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International Journal of Occupational Safety and Ergonomics

ISSN: 1080-3548 (Print) 2376-9130 (Online) Journal homepage: http://www.tandfonline.com/loi/tose20

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To cite this article: Vesna K. Spasojevic Brkic, Zorica A. Veljkovic, Tamara Golubovic, Aleksandar Dj. Brkic & Ivana Kosic Sotic (2015): Workspace Design for Crane Cabins Applying a Combined Traditional Approach and the Taguchi Method for Design of Experiments, International Journal of Occupational Safety and Ergonomics, DOI: 10.1080/10803548.2015.1111713

To link to this article: http://dx.doi.org/10.1080/10803548.2015.1111713

Accepted author version posted online: 14 Dec 2015.

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Publisher: Taylor & Francis & Central Institute for Labour Protection – National Research Institute (CIOP-PIB)
Journal: *International Journal of Occupational Safety and Ergnomics*
DOI: 10.1080/10803548.2015.1111713

Workspace design for crane cabins applying a combined traditional approach and the Taguchi method for design of experiments

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Abstract

Procedures in the development process of crane cabins are arbitrary and subjective. Since approximately 42% of incidents in the construction industry are linked to them, there is a need to collect fresh anthropometric data and provide additional recommendations for design. In this paper, dimensioning of the crane cabin interior space was carried out using a sample of 64 crane operators' anthropometric measurements, in the Republic of Serbia, by measuring workspace with 10 parameters using 9 measured anthropometric data from each crane operator. This paper applies experiments run via full factorial designs using a combined traditional and Taguchi approach. The experiments indicated which design parameters are influenced by which anthropometric measurements and to what degree. The results are expected to be of use for crane cabin designers and should assist them to design a cabin that may lead to less strenuous sitting postures and fatigue for operators, thus improving safety and accident prevention.

Key words: crane cabin workspace, anthropometric measurements, design of experiments, contribution ratio, contribution ratio index

1. Introduction

The construction industry has been recognized historically as having higher rates of fatality, injury, and illness than other industries. Some of the health hazards among operators using heavy construction equipment are: whole-body vibration, awkward postural requirements (including static sitting), psychosocial factors, dust, diesel exhaust, asphalt and/or welding fumes, noise, temperature extremes, time pressure, and shift work [1,2]. Working posture is believed to be influenced by many factors including workstation layout, location and orientation of work, individual work methods, and workers' anthropometric characteristics [3,4].

Cranes are a central component of many construction operations and are involved in a large number of deaths; in fact, estimates suggest that cranes contribute to as many as one-third of all fatalities associated with construction operations [5]. Beavers et al. [6] reported that cranes are one of the major

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causal factors of fatalities in the construction industry. The construction industry has the third highest fatality rate among the major industrial sectors with 13.3 fatalities per 100,000 workers; only agriculture and mining industries have higher rates [6].

Ergonomic analysis is widely recognized as an important part of the design and evaluation of products, jobs, tools, machines and environments for safe, comfortable and effective human functioning. However, according to Chaffin [7], although over 90% of the system designers and engineers in Europe whom he surveyed recognized the need to consider ergonomics early in the product development process, fewer than 10% of engineering degree recipients in the United States have completed even one course in human factors and ergonomics. According to [8], population grouping based on shape is still a technical challenge, while population grouping based on key dimensions is a good strategy for the fitting design. Given this situation, a product or machine designer is highly enlikely to make appropriate decisions about the postures and motions of various people.

To this end, in this work, critical impact factors for crane cabin interior space design have been identified and subjected to ergonomic analysis. Identification by applying the Taguchi approach and design of experiments (DOE) was performed based on a real sample. Given that the goal of the study is to identify impact factors but not to determine the optimality and cost-effectiveness of a developed model in terms of quality, the investigations involved a larger number of output quantities related to anthropometic measurements obtained from real data on crane cabin operators working in Serbia. The results of these investigations should serve as guidelines for crane cabin designers on the importance of certain factors in optimizing crane cabin interior.

Following the introduction in section 1, section 2 through the analysis of previous research points out the need for further optimization of the crane cabin interior in line with operators' needs. Section 3 presents the methodology and its results for the dimensioning of the crane cabin interior by applying the Taguchi approach and DOE, while section 4 gives the results analysis. Section 5 presents the discussion of the results about dimensioning crane cabin interior by applying the Taguchi approach and DOE,and section 6 offers the conclusions.

2. Literature review

The results of the study [9] provide evidence to strongly recommend persons with a history of back complaints not to seek employment as crane operators. Although previous research demonstrated that 42% of all incidents are linked to crane cabin design [10], very little research has been done in the field of the assessment of the anthropometric convenience of crane cabins. The importance of studying this problem greatly exceeds the number of published papers in this area.

There is certainly a need to minimize or remove the anthropometric mismatch, to enhance the visibility for a crane cabin operator in such an enclosed workspace, to improve the layout of the components and controls within the enclosed workspace, and to improve work posture minimizing risk of muscosceletal disorders.

The percentile method is traditionally used in product design to fit the desired percent of population. The utilization of percentiles should ensure that the product matches the population between the 5th and the 95th percentile, thus matching 90% of the population of interest. However, when it comes to the product design problems which involve more than one dimension, this method exhibits significant disadvantages [11]. Firstly, in real life there are no humans whose dimensions are between the 5th and the 95th percentile, but percentiles are combined in different anthropomeasurements. Then, when the design problem includes more than one dimension, using percentiles actually comprises a significantly lower percentage of the population than the desired 90%. Thirdly, in terms of dimensions this method takes only overall large and overall small models for human border line models with reference to dimensions, disregarding populations with different body configurations, e.g., extremely tall people with extremely narrow shoulders. The aforementioned leads to the

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conclusion that in solving design problems that involve a number of dimensions some other method should be used instead of the percentile method. Multivariate methods such as factor analysis and Principal Components Analysis have been employed in solving such problems for several decades [12]. However, Kowalski in [13] has argued that multivariate techniques often do not allow the effective description of a body of data and that a great deal of additional research – both from the standpoint of theory and that of practice – must be done before multivariate analysis can fulfill the promise it holds for anthropometry. As can be seen, both unvariate and certain multivariate methods are criticized in previous literature, so this paper aims new at new methodology – an experiment run via full factorial designs using a combined traditional and Taguchi approach.

