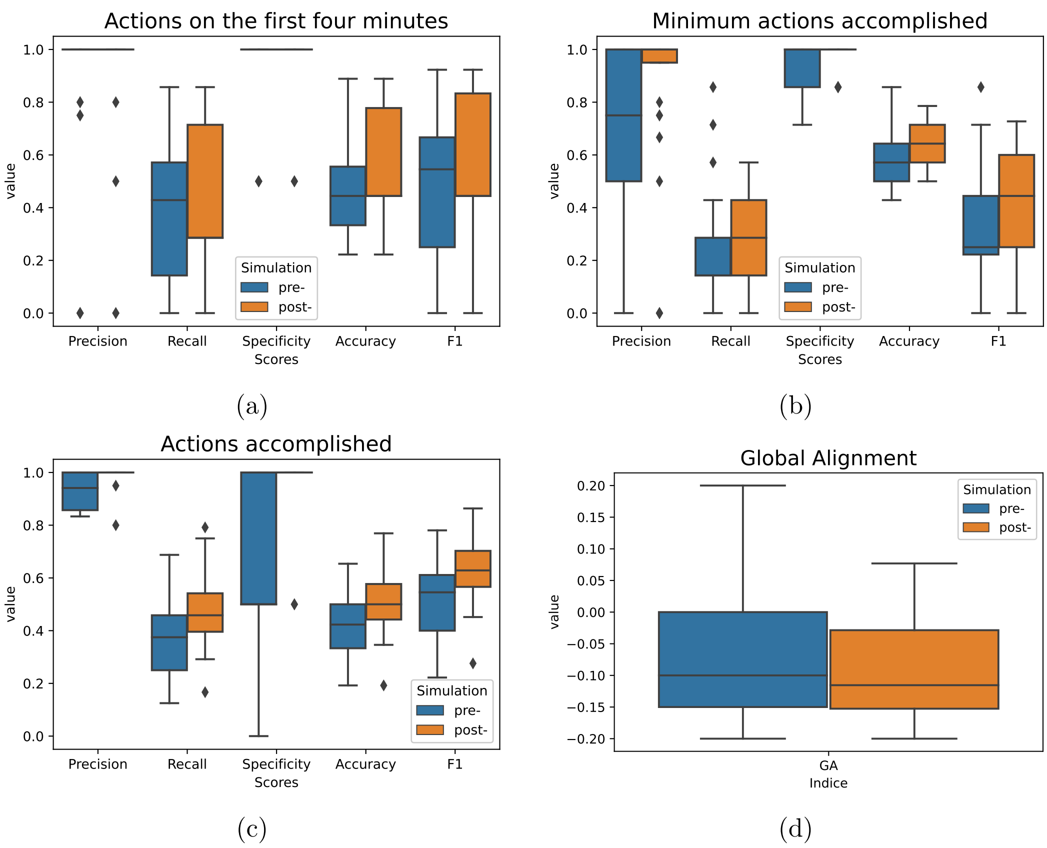
Then, the overall score as per Equation 7.1 was calculated for the hospital pelvic trauma scenarios. The average scores shown in Table 8.2 improve post-training, which shows an overall improvement on managing this trauma scenario by using the WBTS developed.

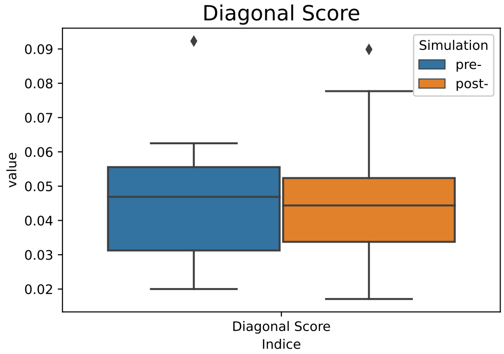
	Mean	**Standar Deviation**
Pre-training	2.97	0.80
Post-training	3.08	0.75

Table 8.2: Trauma management overall score obtained in pre-training and post-training simulations.

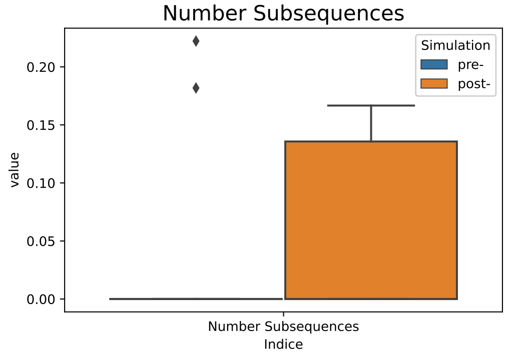
8.2.3 Prehospital Lower Limb Trauma Management

For the lower limb trauma management scenarios, the actions taken on the first four minutes and the actions that should be taken as minimum actions are the same in the prehospital and the hospital settings. Therefore, only a separate analysis would be presented for the analysis of all the actions taken along the simulations. Figure 8.4 (a) shows the improvement obtained after the 2-weeks training period on the actions that should be performed in the first four minutes for a lower limb trauma management. All scores improve in median but none of them show statistical significance. In Figure 8.4 (b), the analysis of the minimum actions that should have been accomplished is shown. In this case, all the scores improve showing significance in all of them except for the recall score. The median of the precision score improves from 0.75 to 1; the median value of the recall score, changes from 0.143 to 0.286; the median value of the specificity score remains the same; whereas from the accuracy and F1, their median values change from 0.571 to 0.643 and from 0.25 to 0.444 respectively. When analyzing all the actions performed during the simulation, the actions taken in the prehospital setting are different from the ones in the hospital one. Figure 8.4 (c) shows an improvement in all the scores of the confusion matrix on the post-training simulation showing significance only for the specificity score which median value increases from 0.5 to 1, obtaining a p-value of 0.013. With respect to the global alignment score shown in Figure 8.4 (d), the score remains practically the same having a median value slightly lower in the post-training simulations. The post-training median value obtained is -0.115 compared whereas the pre-training median value of -0.11. Nevertheless, both median values, pre-and post-training simulations are negative which means that the sequence of actions accomplished is different from the sequence that should have been performed. With respect to the diagonal score, the post-training simulations have a lower value in median than the pre-training simulations but the range of values of this score decreases as shown in Figure 8.4 (e). Finally, with respect to the subsequences score there is a clear improvement on the post-training simulations, see Figure 8.4 (f), but no statistical significance is obtained.





