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Simulation-based design concept evaluation for ambulance patient compartments

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Abstract

To address the inadequacy of ambulance design standards, the Department of Homeland Security Science and Technology Directorate, the National Institute of Standards and Technology, the National Institute for Occupational Safety and Health, and BMT Designers and Planners have collaborated to develop new design standards for ambulance patient compartments. This paper presents a simulation-based approach to evaluate and guide improving patient compartment designs that conform to developed requirements for better performance and safety of ambulance users. Those requirements address hazards stemming from (1) the inability of providers to remain safely restrained while treating patients, and (2) the musculoskeletal damage from awkward body postures. An initial design was developed through the axiomatic design approach with inputs from stakeholders such as emergency medical service providers and ambulance manufacturers. The design was imported into a human task simulation tool. It was tested for performance to identify areas for further improvements, which resulted in a second design concept. This paper shows how computer simulation was used to evaluate the effectiveness of the two successive design concepts in enabling providers to perform a range of medical care tasks while remaining seated and restrained. We also evaluated the musculoskeletal effect of these designs on the providers. The results showed that using a simulation-based evaluation produced patient compartments that better meet user requirements when compared with traditional designs. This research produced a set of requirements and recommendations that we believe will lead to better design standards and guidelines for the next generation of ambulances.

Keywords

Ambulance, emergency medical service, patient compartment design, design requirements, safety and task performance

1. Introduction

1.1 Background

There are three main types of ambulances in the United States: Type I, Type II, and Type III. Types I and III patient compartments consist of a box mounted on a chassis. Type II ambulances are based on passenger/cargo vans. Minimum design guidelines for all ambulances are currently provided by the General Services Administration and described in the Star-of-Life Ambulance KKK-A-1822F specification.[1] This federal specification covers guidelines for overall design, including physical dimensions, weight, payload, power trains, electrical systems, general lighting, communications, and maximum noise levels. However, it does not provide design guidelines to ensure safety, ergonomics, and efficient emergency medical care in the patient compartment. Some design guidelines are provided by the National Fire Protection Association (NFPA) in its NFPA 1917, *Standard for Automotive Ambulances*.[2] This standard includes requirements for safety belts, seats, noise levels, storage, and ingress/egress doors. However, it does not address the relationship between seating positions and location of controls, equipment, and storage in the compartment. Therefore, compliance with these standards does not necessarily offer protection for the patient compartment occupants.

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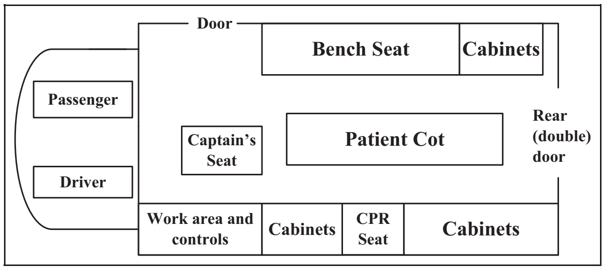


Figure 1. Traditional ambulance layout (Type I/III).

This paper focuses on improvements in the performance and safety for the box-type ambulances that provide both basic and advanced life support services. Figure 1 shows the traditional layout of Type I and Type III ambulances. Although this layout has prevailed for more than 40 years, it does not ensure sufficient safety to either the emergency medical service (EMS) providers or the patient during transit, especially in the case of an accident. Nor does it facilitate efficient emergency medical care. As a consequence, EMS providers work in a hazardous environment that is responsible for numerous musculoskeletal injuries and an alarming number of fatalities.[3]

1.2 Factors affecting safety and performance

To develop design guidelines that would improve safety, it is necessary to identify and examine design factors that contribute to unsafe conditions in current patient compartments. The analysis of these factors will help identify opportunities to control and reduce the prevailing hazards. Ambulances provide both transportation services and medical care simultaneously.[4] This means that while the ambulance is in motion, the EMS providers are attempting to diagnose and treat patients. Based on the layout shown in Figure 1, the EMS providers often have to unbuckle to access and retrieve medical equipment and medication from cabinets or other storage to perform patient care functions. This is the major cause of both accidental and EMS musculoskeletal injuries, and fatalities. The major design factors associated with the traditional design are as follows.

- *Seating and restraints*: the seating arrangement for EMS providers consists of a side-facing bench seat, a rear-facing captain's chair, and a cut-away seat for cardiopulmonary resuscitation (CPR). These seats enable EMS providers to face the patient directly; however, they do not allow the EMS providers to simultaneously remain securely restrained and safely care for the patient.[5,6] It has also been proven that the side-facing orientation exposes EMS providers to greater risks of severe neck injuries in the case of a crash.[7] The bench seats are fitted with lap belts as required by the Federal Motor Vehicle Safety Standards and Regulations.[8] However, these belts are such a hindrance to patient care that up to 87% of respondents in a recent survey indicated that they do not wear them when treating patients.[9] Moreover, lap belts do not offer sufficient protection in the case of an accident.[4] This failure to remain restrained in the ambulance patient compartment has been shown to be the single most risk factor exposing occupants to fatal and incapacitating injuries.[10]
- *Ergonomics*: ergonomics is the discipline concerned with finding ways to keep people safe, comfortable, and efficient at work. EMS providers work in a confined space thereby increasing the risk of musculoskeletal injuries. The most demanding of these tasks include conducting CPR, accessing patients, handling the patient (loading and offloading the ambulance), and accessing equipment.[3] Since the equipment is usually not in close proximity, EMS providers frequently have to bend and stretch to access needed items. In addition, the inadequate leg room forces EMS providers to adopt uncomfortable work postures that can lead to long-term musculoskeletal injuries.
- *Communication*: communication systems enable exchange of information among all occupants of the ambulance and between the ambulance and the rescue scene, dispatcher, or hospital. Radio use is the most common means of external communications. The radio transceiver is usually located at the controls and away from primary care seat and EMS providers have to stand up to reach them. Radio sets tend to disrupt patient care by affecting interaction between the EMS provider and the patient.
- *Workspace, storage, and equipment*: the layout of the patient compartment and availability of sufficient workspace and mobility for the EMS providers has a direct impact on the safety and quality of care.[11] Although standards exist for workspace design and space allocation per person in an office work environment, no similar standards are available for the patient compartment.[12] Moreover, equipment that is not adequately secured can become projectiles and injure EMS providers or patients.

1.3 Potential improvements to the traditional design

There are a number of enhancements that can be made to the traditional layout to improve safety through redesign of the patient compartment. Most of these modifications focus on changes so that EMS providers can perform tasks while seated and restrained. Others include modifications

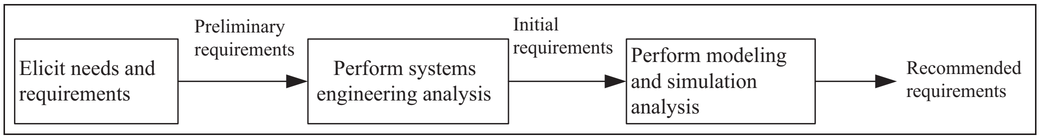


Figure 2. Requirements identification process.

to storage cabinets, equipment locations, seats, and restraints.

Possible modifications are as follows:

- replace lap belts with advanced restraints that lock during sudden deceleration;
- use retractable shoulder straps that stay in place while EMS providers lean forward over the patient;
- use single, movable seats that slide forward towards the patient cot and rotate to access supplies;
- position cabinets with vital supplies and medicines closer to the seated EMS provider;
- locate medical and communications equipment within reach of a seated EMS provider;
- relocate the rear-facing captain's seat to improve patient access while seated and restrained;
- use secure docking ports and/or straps to secure equipment in the case of a crash;
- store extra oxygen tanks externally;
- install turn-signal and brake-lighting indicators in the patient compartment to warn EMS providers of changes in direction and braking.

An example of a design that incorporates some of the above modifications was developed by the Fire Rescue Department City of Winter Park.[13] The Winter Park design incorporates a sliding seat with a fixed five-point restraint system. The design also includes angled curbside storage cabinets fore and aft of the seat for easier access of the stored items. This modification makes commonly used items, such as the radio and electrocardiogram (EKG), easier to reach for a seated EMS provider.

1.4 Obtaining new design requirements

The research of this paper geared to developing better designs began with needs and requirements elicitation, which included a literature review, meetings with subject matter experts, a workshop, task analysis, and a web-based survey.[9,14–16] Many requirements were obtained by analyzing inputs from stakeholders including EMS providers, manufacturers, and service organizations. The EMS providers recommended a preliminary set of needs for the functions and facilities needed to perform patient care tasks safely and effectively. Some of their recommendations were valuable, some were infeasible, and some were conflicting. We used a systems engineering approach to refine their recommendations into a consistent set of requirements that could be analyzed further using a tradeoff analysis.[17] Figure 2 shows the requirements gathering and analysis process. This paper is mainly focused on the last step in the process, that is, a tradeoff analysis through modeling and simulation (M&S) analysis.

1.5 Simulation role

A simulation is a model of a system developed to imitate the behavior of the system under given conditions. Simulation impacts the design of sophisticated products such as aircrafts, training of personnel, and evaluation. Simulation-based design is used to test and select alternatives based on some criteria. M&S methods are an important part of systems development process, to evaluate and make appropriate modifications and corrections to the designs.[18]

We used M&S to evaluate patient compartment designs against the design requirements. To create a simulation model, a three-dimensional (3D) computer-aided design (CAD) model of the patient compartment was imported into a human task simulation tool. The importation created a virtual reality environment of the dynamic interactions between EMS providers, the patient, and the compartment.[19] We then created and manipulated a virtual 3D mannequin to investigate positioning, workflow, accessibility, comfort, visibility, reaching, grasping, ingress, egress, and lifting capabilities. The design was evaluated by comparing simulation results against the requirements and, initially, it demonstrated improvements over the traditional design. Feedback from the evaluation was used to modify the design or the requirements. This process continued until there was alignment between the requirements and the ambulance performance. Figure 3 illustrates this iterative process.

