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Anthropometric Analysis of Selected Body Dimensions and Comparison with the Design Approach for Forestry and Agricultural Machine Operators

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Abstract: The aim of the study was to conduct an analysis of selected anthropometric measurements of sitting posture of the adult male population and to compare the results to the workplace of earth-moving machine operators. Research into this problem is important in several respects, particularly the design approaches taken for the current and future machines, and their impact on the health and safety of operators. The anthropometric analysis was based on dimension measurements of the adult male population gathered in the years 2002–2019. The sample consisted of 1702 subjects aged 18 to 25. Thirteen body dimensions were selected and evaluated according to the European Standard of International Organization for Standardization (EN ISO) Nr. 3411. Anthropometric analysis of individual dimensions was evaluated using descriptive statistics and frequency histograms. The results of the analysis were compared to values recommended in the EN ISO 3411 standard. Results confirmed the growing trend of specific human dimensions within the adult population. In eight of the 13 analyzed body dimensions, descriptive statistics showed above-average values in the analyzed population compared to the values given in the standard. The long-term trend commonly observed in the adult population of developed countries was also confirmed.

Keywords: anthropometry; secular trends; workplace; ergonomy; operators; forestry machines; agricultural machines

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1. Introduction

The significant progress in technology has allowed the adoption of multi-operational technology in forestry and agriculture. Nonetheless, a number of operations are still performed manually due to working conditions, in particular. In cases of extreme slopes, poor access to forests, and lack of multi-operational technologies, the motor-manual method is mainly used in timber harvesting. The higher performance of timber harvesting equipment has resulted in the development of the working environment and subsequent employee comfort [1–6].

Permanent changes in human society can be observed, and technological advances and social changes are an integral part of this process [5]. A correlation can be seen between these social changes and the resulting adaptation of technological regulations [7].

Human comfort and safety at work are gaining increasing importance in the design of new machines for construction. Forestry and agriculture jobs are high-risk jobs in terms of accidents at the workplace [7–9]. Improving the ergonomic parameters is one of the main challenges of machine and equipment designers.

As a result of the development of society, the anthropometric dimensions of the human population have changed according to a secular trend. The term "secular trend" refers to the long-term changes in the anthropometric dimensions of the population. The most frequently analyzed attributes at present are the body heights and weights of adults, teenagers, and children [10–13]. Secular changes result from the interaction of genetic and environmental factors [14]. This mutual interaction is a function of various living conditions in various social groups at a specific time. Nutrition, illness, socio-economic status, and mental wellbeing are responsible for the changes in human growth and the development of the population [14]. During the past century, the secular trend has changed following the changes in nutrition, lifestyle, improvements in the quality of healthcare, etc. Therefore, the secular trend appears to be an important biological indicator that can be used in numerous ways [15].

The secular trend is an interesting phenomenon in terms of biology and sociology, and has been studied by anthropologists and economic historians [16]. Moreover, it can be perceived as an indicator of public health. This trend has changed over time [14], and an overview showing the link between the growth in the trend and the environment has been provided [16]. In addition, several aspects of physiology associated with the intergenerational relationships between growth and anthropometric dimensions have been illustrated [17]. This long-term growth trend in human body dimensions also fundamentally affects the human–machine interface.

As a part of social change, technological progress affects all areas of human life. Anthropologic and ergonomic requirements are crucial to the determination of the shape and size of consumer goods. Comfort, physical health, and performance, in addition to employee safety, can be improved by designing machines and equipment to meet the needs of the human body and correspond to human-related dimensions over a long-term perspective. Therefore, the workplace and equipment used must be designed according to the anthropometric and biomechanical characteristics of its users [18]. Optimization of the work environment, particularly the construction of the main components (seat and controls), should be adapted to the body size of the current population [19]. Anthropometric and ergonomic requirements are important for health protection and workplace safety.

The job of an earthmoving machine operator in forestry continues to be dominated by men [20,21]. This is due to the physical demands, in addition to the willingness and ability to perform physically demanding jobs [22]. The technologies used in timber harvesting and skidding are based mainly on tractor technology (universal tractors and special forestry tractors) and are implementations of multi-operational technology (harvesters and forwarders). [1]. The technology used in agriculture is also based on tractors and combine harvesters. The ergonomic parameters of machine operators are continually improving and affect the operators' health and job safety [23–28]. In the case of machine operators, the sitting position is the most common working position.