Crane cabin design requires the implementation of a large number of standards. NASA [14] has prepared guidelines covering all standards for overhead crane cabs in the aim of helping to reduce the potential for human error due to design. Even after that, Bovenzi et al. [15] found that 40–60% of operators feel low back pain, while Kittusamy & Buchholz [1] also concluded that awkward posture during the operation of heavy construction equipment is a consequence of improper cab design and work procedures, emphasizing that poor visibility of the task, limited room in the cab, excessive force required to operate levers/pedals, and improper seat designs are some of the characteristics of a poorly designed cab. Even when they are treated, workers experiencing muscoskeletal difficulties, may not perform as effectively as they used to and may have to face the risk of losing material assets and psychological well-being they would usually acquire by working [16]. According to Côté et al. [17] tall crane operators are probably the most vulnerable workers. Recently, Ray and Tavari [18] have found many misfits of even the 50th percentile crane operator population on site with the existing work system.

The development of quantitative models that realistically predict how people normally move and interact with systems presents a challenge in the field of ergonomics, since it is very ambitious to attain a dynamic three-dimensional (3D) model with all attributes with sufficient level of sophistication in biomechanical construct as well as a reasonable efficiency in computation [19]. Most previous models were compromised in the sense that they missed one or more desirable attributes [19,20].

It can be concluded from the above mentioned facts,it can be concluded that procedures in the development process of crane cabins are still arbitrary and subjective, and thus require further investigation. This paper aims to help crane cab designers by providing guidelines about the significance of some impact factors to be considered in crane cab interior optimization on the grounds of collected real data.

3. *Dimensioning of crane cabin interior workspace by applying a combined traditional approach and the Taguchi method for design of experiments*

In this work, dimensioning of the crane cabin interior workspace was carried. The goal was to define the boundary values for the workspace based on the sample of collected anthropometric measurements of crane operaters in the Republic of Serbia. The share of crane operators in the general Serbian population is quite low, so our sample comprised 64 participants, which is considered to fulfill the requirements for a representative sample of such a population. A stratified sample that is representative for the intended user group is very important [21]. Previous research [1,15,17,18] used even smaller samples. Standard anthropometric instruments and procedure were used. All dimensions were determined with working clothes and footwear. All operators wear clothing of moderate thickness. All participants were male, with a mean (*SD*) age of 47.64 (10.34) years. The measurements were taken in several hydropower plants, belonging to Electric Power Industry of Serbia, located throughout Serbia, where a large number of cranes are stationed. The sample characteristics ensure the intended representativeness. The sample was formed by means of the static anthropometry method.

The investigations comprised ten measures of the crane cabin operator's workspace such as: seat length and width, sitting length, seat height, backrest width, height and angle, and control panel height, length and width. The design of these workspace measures was performed based on anthropometric

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measurements that included: leg length, upper leg length, lower leg length, hip width, torso and arm length, arm reach, shoulder width and body mass index (BMI).

The investigations were carried out using design of experiments (DOE) and orthogonal arrays. The difference between this and other methods lies in the fact that the experiments are designed for the parts of the workspace but not the coordinate system considered.

3.1 Theoretical assumptions and experimental investigations

The invesigations referred to determining the boundary measures based on the effect some anthropometric measurements have on them. Ten critical workspace measures were identified and observed as factors, where the output quantities, i.e., the corresponding anthropometric measurements represented the effects on those factors.

The experiment was conducted via the design of experiments technique using a combined traditional approach and Taguchi DOE. Two-level factorial designs were employed in adequate designs. To design the experiments, traditional two-level arrays were used, while the experiments were observed as full factorial designs because in these experiments it is easier to extend the experiment by the foldover method without any replicates should additional investigations be necessary.

Data analysis was performed using the analysis of variance for two-level factorial designs. The benchmark for identifying influential anthropometric measurements on some workfield effects was determined via the p valueof the test, according to the following criteria:

- if $p < 0.01$, there is an effect (*),
- if $p < 0.05$, there is a significant effect (**) and
- if $p < 0.001$, there is an extremely significant effect (***)

Post-analysis of the experimental results referred to determining contribution ratios. A contribution ratio represents the “separation of pure variation in factorial effect” [22]. In practice, it indicates the percentage of some factorial effect on total variation. The consequence is that the management of variation and experiment output quantities depends on critical factors management [23] and is obtained by

$$\rho_i = \frac{SS_{EF_i}}{SS_T} \cdot 100(\%), \tag{1}$$

where ρ_i = contribution ratio of factorial ith effect, SS_{EFi} = sum of squares for factorial effect, SS_T = total sum of squares in the experiment.

The Taguchi method was chosen because of the robustness of initial assumptions on the independence of factors and the dispersion of random error following normal distribution [22] and analysis of experimental results through contribution ratio. This was possible to conduct given that in their structure Taguchi’s orthogonal arrays correspond to full factorial experiments [24].

3.2 Experimental design

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An design of three independent two-level full factorial experiments was employed. The first experiment examined 4 factors, while the second and third examined 3 factors each. The criterion for data classification was height as a blocking factor, which was allocated in the column with the highest interaction. The input variables in the experiments were the workspace values. Output variables were the anthropometric measurements for 64 crane cab operators.

The experiments and their sizes are shown in Tab. 1.

INSERT Table 1.

The input factors in the experiments and their abbreviations are given in Tab. 2.

INSERT Table 2.

The abbreviations for anthropometric measurements are given in Tab. 3.

INSERT Table 3.

The input quantities per experiment are shown in Tab. 4.

For each effect examined in experiments E1–E3 a corresponding output variables is obtained which depends on one of the input variables in the experiment, i.e., on a crane cabin operator’s anthropometric measurement having a potential effect on it, defined as

$$\begin{aligned} y_{(E1)EF_i} &= f\left(x_L, x_{LL}, x_{UL}, x_{HW}, x_B\right) \\ y_{(E2)EF_i} &= f\left(x_{TL}, x_{SD}, x_{AL}, x_{AR}, x_B\right) \\ y_{(E3)EF_i} &= f\left(x_{HW}, x_{TL}, x_{SD}, x_{AL}, x_{AR}, x_B\right) \end{aligned} \tag{2}$$

The input and output quantities of the experiments are displayed in Figures 1(a) and 1(b).

INSERT Figure 1(a).Main factorial effectsshown in the cabin *xz* plane

INSERT Figure1(b).Main factorial effects shown in the cabin *xy* plane

The experiment involved the allocation of factors in the corresponding factorial designs, depending on factor allocation in the matrix basic columns and determination of level for factors (Tab. 4).

