Modeling and Simulation for Improving Ambulance Patient Compartment Design Standards

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ABSTRACT: *Emergency medical services (EMS) providers riding in ambulance patient compartments, while caring for patients, are at high risk of suffering injuries in case of a vehicle crash or sudden maneuver. One option to reduce this risk is to have providers use seat belts. However, providers have complained that the seat belts make it difficult to reach equipment and supplies necessary to treat patients. Another option is to redesign the layout of the patient compartment to (1) reduce hazards to both providers and patients and (2) improve access to patients, equipment, and supplies. A new design, based on ergonomic guidelines and user design requirements, has been developed. This paper describes the application of modeling and simulation in evaluating the redesign options. Evaluation is based on the effectiveness of the redesign in facilitating the providers' ability to perform a range of clinical care tasks while seated and restrained. Simulation results and subsequent design revisions of the prototype will be used to recommend new design requirements and guidelines to existing ambulance design standards.*

1. Introduction

It is estimated that ambulance crashes in the United States result in one fatality every 10 days and cost more than $500 million per year [1]. Most fatalities are unrestrained Emergency Medical Service (EMS) providers. The obvious solution is to restrain them. However, if restrained, they (1) would not have access to some supplies and equipment frequently used and (2) would not be able to perform the required emergency medical treatments on the patient. It seems, therefore, that providers need to be unrestrained, at least periodically, to carry out their duties effectively.

This need to be unrestrained, however, is caused by the current design of the patient compartment. That design includes the location of equipment, medicines, and other emergency medical care items. It also includes additional factors such as the type and placement of seats, restraints, and patient(s). Given this, it may be possible to solve the provider-restraint problem by redesigning the layout of the ambulance patient compartment and installing better restraint systems that permit required movements from a seated position [2] and [3].

The First Responders Group of the Department of Homeland Security (DHS) Science and Technology

Directorate has recognized the potential benefits of redesigning the layout. They identified the lack of a uniform performance standard to guide ambulance patient compartment design and construction as a major problem. They noted further that current design standards do not fully address safety concerns.

The major relevant standards are General Services Administration's KKK-A-1822F [4] and the NFPA 1917: Standard for Automotive Ambulance [5] respectively. The KKK-A-1822 does not include comprehensive safety specifications. NFPA 1917 does include requirements for safety belts, seats, and access to the patient; but, it does not address the interior layout from a human performance and safety perspective. To address these limitations, the First Responders Group, the National Institute of Standards and Technology (NIST), the National Institute for Occupational Safety and Health (NIOSH), and BMT Designers and Planners are collaborating to develop new design standards for ambulance patient compartments.

To get a better understanding of the performance and safety design requirements, the team has used multiple data gathering methods, including literature review, practitioner interviews and ride-alongs, a web-based survey, focus group meetings, and a stakeholder workshop [2], [6], and [7]. The team then used the results from these efforts to develop an initial set of ambulance design requirements. The requirements were used to develop an initial design concept that has been evaluated and compared with the traditional design using modeling and simulation.

This paper describes those requirements, the procedure for developing an initial design concept, simulation experiment set up, and the results of the evaluations. The remainder of the paper is organized as follows. Section 2 describes the problems associated with current designs and the process of developing requirements for improved designs. Section 3 describes the design needs, requirements, and evaluation criteria. Section 4 describes the process of developing a design concept from the design requirements, modeling and simulation, and results of the evaluation process. Section 5 concludes the paper.

2. Traditional Designs

2.1 Traditional patient compartment layout

A traditional ambulance patient compartment layout is shown in Figure 1. The cot is located at or near the center with the head of the patient loaded first. A bench seat that can accommodate up to three people is located on the curb side. The captain's seat is located at the head end of the cot and typically off-center with the cot. A small CPR seat is located on the driver side of the compartment. Cabinets for storage of equipment and supplies are attached to the walls opposite the bench seat.

