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The influence of body biomechanics on the geometry of clothing patterns

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ABSTRACT

Research findings in the field of clothing design underline that a garment must ensure a high level of comfort as it interacts with the shape of the human body, regardless of whether the person is in a static or dynamic state. For economic, medical and psychological reasons, it is essential that a garment fits well and adapts to the wearer's body shape in terms of 3D geometry, volume and structure (there are areas where the garment is very close to the body and areas where it is away from the body). Several factors need to be taken into account when producing various soft goods, including garments: factors related to the client (age, posture, proportions and conformation, type and frequency of movements, medical problems, physical disabilities, etc.) and the product (destination, condition of use, characteristics of materials and accessories, etc.). This paper presents the influence of the biomechanics of the human body on the 3D shape of a garment. The geometry and the size of the garment patterns must be determined taking into account the details of the model (silhouette, destination, structure, types of materials, etc.) and, above all, the movement of the human body expressed in terms of the absolute values of the changes in its dimensions or dynamic effects.

Keywords
human body biomechanics,
curve outlines,
garment patterns,
dynamic effect

1 Introduction

Nowadays, people decide upon their outfits according to their needs (freedom of movement, breathing, comfort) and other aesthetic, functional, and ergonomic criteria, etc., determined by their intended purpose.

It is well known that clothing products are characterised by very different shapes and sizes, depending on the ones of the wearer's body, the type of product (in terms of its purpose and aesthetic characteristics) and the particularities of the materials from which they are made. In theory, the product's shape represents the spatial configuration corresponding to how it is arranged when put on the wearer's body or on the mannequin. The three-dimensional shape of the product must be compared to the one of the human body, as the former is not necessarily a faithful copy of the latter. Therefore, the degree of similarity between them depends on the position of the product on the body, the surface on which the former is supported, the characteristics of the model, as well as the wearer's age and activities. The silhouette is an important design feature related to the spatial shape of the product and characterises the degree to which the product covers the body.

For sportswear and protective gear, the specific requirements are influenced by how the products are supposed to ensure the wearer's health and safety in the environment where they must perform their tasks at a specific time. In addition, the properties of materials used to make these products, the configuration of the structural layers and their number, the shape, and the use of the appropriate manufacturing technologies must ensure that the product behaves as expected and provides the user with maximum protection, as well as a reasonable degree of comfort, in both static and dynamic postures.

Materials and technologies must be carefully selected and developed with regard to their destination and conditions of use. Significant results have been achieved regarding the types of materials used to manufacture PPE, as follows: smart textiles that can be either conductive, equipped with optical fibres, chromogenic or with detectors that can communicate with other appropriate detectors [1], high-tech fabrics (such as Kevlar, Dyneema, Spectra, Nomex, etc.), nanofibres layer bonded to a nylon 6 fabric to improve the mechanical properties, air permeability and moisture permeability of protective clothing [2]) and technology (3D printing technology to produce various medical devices [3], wearable technology that can improve safety management and increase the productivity of PPE, nanotechnology to produce higher added value materials for better worker protection [4]).

An important issue for sportswear and protective gear that must be addressed appropriately is providing the wearer with a good degree of comfort in dynamic postures. During the execution of a movement, certain body dimensions vary, depending on the amplitude, as well as the wearer's gender and experience, when compared to the values measured when the body is in a static posture (the dynamic effect evaluates this change). By designing the garment patterns using biomechanical engineering principles, one can be sure that the wearer will be provided with the highest level of comfort, the best fit and optimal interaction with the garments in the product's structure. In this way, one can design products that are specifically adapted to the mechanics of the wearer's body [5-8].

A more complicated case, as far as the degree of comfort in dynamic postures is concerned, is one of the products with support on the shoulder, which completely cover the upper and the lower parts of the whole body. For this type of product, the longitudinal forward bending movement of the trunk towards the front or lateral movement must not be restricted. One possible way of addressing this issue consists of controlling the way in which the geometry of the components is designed with respect to the dynamics of the body for a particular posture.

This paper presents an example of a design solution for the shape of the components of a coverall-type product used as individual protective equipment, where the data provided by the user are directly integrated into the design algorithm and compared to the one specific to the product type (customised/individualised design).