INSERT Table 4.

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All factorial effects examined in the experiments (the main effects and all their interactions) are presented in Tab. 5.

INSERT Table 5.

4. Analysis of experimental results

The analysis of the experimental results identified from maximal number of screened anthropometric quantities where blocking was done according to the subjects' height. Given that the blocking factor coincides with the highest-row interaction in the experiment, it does not have any effect. Thus, in the first experiment, four replicates each were designed for each output quantity under study. In the second and third experiments, the number of replicates per experiment proved to be 8 for all output quantities.

The initial results indicated that the dispersion error is too large, so there are no influential factors. For this reason, the number of replicates was iteratively reduced from the maximum number (4 or 8) to the minimum possible number, i.e., 2. Reduction to a single replicate was not done because for the unreplicated factorial designs is not possible to conduct post-analysis through the contribution ratio (Taguchi, 1991).

Reduction in the number of replicates was performed by eliminating the middle measures of the blocking factor. The criterion for the choice of the optimal number of replicates was the maximum contribution ratio of the main factorial effects in the experiment. It proved that the optimal number of replicates for all designs is two. Descriptive statistics were calculated for all replicates and output values, i.e., the mean, median, SD and coefficient of variation were determined. In all cases the values of the variation coefficient were below 30%, and mean and median were close. Hence, distribution of data could be assumed to be symmetric and homogeneous, i.e., the data show normal distribution.

During the study 97 experiments were conducted for all three designs and their outputs. Further analysis involved 16 experiments, given that examinations were conducted for all antropometric measurements which are the outputs of individual factorial designs, i.e., 5 analyses were carried out for E1 and E2 and 6 for E3.

Values of descriptive statistics for the individual experiments with two replicates are given in Tables 6–8.

INSERT Table 6.

INSERT Table 7.

INSERT Table 8.

Given the large number of conducted experiments, design example is given for E2 (Tab. 9), where all resulting values are shown for the output anthropometric measurements under experimental study.

INSERT Table 9.

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In cases where in E2, e.g., the torso length impact on the observed workspace measures, the design is shown in Tab. 10.

INSERT Table 10.

For the observed design, the results are shown in Tab. 11.

INSERT Table 11.

For other designs the presented results involve *p* values and the contribution ratios for individual outputs of factorial designs.

The results of the influential anthropometric measurements on the factorial effects in E1 (seat length, sitting height, seat width and height as well as their interactions) are displayed in Tab. 12.

INSERT Table 12.

The results of the influential anthropometric measurements on the factorial effects in E2 (seat angle, control panel height, backrest height, and their interactions) are presented in Tab. 13.

INSERT Table 13.

The results of influential anthropometric measurements on factorial effects in E3 (seat angle, backrest height, and their interactions) are shown in Tab. 14.

INSERT Table 14.

The benchmark for the choice of critical influential anthropometric measurements on the operator's workspace was a contribution ratio, despite the fact that *p* values can indicate extremely significant factorial effects their real share in the variation was determined by the contribution ratio. In E2, for example, torso length has an extremely significant effect on determining the quantities for control panel height and backrest height. Consequently, by using the *p*-value criteria, it could be inferred that regulating these two factors is of equal importance. However, when contribution ratio is considered, it proves that the effect of torso length's on the choice of control panel height is 6.27%, but its effect on the choice of backrest is 91.1%.

5. Discussion of experimental results

Since there are several output values for each experiment, there is a two-way dependence in the results analysis. Thus, one anthropometric measurement can affect several workfield parameters and one workfield parameter can be affected by several anthropometric measurements.

Considerations included only the effects of some anthropometric measurements' effects on the main parameters of the workspace, because their values can be changed. It should be noted that there are effects of interactions between these measurements which are worth of consideration in the design process

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(Tables 12–14). The effects of individual anthropometric measurements on individual dimensions of the workfield are expressed via the contribution ratio, for E1, E2 and E3 in Tab. 15.

INSERT Table 15.

Contribution ratio values were obtained for each of the five experiments conducted of the E1 and E2 designs and for each of the six experiments for the E3 design, depending on the anthropometric measurements' values.

Given that the contribution ratios refer to the individual anthropometric measurements related to the individual experiments of the factorial designs E1, E2 and E3, to establish their real effect on each part of the workspace, their reduction was done to the individual examined factors by defining the contribution ratio index. The contribution ratio index for a certain effect may be

$$In\left(\rho_{EF_i}\right)=\frac{\rho_{EF\left(x_{ij}\right)}}{\sum_{j=1}^{m}\rho_{EF\left(x_{ij}\right)}}\cdot 100(\%), i=1,...,k, j=1,...,m_j, \quad (3)$$

where $\rho_{EF\left(x_{ij}\right)}$ = contribution ratios of the individual output quantities of the observed experiment of the *i*th effect, *k* = the number of factors in the observed experiment, *j* = anthropometric measurement (output), m_j = the number of anthropometric measurements that are output quantities of the observed experiment.

INSERT Figure 2.Influence of anthropometric measurements on individual factors in E1 (a) seat length, (b) sitting length,(c) seat heigh and (d) seat width

In the factorial design for E1 (Fig. 2) when which anthropometric measurements affect seat length is considered, it proven that the influence of the upper leg length is the highest (98.8%), but leg length also has some effect (1.2%). It should be noted in the conducted experiments both measurements result in identical $p < 0.001$ (Tab. 11).Lower leg length has major influence on sitting length (95.2%), as well as leg length (4.77%). The influence of anthropometric measurements is more evenly distributed when sitting seat width is considered. It depends for the most part on BMI (40.9%) and hip width (34.77%).

INSERT Figure 3.Influence of anthropometric measurements on individual factors in E2 (a) backrest angle (b) control panel height, and (c) backrest height

In the factorial design for E2 (Fig. 3), when the operator's seat angle is considered, the contribution ratios themselves, i.e., the output variables affecting them are not large, (23%), therefore the sitting angle can be taken as a non-influential factor. Irrespective of this fact, when the anthropometric measurements affecting it are considered, it is proven that BMI has almost absolute priority (97.2%), whereas the operator's torso length participates with 2.8% only. As for control panel height, it is predominantly influenced by arm length (61.94%) and arm reach (30.97%), which accounts for 90% of influence, which should be considered in the design of control panel height, as well as a small degree of influence from torso length (7.09%). The operator's backrest height is largely influenced by torso length (70.09%), but shoulder width and BMI also exert influence, (18.14%) and (11.76%).