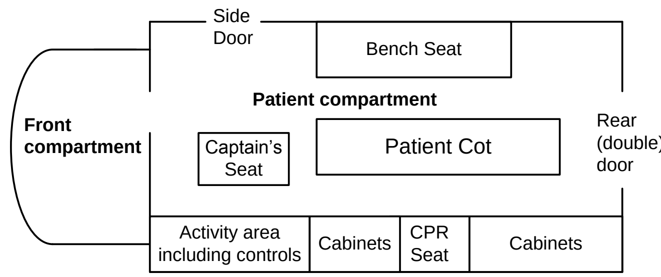

Figure 1: Traditional ambulance layout

2.2 Problems associated with the traditional design

EMS providers have raised a number of issues with this layout [8], and [9]. They include:

- EMS providers cannot be securely restrained in transport while simultaneously providing care to the patient.
- The providers cannot reach all critical equipment and medical supplies while remaining seated and restrained.
- The location of the cabinets relative to the CPR seat creates a "head strike" zone.
- The activity area and the cabinets are too far away from the seated EMS providers.
- The majority of the seats in the patient compartment are side facing. Side-facing seating is less safe than forward-facing seating in the event of a crash.
- The bench seat height is fixed. It is too high relative to the patient cot.
- There is inadequate leg room.
- Equipment and supplies are not securable; they can become projectiles in an accident.
- The captain's seat is too far from the cot.
- Seat belts provide safety, but they limit patient care.
- Confined environment causes physical discomfort and stress for the EMS providers.

3. Design Development and Evaluation Process

3.1 Identification of design needs, requirements, and criteria

The first step in developing new design guidelines is to change the issues mentioned in Section 2.2 into design needs. These needs fall into two classes: those associated with patient care performance and those associated with EMS provider and patient safety. The second step is to develop a set of design requirements, functions, or capabilities that can satisfy the need. An example of a design need is "the EMS provider is able to provide safe and effective patient care from a seated position in the ambulance patient compartment." Corresponding to this need, one of the design requirements is "Seating is adjustable if needed to reach the patient or equipment/supplies from a seated position." The third step is to develop desired performance and safety criteria that can be used to determine if a proposed design meets the requirements. 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. The design needs identified are listed in Table 1. (Space limitations do not permit the full listing of the design requirements and criteria.)

3.2 Design concepts and simulation role

The next step is to determine how well the proposed design concept meets the design requirements. The evaluation of design alternatives is performed by comparing the computed performance and safety parameters of the proposed design concept against the desired criteria. Figure 2 depicts the requirements and design concept evaluation process. The development of the design concepts is described in Section 4.2 and Figure 3. We have done this evaluation using modeling and simulation. The first step in building these models is importing CAD models of the proposed compartment design into a human-task modeling tool. This creates a virtual environment in which it is possible to simulate the effects of different layouts, item placements, tasks, and restraint systems. The second step is to build a detailed model of the EMS provider. The tool allows the human body to be an articulated figure to more accurately duplicate the movements and the actions of the head, limbs, and digits. The models can simulate EMS provider delivery of emergency medical care in the proposed patient compartment designs. The models then estimate the performance and safety of both providers and patients in those changes.

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.
	Ambulance compartment interior surfaces need to be sanitized and cleaned easily.
	If required by state or other regulations, the ambulance is able to transport a second backboarded patient.
Storage	Storage supports the EMS provider to safely and effectively perform patient care.
	EMS providers need the ability to perform inventory management.
	Space is designed 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 allow personnel to communicate efficiently and effectively between the patient compartment, the driver's compartment, and the third party such as a hospital.
	Driver can maintain awareness of activity in the patient compartment.
	EMS provider has awareness of driver actions.
Ingress and egress	Ability to ingress/egress the ambulance patient compartment quickly and safely.
Others	Interior patient compartment design, such as lighting and floor covering, 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.