2 Research methodology

2.1 Theoretical considerations

The movements of the human body can be involuntary (breathing) and voluntary. The latter are ones performed by specific segments of the body. Their frequency and amplitude are determined by the purpose they perform: usual, leisure, exercise, or professional activity.

The body segments and the types of movements that they can execute are the upper limbs (flexion/extension, abduction/adduction, rotation, circumduction), the trunk (flexion/extension in the sagittal plane, lateral tilts in the frontal plane, rotations in the transverse plane), the head and neck (rotations, lateral tilts), the shoulder area (raising/lowering) and the lower limbs (flexion/extension, abduction/adduction, rotation). In these positions, the values of the body measurements change according to the type and amplitude of the movement.

The difference between the value of an anthropometric parameter measured in a given dynamic position and the value measured in a static position is known in the literature [6,9,10] as the absolute dynamic effect (see Eq. (1)). For some professional activities where the worker has to perform specific movements in a certain sequence, it is necessary to design his workplace and protective clothing according to ergonomic principles. Under these conditions, it is necessary to determine the relative value of the dynamic effect of specific body dimensions using relation (2):

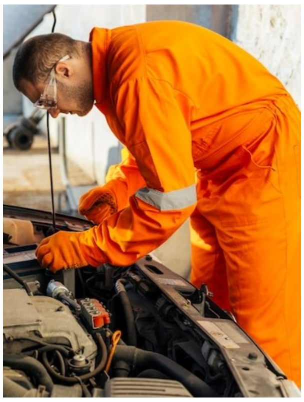
$$d_{ij} = X_{ij}(^{d}) - X_{ij}(^{s}) \quad (1)$$

$$ed_{ij} = \frac{X_{ij}^{(d)} - X_{ij}^{(s)}}{X_{ij}^{(s)}} \times 100\ \% \quad (2)$$

The abbreviations appearing in the formulae stand for the following: d_{ij} and ed_{ij} represent the absolute and relative dynamic effect, in the case of dimension “i” for the subject “j”; $X_{ij}(^{s})$ represents dimension “i” of the subject “j” measured in the static posture; $X_{ij}(^{d})$ represents dimension “i” of the subject “j” measured in a particular dynamic posture.

Overalls are used as individual protective equipment in many occupational activities. Overalls are garments that come in direct contact with hazardous factors in the production environment. As these garment products are worn over others, the entire ensemble must ensure individual protection and allow the wearer to perform the movements required for their specific tasks. The shape of the product and the materials from which it is made are strictly determined by the environment in which the worker carries out their activity, its specific hazards, and the duration and nature of the necessary movements (their frequency and amplitude). The requirements for designing and manufacturing personal protective equipment (PPE) are set out in specific regulations [11].

(a) Chemical field [12]



(b) Mechanical field [13]

Fig. 1 Overall protective equipment.

Occupational standards specify how the various movements must be executed and in which order so that the worker can perform their occupational tasks in a manner that mitigates the risk of severe physical fatigue or accidents. The overall, which is a garment that covers the entire human body (product with a hood, Fig. 1a) or extends from the neck to the lower limbs (Fig. 1b), must allow the wearer to execute the longitudinal and transversal movements that are necessary for their task at hand.

In occupational activities requiring intense physical effort, one of the most common movements is the one which consists of bending the trunk. This must be executed with minimal energy expenditure and must not be restricted by clothing. In the case of the overall product, its longitudinal size must allow the wearer to move their trunk and pelvis in order to obtain a posture similar to the one shown in Fig. 1b. In view of these considerations, information on the dynamics of the rear part of the wearer’s body must be integrated when dimensioning the product in the longitudinal direction. The dynamics of the body are assessed using the absolute or relative values of the dynamic effects of the anthropometric quantities measured at the back (the ones corresponding to the posture shown in Fig. 1b are different from those obtained in the orthostatic posture of the human body).