Designing the workplace of earthmoving machine operators must be in accordance with the EN ISO 3411 standard [29]. Three categories of earthmoving machine operators are distinguished in the standard (small, medium, large). Up-to-date anthropometric trends in the development of the adult population should be taken into account in the standard. The aim of this study was to analyze selected anthropometric dimensions in a sitting position of an adult male population, and to compare the results of the analysis to approaches used in designing earthmoving machines. The aim was also to assess whether the current legislation relating to the design of earthmoving machinery, in the form of a standard, reflects new trends in the anthropometric development of the adult population.

2. Materials and Methods

2.1. Anthropometric Analysis

The anthropometric analysis was based on the measurement of dimensions of adult males during the period 2002–2019. The sampling unit consisted of 1702 men aged 18 to 25. This age group was selected for practical reasons and the measurements were carried out at the Technical University in Zvolen (Slovakia). In addition, this age group is the most important in terms of the applicants for jobs in forestry and agriculture because the trends in ergonomic design of machines used in the near future will be defined to be consistent their anthropometric parameters. The definitions of individual body dimensions and means of measuring them are given a previous study [30]. The 11 body dimensions in the standing position and 20 body dimensions in the sitting position are defined in the EN ISO 3411 standard [29] for the design of the operator's space envelope (Figure 1).

