

Operational Qualification of the Individualisation of Protective Clothing Design Based on the 3D Scanning Technique

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Abstract

The object of the publication is to present the validation process stage (operational qualification) of developed assumptions for customised clothing manufactured in industrial conditions. 12 special clothes were made and adjusted to the individual dimensions of firefighters' silhouettes obtained in the 3D scanning process as well as 12 special clothes adjusted to selected size subgroups after the 3D scanning process from the same identified group of 12 firefighters. Two batches of clothes having undergone the installation qualification were submitted for testing in real conditions (operational qualification). Then, on the basis of data collected from the ongoing functional tests, a batch of six sets of individualised special clothing for the Fire Service was produced in industrial conditions (changing the manufacturer and model of the clothing). A positive result of validation (operational qualification) of this batch of clothing in functional tests conducted in real conditions will allow its introduction to industry through training in production plants and procedures of individualisation of advanced protective clothing design for people working in environments with a high degree of risk to health and life. The individualisation of protective clothing design, through a better fit of the size of the clothing to the body of the user, will significantly affect the comfort of use, ergonomics of the clothing, and the safety of the user.

Key words: protective clothing, design, customisation, personalisation, 3D scanner.

In view of the continued pursuit of high-quality products and services for garment manufacturers, while lowering production costs, interest in improving the 3D scanning methods of clothing users' profiles, both in terms of anthropometric measurements and individualisation of the design of clothing products, continues to increase. Hence, in many scientific centers in the country and the world, research is being conducted on the use of a human silhouette scanner.

Gill [3] carried out a comparative analysis of the various methods of determining the waistline for a sample of 106 women using the automated software on a TC2 scanner. The waist – line is an important point of measurement of the human silhouette and is the control dimension in the garment construction process. Most often it is assumed that the garment should be suitably fitted around the waist. However, unlike other control points on the body, the waistline does not have a specific location for the entire population, which is the reference point for precise designation of the waistline.

A similar theme was explored by Wren [4], who described methods for determining the waistline for different female body types in the 55 + age group. A study of the impact of the thickness of the air layer in the skin space under clothing on the circulation of air under clothing and the transfer of heat by this garment was

carried out by Mert et al. [5]. A 3D scanner was used to measure the thickness of the gap between the garment layer and the body surface as well as the contact surface between them. These sizes depend on the size of the structural clearance, but also on the assumed position of the human body. To simulate realistic human behaviour in the standing and sitting positions, a flexible man-size dummy was used. The test results can be useful to improve the design of functional clothing and to model the transport of heat in garments at the different positions of a human.

Nowadays, manufacturers of clothing are able to satisfy the expectations of approx. 30-40% of customers by adapting their clothing sizes to silhouettes. This situation is due to the absence of updated dimension tables for the modern population. Cool et al. [6] conducted a pilot anthropometric measurement using the latest technology – 3D scanning to fill this gap. As a result of these studies, dimension tables were developed for both women in four age categories and men in three age categories. Based on these studies, avatars – silhouette models, were developed which could serve as virtual mannequins to help evaluate the correct fit of clothing.

The difficulties that may arise when visualising clothing superimposed on an avatar related to the type of textile material used were described by West [7].

Introduction

The aim of the research was to validate the individualisation procedure of advanced protective clothing design for persons working in an environment with a high risk to life and health, based on the 3D scanning technique. This stage was realised by validation (operational qualification) in operational conditions for the individualisation of protective clothing design for a group of people working in an environment with a high risk to health and life, based on the 3D scanning technique. The installation qualification of the research results is described in [1-2].



Figure 1. Front view of individualised clothing (IP code).

The first wide-ranging anthropometric measurements in the Canadian armed forces were described by Chang et al. [8]. 2200 soldiers were subjected to measurements carried out using a 3D scanner and simultaneously, for reference, traditional methods (for selected dimensions). The study aimed to gather detailed and up-to-date information on the dimensions and types of silhouettes of soldiers for military equipment design needs. This information enabled the comparison of anthropometric military personnel data with data of the entire North American population, using the CEZAR database. Scanning technology for human silhouettes is seen as an essential bridge between garment production and computer aided design technology [9]. This technology is not yet widely used, hence it is necessary to conduct research to authenticate procedures and establish examples of good practice. This work assesses one of the methods of individualisation of clothing using a scanner and modern design technology.