(e)



(f)

Figure 8.4: Scores obtained from the pre- and post-training simulations: (a) shows the analysis on the actions that should have been performed during the first four minutes; (b) the minimum actions that should have been taken along the simulations; (c) analysis of all the actions taken along the whole simulation; (d) the global alignment scores; (e) the diagonal score and; (f) the subsequences score.

Once all the individual scores are calculated, the overall score as per Equation 7.1 was calculated. For the prehospital lower limb trauma management, the average scores shown in Table 8.3 improve post-training which shows, again, an overall improvement on managing this trauma scenario by using the WBTS developed.

	Mean	**Standar Deviation**
Pre-training	2.89	0.54
Post-training	3.11	0.56

Table 8.3: Trauma management overall score obtained in pre-training and post-training simulations.

8.2.4 Hospital Lower Limb Trauma Management

The actions performed during the first four minutes and the minimum actions accomplished to manage a lower limb trauma scenario in a hospital setting, in our scenarios, are the same than the ones taken for the prehospital setting. Therefore, the results presented here focus on analyzing all the actions taken during the whole simulation.

With respect to hospital lower limb trauma scenarios, an improvement is also obtained in all the scores as shown in Figure 8.5 (a), showing significance on the accuracy and specificity scores. The medians of the recall, accuracy and F1 increase whereas the precision and specificity median scores remain equal. The improvements obtained are the median value for the recall score which improves from 0.346 to 0.52 obtaining a p-value of 0.051, close to statistical significance. The accuracy score median value changes from 0.357 on pre-training simulations to 0.56 on post-training simulations. And, finally, the median value of the F1 score improves from 0.498 to 0.683. With respect to the global alignment score shown in Figure 8.5 (b), a clear improvement is perceived pre- and post-training, showing statistical significance

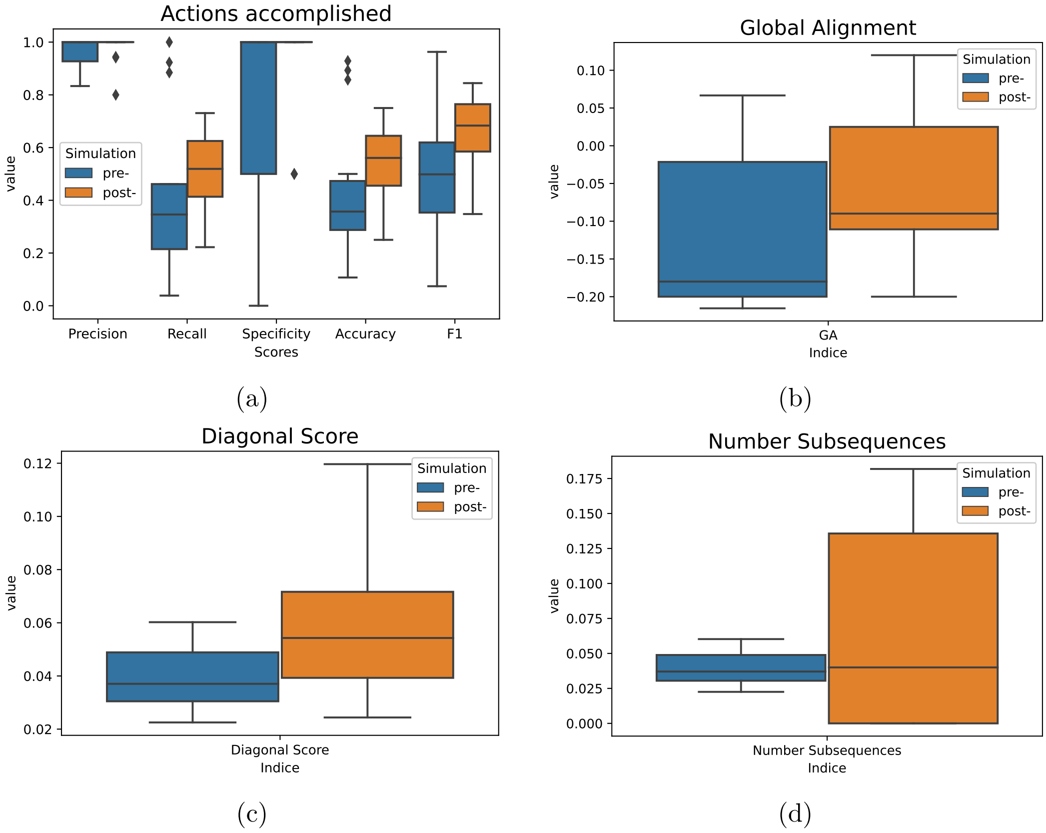


Figure 8.5: Scores obtained from the pre- and post-training simulations: (a) analysis of all the actions taken along the whole simulation; (b) the global alignment scores; (c) the diagonal score and; (d) the subsequences score.

with a p-value of 0.025. The diagonal score, see Figure 8.5 (c), shows also a clear improvement in post-training simulations, obtaining statistical significance with a p-value of 0.03 with a change in median value from 0.037 on pre-training simulations to 0.054 on post-training. Finally, with respect to the subsequences score, Figure 8.5 (d) there is also an improvement on the post-training simulations but, in this case, no statistical significance is obtained.