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INSERT Figure 4.Influence of anthropometric measurements on individual factors in E3 (a) control panel width, (b) backrest width, and (c) control panel length

In the third factorial design, i.e., E3 (Fig. 4), the influence of anthropometric measurements on control panel width can be considered negligible, however it is for the most part affected by BMI (92.79%). Backrest height is primarily affected by shoulder width (58.91%) and hip width (21.12%), but arm length (12.6%) should not be neglected either. Control panel length is affected by arm length (45.45%) and arm reach (33.55%), as well as torso length to a lesser degree (26.01%).

5.1. Workspace design for crane cabin based on experimental results

Based on the experimental results approximate measurements for crane operator workspace could be proposed according to data on anthropometric measurements in the Republic of Serbia. The choice of factor levels is influenced by the contribution ratio of anthropometric measurements. Furthermore, the mean and median values are considered in order to adapt the initial measurements to crane operators in the Republic of Serbia.Although it is not obvious, BMI has an important influence. The BMI of crane operators in Serbia varies from 20.75 to 38.6, where more than 80% of operators can be categorized as overweight or obese.

Seat length, which is mostly influenced by upper leg length with a contribution ratioof 76.35%, should be closer to the lower value that amounts to 400 mm and always under 500 mmso as to be able to accommodate operators with minimal values of upper leg length. This dimension is in accordance with Standards No. EN 547-3:1996+A1:2008[24] and EN 894-4:2010[25], although they are based on percentiles. The seat must be adjustable according to Standard No. EN 13557:2003+A2:2008 [26], but theresults of this survey show that an adjustment of 200 mm horizontally and 110 mm vertically is required in order to accommodate all operators in the sample. Sitting lengthis strongly influenced by lower leg length with a contribution ratio of 74.02, and thanks to chair adjustability could also have a lower value of 205 mm. Finally, seat height, influenced by leg length with a contribution ratio of 81.32%, should have both values (340 and 450 mm) to accommodate all operators.

Seat width is mostly influenced by hip width and BMI (25.09 and 29.52%, respectively) and should have a higher value that equals 550 mm. Backseat width should be designed according to shoulder width (contribution ratio of 71.57%), with values no greater than 590 mm. Backseat height depends mostly on torso height (91.1%), and therefore should be designed in accordance with the lower value of 550 mm in order to accommodate shorter crane operators. Although there was no headrest in the measured crane cabins, it should also be considered, but this extends beyond the scope of this research paper. The backseat angle should also be adjustable, having90^0 and 104^0 values or even more due to the high values of BMI (22.94%).

Due to the impact of arm length and reach (contribution ratios of 69.98 and 84.38%, respectively), the control panel length should have a lower value – 600 mm.Control panel width, with the influence of a high BMI (contribution ratio of 33.45%) should be at higher level of factor, i.e., at least 250 mm. Control panel height depends onarm length and reach (54.77 and 27.39%) and also on seat height and should have the lowest value of 650 mm, preferably around 700 mm. Control panel height is in accordance, in an anthropometric sense, with EN 14738:2008 [27].

The values described in this section are shown in Table 16.

INSERT Table 16. Factor values for workspace design based on experimental results

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6. Conclusion

This paper provides a framework for crane operator's workspace design based on the results from a sample of crane cabin operators' anthropometric measurements, in the Republic of Serbia.

For the needs of the anthropocentric design of operators' workspace, the importance of each factor, although very important, is not equal, as it has been shown in the paper.

The experiments carried out have shown that the determination of seat length is influenced by upper leg length, sitting length by lower leg length, seat width by BMI and hip width, and sitting height by leg length. Although the seat angle can be considered a non-influential factor, its choice can be affected, if necessary, by BMI.The design of control panel height depends on arm length and reach. Seat height depends on torso length, but shoulder width should not be disregarded either. Control panel width is not influential when viewed within the framework of the designed experiments, and is influenced by BMI. The choice of seat width is determined by shoulder and hip width, but arm length may be also considered. Control panel length depends on arm length and reach as well as on torso length. The mutual influences of anthropometric measurements exceed the scope of this work, however, they should be considered in workspace design, especially when it comes to BMI, as the results of this survey show.

The results of this survey should serve crane cabin designers and producers to troubleshoot the dilemmas they encounter, and especially to obtain a cabin thus leading to at may lead to less strenuous sitting postures and fatigue, thus leading to improved safety and accident prevention.

The limitations of this investigation lie in the fact that the sample was collected from the crane cabin operator population working only in the Republic of Serbia, so one of the proposals for further research is the monitoring and investigation of antropometric measurements in the crane operator population from various geographical regions and other countries. Comparing this to available research in the field, the mean and standard deviation values of 1750.30 and 59 mm for the height of crane operators in Serbia are close to the values of 1765 and 74 mm gained by Burdorf et al. [9] on a smaller data sample in the Netherlands, and to those of 1780 and 68 mm obtained by Bovenzi et al.[15] also on a smaller set of data in Italy.

Also, another very important problem in the design of workspace is the interaction between anthropometric variables which ultimately leads to a considerable reduction in the size of the accommodated population. So, it is also proposed that further investigations involve the analysis of factorial interactions, as well as a comparison between countries and geographical regions for the sake of unification on the part of the manufacturers.

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Acknowledgment

This work is supported by a grant from the Eureka E!6761 and TR 35017 project.

Figure 1. Main factorial effects shown in the cabin (a) *xz* plane, (b) *xy* plane
Note: BA = backrest angle, BH = backrest height, BW = backrest width, CH = control panel height, CL = control panel length, CW = control panel width, LS = sitting length, SH = seat height, SL = seat length, SW = seat width.

Figure 2. Influence of anthropometric measurements on individual factors in E1 (a) seat length, (b) sitting length, (c) seat height and (d) seat width.
Note: B = BMI, HW = hip width, L = leg length, LL = lower leg length, UL = upper leg length.

Figure 3.Influence of anthropometric measurements on individual factors in E2 (a) backrest angle (b) control panel height, and (c) backrest height
Note: AL = arm length, AR = arm reach, B = BMI, TL = torso length, SD = shoulder width.
Figure 4.Influence of anthropometric measurements on individual factors in E3 (a) control panel width, (b) backrest width, and (c) control panel length
Note: AL = arm length, AR = arm reach, B = BMI, TL = torso length, SD = shoulder width.