The research works conducted by Hrynk et al [10-11] are among the few that investigated the designing of personal protective equipment using a 3D scanner. The article introduced the concept of using scanners in reverse engineering for the design and construction of personal protective equipment requiring close fitting to the individual. The work developed stop and face models and methodology for handling 3D scanners.



Figure 2. Rear view of individualised clothing (IP code).

The concepts of modelling and numerical simulations of virtual dummies and garments in a three-dimensional space were presented in [12-13]. The aim of the work was to design a virtual dummy in a 3D environment which would take into account the expectations of the garment industry, while also specifying the right strategy for designing clothing in 3D. A combination was proposed: a model of the clothing and a virtual mannequin model, forming an integral part including the key parameters covering the composition of clothing and its proper fit to the user. It was also considered to transform the spatial forms of garments acquired into flat patterns of clothing, readable to industry, meeting the correlation criteria with the shape of the virtual dummy, and taking into account the actual deformation of the materials.

The aim of research described in [14] was to try to propose and develop a new numerical method for designing garments in a three-dimensional space for non-standard silhouettes. These considerations were aimed at obtaining two-dimensional patterns of garments for people with disabilities, in this case those suffering from severe scoliosis. Two methods were proposed for obtaining clothing forms in a 3D space. In the first method, a virtual stick tool (CAD system) was used, which, as an empirical method, is based on the knowledge and experience of the constructor of clothing forms. The sec-

ond method presents the possibility of creating a properly matched garment directly on the 3D silhouette. This method takes into account the irregularity of the construction of the human silhouette, as well as the comfort and well-being of the user, depending on the value of the garment clearance. The results of the work present the potential and possibility of using the solutions proposed both in the production of mass apparel and mass individualisation.

The project “Individualization of the design of multifunctional ballistic vests of hidden wearing” developed a procedure for individualisation of the structure of a newly designed multifunctional ballistic vest for secretive wearing. In the course of the work, a group of 12 users of the target vests were selected, for which individual waistcoats were made according to the individualisation procedure. Validation studies of this procedure were made through the installation, operational and process qualifications. The process of validating multifunctional vests for secret wearing is discussed in [15], where the process of qualification was carried out in detail. Conditions to demonstrate the functionality of the prototype and its compliance with the requirements and quality criteria were adopted in the installation and operational qualifications. The repeatability of the prototype manufacture was verified, under real, industrial conditions, in accordance with the accompanying verified documentation, also in terms of user safety. For this purpose, operational tests were carried out on the comfort and functionality implemented in the traverse conditions.

The validation of technology is mostly performed in two stages: the manufacture of the product in a real industrial environment, with following complex verification (validation) of the product in real conditions of use (by several users in several repetitions). The article describes one stage of the validation: operational qualification, confirming the possibility of manufacture of the product, with following verification of users’ requirements.

The main objective of the research was to achieve, by the procedure of “Individualization of advanced protective clothing for people working in environments with a high risk to life and health” developed, a level of technology readiness con-