Then, the overall score as per Equation 7.1 was calculated. For the hospital lower limb trauma management, the average scores shown in Table 8.4 improve post-training which shows an overall improvement on managing this trauma scenario by using the WBTS developed showing statistical significance with a p-value of 0.00693.

	Mean	Standar Deviation
Pre-training	2.69	0.55
Post-training	3.26	0.53

Table 8.4: Trauma management overall score obtained in pre-training and post-training simulations.

8.3 Discussion

From all the actions taken in all the simulations, an improvement is perceived showing a more homogeneous response to trauma lesions after training with the WBTS. This is important, as the implementation of trauma management algorithms has increased to provide a quick and systematic treatment to patients (Quick, 2018; Biffl et al., 2001; Baker et al., 2020; Wurmb et al., 2008) and this simulator would contribute to that goal. More specifically from the three new scores proposed, improvements are more clearly seen in the diagonal and subsequences scores than in the global alignment one. This could be due to the fact that, in the diagonal and subsequences scores a unique aspect is considered. In the diagonal score, the correct order of the actions is analyzed and in the subsequence score the number of right subsequences and their length is studied. Nonetheless, in the global alignment score, several aspects are considered. This score provides an additional information that could be offered to the trainee as real-time feedback to further improve on the actions to accomplish, when and in which order. It is interesting to see that, in the case of a hospital pelvic trauma, even though the diagonal score increases, which means that more actions are correctly done in the right moment, the global alignment score decreases. This is due to the fact that, even though the right actions and the right moment improve, there is still an important number of mismatches, gaps or contrary actions. It is paramount to highlight that these actions: mismatches, gaps or contrary actions have a negative score value within the global alignment score. Therefore, obtaining a negative global alignment score provides information about the balance between positive actions, matches and equivalent actions performed, and negative actions, contrary actions, mismatches and gaps. It is true that, in the Needleman-Wunsch literature, different scoring values are provided to the match, mismatch and gap penalty but there are no guidelines that provide advice on the criteria to use (Aspland et al., 2021). In general, negative values of the global alignment score mean that the two sequences are different and positive values mean that they are alike. Moreover, including different scores for matches, swaps, gaps, contrary actions and mismatches within the global alignment score provides a really comprehensive information for trauma management. Additionally, it is important to include this information into the web-based simulator. This will provide real-time information to the trainee with respect to his or her performance, highlighting the errors and suggesting what should be done. Having that information integrated into the simulator will support the learning rate of trauma protocols. The diagonal and subsequences scores would provide information not included within the global alignment score, providing a comprehensive set of metrics to evaluate how well a simulation is performed considering a predefined trauma clinical guideline.

With respect to prehospital pelvic trauma management, a clear improvement is shown specially on the actions taken on the first four minutes and on the total actions performed along the whole simulation. The first four minutes are key due to the fact that an important number of trauma patients die during the first minutes after the injury (Lansink et al., 2013; Gunst et al., 2010; Valdez et al., 2016; Saberinia and Kashani, 2019). Improving significantly the recall and the F1 scores means that trainees are improving on taking correct actions on the treatment. When analyzing all the actions, the recall, accuracy and F1 scores show significance. This means that, additionally to the improvement on correct actions, also the actions that should not be taken are correctly managed. Therefore, training with the WBTS developed has a positive improvement not only on treating patients with correct actions but also avoiding treating the patients with actions that do not have a positive impact on their evolution. Considering the rest of scores, there is an improvement on the diagonal and subsequence scores which shows that the trainee is performing better in the post-training simulation. Nevertheless, there is not statistical significance. Additionally, the global alignment score is not improving.

When managing a pelvic trauma scenario on a hospital setting, the pre- and post-training improvement is observed but almost no statistical difference is shown. The main improvements are similar to the ones on the prehospital trauma management: on the correct actions to take and avoiding actions that do not support patient recovery. With respect to the global alignment, diagonal and subsequences scores, this improvement is not so clear as not only the global alignment worsens but also the improvement of the diagonal score is almost imperceptible. Nevertheless, the subsequences score improves but not statistical significance is obtained. When analyzing these simulations with trauma experts, an improvement on the performance is perceived but, having all the information provided by these new metrics supports the trauma teaching process. This allows to gain awareness in which are the areas that should be further strengthened to enhance trauma management protocols learning.

On the lower limb trauma management, for the prehospital and hospital settings, the improvements are the same as the actions to take are not different on the first four minutes and on the minimum actions to take. All the scores show significance for the minimum actions to accomplish along the simulation except for the recall score. Additionally, the actions taken on the first four minutes also improve. Therefore, training with the WBTS has a positive statistically significance improvement in all scores allowing trainees to treat patients in a more efficient and effective manner. When the whole trauma scenario is analyzed for the prehospital lower limb scenario, the improvement is seen on the correct actions taken and on the avoidance of actions with a negative impact on the virtual patient. Therefore, the WBTS also supports improvement for this trauma scenario on the prehospital settings. With respect to the global alignment and diagonal scores, both decrease whereas the subsequences score slightly improves which contrast with the clear improvement on the hospital lower limb trauma scenario. In this scenario, the improvement is statistically significant for the global alignment and diagonal scores, p-values of 0.014 and 0.03 respectively. This is the only trauma scenario in which a statistical difference is perceived for the global alignment and diagonal scores. This means that hospital management for lower limb injuries is better learnt whereas the prehospital setting might be reinforced.

Finally, with respect to the global score proposed as an automated evaluation, it is perceived that, in all trauma scenarios this score improves post-training, showing statistically significance only for the hospital lower limb trauma scenario. In general, the overall score obtained is below 5 which means that there is still improvement to be done in trauma management learning amongst medical students and residents.