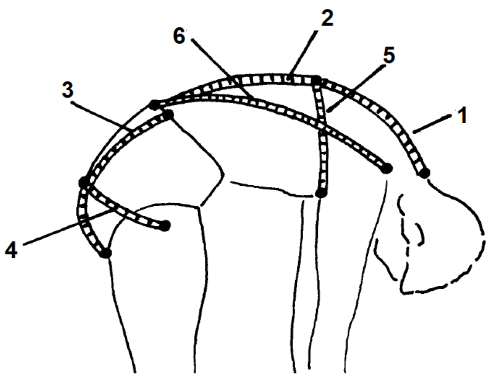
2.2 Research methodology

The steps taken to achieve the objective of this paper are:

- determining the absolute and relative values of the dynamic effects for the specific dimensions of the body segments involved in the movement; analysing the variability of the dynamic effects by interpreting the values of the statistical parameters (indicators of central tendency and variation);
- the design of the 2D shapes of the product components and the creation of the 3D virtual prototype, the verification of the dimensional conformity of the prototype with respect to the shape of the human body (balance and size) in the static and dynamic positions specific to the wearer's professional activity (the 2D shapes are designed using the values of the statically measured dimensions of the body, the ones of the product, and the ones describing the extra amount of material that has been added in accordance to the type of product);
- analysing and evaluating the virtual prototypes; determining whether modifications are necessary or validating the developed solution;
- introducing data regarding the dynamics of the human body into the 2D design algorithm in order to obtain new product shapes and create the 3D prototype;
- analysing and evaluating the new prototype; validating the design solution (the patterns of the product components are later used in the production process).

2.2.1. Determining the absolute and relative values of the dynamic effects

The quality of any piece of individual protective equipment is directly influenced by the way in which it adapts to the wearer's body and the degree of comfort it provides while worn (in static and dynamic conditions). The body posture in Fig. 1b is common for various occupational activities involving physical effort. The bending movement of the trunk, accompanied by the flexion of the forearms, is a specific one whose purpose is to grasp/move or put a specific object down. This movement results from the interaction between the bones, muscles, and joints comprising the body segments involved. This dynamic posture of the body can be analysed by examining the variability of the values of the anthropometric dimensions, shown in Fig. 2.



Anthropometric dimensions included in the analysis [10]:

1 - The length of the back measured from the cervical spine to the level of the posterior axillae (Dimension 1)
2 - The length of the back measured until the waist level (Dimension 2)
3 - The posterior length of the lower part of the trunk (Dimension 3)
4 - The posterior curvature of the buttocks (Dimension 4)
5 - The width of the back measured horizontally between the posterior axillae (Dimension 5)
6 - The oblique curvature of the back (Dimension 6)

Fig. 2 Anthropometric dimensions measured in a dynamic position of the human body

In order to determine the values of the dynamic effects (absolute and relative), an anthropometric study was conducted on a sample of 509 males aged between 18-62 years who wear overalls as personal protective equipment. The sampling of the values of the anthropometric parameters was carried out by using the direct measurement method, in accordance with the designed protocol for an anthropometric study on human subjects, based on the freely expressed participants' consent [9,10].

The individual values of the measured anthropometric variables were statistically processed (Excel, Office 2019 with Data Analysis/Descriptive Statistics) (see Tables 1-3), according to the protocol consisting of the following steps: identification and elimination of outlier values (which could lead to negative conclusions), determination of the mean (Xmed) and testing its significance (Tx), and determination of the values for the variation indicators (Sx-mean square deviation; Cv-coefficient of variation). The values for the above statistical parameters were obtained for the anthropometric dimensions presented and described in Fig. 2. (Dimension 1-Dimension 6). The procedure was applied to the values of the body dimensions taken in the orthostatic position of the body [9] and to the values of these dimensions taken in the dynamic position shown in Fig. 2, a specific one for the mechanical field [11].

The formulas for determining the values of the statistical parameters mentioned above are:

Xmed= (∑Xi)/n (3)

Sx=sqrt[∑(Xi-Xmed)2/(n-1)] (4)

Cv=(Sx/Xmed)*100% (5)

Tx=Xmed/Sx (6)

Where:

Xi is the individual value of the anthropometric dimension (mm);

n is the sample volume;

Xmed is the mean value of the anthropometric dimension (mm);

Sx is the mean square deviation of the anthropometric dimension (mm);

Cv is the coefficient of variation (%);

Tx is the significance test for the mean value.

Table 1. Values for statistical parameters for body dimensions (static position).