The rest of the paper is structured as follows. Section 2 presents related research. Section 3 describes using the requirements to develop a design concept that adheres to the requirements. Section 4 describes the procedure for using M&S methods to predict and evaluate the safety and performance of the design concept. Section 5 identifies the issues that arose from the evaluation of the two successive design concepts. Section 6 presents the results of musculoskeletal analysis. Section 7 concludes the paper.

2. Related and current work

We review previous research in the context of the current project issues addressed in this paper.

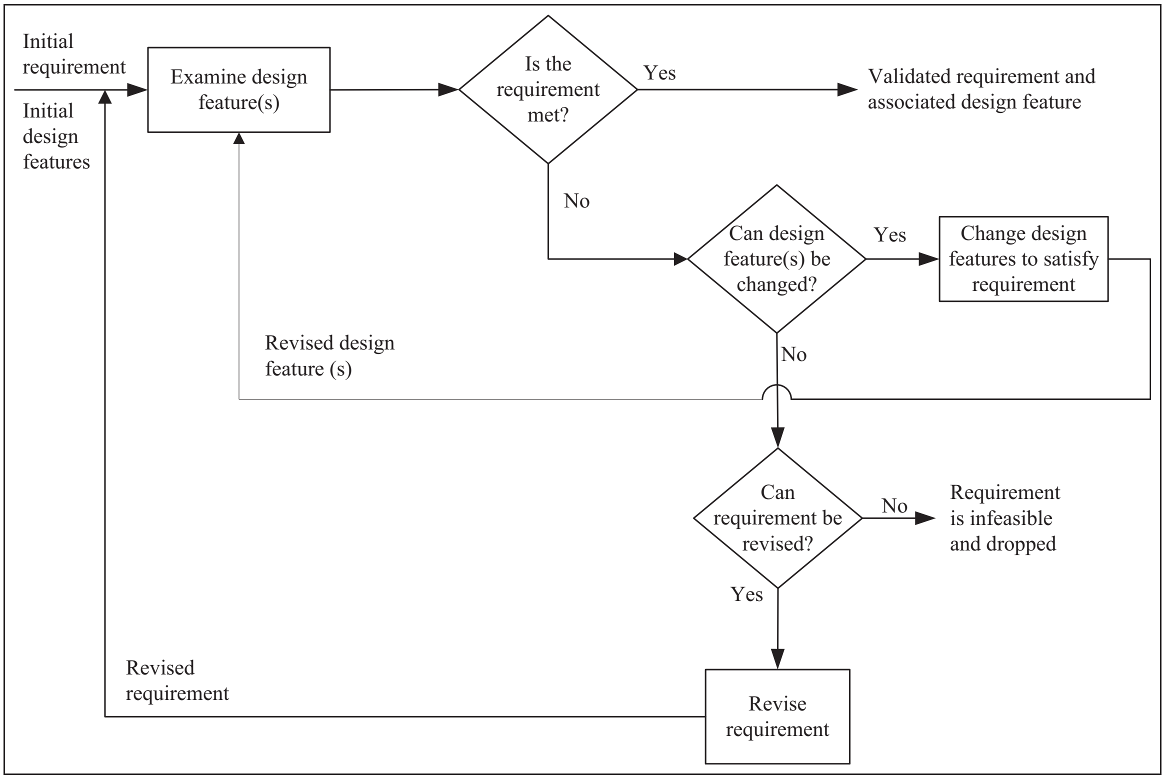


Figure 3. Revision process for a design concept and requirements.

2.1 Background

A number of early studies have shown that EMS providers are frequently injured on the job.[10,20] Reported ambulance crashes in the United States result in more than 2000 injuries every year.[21] They also result in a fatality every 10 days. The total cost of these injuries is more than US$500 million annually.[22] The design and layout of the patient compartment is the major reason for these high numbers. According to Dr Levick, an expert in EMS safety, this is not too surprising since experts in safety engineering, vehicle design, and occupant protection are seldom part of the ambulance design process.[23] Moreover, automotive-industry safety enhancements have not fully made their way into ambulances. We review previous research efforts.

2.2 Previous design improvements research

Most of the relevant research in compartment design started less than 10 years ago. Ferreira and Hignett[24] used link analysis to investigate reaching, accessing, and performing various ambulance tasks. Link analysis is a technique used to evaluate relationships between nodes in a network. In ambulance design, nodes are locations of EMS providers, patients, or items needed for treatment. Links are then the connections between these nodes and it is these relationships that were observed during emergency medical care study. Firstly, they identified the most frequently performed tasks. These are (1) checking blood oxygen saturation, (2) administering oxygen, (3) monitoring the heart, and (4) checking blood pressure. The link analysis showed that EMS providers could reach most of the patient's body if they were to be seated alongside the cot. In this same paper, the authors show that 40% of the working postures were unhealthy and required correction. Other researchers focused on specific factors that might improve safety. The specific factors include restraints[25] and access/egress.[26] There is also formulating the compartment layout problem as a Mixed Integer Programming model for optimizing the placement of equipment, supplies, and furniture. The solution from this model resulted in a grid to locate the necessary materials used for patient care.[27] Another research used data and criteria from health workers to develop an optimization model for a solution where all the medical materials and equipment were located for performing the more critical and frequent operations in the shortest possible time.[28] These research-based improvements fall short of providing comprehensive guidelines that can be more universally adopted by the ambulance manufacturers and EMS organizations.

2.3 Design concept and simulation evaluations

Noting the lack of sufficient previous research to address patient compartment designs, our research was focused on developing new comprehensive design requirements. An analysis of the requirements can be the basis for functional and physical definitions for the ambulance design.[29] It was Gilad and Bryan[30] that proposed M&S as a valuable tool to investigate layout, safety, performance, and ergonomics for a systems view of the ambulance for overall optimal performance. Our design and evaluation approach followed three major steps. The first step was synthesizing the requirements into design needs and criteria. The second was developing the design concepts. The last step was M&S methods for evaluating the design concept with respect to performance and ergonomic safety.

2.3.1 Design needs, requirements, and criteria. Design needs are the high-level patient care performance and EMS provider/patient safety goals. The design requirements are the functions, capabilities, or supports that satisfy the need. Design requirements were obtained by decomposing the design needs. An example of a design need is ''The EMS provider is able to provide safe and effective patient care while in a restrained position within the ambulance patient compartment.'' Corresponding to this need, one of the design requirements is ''The EMS provider is able to quickly move in and out of being in a restraint system (includes all restraints and seat belts).'' A design criterion defines specific elements of restraint design and installation that will support the fulfillment of this design requirement. Typically, there are several design requirements per design need and, in turn, several criteria per requirement, with each criterion addressing a specific element of the requirement.

2.3.2 Design approach. The design process followed an axiomatic approach where customer needs are transformed into design requirements and design criteria.[31] The criteria in turn are the basis for the product specifications. Axiomatic design defines a sequence of design-related activities to be followed in four domains.[32] These are customer, functional, physical, and process.

The customers are the ambulance stakeholders, particularly the EMS providers, who were the main source of the design needs. The major factors affecting performance and safety, as described in Section 1, are seating and restraints, ergonomics, communication, storage, and workspace and equipment. The physical domain is represented by the design features of the ambulance specified to address issues concerned with the factors that affect performance and safety. Lastly, ''process'' refers to the design process, which was executed by a design team brainstorming sessions with additional inputs and evaluations from the ambulance users' community.

2.3.3 Performance evaluation. The design concepts of the patient compartment were represented as iconic CAD models to analyze and simulate behavior.[31] Models are a means of evaluating designs before prototypes of products are constructed. Models fall into three categories: iconic, analog, and symbolic models. Different layout options, items placement, tasks, restraint systems, and human reach and performance can be evaluated with simulation using the CAD models.

An example of simulation application for ambulance patient compartment analysis was conducted by the National Institute of Occupational Safety and Health (NIOSH) for evaluating the reach envelopes of EMS providers when working in two differently designed ambulance patient compartments.[4] One design was the traditional design (shown in Figure 1) and the other was the Winter Park design.[13] Using both male and female mannequins to represent the expected range of users, the results showed that EMS providers could reach more target points on the patient and equipment from a seated and restrained position when working in the Winter Park ambulance design as compared with the traditional ambulance. Although simulation modeling showed that the Winter Park design enhanced safety, some equipment such as suction units were still hard to reach from a seated position and the primary care seat was still in the unsafe side-facing orientation. As exemplified by the Winter Park and other designs, standards that address all relevant safety factors regarding the patient compartment are still needed.

2.3.4 Ergonomic evaluations. Performing physically demanding activities stresses the back, knees, shoulders, and upper body. The tasks associated with such work and the workspace should be designed to take into account human capabilities and limitations. The goal of ergonomics is to fit the task to the human and reduce risk related to musculoskeletal, cumulative trauma, or repetitive strain injuries. Some design requirements that were obtained point to a minimization of the back strain on the EMS providers' musculoskeletal system by, for example, the adoption of seats that are adjustable in height to optimize user comfort and performance. A number of methods and tools have been devised to evaluate ergonomic impact of the work environment. Using these methods, Gilad and Bryan[30] performed ergonomic evaluation of the interior of the traditional design ambulance and found it to be unsatisfactory to both providers and patient.

We brief the tools that we used in ergonomic evaluation for this paper: lower back analysis tool, NIOSH Lifting Analysis tool and the rapid upper limb analysis (RULA) tool. These tools are provided with the human task simulation software.

The lower back analysis tool is purposed to evaluate the spinal forces acting on a virtual human's lower back. This tool enables the following:

- determining whether workplace tasks and postures expose workers to an increased risk of low back injury;

Table 1. Design needs.