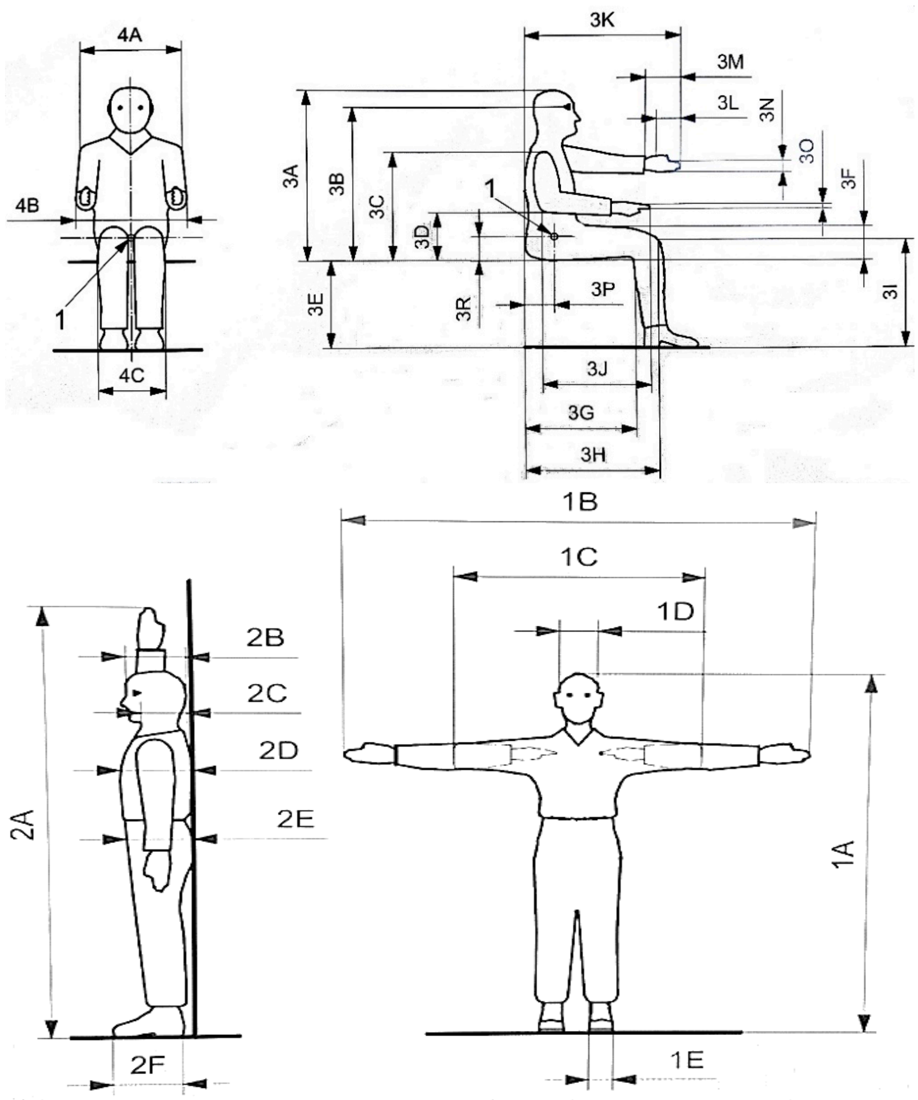

Figure 1. Anthropometric dimensions of the earthmoving machine operator defined by the EN ISO 3411 standard.

Because the most common position of an earthmoving machine operator is the sitting position (Figure 2), anthropometric dimensions in the sitting position were specifically included in the anthropometric analysis. Using the EN ISO 3411 standard, the following body dimensions in the sitting position were selected: sitting height (3A); eye height sitting (3B); elbow height, sitting (3D); knee height sitting with shoes (3I); forearm fingertip length (3J); buttock–knee length (3H); anterior arm reach (3K); hand length (3M); and shoulder (bi-deltoid) breadth (4A). In the case of the anthropometric dimensions in the standing position, two dimensions essential for designing the space for sitting figures were selected (foot length with shoes—2F; and foot width with shoes—1E). To provide a comprehensive analysis, the dimensions of stature height (1A) and body weight in kilograms were also selected. The measurements were conducted using a certified anthropometer. An anthropometer is a basic device for determining, in particular, the linear dimensions of the body. It consists of a 210 cm long metal rod with a 1 mm scale, terminated by a fixed arm that is perpendicular to the axis of the instrument. A sliding arm moves along the bar, which is applied to the respective anthropometric point, and the measured value is read on the line of the arm. To be able to use the device when working in the field, the rod is divided into 4 parts that are connected.

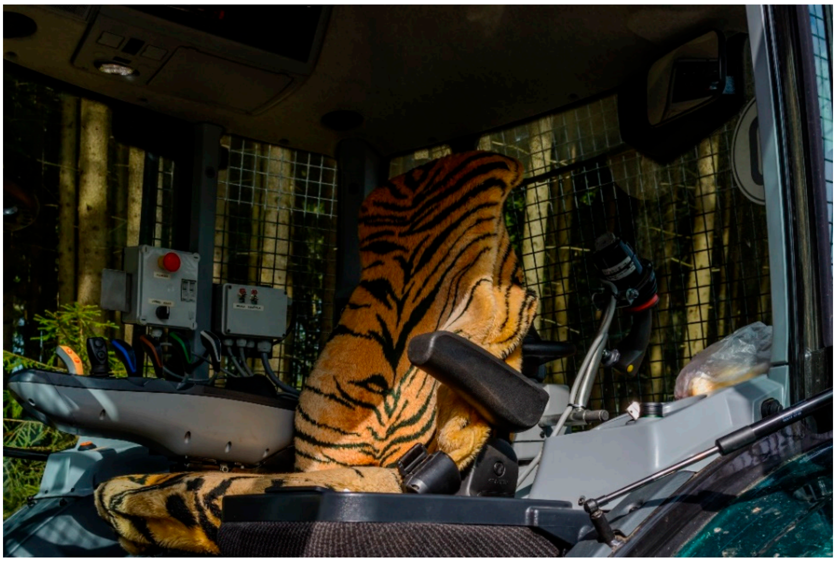

Figure 2. Operator's workplace in a Valtra universal tractor.

2.2. Statistical Analysis

Data measured in all years were summarized and analyzed using descriptive statistical parameters to verify the suitability of the present regulations concerning the ergonomic design of machines used in forestry and agriculture. The number of measured subjects was highly variable during the study period and varied from 24 measured subjects in 2008 to 438 measured subjects in 2016. The measured data cannot be generalized globally but reflect the regional nature of living standards in the European Union.