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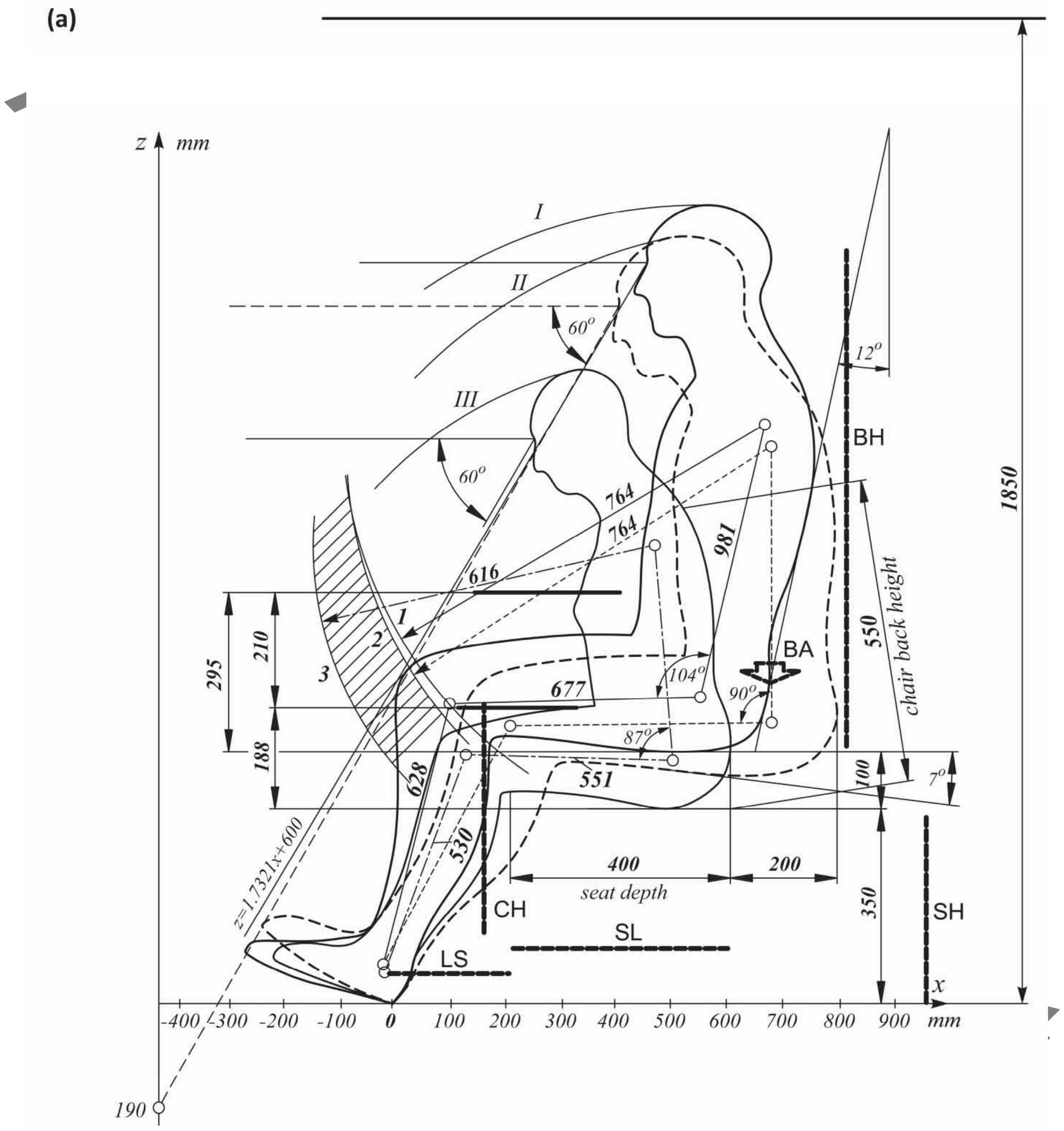

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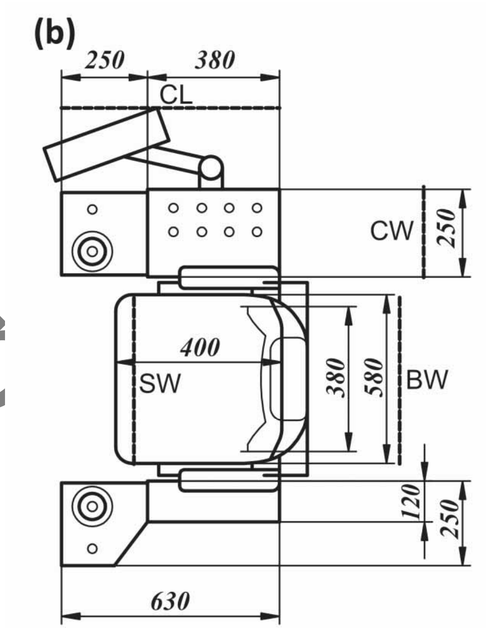

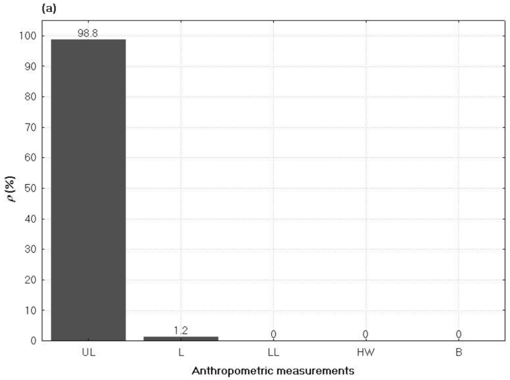

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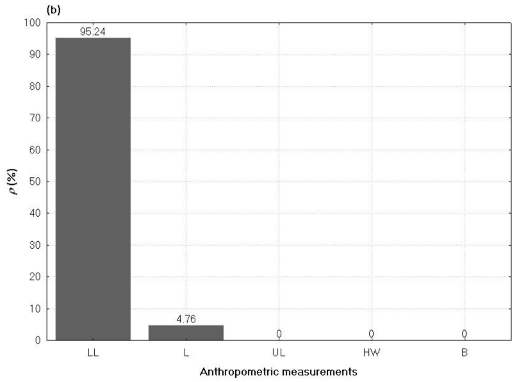

