Designing Emergency-Medical-Service Helicopter Interiors Using Virtual Manikins

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Significant progress in computer graphics over the last three decades has led to advanced graphics software that increases the design process's efficiency and effectiveness. Because many design activities involve creating human-centered objects or systems, the process must take into account human capabilities and constraints. Such knowledge is particularly important in the design of work environments. Adjusting the work space to the worker must consider appropriate body dimensions and proportions. The data come from anthropometrics, an area of anthropology.

The Polish Medical Air Rescue (PMAR) ordered research in conjunction with purchasing emergency medical service (EMS) helicopters. A significant body of literature covers this topic, analyzing their configurations or internal layouts and the resuscitation activities performed in them. Nevertheless, the PMAR had difficulty finding precise anthropometric recommendations, so it conducted its own analysis.

As part of that analysis, we applied Anthropos ErgoMAX human-modeling software to cardiopulmonary resuscitation in an EMS helicopter. (For background on digital human modeling, see the sidebar.) We aimed mainly to determine, by anthropometric analysis, the appropriate dimensions for space and equipment, taking into account the Polish population's physical characteristics.

Anthropometry

Human dimensions and proportions have been subject to analysis since antiquity. Back then, the main interest was the quest for canons of proportions in art. The term "anthropometry" appeared in the 18th century, along with systematic research of human-body diversity. The engineering applications of human-body measurements date to World War II. The popular belief is that inappropriate design solutions in airplane construction led to many catastrophes, which initiated modern ergonomics. Collecting body measurements and studying how to use them to design military equipment have been important parts of this science.

The emphasis on fitting the machine to the human led to anthropometry. As part of this trend, researchers elaborated on many methods and techniques for collecting and processing measurement data in various populations. Furthermore, they developed principles and procedures for applying these data during work space analysis and design.

Usually, statistical data are available for both genders and various age ranges, and comprise height, breadth, depth, length, reach, and circumference measurements. More comprehensive databases might also provide angular ranges of motion for particular joints.

A standard ergonomic approach in using anthropometric data for design purposes involves adjusting solutions to the 95th (or 90th) percentile of the prospective users. So, most anthropometric databases provide human-body measurement values for the 95th and 5th percentiles. Some problems (for example, determining a stool's height) require applying the 50th percentile.

Figure 1 shows human models for various percentile heights. For a more extensive review of anthropometry development, see *Engineering Anthropometry Methods*.[1]

Our Method

We aimed mainly to provide anthropometrical recommendations that would allow the performance of critical rescue activities while serving as criteria for EMS helicopter selection. So, the required output included the set of minimal dimensions based on the human-body statistical data and some predefined premises.

We assumed that the helicopter participates mainly in primary missions. The PN-EN 13718-2

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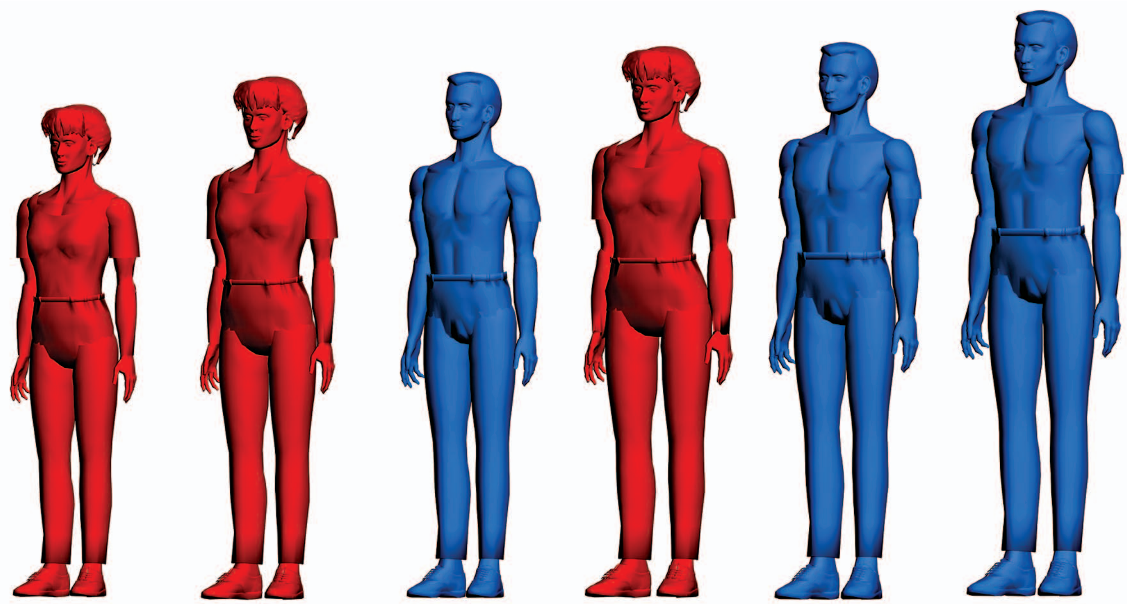