Standard statistical parameters of descriptive statistics were evaluated: arithmetic mean, mode, standard error, standard deviation, and variance. Statistical data were evaluated and values were calculated using standard procedures mentioned in the literature [31–34]. The software Microsof Excel version 2013 (Microsoft Corporation, Santa Rosa, CA, USA) and Statistica version 12.0 (Statsoft Inc., Praha, Czech Republic) were used for calculating and visualizing the results.

The suggested parameters of body dimensions of earthmoving machine operators, in accordance with the EN ISO 3411 standard corresponding to the values of the small, medium, and large operator, were statistically and graphically evaluated. Subsequently, the suggested values were compared to the maximum, mean, and mode of the measured sample of the population. The results of the measurements should provide information about the trends relevant to designing the workplace of machine operators in forestry and agriculture.

3. Results

3.1. Results of Anthropometric Analysis

Figures 3 and 4 show histograms of the analyzed selected anthropometric dimensions in accordance with the EN ISO 3411 standard, and their intervals. Figure 3 shows anthropometric dimensions that are not directly connected with the sitting position. The stature height of half of the analyzed adult men ranged from 175 to 185 cm, and the body weight of more than half of the men ranged between 70 and 90 kg. These ranges were consistent with values that are slightly above the mean in comparison to the parameters of average earthmoving machine operators according to the EN ISO 3411 standard. The forefoot width of almost half of the analyzed sample ranged from 9 to 10 cm, and the foot length with shoes ranged from 26 to 28 cm. These values correspond with values slightly below the mean or the mean values of operators in accordance with the standard. However, in the case of the remainder of the analyzed adult men, significant variability was observed in this body dimension.

The shoulder (bi-deltoid) breadth (4A) is the same in the sitting and in the standing positions, i.e., there is no effect of the body position on the anthropometric dimension. Therefore, the dimension is included in Figure 3 among the dimensions that are not directly connected with the sitting figure. The results of the measurements of the analyzed population were similar to the dimension of the foot length with shoes (2F). The design of the seat and the operator's space envelope, including the option with a rotating seat, is affected by this dimension. Moreover, the position of the controls is also affected by this dimension, and is directly related to other anthropometric dimensions (e.g., vertical grip reach).

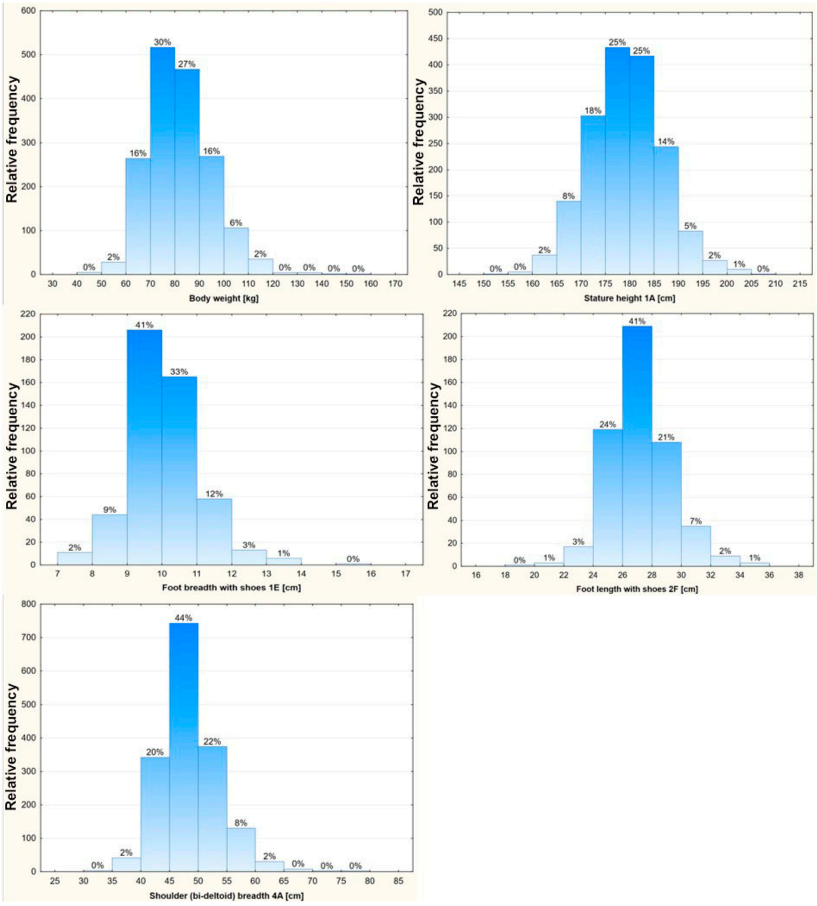

Figure 3. Histograms of analyzed selected anthropometric dimensions.