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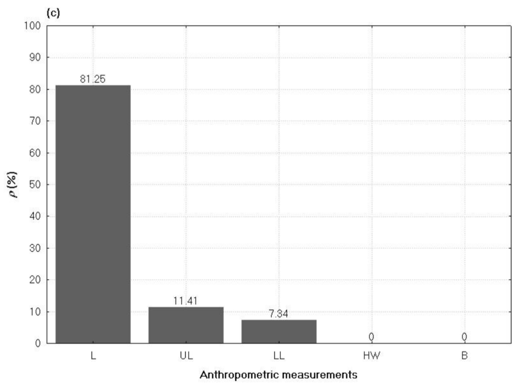

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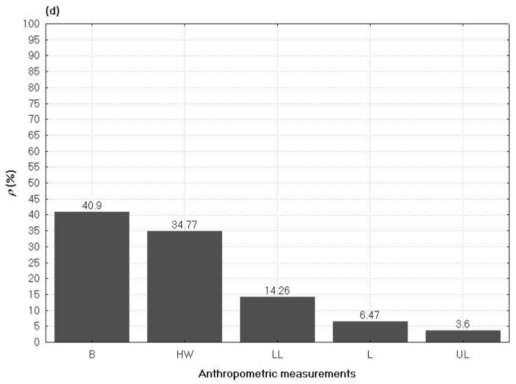

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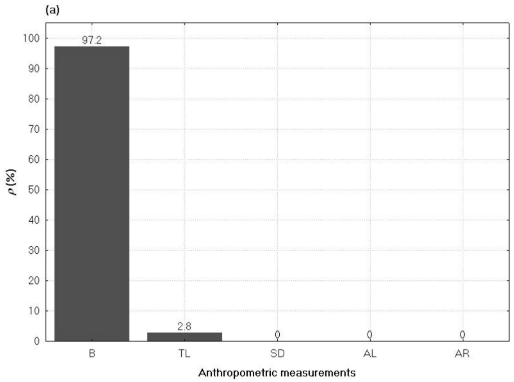

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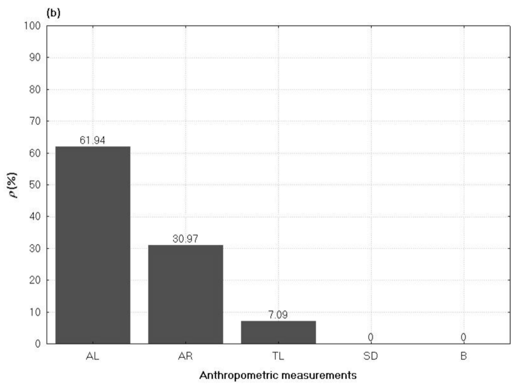

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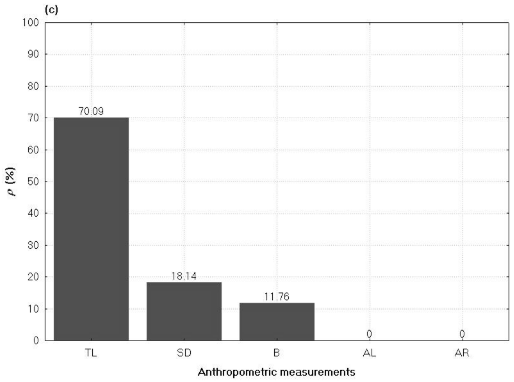

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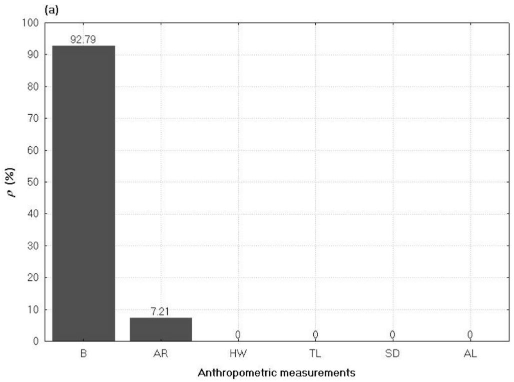

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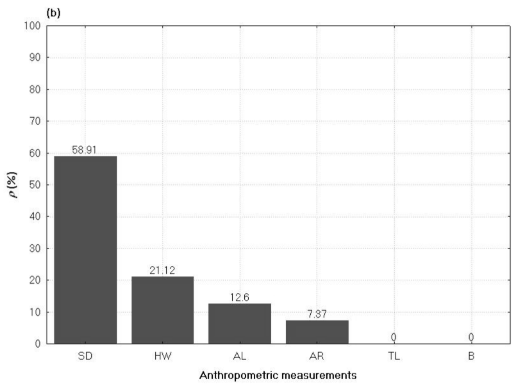

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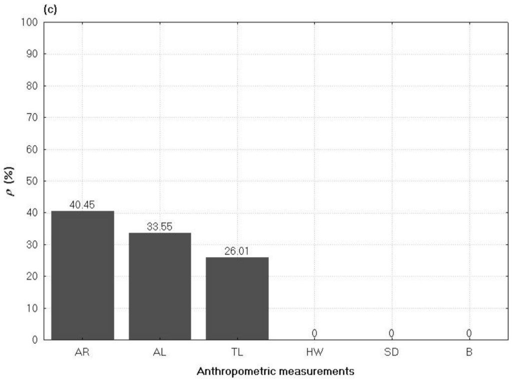

Table 1. Experiments, dimensions and adequate orthogonal designs with dimensions

Experiment	Denotement	No. of factors	Matrix (orthogonal array)	Dimensions	Matrix dimensions
1	E1	4	$2^4\ L_{16}\left(2^{15}\right)$	$\left(2^4-1\right)\times 2^4$	15 × 16
2	E2	3	$2^3\ L_8\left(2^7\right)$	$\left(2^3-1\right)\times 2^3$	7 × 8
3	E3	3	$2^3\ L_8\left(2^7\right)$	$\left(2^3-1\right)\times 2^3$	7 × 8

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Table 2. Input factors in experiments E1, E2 and E3 and their abbreviations

Experiment	**Input factor**	**Abbrev.**
E1		
A	seat length	SL
B	sitting length	LS
C	seat width	SW
D	seat height	SH
E2		
A	backrest angle	BA
B	control panel height	CH
C	backrest height	BH
E3		
A	control panel width	CW
B	backrest width	BW
C	control panel length	CL

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Table 3. Abbreviations for anthropometric measurements

Anthropometric measurement	**Abbrev.**
height	H
leg length	L
lower leg length	LL
upper leg length	UL
hip width	HW
body mass index	B
torso length	TL
shoulder width	SD
arm length	AL
arm reach	AR

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Table 4. Factors allocated in experiments E1, E2 and E3, basic columns of experiments

	E1				E2			E3		
	SL	LS	SW	SH	BA	CH	BH	CW	BW	CL
basic column	1	2	4	8	1	2	4	1	2	4
low	400	205	400	340	104	540	550	200	590	600
high	600	280	550	450	90	650	800	250	650	650
measurement	mm	mm	mm	mm	°	mm	mm	mm	mm	mm

Note: SL = seat length, LS = sitting length, SW = seat width, SH = seat height, BA = backrest angle, CH = control panel height, BH = backrest height.