Anthropometric dimension	**Statistic parameters**			
	Xmed (mm)	**Sx (mm)**	**Cv (%)**	**Tx**
Dimension 1	204.24	2.78	1.36	73.46
Dimension 2	495.06	4.21	0.85	117.59
Dimension 3	287.35	3.04	1.06	94.52
Dimension 4	534.61	4.59	0.86	116.47
Dimension 5	439.81	4.46	1.01	98.61
Dimension 6	532.97	3.6	0.67	148.04

Table 2. Values of the statistical parameters for the absolute dynamic effect d_{ij} of body dimensions.

Anthropometric dimension	**Statistic parameters**			
	Xmed (mm)	**Sx (mm)**	**Cv (%)**	**Tx**
Dimension 1	13.75	0.17	1.23	80.88
Dimension 2	68.37	4.65	6.8	14.7
Dimension 3	64.63	4.07	6.29	15.88
Dimension 4	34.82	4.06	11.66	8.57
Dimension 5	130.44	4.33	3.32	30.12
Dimension 6	95.62	4.45	4.65	21.49

Table 3. Values of the statistical parameters for the relative dynamic effect ed_{ij} (%) of body dimensions.

Anthropometric dimension	Statistic parameters			
	Xmed (%)	Sx (%)	Cv (%)	Tx
Dimension 1	6.41	0.12	1.87	53.41
Dimension 2	11.61	0.78	6.72	14.88
Dimension 3	17.62	0.97	5.5	18.16
Dimension 4	5.7	0.69	12.1	8.26
Dimension 5	22.61	0.65	2.87	34.78
Dimension 6	14.85	0.60	4.04	24.75

The data from Tables 1-3 allow the following conclusions:

- The mean values for the absolute and relative dynamic effect of the body dimensions are positive because in the position shown in Fig. 2 the body bends. In this position, all measured values of Dimension 1-Dimension 6 are higher than those measured in the orthostatic position;
- the values of the mean selection test (Tx) are higher than the t-Student test value for the selected sample size (tS=1.964), so the former is statistically significant and can be used to determine a confidence interval for the mean value of the population from which the selection was taken;
- the small values of squared mean deviation (Sx) indicate a grouping of the values around the mean;
- the value of the coefficient of variation (Cv) is small for dimensions 1, 2, 3, 5 and 6 (for body dimensions measured in orthostatic position; the same for the absolute and relative values of the dynamic effects). The Cv value of the absolute and dynamic effect for dimension 4 is a medium value.

A value below 10% for the CV of the sample corresponds to a high degree of homogeneity (the individual values are close to each other and to the mean), and one between 10% and 20% indicates a medium degree of homogeneity (the individual values are relatively close to each other and to the mean), whereas one between 20% and 30% indicates a lower degree of homogeneity (the individual values are far from each other and from the mean).

So we can say that the individual values of dimensions 1, 2, 3, 5 and 6 (measured in orthostatic position) and the absolute and relative values of these dynamic effects are close to each other and also close to the mean. The variability of the shape of the buttock area determines the average value of Cv for the absolute and relative dynamic effect of dimension 4.

- The mean value of the absolute dynamic effect for dimension 1 is compensated by the mean value corresponding to dimension 2.

2.2.2. The 2D design of the shapes of product patterns and the creation of the 3D virtual prototype, the verification of the dimensional conformity of the prototype with respect to the shape of the human body (balance and size) in the static and dynamic positions corresponding to the wearer's professional activity

In the case of the overall made of fabric (PES and cello-fibre), used as individual protective equipment against mechanical impact, the principles of the 2D geometric method are applied for designing the front, back and sleeve patterns. The flat shapes of the product elements are created in a CAD working environment (Gemini CAD – a Lectra Company), which allows the personalised design of the patterns of the product elements [9,14]. The virtual prototype of the designed product (for the selected static and dynamic position) is created and checked by using Clo3D.

The overall model chosen for the study is shown in Fig. 3. This product has front, back and long sleeves, which are sealed in the middle of the front with a zip (under-quilting). The overall has a collar and cuffs at the end of the sleeves and the trousers.

Fig. 3 PPE garment – overall [15]

Since overalls are worn over other garments, their transverse dimensions must not impede dressing, undressing, and the movements required for professional activity. The design algorithm (mathematical design relations of the construction segments [14], which use as input the values of the body dimensions measured in static postures, the ones of the product dimensions and constructive additions) is verified by elaborating and analysing the 3D virtual prototype for the static posture of the user. In the first phase, the 2D patterns for the bodice, trousers, sleeves and collar are created. The first two are combined in order to create the front and back of the overall. The 2D construction of the pattern is carried out by using commands and functions of the Made-To-Measure/Gemini mode CAD by Lectra (Fig. 4). These patterns are imported into Clo3D in order to create the virtual 3D prototype. This prototype is then analysed by taking into account the dimensional correspondence for the wearer's static and dynamic postures (Fig.5).