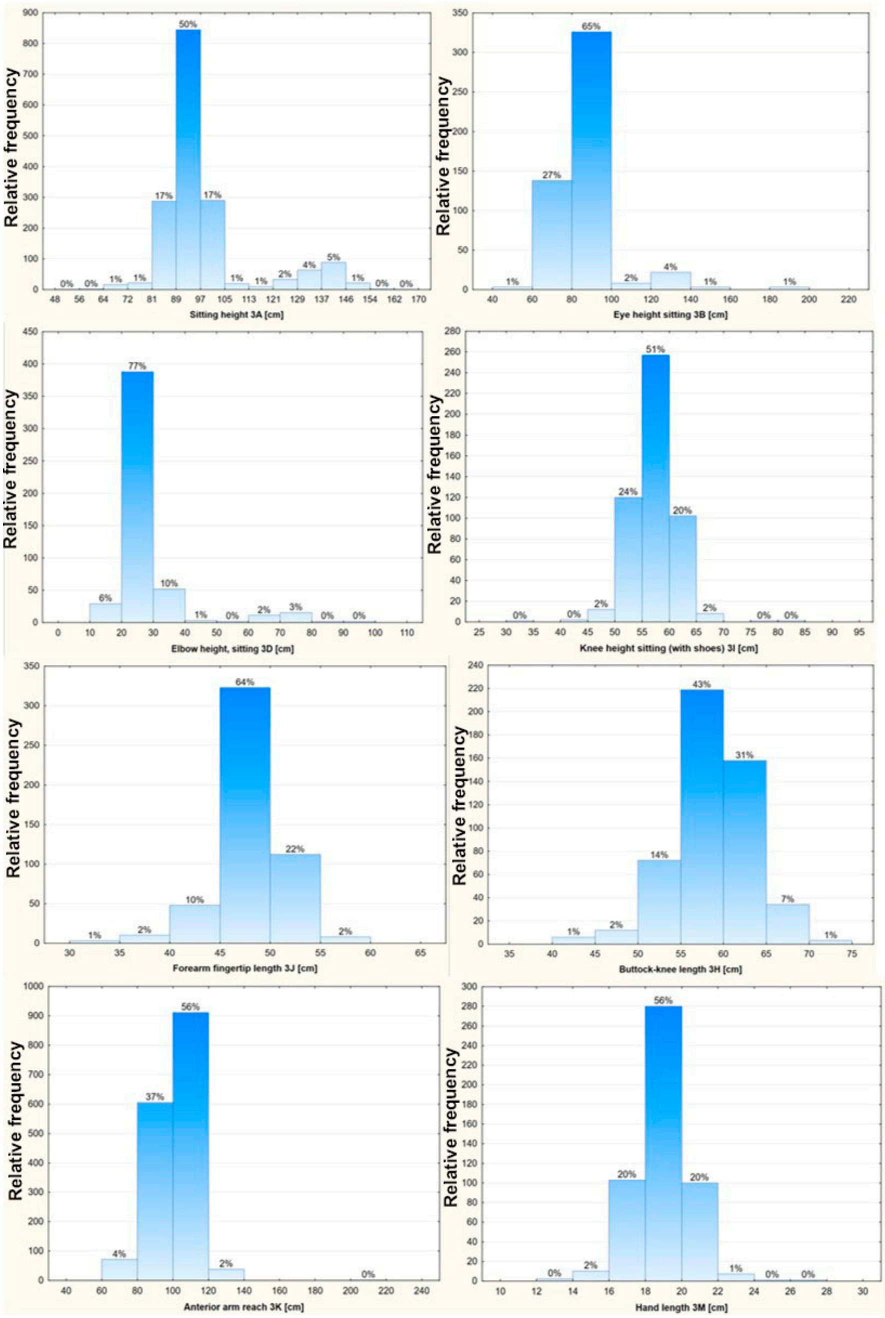

Figure 4. Histograms of analyzed selected anthropometric dimensions for the sitting position.