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Table 5.Examined factors and their effects in each experiment

E1						
main effects – symbols	SL	LS	SW	SH		
two-factor interactions	SL–LS	SL–SW	SL–SH	LS–SW	LS–SH	SW–SH
three-factor interactions	SL–LS–SW	SL–LS–SH	SL–SW–SH	LS–SW–SH		
four-factor interaction	SL–LS–SW–SH					
E2						
main effects – symbols	BA	CH	BH			
two-factor interactions	BA–CH	BA–BH	CH–BH			
three-factor interaction	BA–CH–BH					
E3						
main effects – symbols	CW	BW	CL			
two-factor interactions	CW–BW	CW–CL	BW–CL			
three-factor interaction	CW–BW–CL					

Note: SL = seat length, LS = sitting length, SW = seat width, SH = seat height, BA = backrest angle, CH = control panel height, BH = backrest height, CW = control panel width, BW = backrest width, CL = control panel length.

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Table 6. Descriptive statistics for experiment E1 when $n = 2$

	M	***Mdn***	***SD***	***CV***
L	1190.625	1195.000	89.079	7.482
LL	574.531	575.000	40.408	7.033
UL	616.094	630.000	52.143	8.464
HW	406.094	392.500	78.922	19434
B	27.989	26.398	4.141	14.794

Note: L = leg length, LL = lower leg length, UL = upper leg length, HW = hip width, B = BMI, *CV* = coefficient of variation.

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Table 7. Descriptive statistics for experiment E2 when $n = 2$

	M	***Mdn***	***SD***	***CV***
TL	886.875	900.000	95.357	10.752
SD	493.438	495.000	64.465	13.064
AL	688.125	675.000	54.951	7.986
AR	934.844	935.000	63.209	6.761
B	29.350	28.614	5.138	17.507

Note: TL = torso length, SD = shoulder width, AL = arm length, AR = arm reach, B = BMI, *CV* = coefficient of variation.

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Table 8. Descriptive statistics for experiment E3 when $n = 2$

	M	***Mdn***	***SD***	***CV***
HW	389.688	400.000	41.411	10.627
TL	912.813	905.000	58.280	6.385
SD	458.125	477.500	46.543	10.159
AL	686.750	700.000	81.177	11.820
AR	915.813	926.250	95.358	10.412
B	27.627	28.813	3.043	11.015

Note: HW = hip width, TL = torso length, SD = shoulder width, AL = arm length, AR = arm reach, B = BMI, *CV* = coefficient of variation.

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Table 9. Design of experiment E2 for all resulting anthropometric measurement values

	BA	CH	BA–CH	BH	BA–BH	CH–BH	BA–CH–BH	x_{H}	x_{TL}	x_{SD}	x_{AL}	x_{AR}
1	–1	–1	1	–1	1	1	–1	x_{H1}	x_{TL1}	x_{SD1}	x_{AL1}	x_{AR1}
2	1	–1	–1	–1	–1	1	1	x_{H2}	x_{TL2}	x_{SD2}	x_{AL2}	x_{AR2}
3	–1	1	–1	–1	1	–1	1					
4	1	1	1	–1	–1	–1	–1					
5	–1	–1	1	1	–1	–1	1	...	...	...	...	...
6	1	–1	–1	1	1	–1	–1					
7	–1	1	–1	1	–1	1	–1					
8	1	1	1	1	1	1	1	x_{H8}	x_{TL8}	x_{SD8}	x_{AL8}	x_{AR8}

Note: BA = backrest angle, CH = control panel, BH = backrest height. Summary outputs of individual anthropometric measures in experiment E2, for different combinations of factor levels; $x_{\mathrm{H}i}$ = measurements of height, $x_{\mathrm{TL}i}$ = measurements of torso length, $x_{\mathrm{SD}i}$ = measurements of shoulder width, $x_{\mathrm{AL}i}$ = arm length, $x_{\mathrm{AR}i}$ = measurement of arm reach, where $i = 1, \dots, 8$.

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Table 10. Design of experiment E2 for torso length as a resulting value

	BA	CH	BA–CH	BH	BA–BH	CH–BH	BA–CH–BH	x_{TL}		
1	–1	–1	1	–1	1	1	–1	x_{TL11}	x_{TL12}	x_{TL1}
2	1	–1	–1	–1	–1	1	1			
3	–1	1	–1	–1	1	–1	1			
4	1	1	1	–1	–1	–1	–1			
5	–1	–1	1	1	–1	–1	1	..	...	...
6	1	–1	–1	1	1	–1	–1			
7	–1	1	–1	1	–1	1	–1			
8	1	1	1	1	1	1	1	x_{TL81}	x_{TL82}	x_{TL8}

Note: BA = backrest angle, CH = control panel, BH = backrest height, $x_{\text{TL}i}$ = summary of two replication measures for torso length for *i*th combination of factor levels.

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Table 11. Analysis of variance (ANOVA) table for torso length in experiment E2

Effect	***SS***	***df***	***MS***	***F***	***p***	***es***	***ρ* (%)**
BA	900	1	900	**8.727**	**0.013**	*	**0.66**
CH	8556.25	1	8556.25	**82.970**	**0**	***	**6.27**
BH	124256.25	1	124256.25	**1204.909**	**0**	***	**91.10**
BA–CH	25	1	25	0.242			0.02
BA–BH	25	1	25	0.242			0.02
CH–BH	1806.25	1	1806.25	**17.515**	**0.002**	**	**1.32**
BA–CH–BH	0.000	1	0.000	0.000			0.00
e	825	16	103.125				
T	136393.75	8					

$F(0.05, 1.15) = 4.543$

Note: BA = backrest angle, CH = control panel height, BH = backrest height, *e* = experimental error, *T* = total, *es* = *p* estimate, ρ (%) = contribution ratio. Significant values are shown in bold (*$p < 0.05$ **$p < 0.01$ ***$p < 0.001$).