Figure 1. Human models generated in Anthropos ErgoMAX with heights of percentile values commonly applied in anthropometrical analysis.

standard contains definitions of EMS helicopters and primary missions.[2] In accordance with this standard, the helicopter should have a place for at least one patient on a stretcher and two members of a medically trained EMS team. We also assumed that the team might include both male and female Polish adults. The PMAR representatives defined the stretchers' positions and dimensions and the helmet dimensions.

Section 4.10.1 of PN-EN 13718-2 recommends ensuring "unconstrained access of the medically trained personnel to life-important patient(s) body segments, for example, head, chest, and abdomen."[2] Such access is necessary because EMS helicopters often transport patients in critical condition. So, EMS teams must be able to conduct cardiopulmonary resuscitation in the helicopters.

Resuscitation activities include manual indirect heart massage, tracheal intubation, and ventilation. Massage is the most important procedure and requires significant space. In adults, it involves rhythmic compressions of the chest wall to a depth of at least 5 cm, with a frequency of 100 per minute. The caregiver's arms must be straight, and his or her trunk angle should be about 45 degrees. Such a posture is a compromise between minimizing the energy expended for pressing the chest by exploiting upper-body weight and minimizing the energy expenditure for the return movements.

Tracheal intubation, from a modeling viewpoint, is decidedly more demanding than ventilation because it requires a forced posture that allows for correct placement of the tube. Ventilation doesn't require a forced posture and thus doesn't much affect the minimal space needed for resuscitation.

Our Ergonomic Approach

First, we employed the threshold manikin approach we described in the section "Anthropometry." It meant positioning extremely small (5th-percentile female) and extremely large (95th-percentile male) manikins in similar configurations. In ErgoMAX, we selected the Central European population. Comparing this group's dimension parameters with the anthropometric data for the Polish population[3,4] produced only minor differences in the basic dimensions. The Polish population was barely shorter—by two centimeters.

The simulations didn't take into account the somatotype or clothing. Instead, we employed 10-cm buffer zones. These zones represented the distance between objects in the medical cabin—for example, between chairs and between the chairs and the walls. This area included all the differences in dimensions for distinct somatotypes along with a surplus to account for clothing, which is commonly used in ergonomics.

We used the contours of a 95th-percentile male manikin and the equipment to determine the overall cubicoid envelope (bounding box). This ensured good ergonomics for the required rescue activities, for 95 percent of the population.

We constructed the simulated body postures for four stretcher mattress locations: 100 mm, 300 mm, 450 mm, and 520 mm from the medical-cabin floor. Moreover, our analysis took into account both

Digital Human Modeling

Originally, systems for modeling humans allowed only the creation of simple 2D manikins. However, some systems—for example, COMBIMAN (the Computerized Biomechanical Man Model) and Crew Chief—already supported ergonomic analyses such as assessing biomechanical loads. In the 1980s, systems for creating 3D human models arose—for example, SAMMIE (System for Aiding Man–Machine Interaction Evaluation). These systems could generate different percentiles of 3D individuals with various somatotypes, and they included algorithms for generating a field of view and reach boundaries.