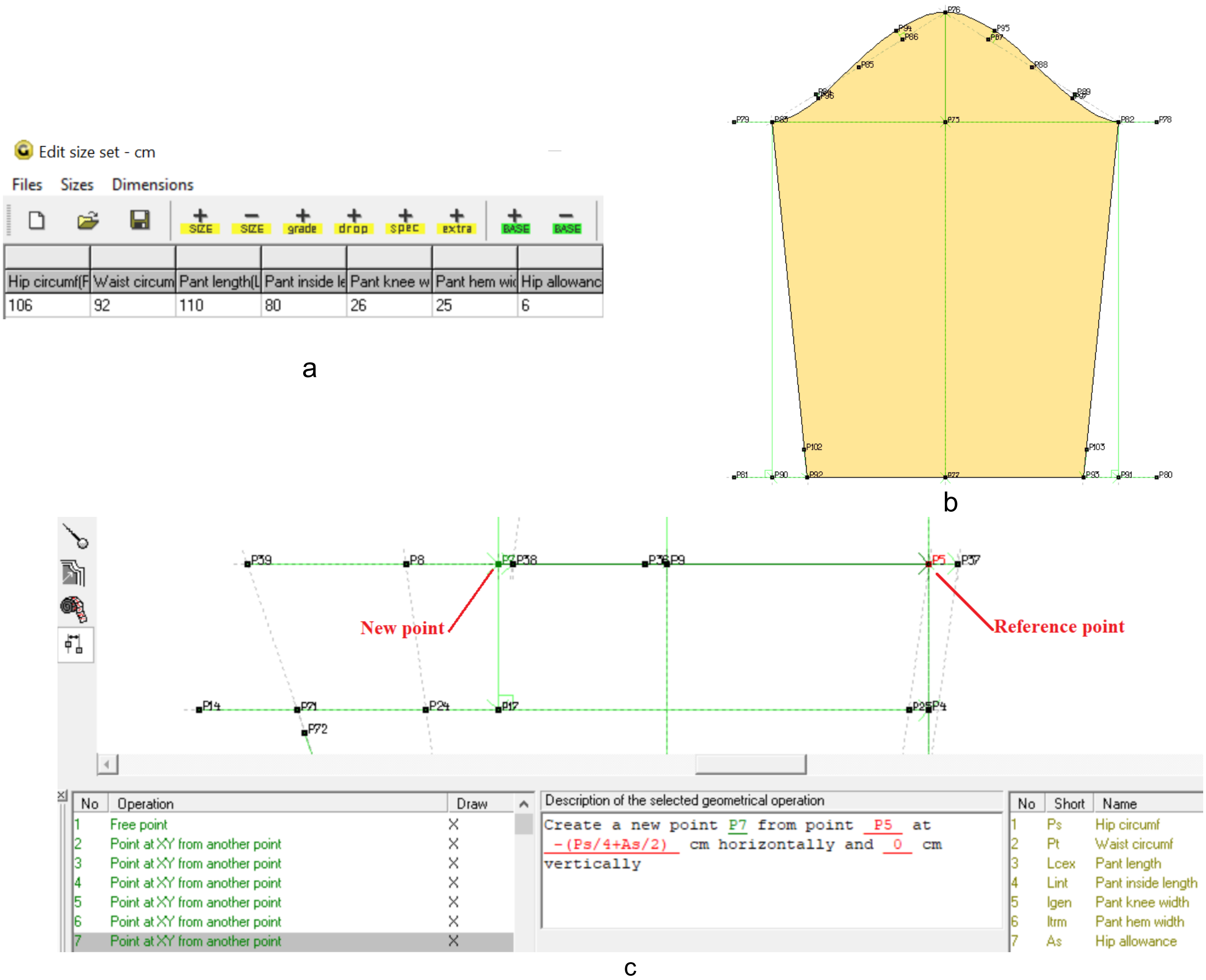


Fig. 4 (a) Initial data (selection); (b) sleeve (geometric layer and the final pattern); (c) geometric layer for the trouser patterns

Fig. 5 PPE overall (a) static position of the wearer; (b) dynamic position of the wearer.