PART III

Conclusions

9 Conclusions and Future Works

This Chapter summarizes and concludes this Thesis. This Chapter is divided in three sections. Section 9.1 presents an overview of the developments, improvements and results obtained within the hypotheses and objectives proposed in the present Thesis. Section 9.2 shows some proposals of future research lines for this Thesis. Finally, Section 9.3 summarizes the main contributions of the author over the course of fulfilling this dissertation.

9.1 Conclusions

The main conclusion that is obtained from any PhD work results from the acceptance or rejection of its research hypotheses. Following the hypotheses defined in Chapter 2, their validity is evaluated considering the results obtained within the development of this Thesis.

H1. An objective evaluation system can be designed and implemented to measure trauma management knowledge acquisition.

Hypothesis confirmed.

An evaluation system to measure trauma management learning has been designed and implemented within this Thesis. This allows to analyze the trauma management knowledge acquired after a specific trauma training. The analysis has been performed on an experimental test in which an automatic evaluation was successfully accomplished. The main conclusion is that, the learning process of trauma management protocols improves for all the trauma scenarios defined. Additionally, a comprehensive analysis is obtained, providing more information on the improvements achieved and on the areas to further improve.

- *Actions taken on the first four minutes:* The actions taken on the first four minutes are clearly improved with the training developed; therefore, an impact on immediate deaths management might be expected when these knowledges are transferred to real cases management.

- *The minimum actions to take:* The minimum actions to take in a trauma management scenario also improve for all trauma management scenarios. Therefore, actions that must be accomplished in any case are easily learnt with the simulator developed.

- *The global alignment:* With respect to this score, which provides a quite comprehensive information, a clear improvement is not achieved. Therefore, this has to be addressed to improve the balance of correct and incorrect actions performed along the simulation.

- *The diagonal score:* Considering the correct order of the actions taken generally improves when using the simulator developed. Nevertheless, this improvement does not show statistical significance in any case. This has to be further improved.
- *The subsequences score:* Having in mind that some actions have to be taken in a specific order. This has been analyzed and an improvement is perceived in all cases, but still the number of correct subsequences is small.

Therefore, this shows that it is possible to automatically incorporate this evaluation system to obtain information about the knowledge acquisition and that, there are still improvements to consider to improve all the trauma management key aspects. To have all this information within a simulator supports both, the need to improve trauma management trainings and the need to incorporate an evaluation system.

H2. A clinical simulator modality that allows to incorporate trauma management protocols and the evaluation system defined can be developed. This simulator has to allow gathering all the relevant aspects to analyze how a trauma patient treatment has been done.

Hypothesis confirmed.

In this Thesis, a Web-based Trauma Simulator (WBTS) has been designed and implemented. As several clinical simulation modalities exist, selecting the one that could better support a specific trauma management training is key, because not all the simulation modalities may seem appropriate for all the trainings. Therefore, understanding the advantages and disadvantages of all of them is of great importance. The development of the WBTS is made with the basis to be able to include any trauma scenario in which all the necessary actions to stabilize a patient are included. Additionally, once an action is accomplished, there is an impact on the virtual patient, either on the external circumstances such as giving him/her a thermal blanket or on the vital signs of the patient. This provides realism to the simulation case. All the information generated is gathered into the WBTS database which allows to automatically compare how the simulation was done with the a protocol previously defined. Moreover, this simulator was used on an experimental test in which the need to train medical students is confirmed as well as the general need to provide refreshing trauma trainings regularly. Therefore, this simulation modality incorporates trauma management protocols allowing the access to all the data gathered. Finally, the evaluation system previously defined is integrated into the WBTS developed.

H3. Trauma management protocols which combine general trauma management guidelines together with experts' experience can be defined. A step by step action protocol will make trainees to learn protocols more easily. Additionally, these protocols have to be flexible, to include, if necessary, any changes due to new procedures and/or techniques that may appear.

Hypothesis partially confirmed.

Defining trauma management protocols has been accomplished for four different trauma scenarios. All the different circumstances that may occur in a trauma scenario are taken into consideration. According to trauma experts, these protocols should be revised and updated frequently. Additionally, in this Thesis, new simulation prototypes have been developed to test the protocol learning process with two protocols that have been set for a long time. The main conclusions of this part of the Thesis is that, the real-time information that can be extracted by the simulation modalities is not usually used to measure knowledge acquisition. The experiences with the prototypes developed were necessary to have a live lessons learnt experience. With respect to trauma protocols, they were built considering the general guidelines provided by Advanced Trauma Life Support (ATLS) together with the trauma experts' experience. To better standardize these protocols, an action protocol is proposed in which different options are possible. It is important to highlight that, this Thesis considers trauma management protocols for pelvic and lower limb trauma scenarios. Therefore, different protocols are defined for these two trauma scenarios and for two specific settings: prehospital and hospital. Several possibilities are considered, and therefore, the flexibility that a trauma management protocol should consider is included in the proposal. These protocols are embedded into a simulator developed with the purpose to train trauma management. There is still work under development in order to consider other trauma scenarios.

H4. A set of metrics can be designed and implemented to measure compliance with trauma management protocols. These metrics have to consider all trauma management relevant aspects.

Hypothesis confirmed.