The rapid development of computer hardware and graphics technology led to further advancements in CAD software and made it available on PCs. Simultaneously, digital human models' quality improved considerably. For example, compare the relatively simple manikins from Apolinex in Figure A with the manikins generated by Anthropos ErgoMAX in the main article. In addition, ergonomic-analysis tools have become more effective and efficient. Current human models not only have the desired statistical features but also wear clothes and look like real people. You can even obtain naturally shaped digital manikins by 3D-scanning a real human body (for example, with Ramsis).

Many commercial systems for ergonomics design (for example, the Boeman mannequin, Tadaps, and Ramsis) are standalone packages, with more-or-less developed functions focusing on human-body representations. Most often, the digital manikin is a geometrical model consisting of linked segments that designers can move. The resulting human models usually are exported to a specific CAD system equipped with full design capabilities, in which the rest of the project analysis takes place.

Other CAD systems implement digital-modeling software as a plug-in or subsystem. For example, ErgoMAX is available as a 3D Studio Max plug-in, Ramsis is a Catia plug-in, and Apolinex is an AutoCad subprogram. In these solutions, the human models are available at any time, directly in the CAD system, and are consistent with the designed virtual-environment models.

One of this type of software's latest features is inverse kinematics (for example, in ErgoMAX and Ramsis). This enables automatic determination of the kinematic chain joint angles (for example, the arm) necessary to reach a given target point. Another new capability is the application of finite elements (for example, in Ramsis). This method lets users foresee how the digital manikin would behave on the basis of the forces applied and the internal structure of the materials in the modeled environment. An example application is the modeling of vehicle crashes.

Figure A. Human models generated in the AutoCAD environment by the two versions of the Apolinex software, which was initially developed in the 1990s. Human models' quality has improved considerably over time.

For more on digital human models, see "Workload Assessment Predictability for Digital Human Models"[1] and *Ergonomic Software Tools in Product and Workplace Design.*[2]

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the chair variant of the stretcher with a patient transported in a seated position (as recommended in PN-EN 13718-2) and EMS personnel standing while loading and unloading a patient.

Using ErgoMAX

To simulate specific postures, we used ErgoMAX 6.0.2[5] within 3D Studio Max 6.0 (now Autodesk 3ds Max).

The human model. The ErgoMAX human model comprises 86 joints with a detailed spine model including 24 additional elements. The virtual manikin consists of six kinematic subsystems: two legs, two arms, the upper body, and the head. The human's graphical representation is supplemented by the appropriate motion limits for all available joints, which prevents unrealistic and infeasible postures.

ErgoMAX supports changing body parts' locations, which is necessary for modeling. Users first select a specific joint on the ErgoMAX picture, located in the software's Animation section. They can change the joint angle by entering an appro-

Figure 2. Digital human models in various predefined postures, with clothes generated in ErgoMAX. ErgoMAX offers predefined postures in seven categories: bagger (putting things into bags), bending, kneeling, lying, sitting, standing, and walking.

priate value or clicking on buttons to increase or decrease the angle. Any changes to angles appear instantly on the virtual manikin in 3D Studio Max views. Instead of changing the joint settings manually, users can employ ErgoMAX's inverse-kinematics algorithms. In this case, the software automatically computes the joint angles on the basis of physiological restrictions and target points specified for the extremities and eyes.

ErgoMAX also offers predefined postures in seven categories: bagger (putting things into bags), bending, kneeling, lying, sitting, standing, and walking (see Figure 2). Predefined hand postures are also available. The posture definitions are stored in files; users can create and save posture files to use in other projects.

Because ErgoMAX is integrated into 3D Studio Max, practically all functions and plug-ins from the rich graphical environment can be used with the created digital individuals. Some basic functions include moving, rotating, and rendering manikins. ErgoMAX also includes predefined clothing textures, which are available in the 3D Studio Max mapping module. Users can freely modify them and easily apply them to the human models by simply dragging them onto a model. Figure 2 shows some possibilities.

More sophisticated features are available; for instance, users can employ inverse-kinematics movements along with the standard 3D Studio Max animation functions to create movies. They can also integrate digital individuals created by ErgoMAX with 3D Studio Max's Character Studio Biped system, which can animate walking, running, skipping, and so on.

Anthropometry. The ErgoMAX human models are based on real anthropometric databases of 10 nations and 18 world regions, covering both genders, five percentile levels, and 12 age ranges (but only for the German population).