Factor	Design needs
Seating and restraints	• The EMS provider is able to provide safe and effective patient care from a seated position in the ambulance patient compartment. • The EMS provider is able to provide safe and effective patient care while in a restrained position within the ambulance patient compartment. • Patient compartments are able to accommodate more than one EMS provider or passenger.
Workspace	• Workspace supports the ability of the EMS provider to safely and effectively perform patient care. • Ambulance needs to be easily maintainable. • Improved means of sanitizing/cleaning interior compartment surfaces. • If required by state or other regulations, the ambulance is able to transport a second back-boarded patient.
Storage	• Storage supports the EMS provider to safely and effectively perform patient care. • EMS providers need the ability to perform inventory management. • Ability to stow patient's equipment/belongings.
Equipment	• Cots and cot locking mechanisms are designed to allow the EMS provider to safely and effectively treat the patient. • Equipment is designed to allow the EMS provider to safely and effectively treat the patient. • Equipment and patient compartment design allows EMS providers to safely and readily access secured first-in supply kits while providing patient care.
Communication	• Ability to communicate efficiently and effectively between the patient compartment, the driver, and others. • Driver awareness of activity in the patient compartment. • EMS provider awareness of driver actions.
Ingress and egress	• Ability to quickly and safely ingress/egress the ambulance patient compartment.
Other	• Interior patient compartment allows EMS providers to safely and effectively treat patients. • The patient compartment includes safety measures to reduce hazard risks. • Provide sufficient sharps and trash disposal.

EMS: emergency medical service.

- evaluating jobs in real-time, flagging the exact moments when the compression forces on a worker's low back exceed NIOSH limits; and
- estimating low back compression, and anterior/posterior shear and lateral shear.

The NIOSH Lifting Analysis tool[33] helps evaluating lifting tasks. The tool provides:

- the expected weight or load, under given postural conditions, that most healthy workers could safely lift over a substantial period of time; and
- a relative estimate of the level of physical stress associated with a manual lifting task or a job involving multiple lifting tasks.

RULA is a postural targeting method for estimating the risks of work-related upper limb disorders. RULA was developed through the evaluation of the postures adopted, forces required, and muscle actions operators working in manufacturing and other tasks.[34] There are risks of upper limb disorders present in such work environments. For a given manual task, RULA does the following:

- assesses the risk of upper limb disorders based on posture, muscle use, the weight of loads, task duration, and frequency; and
- assigns the evaluated task a score that indicates the degree of intervention required to reduce the risk of an upper limb injury.

3. Developing a patient compartment design concept

To develop an initial design concept, we first identified design needs through a process described in Section 1.2. They are listed in Table 1. The design requirements were obtained from the design needs.[35] The requirements impact the following identified design categories: seating and restraints, storage, ingress and egress, workspace, equipment, and communications. Table 2 lists a sample of the requirements in each category.

3.1 Key design requirements and assumptions

Three key design requirements were identified as follows:

- the EMS provider shall be able to *reach the patient's body* from head to knee while in a seated and restrained position;

Table 2. A sample of the initial set of design requirements.

Category	Requirements
Seating and restraints	• The EMS provider is able to reach the patient's body from head to knee while in a seated position. • The EMS provider is able to face and interact with the patient while in a seated and restrained position.
Workspace	• Oxygen port placement allows for the EMS provider to readily access and use oxygen for patient care while not introducing risks to the safety of the patient or EMS provider. • There are no head strike obstacles when the EMS provider is in a restrained position.
Storage	• Storage compartments provide adequate storage space for all required equipment and supplies. • Interior storage cabinets, shelves, and/or drawers are accessible while standing.
Equipment	• The cot patient restraints do not hinder the ability of the EMS provider to provide safe and effective patient care. • Placement of equipment that requires EMS provider interaction shall allow EMS providers to complete this interaction while seated and restrained.
Communication	• Communication systems, when in use, allow the EMS provider to continue providing safe and effective patient care.
Ingress and egress	• Doors do not intrude on an EMS provider's workspace and are not a potential striking hazard.

EMS: emergency medical service.

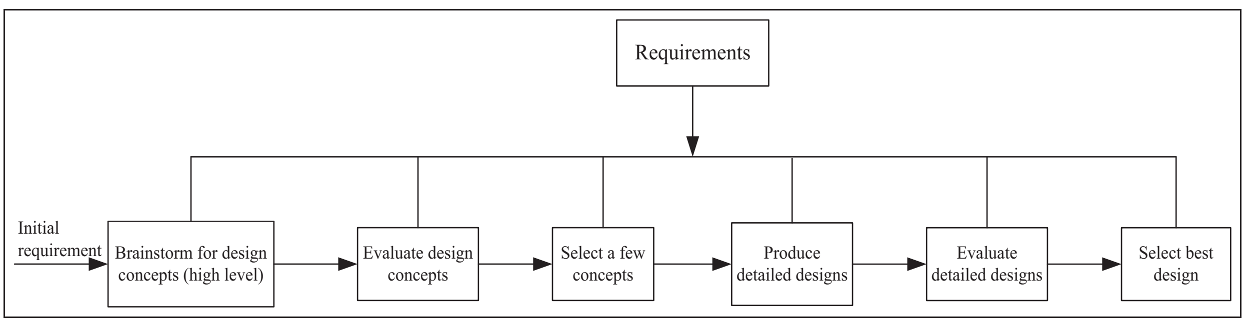


Figure 4. The design concept development process.

- the EMS provider shall be able to *reach common and critical equipment/supplies* from a seated and restrained position;
- the EMS provider shall be able to *face and interact with the patient* while in a seated and restrained position.

In addition, we made several assumptions so as to eliminate constraints that are imposed by some requirements. The assumptions are as follows:

- immediate care supplies and equipment are carried in either a "First-In Kit,""jump bag," or "airway bag" (depending on the type of service needed), which is filled and brought with the ambulance while responding to a rescue call;
- the patient compartment dimensions are: 239 cm (94 in) wide, 356 cm (140 in) long, and 193 cm (76 in) high;
- all equipment specified is currently available on the market;
- intubation must be performed with the EMS provider above the patient's head;
- CPR and intubation will be performed unrestrained while the ambulance vehicle is stationary;
- design does not necessarily address crash worthiness other than to the extent that equipment is secured;
- the ambulance carries a single patient.

3.2 Developing design concepts

Using key design requirements, the research team brainstormed, reviewed, and refined design ideas in an iterative process. During this process, tradeoffs are performed to determine the ideal implementation of the guidelines, and to reduce the number of concepts to one. Figure 4 is a simplified illustration of the process. To smoothen the process, a facilitator was selected to guide the discussions.

The design process started at a high level, with basic concepts such as general layout, size of cabinets, and location of major equipment such as the monitor. A number of ideas were developed, including side entrance of the cot and

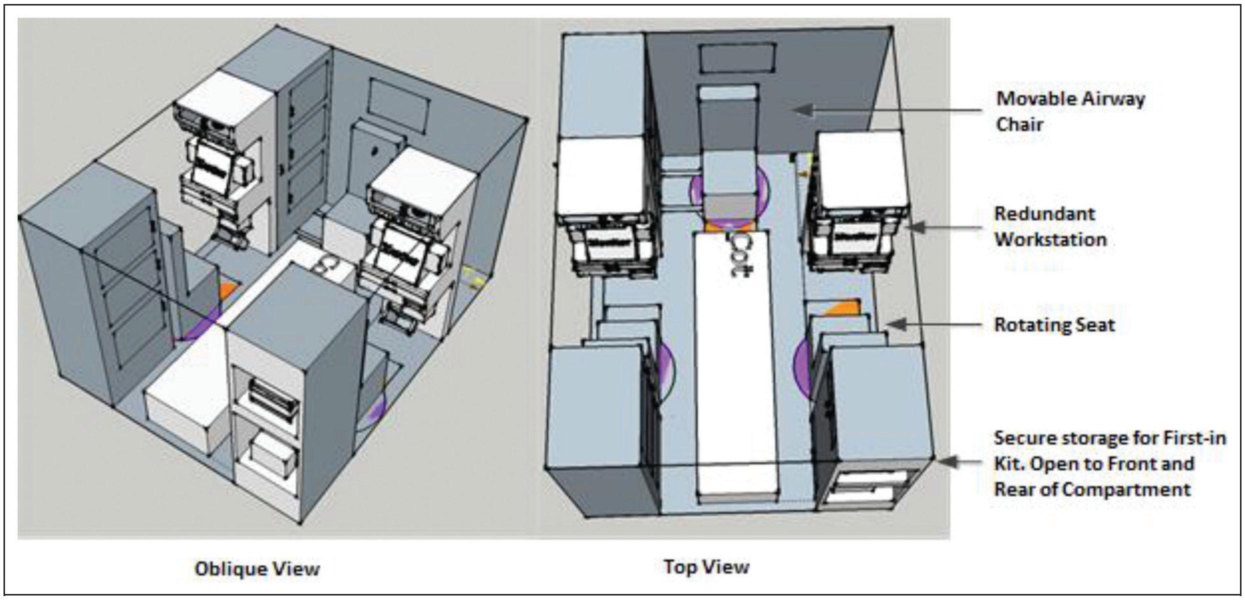


Figure 5. Design Concept 1 of the patient compartment.