A set of metrics are developed and implemented within this Thesis, allowing to measure compliance with trauma management protocols. It is a novel approach that includes all the relevant aspects to evaluate knowledge acquisition. Some of these metrics come from the confusion matrix; two of them, the subsequences and the diagonal scores have been developed within this Thesis and the global alignment has been based on the Needleman-Wunsch algorithm. This algorithm was modified according to specific trauma management requirements which is not found elsewhere. These requirements are important as the time to stabilize a trauma patient is short and quick actions need to be taken. Therefore, to take actions that are not exactly the ones that should be accomplished will take time, which will not leave enough to counteract. Therefore, new parameters are included within this algorithm to reward actions that are correctly done, that are similar to the ones to accomplish, to punish the actions that are not correctly performed, that have a negative impact on the vital signs of the patient or that are, simply, not done. All these aspects are combined together in the proposed algorithm explained in Chapter 6. These novel trauma management metrics present one of the main outcomes of this Thesis and provides detailed information about how the compliance with the protocols is achieved.

Finally, from the features that the evaluation system must satisfy, as stated in Section 1.2, the following achievements have been accomplished:

- *Objectivity:* the information used to propose the evaluation of the knowledge acquisition is totally objetive. All the information comes directly from the database of the simulator which gathers the actions taken, the moment in time they were taken, the impact that each of them has on the vital signs of the patient and all the details with respect to the trauma scenario and the trainee profile. Therefore, this has been successfully fulfilled.

- *Automatic:* the evaluation is automatically provided after the simulation. From one side, the data is automatically generated and gathered into the database. From the other side, the algorithms are already developed which allow a fast and quick analysis of all the metrics proposed. The final evaluation score is provided within seconds after the algorithms are run.

- *Flexibility:* the evaluation system proposed could be easily modified by introducing new variables or changing any algorithm attribute. The only requirement is to have access to the part of the simulator in which all the metrics are developed.

- *Robustness:* this evaluation system can be integrated in any simulation modality that gathers all the actions performed and when they are done. If the simulation modality is not able to provide that information, this evaluation system can not be automatically integrated but, after analysing all the possible trauma simulation modalities, only standardized patients will not allow this option.

- *Quick deployment:* this evaluation system has been really easy to deploy for the web-based simulator developed. For any other simulation modality, it should be done exactly the same. As perviously mentioned, the important aspect is that it allows to have a register of the actions accomplished along a simulation.

9.2 Future Work

This Thesis has explored and combined two very different fields: the trauma management training simulators and the objective evaluation systems of simulations. For both fields, this Thesis has presented a novel approach that may be further developed. These improvements are listed as follows:

- **Virtual patient interaction.** The current virtual patient developed for the web-based trauma simulator interacts with the trainee in predefined questions. Some actions show an effect on the virtual patient such as a blanket appears when the trainee select that action, but not all of them have this feature included. This should be done for all the actions that may have a visual impact on the patient. Additionally, there are some sounds when the auscultation is done but more sounds should be included so that other illnesses could be treated in parallel to the main trauma scenario set. Similarly, there are four different X-rays implemented and this could be further enlarged. Moreover, a general physical examination could be available by moving the mouse along the patient obtaining information about the health conditions of the patient.

- **Customized training.** There are different profiles that could have access to this simulator: medical students, residents, emergency services personnel, nurses or doctors amongst others. The clinical scenarios could be adapted to the level of knowledge by including several profiles. In fact, the database of the simulator already distinguishes between medical students, residents and doctors; therefore, this could be easily extended to other profiles. The clinical scenarios have to be adapted from the original message shown when the patient arrives to treatment, following with the actions to accomplish as well as the resources available to treat the patient for each different profile. Additionally, even distinctions between residents from different years can be included in order to make the training program more adapted to their needs.

- **Additional tests/information.** The number of additional tests that could be performed to a patient should be increased providing options to include tests such as a computerized axial tomographies or a sonographies. Additionally, results to those tests should be included, providing not only the option to request the test but also the results obtained. This will support the critical and quick thinking needed in trauma management in which fast but firm decisiones need to be taken. Providing more or less complex results to tests will improve the training process on trauma management. With respect to additional information, a new field in which either information is provided with respect to the different trauma severity scores or even a calculator could be included so that the trainee could calculate the score values could be developed. This should be adapted depending on the role and level of knowledge of the trainee.

- **Polytraumas.** When a patient suffers a trauma, he or she might suffer several injuries. Therefore, combined trauma scenarios could be defined. To do so, all the actions needed to accomplish for any trauma should be included. Therefore, tests and resources might be different as well. Additionally, other illnesses could be included into the clinical scenarios in which a patient could additionally suffer diabetes, for example. At the end, including real cases scenarios in which different treatments should be considered in parallel. This is key in order to learn priorities and decision making. Moreover, it integrates knowledge from different areas of expertise.

- **Connection to physical simulators.** The web-based simulator could be connected to physical simulators such as the Cardiopulmonary Resuscitation (CPR) or the hemorrhagic trauma simulator presented in this Thesis. By doing this, an integration of trauma management protocols with practicing technical skills could be achieved. Additionally, the information gathered from the physical simulators could be integrated into the web-based simulator allowing the trainees to see the performance of the technique delivered to the patient. Providing real-time information has been proved to increase knowledge acquisition and therefore, this could be accomplished and easily integrated into the simulator.

- **Interaction with the evaluation system.** The web-based trauma simulator supports and improves the trauma management learning process but, incorporating the information provided by the scores developed in this Thesis into the simulator, will provide more information to the trainee. This could further improve the learning process of the trainee. Additionally, some messages could appear during the simulator to guide the training process of the trainee. This could vary depending on the level of expertise of the trainee. After four minutes, the web-base simulator could incorporate a message with a warning if some of the key actions are not accomplished or the patient could even die. Once the minimum actions are taken, another message could be programmed in which a Well done! message is shown, guiding the simulation considering the results achieved. Moreover, if some actions should be accomplished in order and it is not done, different scenarios should be defined. For example, the patient could die or require a different treatment or even the time to treat the patient decreases as the lifespan of the patient is dramatically reduced.