Users can set additional properties. For example, three types of legs-versus-torso proportions (normal; short legs, long torso; and long legs, short torso) and three lengths of arms (normal, long, and short) are available. In addition, the somatotypes specify body size in nine locations between the shoulders and the stomach. There are nine grades, from extremely slim (–4) to extremely large (+4). Finally, the acceleration parameter lets users generate manikins with prognosed anthropometric properties. The anthropometric-data simulation is possible for the years 1980 through 2030. Figure 3 presents several manikins.

Ergonomic analysis. ErgoMAX supports a variety of ergonomic analyses. First, because the generated manikins are based on real anthropometric data, you can use them to analyze reachability and accessibility. This involves checking what space is available for a given percentile individual's hands, legs, feet, and so on. Inverse kinematics can assist these analyses.

ErgoMAX also enables static posture analysis. Five indices of postural discomfort are available: the discomfort index, posture index (angular

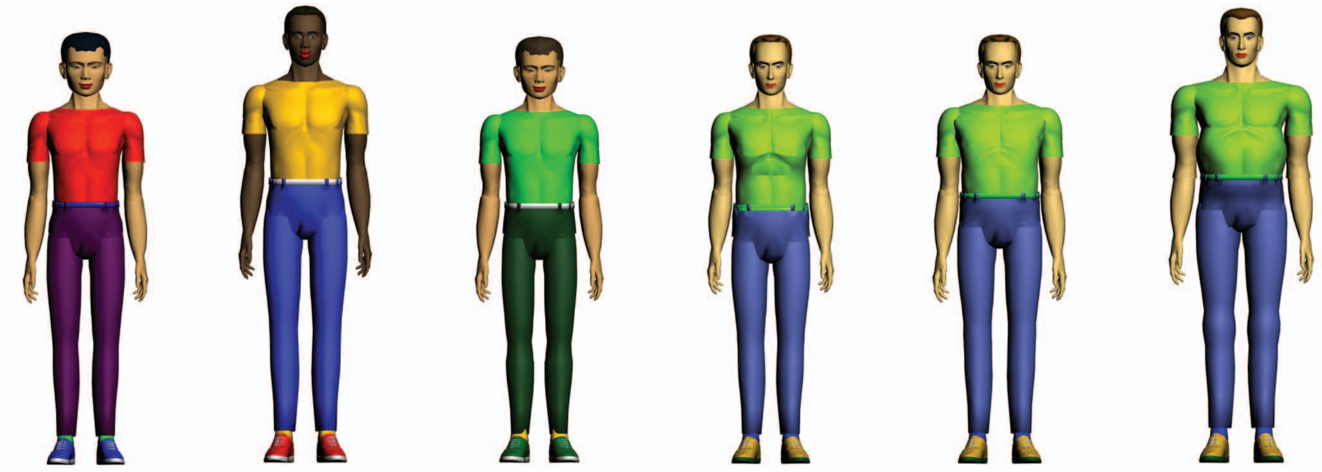

Figure 3. Example manikins with 50th-percentile body height from diverse populations generated in ErgoMAX. The three German manikins have various somatotypes and proportions. Users can indicate body proportions, somatotypes, and acceleration.