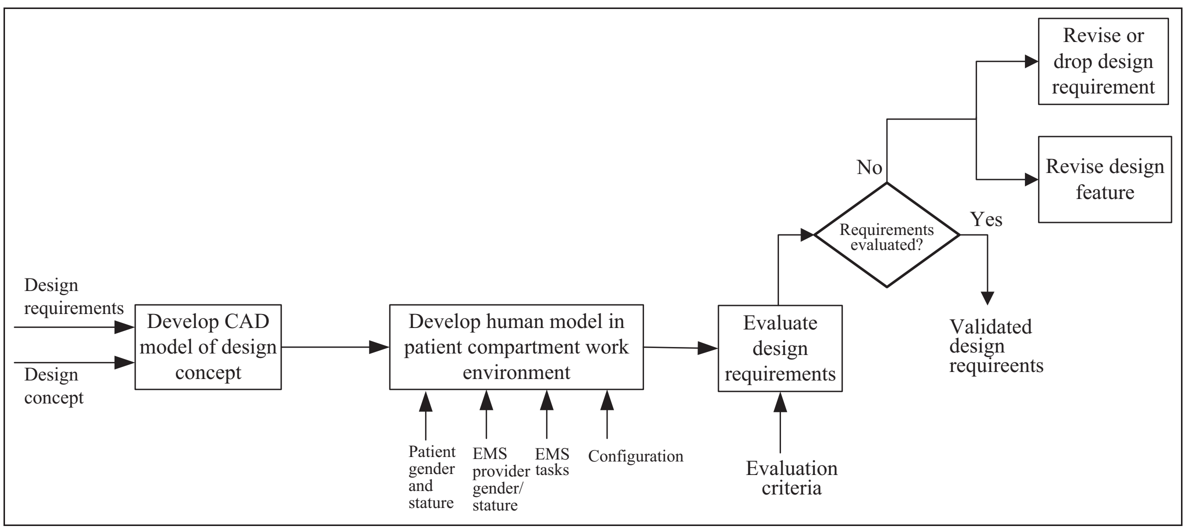


Figure 6. Design concepts and requirements evaluation process using modeling and simulation.

loading a patient with legs first. Based on the initial concept assessment and tradeoffs against requirements, the concepts determined to be feasible were expanded and detailed to determine storage locations, oxygen ports, glove boxes, and other items. The selected concepts were further evaluated until the best concept was selected. The key areas of proposed design features for the following factors are as follows:

- *Seating and restraints*: the bench seat is replaced by bucket seats. Each seat is sized so that it (1) does not intrude into the space around the cot and (2) it is capable of rotating to side and forward-facing positions. This should allow EMS providers to access the patient and wear restraints simultaneously. The ability to face forward provides a safer orientation than side facing. The seat height from floor to top of the seat pan is between 38 cm (15 in) and 53 cm (21 in) to accommodate EMS providers of various sizes. The simple lap belts are replaced by three- or four-point restraints.
- *Ergonomics*: to reduce the need to stretch when reaching common and critical supplies or equipment, these items are located within easy reach of a seated and restrained EMS provider. The seats are designed to rotate to improve access to the patient with minimal torso twisting.

- *Communication*: the communications systems are located, along with other controls, on the wall or workstation and within reach of a seated position.
- *Workspace and equipment*: the traditional design allows the bench seat to be used as a work surface to place equipment and kits while in use. Although this arrangement put equipment within easy reach it also increased the amount of potential ''projectiles'' in the case of a crash. Removing the bench seat and the creation of a workstation provides workspace where the equipment can be strapped or stored in cabinets or drawers.

Lower level design features include the following.

- A workstation that includes a slide out work surface and a slide out drawer for a laptop computer.
- A drawer that slides out towards the patient cot for storing intravenous (IV) equipment, scissors, and a first aid kit. An oxygen port facing the patient cot is also included at the workstations.
- The first aid kit, ice pack, laptop computer, communication equipment, and controls are accessible from the workstation.
- Two identical workstations for medical care.
- A rear-facing seat to allow an EMS provider to perform airway management on the patient. The chair should be placed on tracks so that it can be moved sideways to allow the EMS provider access to items from the storage cabinets while seated and then move the chair back to offer care while seated and restrained. If needed, the EMS provider can leave the chair and intubate the patient while squatting above their head.
- Oxygen ports at the workstations where they can easily be accessed from the airway seat when it is slid towards the station

Our first design, named Design Concept 1, is shown in Figure 5. Two identical workstations are located on either side of the patient cot. Each is equipped with drawers that hold common and critical equipment and supplies. Both workstations also allow controls and glove boxes to be accessed while seated and restrained. The sharps and trash containers are located in front of each workstation seat. The captain's seat is located in the center at the head of the patient cot. The communication equipment, O_2 outlets, suction, and heating, ventilation, and air conditioning (HVAC) controls are located in reach of each workstation. The First-In Kit and trauma and drug bags are stored in shelves adjacent to and accessible from the primary workstation, which is shown on the curbside in this design.

The cables from the monitor and tubing from O_2 outlets and suction units to the patient are routed alongside the workstation, in the ceiling, and then drop down to the patient from the ceiling so as to eliminate chances of entanglement with personnel or other equipment. The less frequently used equipment and supplies are stored in cabinets located further from a seated position. As the design process proceeds, balance is made between the need for individual seats (which can reduce space between seat and cot) and the need for clear path around the cot.

4. Design concept evaluation for performance using simulation

This section describes the process we used to evaluate a concept using M&S methods (see Figure 6). These methods can predict how well EMS providers will perform a variety of patient care tasks in the proposed design concept. They can also predict body posture, positioning, comfort, walking, angle of vision, reach, and grasping. To make these predictions, we first developed a virtual patient compartment using a 3D model of the design concept. We then imported the model into a human simulation tool. The tool can simulate details of human movements and task performance, including the ability of humans to grasp/release objects and to detect/avoid collisions with surrounding objects. Humans were modeled as articulated mannequins composed of different segments to more accurately duplicate the movements and actions of limbs and digits.

The tasks are performed while the patient is lying on a cot. The simulation replicated patient care tasks by manipulating the mannequin to represent the postures and positions that an EMS provider would assume as they perform their tasks. It also replicates the path and postures EMS providers must use to access medicines, equipment, supplies, and body parts of the patient.

4.1 Human models used

Our models used human mannequins representing EMS providers of a 5th percentile female and a 95th percentile male by weight and stature. Percentiles represent the relative positioning of the anthropometric measurement of a person compared to the rest of the population under study. A person in the 5th percentile is smaller than 95% of that population, whereas a person who is in the 95th percentile is larger than 95% of the population.

We selected the 5th percentile female to the 95th percentile male because we believe that the design of an ambulance should consider such wide range in anthropometric data for most potential EMS providers to effectively perform patient care while remaining seated and restrained. Both male and female humans of 50th percentile stature in length and size were used for the patient. The anthropometric data were obtained from the Fire Apparatus Manufacturer's Association Firefighter Anthropometric

Data White Paper.[36] The data from this population are very similar to those of the EMS providers' community. From this data, we have the following provider body size:

- standing height range of 63.9–76 inches (1623.06–1930 mm);
- seated height range of 32.9–38.8 inches (836–986 mm);
- weight range of 129–263 pounds (58.5–119.3 kg);
- waist circumference range of 38–56 inches (965–1422 mm).

4.2 Failure Mode and Effects Analysis

Failure Mode and Effects Analysis (FMEA) was used in the design concept evaluations. FMEA is a methodology for identifying potential problems in new or existing designs.[30] In applying FMEA to the patient compartment, a failure refers to any part of the design that does not meet performance and safety needs. We first identified the most commonly occurring emergency care events that EMS providers routinely encounter in the compartment. From these events, we determine the activities and tasks associated with the events. The objective is to see how effective the EMS provider would be in carrying out those activities while remaining seated and restrained. Inability to perform those tasks by EMS providers would indicate a failure in the feature of the concept design that should have facilitated that task. The critical care events are trauma, cardiac arrest, pregnancy, burn, hazard materials (HAZMAT) exposure, substance overdose, seizure, stroke, and respiratory failure. However, responding to these incidences requires performing similar clinical care activities and tasks. Therefore, we used cardiac arrest and trauma events, the patient care of which requires performing the following set of tasks:

1) check for airway, breathing, and circulation;
2) stabilize breathing and secure airway;
3) get additional equipment;
4) perform a physical examination;
5) stop excessive bleeding;
6) check for vital signs and EKG;
7) perform IV insertion;
8) administer drugs;
9) test glucose;
10) collect patient information;
11) perform CPR;
12) communicate with the hospital.

4.3 Evaluation of Design Concept 1 against the traditional design

The location of the most frequently used items in both the traditional design and Design Concept 1 are shown in Figures 7 and 8, respectively. We simulated the same patient care scenarios to compare Design Concept 1 against the traditional design. An example of a comparison between the two designs is the reach of items. To reach medicines, equipment, or the patient's body, EMS providers in the traditional design have to turn their torso while restrained on the bench seat. In Design Concept 1, however, EMS providers perform the same tasks by rotating the bucket seats thereby eliminating the need to turn the torso (see Figure 9). Without the bench seat, the First-In Kit that carries many of the common supplies and equipment required for patient care (usually on a bench seat for traditional design) must be located in close proximity to the seated position and the patient. Therefore, a final conclusion on which design scores better would have to examine several patient care scenarios.