- **Clinical validation.** The clinical validation should be extended to a larger community and additional feedback on its use should be gathered. This will allow to reinforce the conclusions and contributions made on this Thesis and to analyze a larger amount of data. Obtaining an important amount of data is key to continue with this work and to further develop and customize the simulator to the training needs. Additionally, this will make the simulator alive and open to the clinical staff taking the lead on providing ideas and areas for improvement. Moreover, a lot of global trauma management scores will be generated creating an important score database that will provide a consistent approach to measure trauma management knowledge acquisition.

- **Readjust score values.** This improvement focuses on the global alignment score proposed. The modified Needleman-Wunsch algorithm proposed uses different scores which value has been provided according to practice and the results obtained. If a further clinical validation is made, the value of these scores should be further analyzed to verify if the values provided are the most appropriate ones or if they should be updated. Within the experimental test, some adjustments were done but this could be readjusted after analyzing a larger amount of data.

9.3 Review of Contributions

This dissertation describes original research carried out by the author. Some studies have been done to study different aspects of clinical simulation and evaluation methods used. In this Section, all papers published or accepted for publication by the author (2 journals and 3 conferences), together with a number of co-workers, are explained and linked with this Thesis. The corresponding publications are detailed in the following.

The early work published by the author was in 2019 in the CASEIB Conference (Calpena et al., 2019). This work showed a first hemorrhage module simulator that created, automatically, different type of bleeding injuries. The idea behind this work was to create a module that could be easily integrated into another simulator or even a standardized patient in order to complete trauma scenarios with a realistic module for bleeding injuries. The main contribution was the automation of the module being able to produce bleeding injuries automatically and with a reduced cost. This makes this module unique in the market. Additionally, once the module was created, a new idea was envisioned in order to enrich this concept. Considering the important impact that amputations have in both patients and healthcare institutions, a hemorrhagic lower limb simulator was created. The idea behind this simulator was to support hemorrhagic trauma management by practicing a particular scenario in which different actions could be accomplished. Therefore, the simulator was designed and built. It was published in *Sensors* in May 2021. This paper is entitled *Design and Development of a Hemorrhagic Trauma Simulator for Lower Limbs: a Pilot Study* (Larraga-García et al., 2021b). This paper presents the design of all the components of the lower limb simulator together with some experimental tests accomplished to prove that the simulator is appropriate for teaching and learning hemorrhagic trauma protocols. Additionally, some works related to this simulator have been further performed. These works are related to improvements on the lower limb trauma simulator to be able to practice others techniques such as tourniquet application. Moreover, the simulator includes more than just one injury as, in lower limb lesions, it is common than more than one important vessel is compromised. This makes the simulator more complete and it allows to practice all the techniques to control hemorrhagic lesions. Finally, all the actions are registered and gathered in a database, allowing the integration of an evaluation module.

Additionally, some further works related to the design and development of more trauma simulators have been done. One of them was presented in 2020 in the CASEIB conference and it was related to the electronic control of the simulators developed (Larraga-García et al., 2020). Up to that point, a pelvic trauma simulator was designed together with the lower limb simulation. The idea behind the electronic module developed was to manage and control different trauma scenarios from the same platform. Therefore, a web interface is developed and connected to both simulators allowing a trainer and a trainee interact. This web interface allows a trainer to create trauma scenarios and then, to send that information to the physical simulator so replicate the scenario. Then, when a trainee is dealing with the scenario created, all the data is automatically gathered thanks to the information that all the sensors are registering, according to the trainee performance. The main contributions of this work are, first of all the design of a pelvic simulator in which different pelvic fractures can be generated. Additionally, sensors will measure the pelvic management technique performed by providing information with respect to several aspects: one of them is if a pelvic binder was placed or not. Moreover, if the binder was placed, information with respect to its position and the force applied is provided. Another aspect is to provide information about the movement of the bones after pelvis stabilization. There are currently no physical simulators that provide such information and that supports protocol learning with a practical experience of having a real pelvis fracture simulated. Secondly, a unique electronic design that combined both simulators is created. This allows simplicity and provides a tool with multiple trauma scenarios which makes possible to combine them. This is important as in trauma injuries, more than one lesions are usually suffered by patients. By using this electronic platform, this objetive was accomplished.

Up to that point, some simulators were developed, used and tested gathering information about performance of different protocols, but the whole trauma management process wanted to be addressed. Therefore, these prototypes were considered as learning experiences and as previous steps to the design the web-based trauma simulator presented on this Thesis. In fact, in September 2021, the article *Design and Development of an interactive web-based simulator for Trauma Training: a Pilot*

Study (Larraga-García et al., 2021a) was published in the journal *Medical Systems*. The details of this simulator as well as the new aspects that it proposes are detailed in Chapter 7 of this Thesis. In the meantime, the physical pelvic simulator was developed was presented in the CASEIB conference in 2021, in which a first pilot test was performed (Larraga-García et al., 2021c). Thanks to this work, the design previously defined was tested.