2.2.3. *Analysis and evaluation of virtual prototypes; determination of necessary changes or validation of the developed solution*

The following conclusions can be drawn from the analysis of the images in Fig. 5:

- In the orthostatic posture, the designed product is longitudinally stretched (undersized) and not properly fitted in the lower region;
- in the dynamic posture of the trunk, the problematic areas are the pelvic and upper arm regions;
- the elastic properties of the textile material cannot guarantee the freedom of movement necessary for occupational activity. The one chosen for this product category must be resistant to repeated stretching/bending and friction and should provide protection against environmental factors (risk of pinching or tearing).

2.2.4. *Introducing data pertaining to the dynamics of the human body into the 2D design algorithm, obtaining new product shapes and creating the 3D prototype*

Based on the central information in Table 1 and the analysis of the virtual prototype (in dynamic postures, Fig. 5b), we infer that it is necessary to introduce the dynamic effect values for dimensions (2) and (4) into the design algorithm, as these anthropometric parameters undergo important changes.

The new shapes of the product elements are used to create the virtual prototype, which is then tested on the same mannequin with the same material under static and dynamic conditions. In the design algorithm, the values of the constructive additions and the way in which they are distributed are identical to the previous version, as the product meets the volumetric requirements (it can be worn over other garment products).

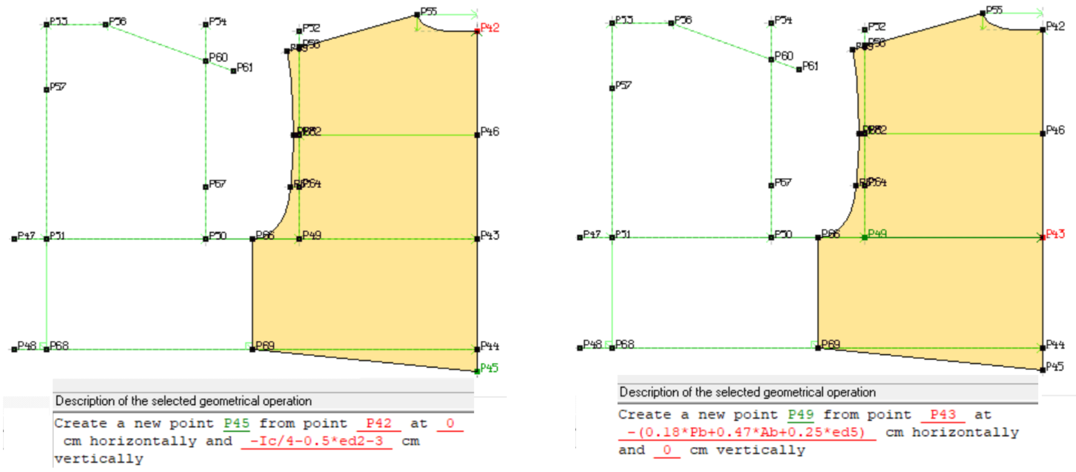


Fig. 6 Cont.

c d

Fig. 6 Newly designed overall: (a) Mathematic relationship for the back length; (b) mathematic relationship for the back width; (c) overall in a static position of the wearer; (d) overall in a dynamic position of the wearer

The following changes were made in the design algorithm in order to ensure the comfort of movement:

- Since the waistline for the back component is oblique, the absolute value of the dynamic effect of dimension (2) was partially taken into account when determining the position of the point on the centre of the back (point P45, Fig. 6a);
- in the mathematical relation used to determine the position of the point (P49), which is used to determine the width of the back, the value of the dynamic effect of dimension (5) was partially taken into account (Fig. 6b);
- in order to determine the height of the step line or fly, the absolute value of the dynamic effect of dimension (3) was partially used in the mathematical relations describing the position of point P4 (see Fig. 4).

2.2.5. Analyzing and evaluating the new prototype; validating the design solution

The analysis and evaluation of the new prototype show the following: due to the new shapes and dimensions of the product elements, the virtual prototype was better adapted to the shape of the body (in static and dynamic postures) and to the longitudinal and transversal tensions developed in the clothing on the body (static position and in the specific position depicted in Fig. 5a).