We used visual observations of EMS providers performing various tasks in the virtual environment. The human modeling tool can indicate reach and measure distances so that the analyst can determine whether the EMS provider would perform the task or not. Tables 3 and 4 summarize the observations of performance of the tasks in

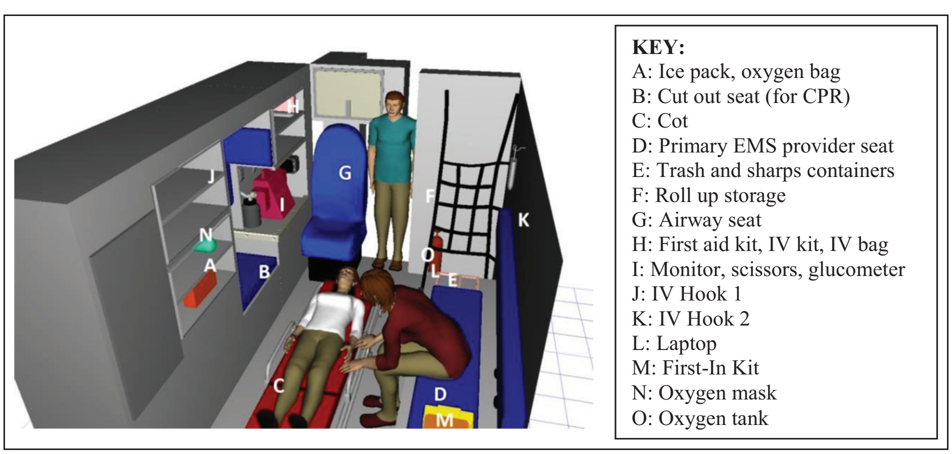
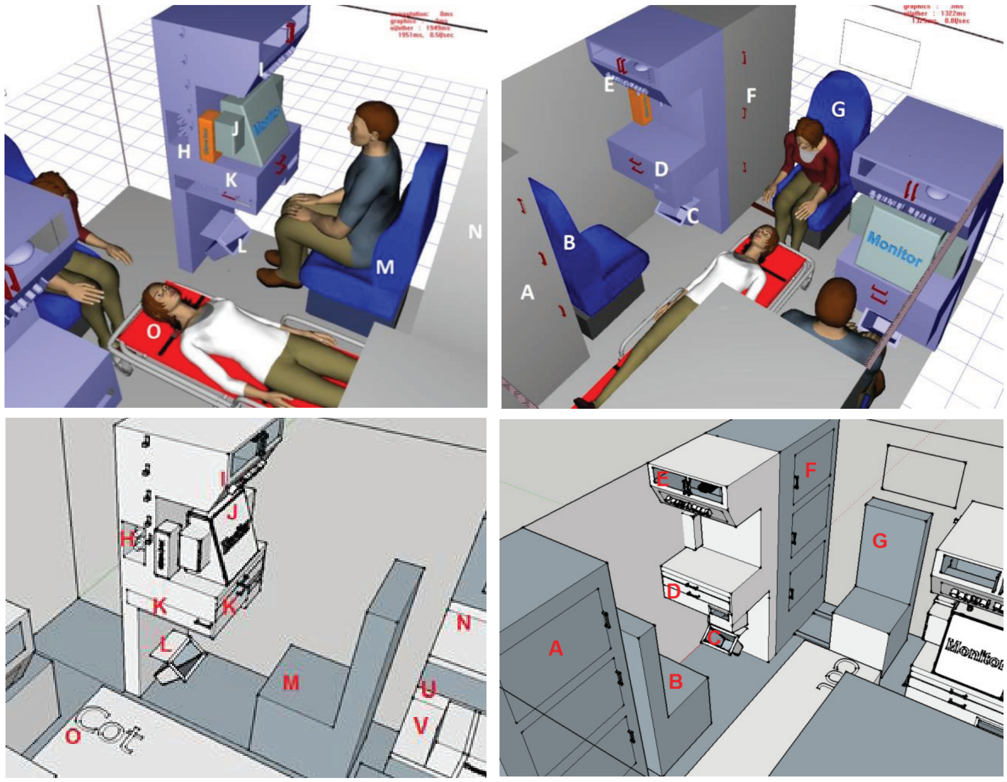


Figure 7. The layout of the traditional patient compartment design.



KEY:

A: Storage compartment
B: Roadside bucket seat
C: Roadside trash
D: Roadside workstation drawers
E: Roadside control panel and overhead storage
F: Airway seat storage
G: Airway seat
H: Curbside O_2 ports
I: Curbside control panel and overhead storage
J: Curbside monitor
K: Curbside workstation drawers and storage for various items (e.g., first aid kit, ice pack, oxygen mask)
L: Curbside trash
M: Curbside bucket seat
N: Curbside storage compartment
O: Cot
P: IV hook
U: Drug bag
V: First-In Kit

Figure 8. Design and location of various items in Design Concept 1.

Figure 9. Observation of a 95th percentile male emergency medical service (EMS) provider reaching out to touch the patient's head. The left-hand side shows the traditional design, while the right-hand side shows Design Concept 1.

Table 3. Observations of simulated task performance for the 5th percentile female EMS provider[a].

Task	Equipment needed	Observations of task performance		Preferred design
		Traditional design	Design Concept 1	
Check for airway, breathing, and circulation	Trauma bag	• **Can access items from the First-In Kit** • **Has to stand to reach patient's head**	• Difficult to access some items from the First-In Kit while seated • Has to stand to reach patient's head	Traditional design
Stabilize breathing and secure airway	Monitor, oxygen mask, portable oxygen tank	• Has to get up from seat and walk to access oxygen mask, oxygen tank, and to do connections • Has to stand to reach patient's head to put on the oxygen mask	**No need to leave seat except while accessing the oxygen mask**	Design Concept 1
Get additional equipment	First aid kit, ice packs	Has to get up and walk to get the required equipment	**Can access items while seated but needs to stretch**	Design Concept 1
Physical examination	None	Can access all parts of the patient while seated except the head, lower leg and feet	Can access all parts of the patient while seated except the head, lower leg and feet	No preference
Stop excessive bleeding	First aid kit (at bench seat)	Can access first aid kit while seated but has to stand to reach patient's lower leg	**No need to leave seat**	Design Concept 1
Check for vitals and EKG	Monitor, monitor leads, stickers, BP cuff	Has to walk to access monitor	**No need to leave seat**	Design Concept 1
Perform IV	IV kit, IV bag, IV hook, scissors	• Has to walk to access IV kit, scissors, and to attach IV hook 1 • Has to stand up to reach the patient's right arm	• **Can access most items while seated** • **Need to stand up to insert IV into the IV hook**	Design Concept 1
Administer drugs	Drug bag	• **No need to leave seat to access items from First-In Kit** • **Has to leave seat and stand to reach patient's head**	• Has to stretch to reach First-In Kit while seated • Has to leave seat and stand to reach patient's head	Traditional design
Test glucose	Glucometer	Has to leave seat and stand to access the glucometer	**No need to leave seat**	Design Concept 1
Collect patient information	Laptop	Has to leave seat and walk to access the laptop	**No need to leave seat**	Design Concept 1
Communicate with hospital	Wall radio	Has to walk to pick the phone and sit to make the call	**Has to leave seat and stand up (but not walk) to reach the phone and controls**	Design Concept 1

[a]Boldfaced text indicates the preferred design for carrying out the particular task.
EKG: electrocardiogram; BP: blood pressure; IV: intravenous.

Table 4. Observations of simulated task performance for the 95th percentile male emergency medical service (EMS) provider[a].

Task	Equipment needed	Observation of task performance		Preferred design
		Traditional design	Design Concept 1	
Check for airway, breathing, and circulation	Trauma bag	• Can access items from the First-In Kit • Can access the patient's head	• Can access some items from the First-In Kit • Can access the patient's head	No preference
Stabilize breathing and secure airway	Monitor, oxygen mask, portable oxygen tank	Has to leave seat and walk to access all needed equipment	**No need to leave seat**	Design Concept 1
Get additional equipment	First aid kit, ice packs	Has to leave seat and walk to access all needed equipment	**Can access most items while seated. But a few items require standing up (but not walking) to access them**	Design Concept 1
Physical examination	None	Can reach the head, chest, pelvis, and arms while seated	Can reach the head, chest, pelvis, and arms while seated	No preference
Stop excessive bleeding	First aid kit (at bench seat)	• Can reach the chest, pelvis, and arms while seated • Can reach head with one hand	**Can reach the head, chest, pelvis, and arms while seated**	Design Concept 1
Check for vitals and EKG	Monitor, monitor leads, stickers, BP cuff	• Has to leave seat and walk to access the monitor • Can reach the chest, pelvis, and arms while seated. Can reach head with one hand	• **Can access the monitor while seated** • **Can reach head, chest, pelvis, and arms on the patient while seated**	Design Concept 1
Perform IV	IV kit, IV bag, IV hook, scissors	• Has to leave seat and walk to access all items • Need to stand up to insert IV into the IV hook	• **No need to leave seat for some items** • **Need to stand up to insert IV into the IV hook**	Design Concept 1
Administer drugs	Drug bag	**No need to leave seat**	No need to leave seat, but can only access some items from the First-In Kit	Traditional Design
Test glucose	Glucometer	Has to leave seat to pick the glucometer	**No need to leave seat**	Design Concept 1
Collect patient information	Laptop	Has to leave seat and walk to collect the laptop	**No need to leave seat**	Design Concept 1
Communicate with hospital	Wall radio	Has to leave seat and walk to pick the phone and sit to make the call.	**No need to leave seat**	Design Concept 1

[a]Boldfaced text indicates the preferred design for carrying out the particular task.
EKG: electrocardiogram; BP: blood pressure; IV: intravenous.

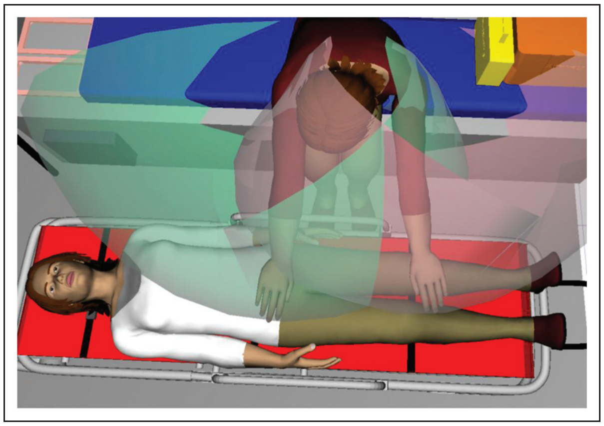


Figure 10. Reach zone of the 5th percentile female from a seated position in the traditional design.

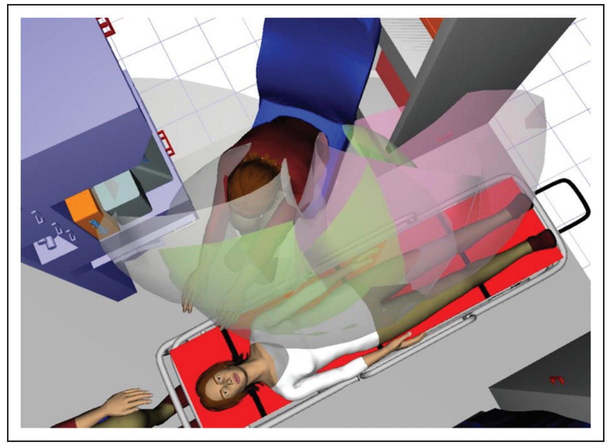


Figure 11. Reach of the 5th percentile female from seated positions accorded to a rotating seat in Design Concept 1.

the traditional design and the design (Design Concept 1) when the EMS provider is working from the primary workstation (curbside). Similar observations would be obtained if the EMS provider was seated at the roadside workstation. Table 3 gives performance observations for the 5th percentile female EMS provider. Table 4 gives performance observations for the 95th percentile male EMS provider.