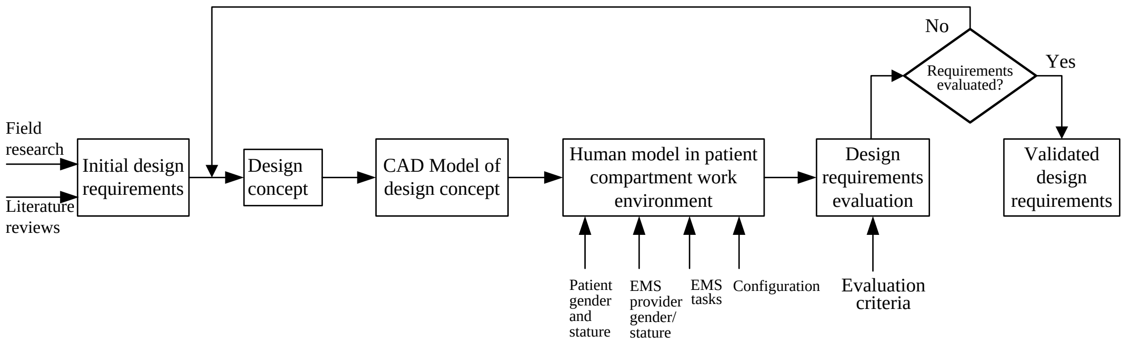

Figure 2: Requirements evaluation process

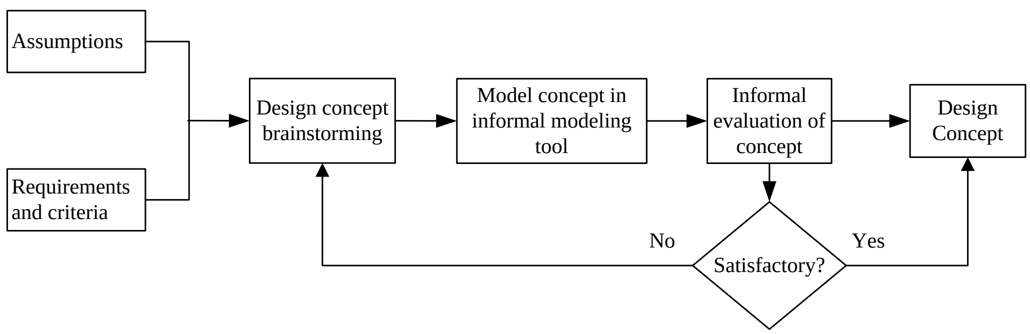

Figure 3: The design concept development process

4. Case Study of Simulation-based Design Evaluation

4.1 Key performance criteria

Before developing the model of the design concept, we identified an initial set of key performance criteria:

- The EMS provider shall be able to reach the patient's body from head to knee while in a seated and restrained position.
  - Seating shall be designed such that a 5th percentile female EMS provider with a maximum functional reach of 67.8 cm (26.7 inches) can reach a secured patient's body from the crown of the head to the kneecap to provide care for patients to 95th percentile male stature.
- The EMS provider shall be able to reach common and critical equipment/supplies from a seated and restrained position.
- The EMS provider is able to face and interact with the patient while in a seated and restrained position.

4.2 Developing the design concept

Figure 3 graphically describes the process we used to develop design concepts. We first developed a set of assumptions about the design and performance. Using these assumptions and knowledge of the requirements and criteria as guides, we had a series of brainstorming sessions to create some preliminary designs. We then evaluated and refined the preliminary designs. After several iterations of this process, we settled on the final, initial design concept (See Figure 4).

In the development of the first design concept, the following assumptions were considered:

1. There are two workstations each, on opposite sides of the cot, with the primary workstation at the curbside.
2. Communications, O_2 and suction, and heating, ventilation, and air conditioning (HVAC) controls are located at each workstation.
3. There is a storage space below the control panels used for surplus supplies and not typically used for immediate patient care.

4. The “First in” Bag is the primary storage for immediate care supplies and equipment.
5. The “First in” Bag is stored adjacent to the primary workstation with storage designed to allow:
    a) access from the primary workstation when the seat is rotated 90 degrees, and
    b) easy removal from the rear of the patient compartment when the doors are open.
6. Trauma and drug bags are stored just above the “First in” Bag using the same storage design.
7. Seat sizes are based on standards.
8. Cables from the monitor to patient and from O_2 and suction are routed alongside the workstation, along ceiling, and then drop down to patient from ceiling.
9. Intubation must be performed with EMS provider above the patient’s head. Therefore, the airway management chair can be slid to the roadside to be out of the way during the intubation procedure and be slid back to continue care while seated and restrained.
10. The ambulance carries a single patient.

One of the initial design concepts is shown in Figure 4. Its main distinguishing feature is the presence of two identical workstations on either side of the cot. All common and critical equipment and supplies are within reach while seated and restrained at the workstations. The sharps containers are located in front of each seated position. The captain's seat is located in the center with the patient cot on a track. There are trays that can slide out from each workstation for placement of items during emergency care delivery. The seats at the workstations can rotate 90º to allow access to items stored in the jump bag located at the rear of the workstations. Oxygen and intravenous therapy (IV) hooks are located on the sides of the storage of the main workstation for access by the EMS provider at the captain seat.