Selected analyzed anthropometric dimensions that are directly defined for machine operators in the sitting position are shown in Figure 4. The value of the sitting height (3A) ranged between 89 and 97 cm in the case of half of the analyzed sample. In the case of the values of the analyzed dimension of the remaining half of the population, significant variability was evident. In the measure of the eye height sitting (3B), the values of almost two-thirds of the analyzed men ranged between 80 and 100 cm. The dimensions of the buttock–knee length (3H) and hand length (3M) showed relatively variable results. When evaluating the vertical grip reach and shoulder grip length, the values obtained were almost identical for both dimensions.

To carry out a comprehensive evaluation of individual anthropometric characteristics and, in particular, to show their development over time, simple methods of descriptive statistics were used. Using these methods, the values corresponding to the characteristics analyzed over time are provided (2002–2019). These results can be compared to the values mentioned in the standard, and the trend and its applicability to the present regulations regarding the design for earthmoving machine operators can be determined.

The results of the descriptive statistics of the selected sampling unit of the male population related to individual anthropometric characteristics following the EN ISO 3411 standard are provided in Table 1. All of the measured values over time are summarized and the median of the total development is shown using the arithmetic mean. However, the mode can be considered to be the most appropriate value for analyzing and comparing the latest trends in the context of designing the workplace of earthmoving machine operators. The mode provides an overview of the highest relative frequency of a given dimension in the analyzed sample. In addition, the time of changing and developing the characteristics is taken into consideration.

Table 1. Descriptive statistics from the analyzed population for anthropometric dimensions according to EN ISO 3411 during 2002–2019.

Dimension	Arithmetic Mean	Median	Mode	Minimum	Maximum	Variance	Std. Deviation	Std. Error
Body weight (kg)	83.0	82.0	80.0	49.0	151.0	178.12	13.35	0.323
1A (cm)	180.0	180.0	180.0	155.0	208.0	54.32	7.37	0.179
4A (cm)	49.2	49.0	50.0	34.0	78.0	26.23	5.12	0.125
3A (cm)	98.0	94.0	95.0	48.0	170.0	260.46	16.14	0.391
3B (cm)	86.1	83.0	83.0	60.0	188.5	214.00	14.63	0.652
3D (cm)	29.1	26.0	27.0	14.0	100.0	148.26	12.18	0.542
3I (cm)	57.8	58.0	60.0	34.0	85.0	17.26	4.16	0.185
3J (cm)	48.5	49.0	49.0	33.0	59.0	11.31	3.36	0.150
3H (cm)	59.2	60.0	60.0	42.0	71.0	20.29	4.50	0.201
3K (cm)	101.2	103.0	110.0	68.0	211.0	139.03	11.79	0.292
3M (cm)	19.5	19.5	20.0	13.0	27.0	2.21	1.49	0.066
1E (cm)	10.5	10.0	10.0	8.0	16.0	1.14	1.07	0.048
2F (cm)	27.7	28.0	28.0	19.0	36.0	4.63	2.15	0.096

3.2. Analysis of Normalized Dimensions and Comparison with an Anthropometric Analysis

The intervals of selected anthropometric characteristics of machine operators following the EN ISO 3411 standard, divided into three groups—small, medium, and large—are given in Figure 5. The results of the anthropometric analysis were also evaluated in these intervals.

The analysis provides an overview of the standardized dimensions of earthmoving machine operators, and assesses whether these dimensions are current. The body weight value could not be analyzed because it is not specified in the EN ISO 3411 standard. Figure 5 shows that the mean and most commonly occurring dimensions were slightly above the mean values of the operator, in the case of the characteristics of stature height (1A); sitting height (3A); eye height sitting (3B); elbow height, sitting (3D); knee height sitting with shoes (3I); forearm fingertip length (3J); anterior arm reach (3K); and shoulder (bi-deltoid) breadth (4A).