4.4 Results of modeling performance of the 5th percentile female EMS provider

The data from the Table 3 show that the EMS provider cannot reach the monitor, oxygen mask, oxygen port, first aid kit, ice pack, IV kit, IV bag, IV hook, scissors, glucometer, laptop computer, communication systems and controls, and patient lower body while working in the traditional design. The observations also show that the EMS provider has to routinely stand up while working in the traditional design. Of the 12 tasks included in the study, the model shows that the EMS provider cannot fully perform any of the tasks without leaving the seat for at least one of the sub tasks. The EMS provider can, however, readily access the First-In Kit (located on the bench seat beside the EMS provider) and the middle section of the patient's body (excluding the head and feet). Figure 10 shows the reach of a seated 5th percentile female while in a seated and restrained position on a bench seat. The reach zones for both hands of the EMS provider are shown by the shaded area in the figure.

With Design Concept 1, the EMS provider mannequin was able to reach the first aid kit, ice pack, patient's lower body and right arm, monitor, IV kit, laptop computer, and communication. However, there was still difficulty in reaching the oxygen mask, oxygen port, suction unit, IV hook, patient's head and lower body, communication systems, and controls. The First-In Kit can be accessed but not fully because the arm for the 5th percentile female would not extend far enough to retrieve all items in the bag. The performance from a seated position is improved because storage is located close to the seated position at each workstation. The rotating seats can also enable a wider reach zone for both the patient and required items. Even though the 5th percentile female is still unable to access the patient's head and feet and has some difficulty reaching the First-In Kit while seated, the overall result is significantly better than the traditional design. Figure 11 shows the reach of the 5th percentile female from different positions of the rotating bucket seat.

4.5 Results of modeling the performance of the 95th percentile male

The 95th percentile male has greater reach of the patient's body from a seated position than the female. While working in the traditional design, the male can readily reach the First-In Kit since it is often located on the bench seat. The patient's head, chest, pelvic area, arm, and lower legs are also within reach. However, the EMS provider still has to leave the seat to access the oxygen mask, oxygen port, first aid kit, ice pack, patient lower body, monitor, IV kit, IV hook, laptop computer, communication systems, and controls. Many of the items and drugs would require the EMS provider to stand and walk around the cot to access them. The 95th percentile male can perform tasks if the necessary medicine and other items are carried in the First-In Kit and fully accessible. Although the 95th percentile male can perform the following tasks, he would need to stretch to check airway, breathing and circulation, perform physical examination, and administer drugs.

With Design Concept 1, the EMS provider can perform more tasks from a seated position. One of the major

Table 5. Sample of identified problems and solutions to unsatisfied design requirements.

Safety/performance problem	Affected requirement(s)	Proposed solution
EMS provider cannot reach the patient's lower body (lower legs and feet) from a seated position.	The EMS provider is able to reach the patient's full body from a seated position.	*Modify the requirement* Define that the patient care from a seated position requires access only from head to the knee.
The EMS provider cannot properly reach the First-In Kit with both hands because the upper storage is at a high elevation (5th percentile female).	Interior storage cabinets, shelves, and/or drawers whose contents include common and critical equipment/supplies are accessible while seated and restrained.	*Modify the design feature* Lower the height of the shelves and redesign so that they can be opened from the cot side for easy access. Add a third shelf on top for the least used bag.
The EMS provider cannot access the laptop storage if the working surface tray at the workstation is pulled out.	Interior storage cabinets, shelves, and/or drawers whose contents include common and critical equipment/supplies shall be accessible while seated and restrained.	*Modify the design feature* Lower the height of the shelf that carries the laptop.
Cannot reach the control panel and communication equipment while seated.	Means for communicating between the EMS provider, the driver, and third parties, such as the hospital, are provided and accessible from all EMS provider workstations.	*Modify the design feature* Locate control panel closer to a seated EMS provider and angled or adjustable for easy access.

EMS: emergency medical service.

difficulties is the inability to easily access drugs/items from the First-In Kit from the designated locations. It is to be noted that, although the 95th percentile male's stature accords him greater reach, he has difficulty with performing some tasks in the relatively confined environment because of the awkward postures that he has to adapt to access and retrieve medicines from the kit.

5. Evaluation for performance with design enhancements

Design Concept 1 has demonstrated improvement over the traditional design; however, as shown in Tables 3 and 4, difficulties with performing some activities still remain. These problem can be linked to particular requirements. As such, the requirement(s) can be either revised or eliminated, if deemed possible, or new design concepts must be explored that (1) meet the problematic requirements and (2) do not negatively affect the already satisfied requirements. Table 5 shows a sample of the unsatisfied requirements and the proposed solution using a procedure illustrated in Figure 3. The suggested modifications to Design Concept 1 provided inputs to an improved design.

5.1 The capabilities of the enhanced design

The features of Design Concept 1 were enhanced to satisfy the problematic requirements. Furthermore, it was desired to include additional design requirements that were not considered in either the traditional design or Design Concept 1. The additional requirements are shown in Table 6. The modifications resulted in the design illustrated in Figure 12, termed Design Concept 2.

5.2 Evaluation of Design Concept 2

We evaluated Design Concept 2 by simulating an EMS provider's performance of various tasks from all three seated positions. Since all tasks require access to items and the patient, we first carried out a static reach analysis. The results of static reach analysis are shown in Tables 7 and 8. The labeled points specified in the tables are shown in Figure 12.

5.3 Observation

The modeling of task performance in Design Concept 2 has shown incremental performance improvement over Design Concept 1. For example, as shown in Figure 13, lowering the glove boxes enabled both the 5th percentile female and the 95th percentile male to reach them, while Figure 14 shows that relocating the opening for the drawer enables access from a seated position. Figure 15 demonstrates how far the drawers can be pulled back so that the EMS provider can work on top of them. Figure 16 shows that the modifications enable carrying a second backboarded patient. Additional improvements can still be achieved by further fine-tuning the design. Some features that can be improved include (1) adjusting the glove box location to improve reach for the 5th percentile female, (2) improving the location of side drawers for the 5th percentile female to withdraw needed items, (3) shifting

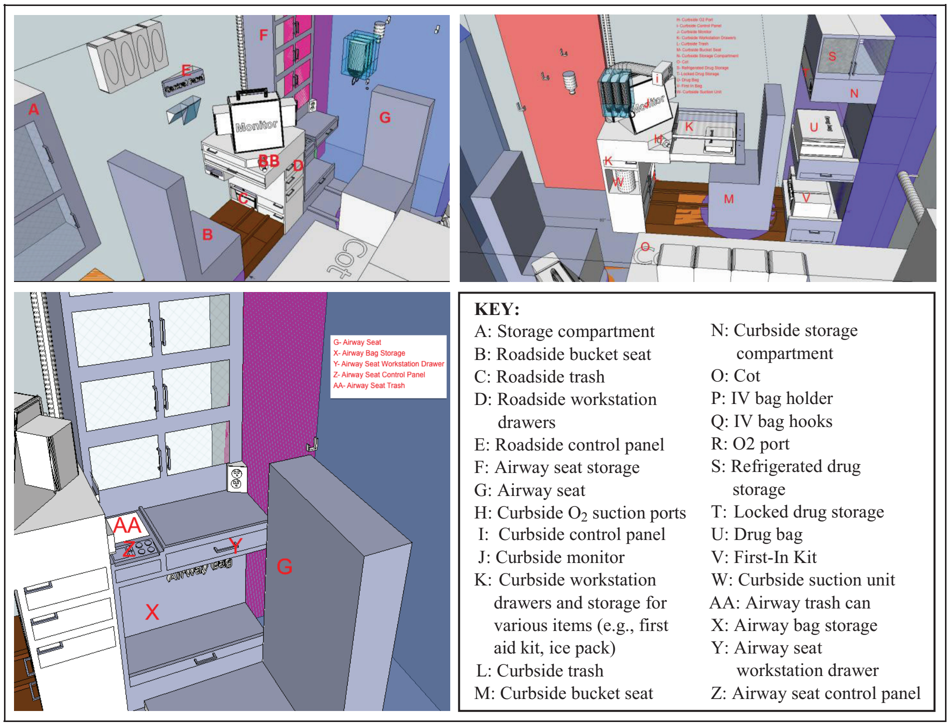


Figure 12. Different views of Design Concept 2.

Table 6. Additional requirements and suggested solutions.

Design requirements	Suggested design solution
The ambulance is able to carry a second back-boarded patient.	Divide the rear storage compartment on roadside into a lower and upper compartment and rest the backboard on the lower compartment, which should be at the same level as the roadside seat.
The airway bag is accessible from the airway seat.	Revise the front storage compartment on roadside of the airway seat to accommodate an airway bag, a simplified control panel, a trash bag, and a sharps container.
The EMS provider is able to access a headset port from the airway seat.	Revise the front storage compartment on the roadside of the airway seat to accommodate, among others, a headset port.
The ambulance is able to provide improved access to glove boxes from both workstation seats	Lower the location of the glove boxes.
The ambulance has increased workstation space.	• Revise the workspace at the workstation to be 76.2 cm (30 in) wide by 40.6 cm (16 in) deep minimum. • Install translucent work-surface drawer.
The ambulance enables comfortable seating for the 95th percentile male.	Revise the chair backrest to accommodate a 95th percentile male whose shoulder is 59.2 cm (23.3 in) wide from the current 45.7 cm (18 in).
The ambulance enables improved access to the control panel from all workstations.	• Place control panel closer to a seated EMS provider and angled or adjustable for easy access. • Locate a simplified panel, angled and next to airway workstation.