4.3 Preliminary reach analysis from EMS provider to patient, equipment, and supplies

As part of the iterative process shown in Figure 3, we carried out an analysis on the reach EMS providers in various seated positions. Figure 5 shows the final analysis result obtained before creating the simulation model. It shows the parts of the patient, equipment, and supplies that need to be accessed for key use cases. Given the importance for the EMS provider to remain seated and restrained while performing various tasks, the figure indicates what can be fully reached (green), partially reached dependent on the size of the medic or personal preference in where items are stored (orange), or not reached (pink) from the passenger-side seat, driver-side seat, and captain seat. Areas not requiring access have been grayed out. The figure shows that there are numerous improvements with the passenger-side and driver-side seating, although not as many for the captain seat.

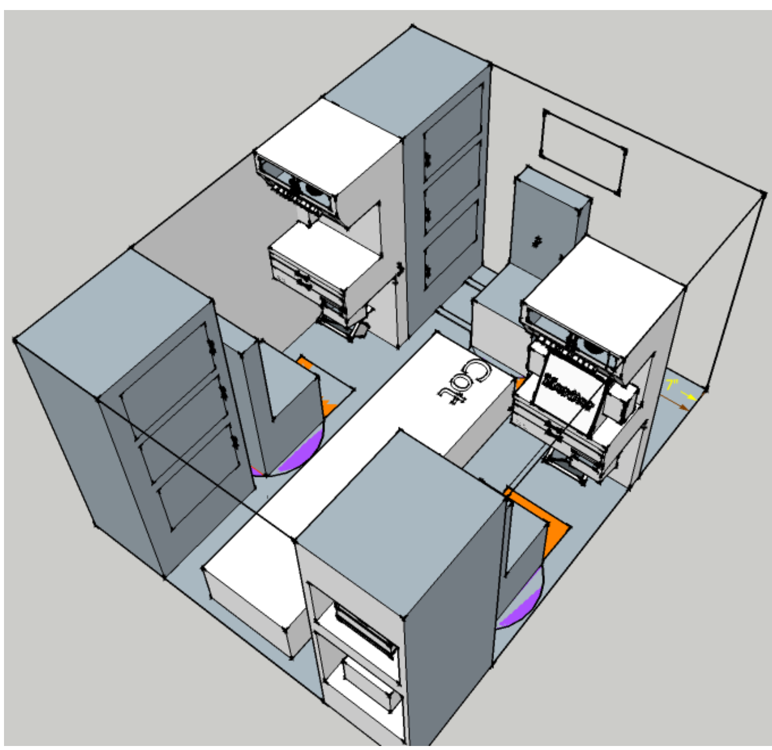

Figure 4: The 3-D view of the design concept

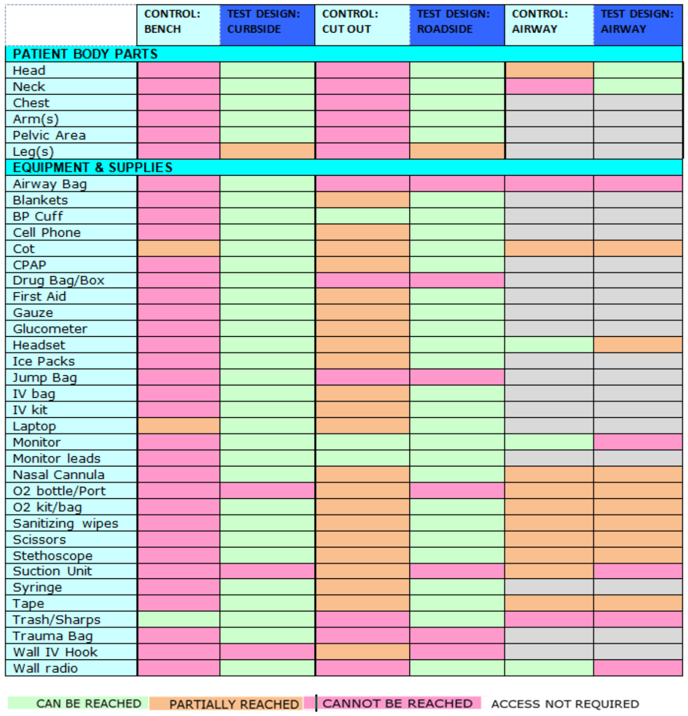

Figure 5: Comparison between traditional (control) and test designs for patient reach and access to equipment and supplies from a seated position