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Appendices

Action Numbers

Action	Action Number
Oxygen mask	7
Cervical collar	8
Thermal blanket	10
Pelvic binder	12
X-rays	16
Airway cleaning	19
Intubation	15
Tourniqute	28
Auscultation	29
Pulse oximeter	30
Oropharingeal cannula	32
Nasal cannula	34
Capnography	35
Bag valve mask	37
Occlusive dressing	38
Thoracentesis	39
Thoracic drainage	40
Vacuum splint	41
Cervical manual control	42
Vacuum mattress	43
Manual pressure	48
Hemostatic agent	49
Peripheral venous line	50
Intraosseous cannulation	51
Digital blood pressure measurement	52
4-led monitoring	53
12-led monitoring	54
Urinary catheterization	62
Nasogastric catheterization	63
Fentanyl 50 mcg	65
Midazolam 2 mg	66
Tranexamic acid 1g	67
Noradrenaline	68
Saline solution 20 ml/Kg in 10 min	69
Saline solution 500ml maintenance	70
Voluven 250 ml	71
SG 5%	72
Anamnesis	78,83,88,93,98,103,108,113,118,126,128
Mechanical ventilation	129
Remove all cloths	130
Massive transfusion protocol	131
Transfer to other specialty	132

Table A.1: All the actions and their corresponding number of action. With respect to anamnesis, as different questions are possible to pose to the patient, all of them are considered under the anamnesis action

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Target Possible Solutions

Target solutions for a prehospital pelvic trauma scenario
7,30,29,19,25,129,35,50,52,53,51,54,12,42,8,130,78,70,69,67,65,66,68,71
7,30,29,19,25,129,35,50,52,53,51,54,12,42,8,130,78,70,69,67,65,66,68,71
37,30,29,19,25,129,35,50,52,53,51,54,12,42,8,130,78,70,69,67,65,66,68,71
50,52,53,51,54,7,30,29,19,25,129,35,70,69,67,65,66,68,71,12,42,8,130,78
50,52,53,51,54,32,30,29,19,25,129,35,70,69,67,65,66,68,71,12,42,8,130,78
50,52,53,51,54,37,30,29,19,25,129,35,70,69,67,65,66,68,71,12,42,8,130,78
7,30,35,19,25,129,29,50,52,53,51,54,12,42,8,130,78,70,69,67,65,66,68,71
32,30,35,19,25,129,29,50,52,53,51,54,12,42,8,130,78,70,69,67,65,66,68,71
37,30,35,19,25,129,29,50,52,53,51,54,12,42,8,130,78,70,69,67,65,66,68,71
50,52,53,51,54,7,30,35,19,25,129,29,70,69,67,65,66,68,71,12,42,8,130,78
50,52,53,51,54,32,30,35,19,25,129,29,70,69,67,65,66,68,71,12,42,8,130,78
50,52,53,51,54,37,30,35,19,25,129,29,70,69,67,65,66,68,71,12,42,8,130,78
7,30,29,19,50,52,51,12,42,8,130,78,70,69,67,65
32,30,29,19,50,52,51,12,42,8,130,78,70,69,67,65
37,30,29,19,50,52,51,12,42,8,130,78,70,69,67,65
50,52,51,7,30,29,19,70,69,67,65,12,42,8,130,78
50,52,51,32,30,29,19,70,69,67,65,12,42,8,130,78
50,52,51,37,30,29,19,70,69,67,65,12,42,8,130,78
7,30,19,29,50,52,51,12,42,8,130,78,70,69,67,65
32,30,19,29,50,52,51,12,42,8,130,78,70,69,67,65
37,30,19,29,50,52,51,12,42,8,130,78,70,69,67,65
50,52,51,7,30,19,29,70,69,67,65,12,42,8,130,78
50,52,51,7,30,19,29,70,69,67,65,12,42,8,130,78
50,52,51,37,30,19,29,70,69,67,65,12,42,8,130,78

Table B.1: Sequences of all the possible target solutions provided by the panel of experts for a prehospital pelvic trauma scenario

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Target solutions for a hospital pelvic trauma scenario
7,30,29,19,25,129,35,50,52,53,51,54,12,42,8,130,78,70,69,67,65,66,68,71,16,132
7,30,29,19,25,129,35,50,52,53,51,54,12,42,8,130,78,70,69,67,65,66,68,71,16,132
37,30,29,19,25,129,35,50,52,53,51,54,12,42,8,130,78,70,69,67,65,66,68,71,16,132
50,52,53,51,54,7,30,29,19,25,129,35,70,69,67,65,66,68,71,12,42,8,130,78,16,132
50,52,53,51,54,32,30,29,19,25,129,35,70,69,67,65,66,68,71,12,42,8,130,78,16,132
50,52,53,51,54,37,30,29,19,25,129,35,70,69,67,65,66,68,71,12,42,8,130,78,16,132
7,30,35,19,25,129,29,50,52,53,51,54,12,42,8,130,78,70,69,67,65,66,68,71,16,132
32,30,35,19,25,129,29,50,52,53,51,54,12,42,8,130,78,70,69,67,65,66,68,71,16,132
37,30,35,19,25,129,29,50,52,53,51,54,12,42,8,130,78,70,69,67,65,66,68,71,16,132
50,52,53,51,54,7,30,35,19,25,129,29,70,69,67,65,66,68,71,12,42,8,130,78,16,132
50,52,53,51,54,32,30,35,19,25,129,29,70,69,67,65,66,68,71,12,42,8,130,78,16,132
50,52,53,51,54,37,30,35,19,25,129,29,70,69,67,65,66,68,71,12,42,8,130,78,16,132
7,30,29,19,50,52,51,12,42,8,130,78,70,69,67,65,16,132
32,30,29,19,50,52,51,12,42,8,130,78,70,69,67,65,16,132
37,30,29,19,50,52,51,12,42,8,130,78,70,69,67,65,16,132
50,52,51,7,30,29,19,70,69,67,65,12,42,8,130,78,16,132
50,52,51,32,30,29,19,70,69,67,65,12,42,8,130,78,16,132
50,52,51,37,30,29,19,70,69,67,65,12,42,8,130,78,16,132
7,30,19,29,50,52,51,12,42,8,130,78,70,69,67,65,16,132
32,30,19,29,50,52,51,12,42,8,130,78,70,69,67,65,16,132
37,30,19,29,50,52,51,12,42,8,130,78,70,69,67,65,16,132
50,52,51,7,30,19,29,70,69,67,65,12,42,8,130,78,16,132
50,52,51,7,30,19,29,70,69,67,65,12,42,8,130,78,16,132
50,52,51,37,30,19,29,70,69,67,65,12,42,8,130,78,16,132