EMS: emergency medical service.

Table 7. Results of static reach analysis inside the patient compartment with Design Concept 2.

Location	Points to reach	Observations (both 5th percentile female and 95th percentile male)
Roadside workstation seat	• Glove box (E) • Control panel (E) • Storage (E) • Workstation port (BB) • Drawers (D)	• Glove box (E): Can be reached by only the 5th percentile female • Control panel (E): Can be reached by both • Storage (E): Can be reached by both • Workstation port (BB): Can be reached by both • Drawers (D): Can be reached by both (Figures 13 and 14 show glove box and drawer reach)
Curbside workstation seat	• Refrigerated drug storage (S) • Locked drug storage (T) • Workstation O_2 port (H) • Suction unit (W) • Drawers (K) • First-in-bag (V) • Sharps container (L) • Control panel (I) • Patient (from head to knee)	• Refrigerated drug storage (S): Can be reached by both • Locked drug storage (T): Can be reached by both • Workstation O_2 port (H): Can be reached by both • Suction unit (W): Cannot be reached by either • Drawers (K): Can be reached by both • First-in-bag (V): Can be reached by both • Sharps container (L): Can be reached by both when drawers are closed • Control panel (I): Can be reached by both • Patient (from head to knee): The 5th percentile female cannot reach the patient's head
Airway seat	• Airway bag (X) • Drawer (Y) • Control panel (Z) • Trash container (AA) • O_2 port (BB) • O_2 port (H)	• Airway bag (X): Can be reached by both • Drawer (Y): Can be reached by both • Control panel (Z): Can be reached by both • Trash container (AA): Can be reached by both • O_2 port (BB): Can be reached by both • O_2 port (H): Can be reached by both

Table 8. Additional model investigations.

Investigation	Observations (both 5th percentile female and 95th percentile male)
How far can a seated EMS provider pull the laptop and working surface drawers?	It is 16 in (40.6 cm) for 5th percentile female and 2.5 in (6.35 cm) for 95th percentile male (Figure 15 shows how far the drawers can be pulled back)
Is there sufficient space for the knees under the workstation?	There is sufficient room but the worktable must be at least 27 in (65.6 cm) above the EMS provider's feet level for the 95th percentile male
What is the effect on lower back strain of the EMS provider for current cot height of 18 in (45.7 cm) and for 28.9 in (73.4 cm) above the floor?	The stretch reduces when patient is on the cot with height 28.9 in (73.4 cm) above ground compared to the bed of 18 in (45.7 cm)
Can a standing EMS provider reach: • IV bag hooks (Q)? • IV bag holder (P)? • Ceiling O_2 port (R)? • Refrigerated drug storage (S)? • Locked drug storage (T)? • Interior storage compartments (A, F, and N)	Points to reach: • Q: Yes • P: Yes • R: Yes • S: 5th percentile female (Yes); 95th percentile male (No) • T: 5th percentile female (Yes, with one arm); 95th male (No) • A: (Yes); F: (Yes, but has to squat for low cabinets and 5th percentile female would not reach items close to the wall); N (Yes, but with only one arm for the 95th percentile male)
Can a backboard fit in the space between compartment location (A) and bucket seat (B)?	Yes, the backboard can be placed at the location (see Figure 16)

EMS: emergency medical service.

refrigerated common drug storage and restricted drug storage for the 95th percentile male reachability, and (4) improving access, from the airway seat, to both workstation O_2 ports. Such improvements would have to be balanced against the impacts to other features and ability to perform patient care in a practical ambulance.

Figure 13. Model of emergency medical service (EMS) provider reach for the glove box.

Figure 14. Model of emergency medical service (EMS) provider reach for the lowest level drawer.

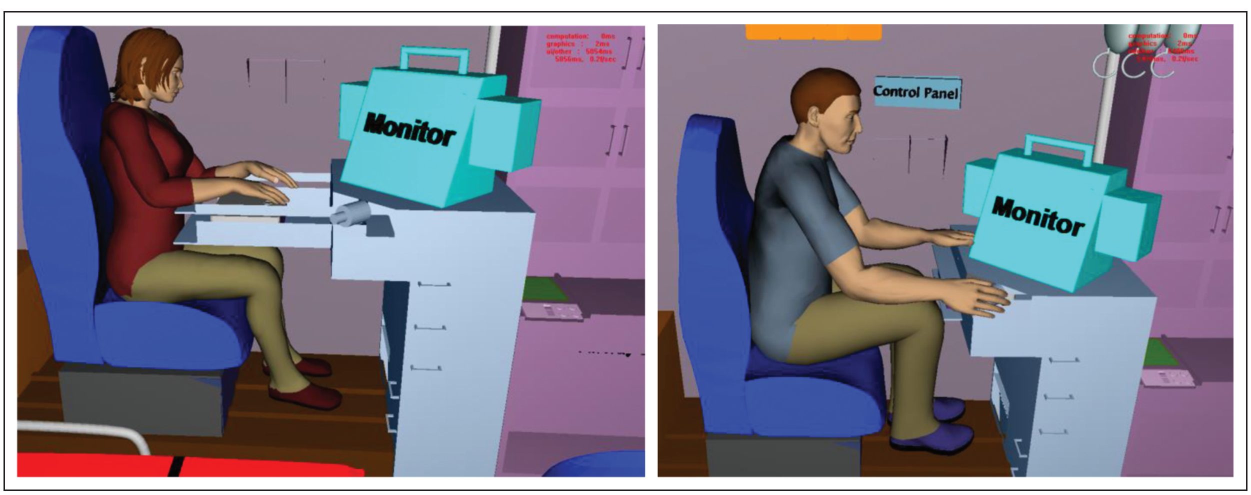


Figure 15. Model showing how far the emergency medical service (EMS) provider can pull back the workstation drawers.

Figure 16. Investigating the capability to carry more than one back-boarded patient.

6. Ergonomic analysis

While safety is improved when the EMS provider remains seated and restrained, it was felt necessary to investigate the effect of the requirement for EMS providers to remain seated and restrained on the ergonomic effects. Previous research by Morrisey[37] showed that insufficient workspace forces EMS providers to adopt poor working postures. When an ergonomic evaluation of the interior of the traditional ambulance was carried out, it was found to be unsatisfactory to both EMS providers and the patient.[29] We carried out a similar evaluation in Design Concept 2 to investigate the strains experienced by EMS providers on the back and upper body. Our suspicion was that while remaining seated and restrained is the best protection against injuries in an accident, it could lead to overstretching to access items thereby exposing EMS providers to a high risk of musculoskeletal injury. The back strains and upper body were analyzed using the Lower Back compression and RULA tools, respectively. The studies were carried out using patient care activities for both seated and standing postures. The patient care activities are listed in Table 9.

For back strain, we compared performing activities while seated with the NIOSH Back Compression Action Limit (AL) of 3400 newtons (N). If compression forces on the lumbar spine exceed this limit, design or policy measures are needed to protect against lower back injury. Table 9 shows the results. The results show that the lower back compression forces are safely below the back compression allowable limit. These forces are shown in the images in Figure 17 in the "green" or safe level of the graph. Modeling results of the anterior-posterior (A-P) shear force on the lower back and strain on the hip and knee are also within the safe range for both scenarios. Back compression forces and some other strains on the human body are higher for the seated postures than when standing; however, these values are all below the allowable limits and, therefore, represent safe levels. Any additional risk from slightly higher forces while seated is offset by the significantly higher risk of injury of performing patient care activities while standing in a moving ambulance.

The RULA results for upper body evaluation are shown in Figure 18. RULA uses a scoring method to assess the risk associated with a task, as follows:

Score: Level of musculoskeletal damage
1–2 negligible risk, no action required
3–4 low risk, change may be needed
5–6 medium risk, further investigation, change soon
6 + very high risk, implement change now

We first examined the impact on the 5th percentile female. The seated position for patient examination results in a RULA index of 4, while an index of 3 results for examining the upper leg of the patient. When the 95th percentile male seated in the airway seat is accessing the oxygen port the RULA index is 4, mostly due to stretching of the upper arm. While the recommendation for these indexes is that the work environment may need to be changed, they are of little risk. It is also noted that these tasks are performed for a very short period of time during patient care.

Table 9. Lower back compression force.

	Seated and restrained		Standing (restrained or unrestrained)	
Activity	5th percentile female	95th percentile male	5th percentile female	95th percentile male
Accessing the chest of the patient from the curbside workstation	2288 N	2601 N	1394 N	2539 N
Accessing the legs of the patient from the curbside workstation	1984 N	3122 N	1764 N	2804 N
Accessing the oxygen port at the roadside workstation from the airway seat	1678 N	2945 N	1582 N	2230 N