4.4 Use cases and tasks

We used functions typically performed by EMS providers to define use cases. The use cases are trauma, cardiac arrest, pregnancy, burn, HAZMAT exposure, substance overdose, seizure, stroke, and respiratory failure. Each of these cases involves a sequence of tasks to be performed. Some of the tasks are common for each use case. Each task performed by an EMS provider of given stature and gender represents a scenario. The requirements specify critical or extreme positions that should be reached by EMS providers from a seated and restrained position. For example, the critical points on a prone or seated patient include lower arm (for IV insertions), mouth (for ventilation and other procedures), and upper arm (for blood pressure). The locations of the equipment, medicines, and supplies are also part of the design concept. The simulation model will ascertain whether or not the EMS provider can reach for the items and perform various clinical care activities on the patients. Figure 6 shows the EMS provider trying to access items from the jump bag for both the traditional design, used as a control, and the new design concept.

4.5 Comparing traditional and new design concept

The tasks used in the simulation model are shown in the first column of Table 2 (for females) and of Table 3 (for males). This column was created prior to the simulation experiments while the subsequent columns were filled afterwards and are based on the observations that were made. Each table has two design options: control and test. Control captures the current methods for executing the task; test describes the proposed method for executing the task. The observations made while performing these tasks regarding access to supplies, equipment, and the patient are also summarized in the tables. The shading in each row indicates the preferred design for that task. Maintaining seated and restrained are the ultimate practice solution to ensure EMS provider safety while delivering patient care, however, there are tasks that could not be accomplished without leaving the seat. Performing cardiopulmonary resuscitation (CPR) and retrieving IV supplies are examples of those tasks. With this understanding, when choosing the preferred design for that type of task, comparison criteria then focuses on distance of movement made should the provider leave the seated position. The objective is to show which of the two designs would better enable the performance of the tasks while maintaining safety. The experiments used mannequins of a 5th percentile female and a 95th percentile male EMS providers, and 50th percentile female patient. The anthropometric data was obtained from the FAMA Firefighter Anthropometric Data White Paper [10]. The results show that, for more tasks, the test case (new design) performs better than the control case.

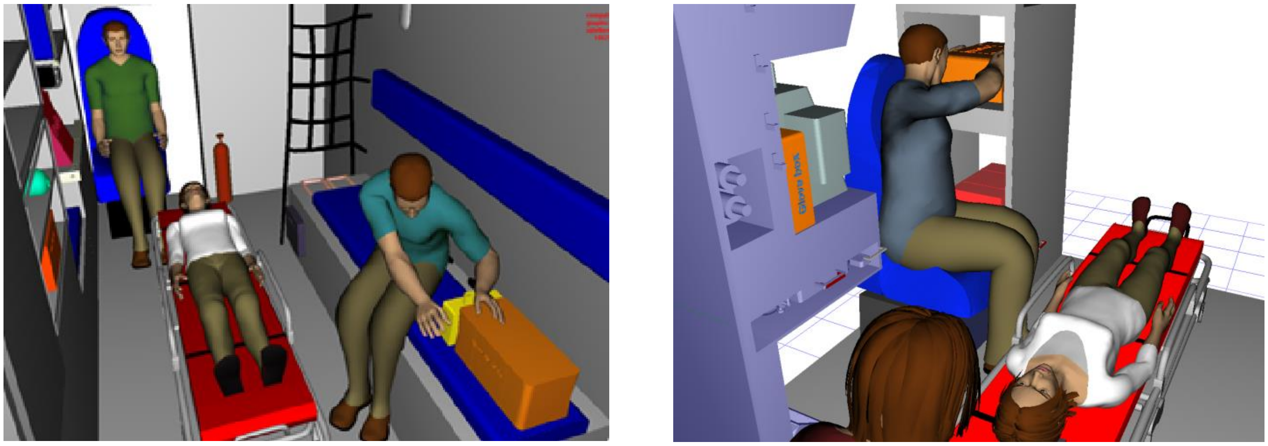

Figure 6: Models of EMS provider activity for traditional (left) and new design concept (right)

Table 2: Observations of simulated task performance for the 5th percentile female EMS provider