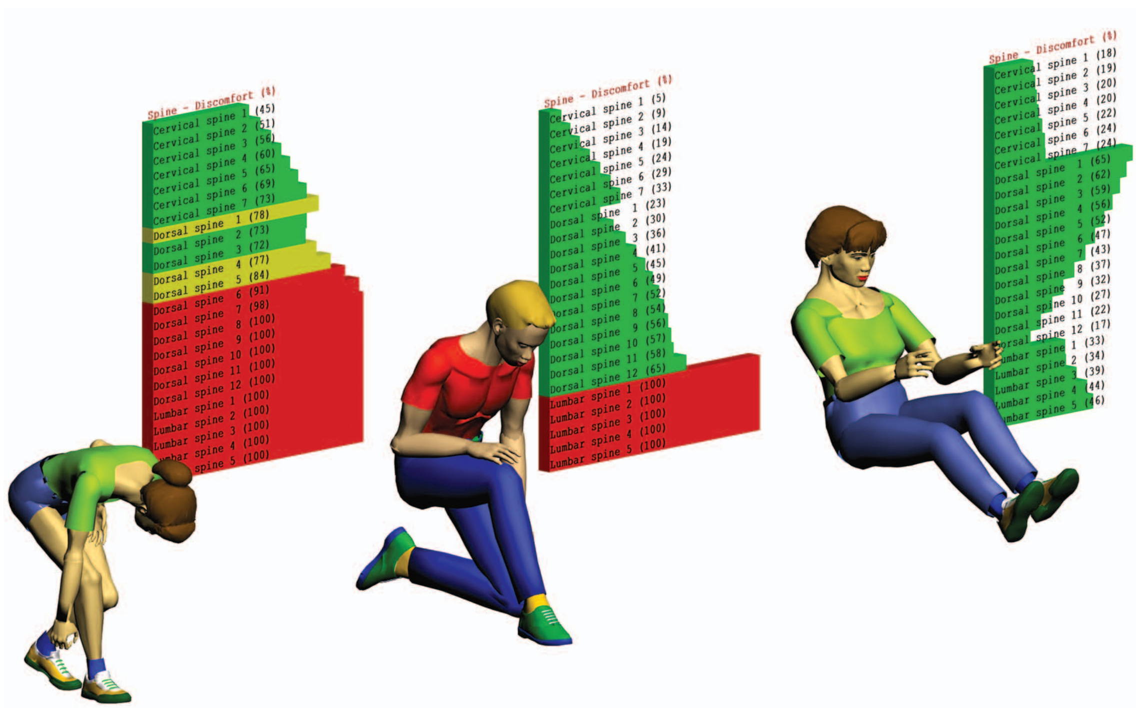

Figure 4. ErgoMAX discomfort index values for three static postures. Posture load analysis takes into account support for the selected body segments and assignment of weights to the hands, feet, and head.

joint position within motion limits), joint resistance, joint torque, normal forces, and difference between the current posture angles and a NASA neutral posture.[6] Posture load analysis takes into account support for the selected body segments and assignment of weights to the hands, feet, and head. All measures fall into three zones according to the increasing load level: green (<70 percent), yellow (71–90 percent), and red (>90 percent). Figure 4 presents discomfort index values for spine segments in three postures.

You can also simulate and analyze the human model's field of view. ErgoMAX uses 3D Studio Max's built-in cameras to simulate the human visual system (see the top-right view in Figure 5).