Table B.2: Sequences of all the possible target solutions provided by the panel of experts for a hospital pelvic trauma scenario

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Target solutions for a hospital lower limb trauma scenario
7,29,30,19,25,129,35,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71,16,132
32,29,30,19,25,129,35,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71,16,132
37,29,30,19,25,129,35,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71,16,132
7,30,29,19,25,129,35,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71,16,132
32,30,29,19,25,129,35,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71,16,132
37,30,29,19,25,129,35,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71,16,132
7,29,30,19,25,129,35,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78,16,132
32,29,30,19,25,129,35,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78,16,132
37,29,30,19,25,129,35,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78,16,132
7,30,29,19,25,129,35,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78,16,132
32,30,29,19,25,129,35,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78,16,132
37,30,29,19,25,129,35,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78,16,132
7,35,30,19,25,129,29,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71,16,132
32,35,30,19,25,129,29,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71,16,132
37,35,30,19,25,129,29,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71,16,132
7,30,35,19,25,129,29,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71,16,132
32,30,35,19,25,129,29,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71,16,132
37,30,35,19,25,129,29,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71,16,132
7,35,30,19,25,129,29,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78,16,132
32,35,30,19,25,129,29,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78,16,132
37,35,30,19,25,129,29,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78,16,132
7,30,35,19,25,129,29,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78,16,132
32,30,35,19,25,129,29,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78,16,132
37,30,35,19,25,129,29,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78,16,132
7,29,30,19,50,52,51,48,28,42,130,78,70,69,67,65,16,132
32,29,30,19,50,52,51,48,28,42,130,78,70,69,67,65,16,132
37,29,30,19,50,52,51,48,28,42,130,78,70,69,67,65,16,132
7,30,29,19,50,52,51,48,28,42,130,78,70,69,67,65,16,132
32,30,29,19,50,52,51,48,28,42,130,78,70,69,67,65,16,132
37,30,29,19,50,52,51,48,28,42,130,78,70,69,67,65,16,132
7,29,30,19,50,52,51,48,28,42,130,70,69,67,65,78,16,132
32,29,30,19,50,52,51,48,28,42,130,70,69,67,65,78,16,132
37,29,30,19,50,52,51,48,28,42,130,70,69,67,65,78,16,132
7,30,29,19,50,52,51,48,28,42,130,70,69,67,65,78,16,132
32,30,29,19,50,52,51,48,28,42,130,70,69,67,65,78,16,132
37,30,29,19,50,52,51,48,28,42,130,70,69,67,65,78,16,132
7,30,19,29,50,52,51,48,28,42,130,78,70,69,67,65,16,132
32,30,19,29,50,52,51,48,28,42,130,78,70,69,67,65,16,132
37,30,19,29,50,52,51,48,28,42,130,78,70,69,67,65,16,132
7,30,19,29,50,52,51,48,28,42,130,78,70,69,67,65,16,132
32,30,19,29,50,52,51,48,28,42,130,78,70,69,67,65,16,132
37,30,19,29,50,52,51,48,28,42,130,78,70,69,67,65,16,132
7,30,19,29,50,52,51,48,28,42,130,70,69,67,65,78,16,132
32,30,19,29,50,52,51,48,28,42,130,70,69,67,65,78,16,132
37,30,19,29,50,52,51,48,28,42,130,70,69,67,65,78,16,132
7,30,19,29,50,52,51,48,28,42,130,70,69,67,65,78,16,132
32,30,19,29,50,52,51,48,28,42,130,70,69,67,65,78,16,132
37,30,19,29,50,52,51,48,28,42,130,70,69,67,65,78,16,132

Table B.4: Sequences of all the possible target solutions provided by the panel of experts for a hospital lower limb trauma scenario

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Target solutions for a prehospital lower limb trauma scenario
7,29,30,19,25,129,35,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71
32,29,30,19,25,129,35,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71
37,29,30,19,25,129,35,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71
7,30,29,19,25,129,35,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71
32,30,29,19,25,129,35,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71
37,30,29,19,25,129,35,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71
7,29,30,19,25,129,35,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78
32,29,30,19,25,129,35,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78
37,29,30,19,25,129,35,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78
7,30,29,19,25,129,35,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78
32,30,29,19,25,129,35,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78
37,30,29,19,25,129,35,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78
7,35,30,19,25,129,29,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71
32,35,30,19,25,129,29,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71
37,35,30,19,25,129,29,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71
7,30,35,19,25,129,29,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71
32,30,35,19,25,129,29,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71
37,30,35,19,25,129,29,50,52,53,51,54,48,28,42,130,78,70,69,67,65,66,68,71
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32,35,30,19,25,129,29,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78
37,35,30,19,25,129,29,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78
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32,30,35,19,25,129,29,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78
37,30,35,19,25,129,29,50,52,53,51,54,48,28,42,130,70,69,67,65,66,68,71,78
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32,30,29,19,50,52,51,48,28,42,130,70,69,67,65,78
37,30,29,19,50,52,51,48,28,42,130,70,69,67,65,78
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37,30,19,29,50,52,51,48,28,42,130,78,70,69,67,65
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37,30,19,29,50,52,51,48,28,42,130,78,70,69,67,65
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37,30,19,29,50,52,51,48,28,42,130,70,69,67,65,78
7,30,19,29,50,52,51,48,28,42,130,70,69,67,65,78
32,30,19,29,50,52,51,48,28,42,130,70,69,67,65,78
37,30,19,29,50,52,51,48,28,42,130,70,69,67,65,78

Table B.3: Sequences of all the possible target solutions provided by the panel of experts for a prehospital lower limb trauma scenario

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