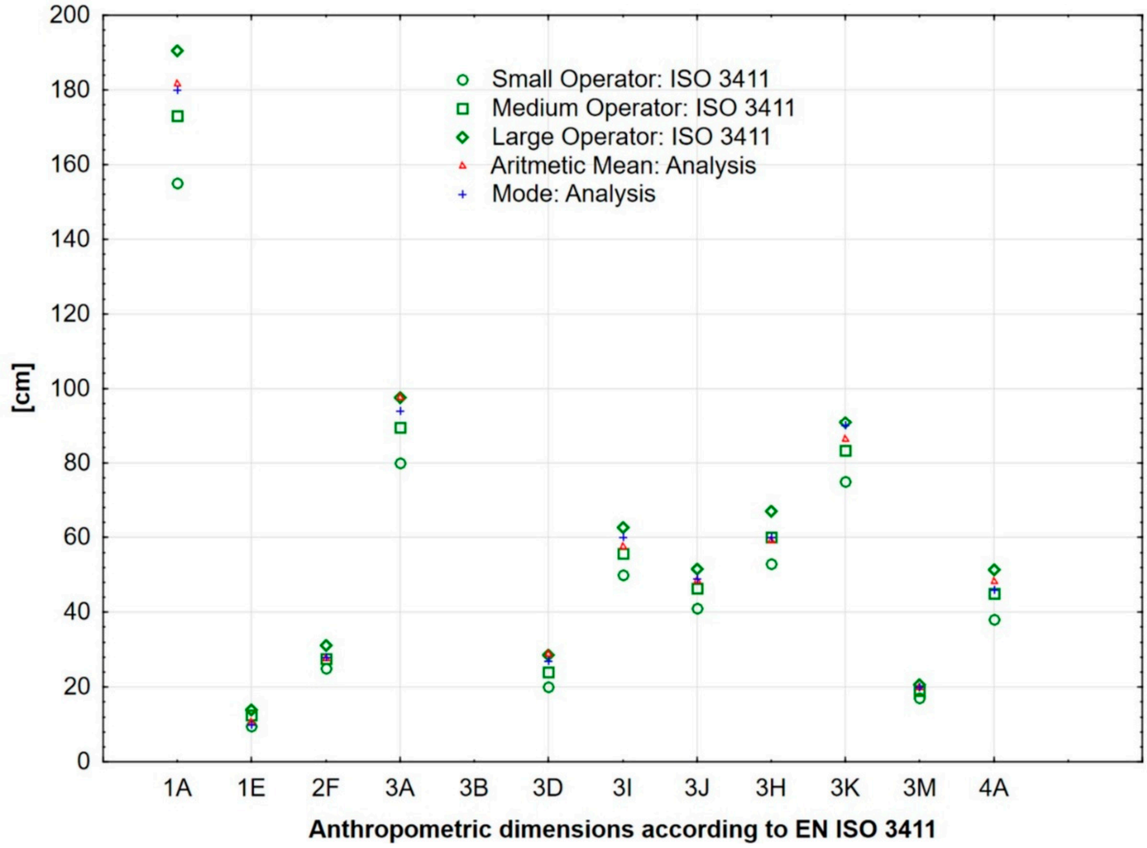

Figure 5. Range of anthropometric dimensions according to EN ISO 3411 compared to statistical values from the analysis of the male population (2002–2019).

The values of 12 anthropometric dimensions were compared in the analysis, and in the case of eight of these, the values of the arithmetic mean and mode were above average. A significant difference was observed in the case of the values of anterior arm reach (3K), in which the mean values obtained from the anthropometric analysis were significantly above the values corresponding to an operator classified in the EN ISO 3411 standard as "large". Comparable mean values corresponded with the values determined in the standard only in the case of four body dimensions: foot width with shoes (1E), foot length with shoes (2F), buttock–knee length (3H), and hand length (3M). These dimensions are essential for positioning the controls and determining the minimum normal operating space envelope around the operator enclosures. The analysis shows that there will be increasing demand for seats that are constructed to be suitable for the size of the operator space envelope in earthmoving machinery.