Results and Discussion

EMS helicopters differ from standard helicopters

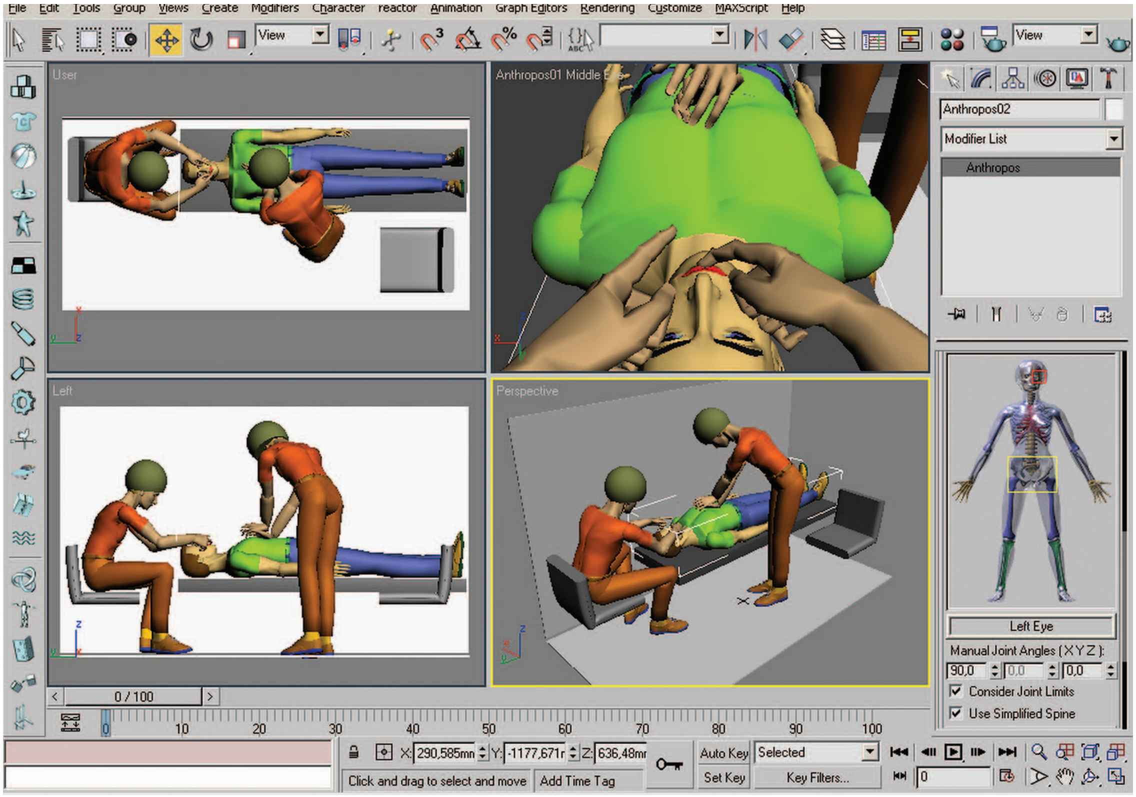

Figure 5. A screenshot of the ErgoMAX plug-in interface in the 3D Studio Max environment. ErgoMAX uses 3D Studio Max's built-in cameras to simulate the human visual system.

Table 1. Bounding-box dimensions and EMS personnel trunk angles for simulated activities.

Simulation type	Manikin percentile and gender	Mattress surface height	Minimal bounding-box dimensions (mm)*		EMS personnel trunk angle (°)
			Width	Height	
Indirect heart massage and tracheal intubation	5th, female	100	1,400	1,160	56
		300		1,210	60
		450	1,300	1,360	52
		520		1,560	33
	95th, male	100	1,600	1,400	50
		300		1,420	70
		450	1,300	1,540	58
		520		1,690	48
Sitting patient	5th, female	450	1,300	1,400	—
		520		1,430	—
	95th, male	450		1,500	—
		520		1,540	—
Standing EMS personnel	5th, female	520	1,300	1,720	—
	95th, male			2,000	—

In each case, the length was 2,820 mm.

in their internal layout and equipment. However, both types of helicopters have the same dimensions and thus the available interior space, although these features differ across particular models. According to PMAR representatives, the medical equipment's location is less important than the space needed for resuscitation. So, our analysis took into account only a standard stretcher, two seats, and digital manikins. Thus, our results are more general and allow for purchasing the equipment that fits best in the remaining space.

Table 1 presents the breakdown of the appropriate envelopes (bounding boxes) for the studied variants. Figures 5 and 6 show example analyses.