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Table 12. Identification of influential measurements on factorial effects in experiment E1

Effect	p_{L}	*es*	ρ_{L} (%)	p_{LL}	*es*	ρ_{LL} (%)	p_{UL}	*es*	ρ_{UL} (%)	p_{HW}	*es*	ρ_{HW} (%)	p_{B}	*es*	ρ_{B} (%)
SL	**0**	***	**0.93**			0.68	**0**	***	**76.35**			0.15			0.58
LS	**0**	***	**3.70**	**0**	***	**74.02**			1.01			1.31			0.75
SW	**0**	***	**10.29**	**0.006**	**	**4.67**	**0.005**	**	**2.60**	**0.004**	**	**25.09**	**0**	***	**29.52**
SH	**0**	***	**81.32**	**0**	***	**7.35**	**0**	***	**11.42**			0.15			0.82
SL–LS			0.06			0.08			0.11			9.23	**0.041**	*	**8.29**
SL–SW			0.01			0.19			0.05			0.18			1.40
LS–SW			0.08			0.08			0.01			1.71			0.15
SL–SH			0.01			0.00			0.16			3.06			1.38
LS–SH			0.08			0.08			0.01			1.71			0.15
SW–SH	**0.021**	*	**0.29**			2.11			0.41			0.50			0.03
SL–LS–SW			0.06			0.08			0.68			7.59	**0.014**	*	**12.28**
SL–LS–SH			0.06			0.08			0.68			7.59	**0.014**	*	**12.28**
SL–SW–SH	**0**	***	**0.73**			0.19	**0.047**	*	**1.27**			0.09			0.11
LS–SW–SH	**0**	***	**1.56**			1.68			0.01			0.03			0.38
SL–LS–SW–SH			0.05			0.19			0.49			0.97			2.49

Note: SL = seat length, LS = sitting length, SW = seat width, SH = seat height, *es* = *p* estimate, ρ (%) = contribution ratio, L = leg length, LL = lower leg length, UL = upper leg length, HW = hip width, B = BMI. Significant values are shown in bold (*$p < 0.05$ **$p < 0.01$ ***$p < 0.001$).

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Table 13. Identification of influential measurements on factorial effects in experiment E2

Effect	**p_{TL}**	***es***	**ρ_{TL} (%)**	**p_{SW}**	***es***	**ρ_{SW} (%)**	**p_{AL}**	***es***	**ρ_{AL} (%)**	**p_{AR}**	***es***	**ρ_{AR} (%)**	**p_{B}**	***es***	**ρ_{B} (%)**
BA	**0.013**	*	**0.66**			0.00			4.47			3.29	**0.004**	**	**22.94**
CH	**0**	***	**6.27**			5.54	**0.005**	**	**54.77**	**0.04**	*	**27.39**			2.14
BH	**0**	***	**91.10**	**0.007**	**	**23.58**			0.88			2.75	**0.012**	*	**15.29**
BA–CH			0.02			7.04			6.68			**12.96**			1.33
BA–BH			0.02			5.08			0.01			1.56	**0.000**	***	**46.32**
CH–BH	**0.002**	**	**1.32**	**0.001**	***	**44.34**			0.22			**14.47**			0.08
BA–CH–BH			0.00			0.00			1.12			1.32			0.00

Note: BA = backrest angle, CH = control panel height, BH = backrest height, *es* = p estimate, ρ (%) = contribution ratio, TL = torso length, SD = shoulder width, AL = arm length, AR = arm reach, B = BMI. Significant values are shown in bold (*$p < 0.05$ **$p < 0.01$ ***$p < 0.001$).

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Table 14. Identification of influential measurements on factorial effects in experiment E3

Effect	p_{HW}	*es*	ρ_{HW} (%)	p_{TL}	*es*	ρ_{TL} (%)	p_{SD}	*es*	ρ_{SD} (%)	p_{AL}	*es*	ρ_{AL} (%)	p_{AR}	*es*	ρ_{AR} (%)	p_{B}	*es*	ρ_{B} (%)
CW			0.15			0.00			0.08			3.29	**0.02**	*	**2.60**	**0.02**	*	**33.45**
BW	**0.04**	*	**25.66**			9.96	**0**	***	**71.57**	**0.003**	**	**15.31**	**0**	***	**8.95**			5.20
CL			9.24	**0.002**	**	**54.25**			1.92	**0**	***	**69.98**	**0**	***	**84.38**			0.15
CW–BW			0.15			4.20			0.31			0.29			0.02			15.48
CW–CL			12.30			9.28			1.56			0.74			0.35			1.19
BW–CL			18.37			1.11			4.92			1.87			0.39			13.11
CW–BW–CL			0.00			0.00			0.94			1.38			0.59			0.22

Note: CW = control panel width, BW = backrest width, CL = control panel length, *es* = *p* estimate, ρ (%) = contribution ratio, HW = hip width, TL = torso length, SD = shoulder width, AL = arm length, AR = arm reach, B = BMI. Significant values are shown in bold (*$p < 0.05$ **$p < 0.01$ ***$p < 0.001$).

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Table 15.Comparison between percentages of individual anthropometric measurements’ share in workfield parameters in experiments E1, E2 and E3 expressed through the contribution ratio value ρ (%)

E1					E2				E3			
	SL	LS	SW	SH		BA	CH	BH		CW	BW	CL
L	0.93	3.70	10.29	81.32	TL	0.66	6.27	91.1	HW		25.66	
LL		74.02	4.67	7.35	SD			23.58	TL			54.25
UL	76.35		2.60	11.42	AL		54.77		SD		71.57	
HW			25.09		AR		27.39		AL		15.31	69.98
B			29.52		B	22.94		15.29	AR	2.6	8.95	84.38
									B	33.45		

Note: SL = seat length, LS = sitting length, SW = seat width, SH = seat height, BA = backrest angle, CH = control panel height, BH = backrest height, CW = control panel width, BW = backrest width, CL = control panel length, L = leg length, LL = lower leg length, UL = upper leg length, HW = hip width, B = BMI.

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Table 16 Factor values for workspace design based on experimental results

SL	LS	SW	SH	BA	CH	BH	CW	BW	CL
400 mm	205 mm	550 mm	340 and 450 mm	90–104°	650 mm	550 mm	250 mm	590 mm	600 mm

Note: SL = seat length, LS = sitting length, SW = seat width, SH = seat height, BA = backrest angle, CH = control panel height, BH = backrest height, CW = control panel width, BW = backrest width, CL = control panel length

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