Task	**Observation (items and equipment reach, patient access, facing the patient)**		**Preferred design**
	Control design	**Test design**	
ABC (Airway, breathing, and circulation)	• Can access items while seated • Has to move from seat to stand to reach patient's head	• Difficult to access the bag while seated • Has to stand to reach patient's head	Control design
Stabilize breathing and secure airway	• Has to get up from seat and walk to access mask, oxygen and to do connections • Has to stand to reach patient's head to put mask	No need to leave seat except while accessing the mask	Test design
Get additional equipment	Has to get up and walk to get any required equipment	Need to leave seat to access most items	Test design
Physical exam	Can access all parts of the patient while seated except the lower leg and feet	Can access all parts of the patient while seated except the lower leg and feet	No preference
Stop excessive bleeding	Can access first aid kit while seated but has to stand to reach patient's lower leg	No need to leave seat	Test design
Vitals & EKG	Has to walk to access monitor	No need to leave seat	Test design
IV	• Has to walk to access IV kit, scissors, and to attach IV hook • 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	Test design
Push drugs	• No need to leave seat to access items from bag • Has to leave seat and stand to reach patient's head	• Has to strain to reach bag while seated • Has to leave seat and stand to reach patient's head	Control design
Test glucose	Has to leave seat and stand to access the glucometer	No need to leave seat	Test design
Collect patient info	Has to leave seat and walk to access the laptop	No need to leave seat	Test design
CPR	Has to leave seat and stand up	Has to leave seat and stand up	No preference
Communication with hospital	Has to walk to reach the phone and sit to make the call	Has to leave seat and stand up (but not walk) to reach the phone and controls	Test design

Table 3: Observations of simulated task performance for the 95th percentile male EMS provider

Task	Observation (items and equipment reach, patient access, facing the patient)		Preferred design
	Control design	Test design	
ABC (Airway, breathing, and circulation)	• Can access items while seated • Has to reach end of seat to access the patient's head, but remain seated	• Can access items while seated, but only those at his/her side of the bag • Has to reach end of seat to access the patient's head, but remain seated	No preference
Stabilize breathing and secure airway	Has to leave seat and walk to access all needed equipment	No need to leave seat	Test design
Get additional equipment	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 walk) to access them	Test design
Physical exam	Has to leave seat and stand to reach patient's head, chest, pelvic area, arms, and feet	Can reach patient's head, chest, pelvis, and arms while seated.	No preference
Stop excessive bleeding	Can reach patient's head, chest, pelvis, and arms while seated.	Can reach patient's head, chest, pelvis, and arms while seated.	No preference
Vitals & EKG	• Has to leave seat and walk to access the monitor • Can reach patient's head, chest, pelvis, and arms while seated	• Can access the monitor while seated • Can reach patient's head, chest, pelvis, and arms while seated	Test design
IV	• 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	Test design
Push drugs	No need to leave seat	• No need to leave seat, but for items at edge of the bag	Control design
Test glucose	Has to leave seat to pick the glucometer	No need to leave seat	Test design
Collect patient info	Has to leave seat and walk to collect the laptop	No need to leave seat	Test design
CPR	Has to leave seat and stand up to do CPR	Has to leave seat and stand up to do CPR	No preference
Communication to hospital	Has to leave seat and walk to reach the phone and sit to make the call.	No need to leave seat	Test design

5. Discussion and Conclusion

This paper has described (1) the development of a new design concept for an ambulance patient compartment and (2) the use of modeling and simulation to analyze the design concept in order to evaluate whether the design requirements were met. Two such requirements were discussed in this paper, both associated with adequacy of EMS providers' reach. Providers should be able to reach common equipment and supplies and most body parts of the patient while remaining seated and restrained. An initial graphical analysis showed that the new concept design offers the EMS provider better access to the patient, equipment, and supplies.

To facilitate modeling and simulation of emergency medical care, we decomposed the major functions carried out in the ambulance into a set of executable tasks. We then imported the initial design, represented as CAD models, into a human task modeling tool. This created a virtual environment suitable for simulation experiments. We used the results of those experiments to compare the EMS providers' performance in the new concept design against their performance in the traditional design. Those Institute of Standards and Technology or BMT Designers and Planners is intended or implied. And neither does the results showed that the new design satisfies more elements of the criteria.

This project has also shown that modeling and simulation analysis can be applied to reduce or eliminate the need to develop physical prototypes to test human performance. The proposed initial design will be refined and analyzed until we can recommend new design requirements for existing ambulance design standards.

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Certain commercial software systems are identified in this paper to facilitate understanding. No approval or endorsement of any commercial product by the National identification imply that these software systems are necessarily the best available for the purpose.

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