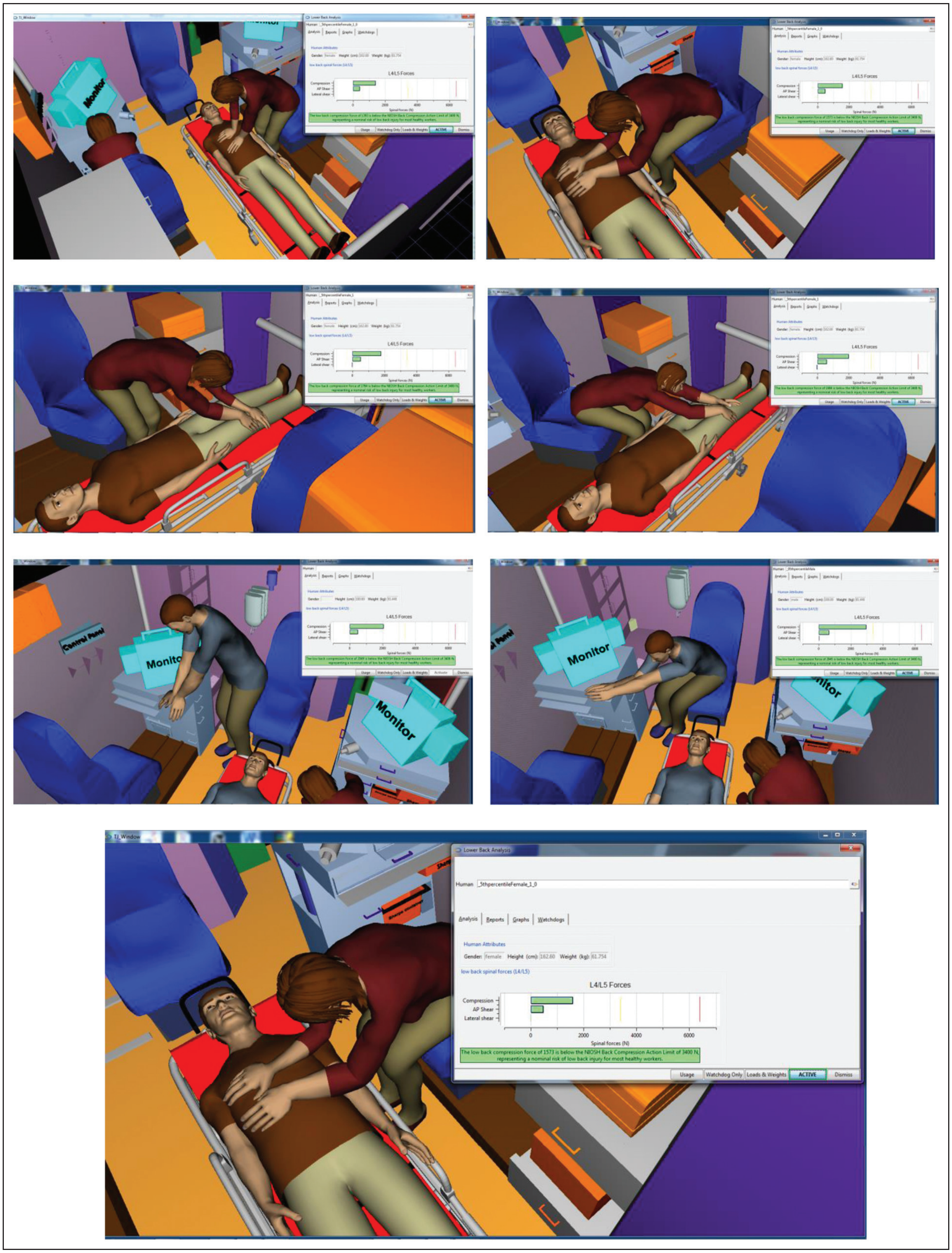


Figure 17. The postures adopted to perform various tasks and resulting back strains.

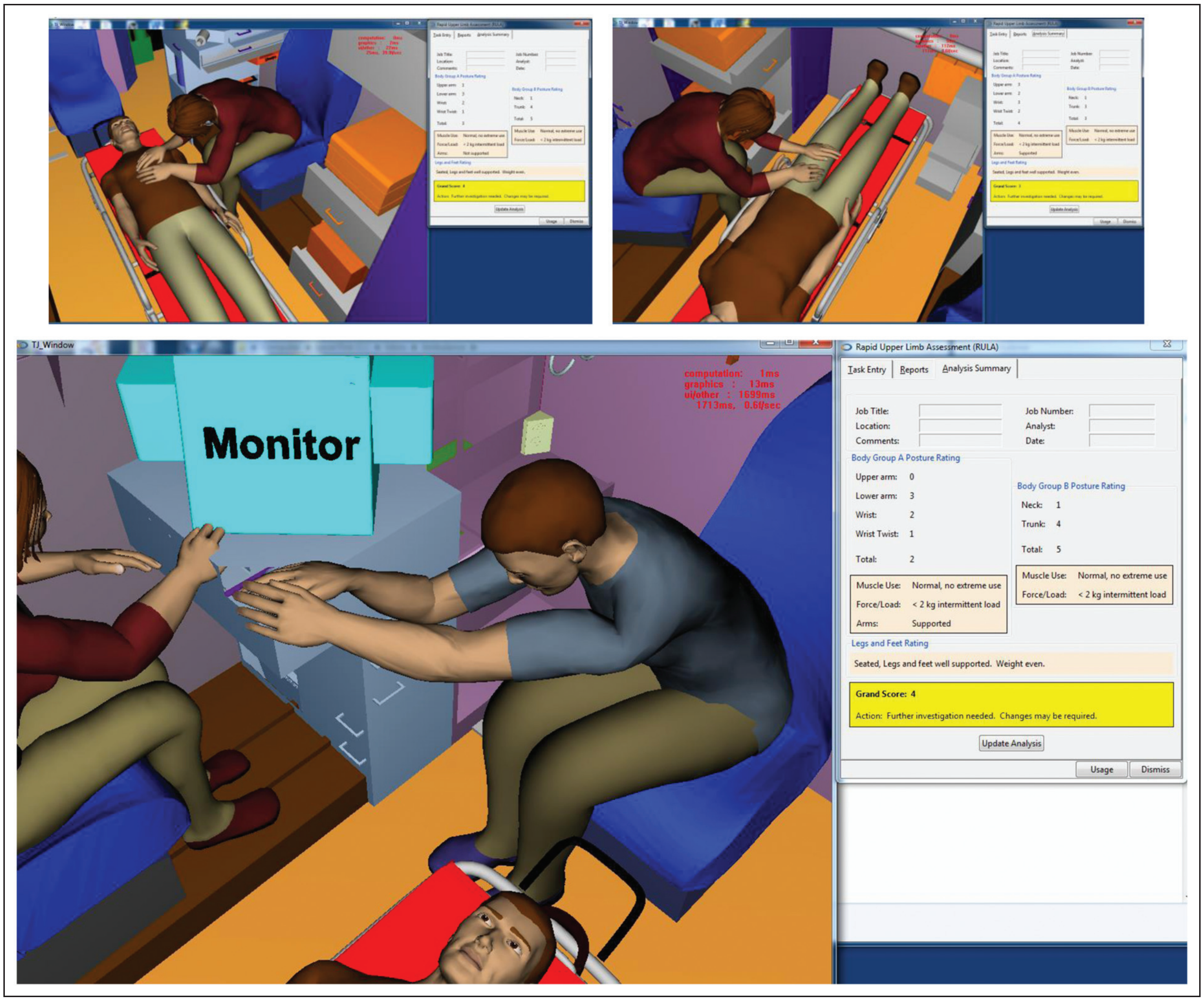


Figure 18. Rapid upper limb analysis (RULA) analysis of upper body strains for performing reach to patient (5th female) and the oxygen port (95th male).

For example, accessing and connecting to the oxygen port is a momentary activity that lasts a few seconds before the EMS provider has to return to an upright seated position.

Based on this ergonomic analysis and the risks associated with performing patient care activities unrestrained, a seated and restrained position has a minimal risk of lower back injury, and protects in the event of a crash or evasive maneuver. Therefore, a seated and restrained position is the safest position for an EMS provider in the patient compartment.

7. Discussion and conclusions

Current standards and guidelines do not result in designs that ensure the optimal safety and performance of the EMS providers. In this paper, we presented an M&S approach to evaluate new design requirements that are intended to address those inadequacies. These new requirements were obtained using a user-centered research and analysis of ambulance work environments. An initial design concept was developed from these requirements and analyzed using human task simulations in a virtual work environment. Although the first design showed improvement over the traditional design, enhancements were still needed to enable performing tasks such as reaching the head and feet of the patient's body, reaching the oxygen and suction units, and retrieving items from the First-In Kit that could not be performed. An improved design showed improvements in safety and delivery of emergency medical care from a safe seated position.

The overall objective of this research was to develop requirements that result in better designs compared with existing ambulances. We first identified performance and safety issues in providing emergency medical care in existing designs. The objective of this paper was not to show how one can develop an optimal ambulance design, but rather to develop viable designs, complying with the requirements, that show performance and safety improvements. This was demonstrated through M&S. The requirements are to eventually be refined into specifications and standards for future ambulances. Future ambulance users and manufacturers would then be able to design ambulances that conform to the standards. It is anticipated that different design teams would produce different designs, with each design representing the particular preferences of the end users. It is expected that a succession of design concepts will be developed in an iterative matter, with each design being evaluated by the design team and end users to identify strengths, weaknesses, and recommending improvements, with each successive concept being an improvement over the previous one. This paper has demonstrated the use of M&S methods in the iterative design and improvement processes.

There were challenges associated with this research. The first challenge was developing a design concept from the requirements. This research used approaches that relied on an understanding of human factors and extensive knowledge of ambulance design needs and criteria. The resulting designs may not necessarily be the best or optimal. Secondly, modeling the capability of humans to perform a task element or reach a particular location requires significant modeling skills. Verifying that the tasks are performed successfully was by visual observations. Thirdly, expertise and patience are paramount to accurately position mannequins within the virtual ambulance work environment. This point has to be emphasized because the postures adopted while seated, standing, or reaching out for items affect the final results in terms of the ability to reach or the musculoskeletal effects on the body.

The challenges notwithstanding, our research has shown that M&S methods can be used successfully for evaluating design concepts. The modeling of work flow and reach of equipment, medicines, and patient in improved design concepts show that EMS providers are able to safely perform necessary patient care activities in the patient compartment. The ergonomic modeling also showed that EMS providers do not experience unsafe levels of lower back compression force while remaining seated and restrained. M&S is a valuable tool to understand the relationship between requirements and the application of those requirements in order to evaluate and validate novel design concepts.

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Author note

Certain commercial software systems are identified in this paper to facilitate understanding. No approval or endorsement of any commercial product by the NIST or BMT Designers and Planners is intended or implied. Neither does the identification imply that these software systems are necessarily the best available for the purpose.

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