Increasing trends in several anthropometric characteristics over time can be observed in the results. Moreover, these changes have been confirmed by research studies on secular trends conducted in numerous developed countries. The results of the analysis also show the importance of a reassessment of the present trends in the design of workplaces for machine operators, which do not adequately reflect the growth in body dimensions of the adult population. New regulations must be developed due to the findings of our research. This research confirmed that the standards do not correspond with the anthropometric dimensions in practice, and the standardized intervals must be changed to enable the future design of the machines to follow the trends in the body dimensions of an adult population.

4. Discussion

The positive secular trends in the anthropometric characteristics of the adult population have not only been observed in Slovakia during the past two decades [35–38]. It can be supposed that these trends are mainly due to the better nutrition, psychosocial factors, and socio-economic conditions that exist at present. The development of secular trends in the adult population was also confirmed in our research. The design of workplaces of earthmoving machine operators has not adequately reflected these trends, as also confirmed in previous studies [20,39–41].

In states with no single European legislation, the workplaces of operators and their components are designed in line with the results of anthropometric analyses. A relatively large discrepancy between the individual sizes of seats in harvesters was identified in an Iranian study [42]. Following the anthropometric analysis of 200 operators, new parameters for the size of a seat were suggested, obtaining conformity with 77 to 100% of the analyzed sample.

Anthropometric analysis of forest harvester operators carried out in Turkey [43] examined four anthropometric dimensions (average stature, knee height, sitting height, buttock to knee length). With the exception of the dimension of buttock–knee length (3H), the values of all other dimensions mentioned in our analysis were greater on average. The result of this previous study was a proposal to design seats in forest harvesters with greater variability in the horizontal and vertical positions.

Fifteen representative types of the human body, that affect the design of the space envelope in earthmoving machinery and have an impact on the position of the steering wheel and gear box, were identified in a study conducted in 2005 [44]. The study used the 3D scans of nine body dimensions of 100 agricultural operators. The study found that the standard used in the USA (the SAE International J2194 standard) is not suitable for designing the workplace in a sitting position, based on an anthropometric database collected in the years 1994 and 2002.

In contrast, an anthropometric analysis of operators conducted in India did not show a significant discrepancy compared to the standardized dimensions associated with the design of the machines, with the exception of the dimension of chest depth [45].

These results have also been confirmed by socio-economic research. These studies show that the opinion of earthmoving machine operators has no effect on the design of the space envelopes in earthmoving machinery. A questionnaire-based study showed that the cabin comfort was evaluated by the operators as average or poor [46]. In this study, the options to improve the seat design, cabin construction, view, and air-conditioner controls were specified by the operators.

Following the results of similar research, it can be seen that the legislation associated with designing the workplace for earthmoving operators is inadequate in most countries in which the research was conducted. Secular trends and anthropometric analyses indicate the need for a reassessment of the legislation classifying the parameters for designing earthmoving machinery.

The limitations of our results mainly relate to the narrow specification of the sample of the adult population, in addition to the varying amounts of data collected during the individual years of the analysis. However, it is possible to identify the resulting trend in the growth of body size, which can be generalized to countries with a similar standard of living within the European Union.

5. Conclusions

The population trends described in our paper will persist. Values relating to anthropometric characteristics are used in the process of establishing the ergonomics, hygiene, and construction standards and regulations linked with the earthmoving machinery. Therefore, it is necessary to reassess the suitability of the relevant dimensions. Because the secular trends can be observed not only in Slovakia, but in all countries, these standards must be updated globally. If these standards are not discussed by regulators in the near future, serious risks to human health will arise.

The modification of standardized dimensions requires the interdisciplinary cooperation of designers, developers, anthropologists, ergonomists, and doctors. Only an interdisciplinary approach can result in the manufacture of high-quality machines. Several standards and regulations are based on outdated or old data, and do not take into account actual trends. A comprehensive approach will be beneficial, not only for the higher comfort of operators, but also for the improvement of workplace health and safety conditions. Due to the improved qualifications of the operators in forestry and agriculture, new technological challenges and requirements will arise for machinery designers.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are contained within the article.

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