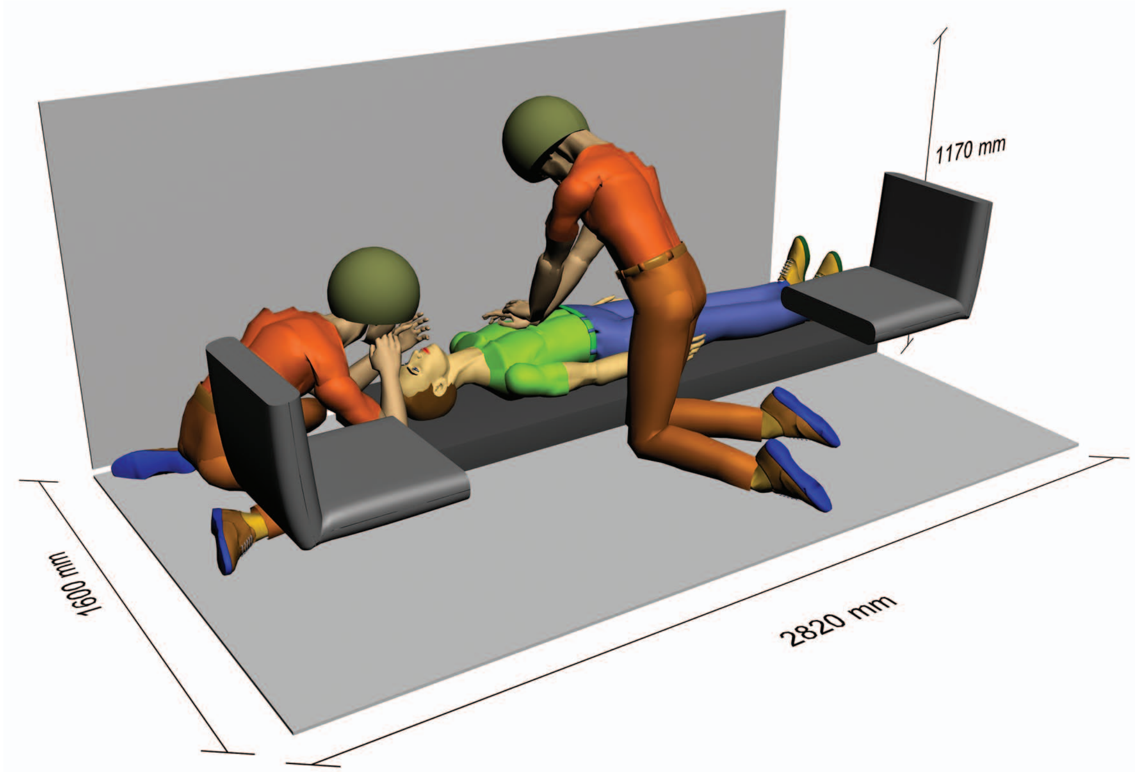

Figure 6. Two 50th-percentile males performing resuscitation. The figure also presents the overall bounding-box dimensions with a mattress on the floor.

Table 2. Minimal medical-compartment heights (mm) for simulation of indirect heart massage and tracheal intubation on a male manikin.

Manikin percentile	Measurement type	Distance	Distance and buffer zone
50th	Floor to ceiling	1,070	1,170
	Mattress to ceiling	970	1,070
95th	Floor to ceiling	1,140	1,240
	Mattress to ceiling	1,040	1,140

The envelopes for the 95th percentile enable persons with almost any anthropometric features to perform resuscitation in good ergonomic conditions. Using the values for 5th-percentile females would mean that as many as 95 percent of randomly chosen EMS personnel wouldn't be working in optimal conditions. An intermediate solution based on the 50th percentile denotes adjusting the medical compartment space to half of the given population.

We also performed investigations that took into account constraints related to the class of helicopters the PMAR selected—small helicopters that can land in small areas. We aimed to determine the minimal acceptable distance between the top stretcher mattress surface and medical compartment ceiling. Anything less than that distance would make resuscitation practically impossible because EMS personnel couldn't straighten their upper extremities. Table 2 presents the results for average and tall males.

Table 1's last column shows the trunk angles of EMS personnel performing heart massage, which are available in ErgoMAX. Considering this criterion, the best stretcher positions were at a height of 450 mm for short males and 520 mm for tall males. If the stretcher was on the floor, the body trunk angles wouldn't differ significantly from the recommended value. However, this solution would place considerable pressure on delicate knee structures, which could necessitate knee pads.

We ran into several difficulties during our analysis. For example, the Polish population data in ErgoMAX were outdated. Although ErgoMAX lets you specify custom digital manikins, this requires plenty of effort. To address this issue, we compared the data for the available populations with more current Polish anthropometrical data and chose the most similar population.

Also, the available inverse kinematics works quite well in 2D views, but using it in the 3D view is impossible. Moreover, turning this option on and off resets the manikin posture. Selecting a predefined posture and making appropriate adjustments by changing specific joint settings was much faster than using inverse kinematics.

In addition, ErgoMAX doesn't automatically calculate envelopes of multiple objects, so we had to obtain them manually with 3D Studio Max's tape tool. Moreover, no collision-detection algorithms are available. Such features would improve the software's usability and speed up anthropometric analysis.

Despite these shortcomings, ErgoMAX enabled us to successfully obtain the required results. The recommendations made on the basis of this analysis played an important role in deciding which helicopters to acquire. The analysis results also served as crucial evidence in litigation regarding the purchase decision's validity.

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