3 Results

An overall, as a piece of protective equipment, as it is mainly used in the mechanical field, should ensure a high degree of comfort and not restrict the movements necessary for occupational activity. The geometry and the size of the product elements, which result from the design process, have a decisive impact on the quality of the product and worker performance.

In the case of the selected product (Fig. 6c and 6d), the virtual shape of the product was evaluated in static and dynamic postures.

- In the static position, the product was found to be adequate in what concerns the fitting degree along the transversal planes (it corresponds to the shape and size of the body and ensures freedom of movement). The value of the constructive addition at the level of the depth line is appropriate (we tested values in the 10-13 cm range, distributed differently among the constructive areas of the product: rear (47%), lateral (18%) and front (35%)). The value of the constructive addition was also determined depending on the material's properties that can be used for manufacturing the product.
- In dynamic position, when performing a movement with a large amplitude, the values of the body dimensions specific to the involved body segment change significantly compared to the ones measured in static mode. The product was tense in the longitudinal planes (Fig. 5a). The product was too short and exerted some pressure on the shoulder area. This problem was solved by partially

using the absolute value of the dynamic effect of dimension (2) to determine the height of the waistline.

- The dynamic effect of dimension (1) is compensated by the one of the dynamic effect of dimension (2) and the one of the constructive addition at the height of the depth line. The absolute value of the dynamic effect for dimension (5) was partially used in the mathematical relation for determining the value of the back width. This method compensated for the value of the dynamic effect for dimension (6) and eliminated the tension created in the product when it is worn in the shoulder area.
- To ensure movement comfort, the following changes were made to the design algorithm:
  - The position of the point (centre of the back) was calculated using partially the absolute value of the dynamic effect of dimension (2);
  - In the mathematical relationship describing the position of the point used to determine the width of the back, the value of the dynamic effect of dimension (5) has been partially taken into account;
  - To determine the height of the step line or fly, the value of the dynamic effect of dimension (3) was partially used in the mathematical relation describing the position of the point.
- After the changes, the virtual prototype adapts better to the shape of the body (static and dynamic positions) due to the new shapes and dimensions of the product. In this way, the body's pressure was eliminated in the longitudinal and transverse directions (static position and in the specific position depicted in Fig. 5a).

The obtained results show that if the relevant pieces of information pertaining to the dynamics of the human body (dynamic effects) are correlated in the mathematical relations describing the dimensions relevant to the shape of the elements for products that are designed for intensive physical effort, then the latter will provide the wearer with a good degree of comfort and enhance their work performance.

4 Conclusions

Individual protective equipment is clothing that must meet the specific requirements of the professional activity for which it has been designed/manufactured. The implementing rules of PPE are strict and specific to the different sectors of activity because they must ensure the wearer's protection against environmental hazard factors while allowing them to carry out their tasks in the best conditions.

Professional activities requiring physical movements should not impair the health and safety of the person performing them in the long run. Their amplitude and frequency instil a certain degree of dynamism in the body, a change in the dimensions that are involved in their execution, and consumption of muscular energy along with the simultaneous occurrence of a certain degree of physical fatigue. The layer structure, volume, and mass of the garment employed as PPE as well as the pressure it exerts on the wearer must enable the person to execute movements with a minimum consumption of muscular energy (a balanced body dynamic). As a rule, the absolute value of the dynamic effect can be compensated by the elasticity properties of the textile materials in the product structure and by employing various technological solutions for the extremities of the products or for the fastening systems (e.g. the use of Velcro fasteners at the ends or as a system fastener, the fitting of cuffs with elastic, etc.).

The possibility of designing the geometry of the components in the structure of the product by directly integrating the user data with the one specific to the type of the product (personalised/individualised design) and using modern constructive design programs ensures a high degree of comfort and adequate protection against environmental hazard factors.

The presented study could provide a basis for future research on the design algorithm for other personal protective clothing or medical devices with different structures, taking into account the influence of the properties of textile materials and the human figure (different proportions, postures and conformation).

Author Contributions

M. Avadanei: conceptualisation, methodology, investigation, writing – review and editing; A. D. Vatra: methodology, validation, writing – original draft preparation; M. I. Rosca: conceptualisation, formal

analysis, writing – original draft preparation. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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