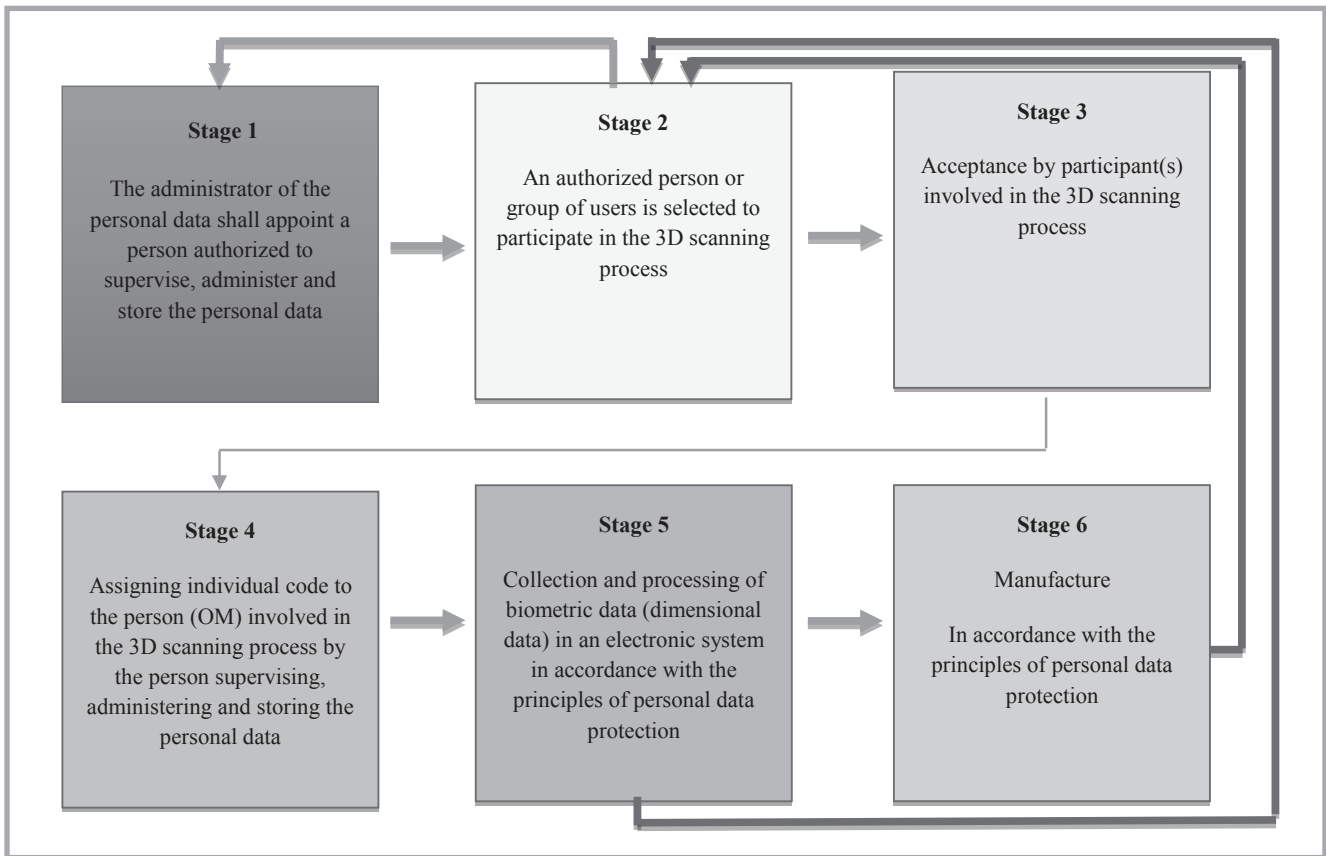


Figure 3. Stages of the process of personal data protection (biometrics).

firmed by tests in operational conditions (demonstration of industrial-scale and a prototype batch made during operational demonstration and use).

Thus, the aim of the study was to confirm reproducibility of the individualisation technology elaborated, described by the above-mentioned procedure, using the results of one stage of the validation – operational qualification.

This will allow to indicate that the procedure developed has reached its required form and can be implemented both in industrial practice (executive capabilities) and in standard use (application capabilities and functionality confirmation).

The above should be confirmed by validation of the process of manufacturing individualised clothes in real industrial conditions (the highest level of technological processes) and by use in real conditions (level of final use – Disposer). The objective of the research was to present the process of validation of the procedure of individualisation of advanced clothing design (operational qualification – OQ).

Materials

To carry out the validation of the process of individualisation of clothing design in industrial conditions, fire brigade clothing in sand colour was selected, with a shorter jacket, currently in force, made of aramid fabric with a PTFE membrane, including a tape system, fulfilling the requirement of Order No. 9 of the Polish Chief Commandant of the State Fire Service [16]. The clothing complies with the CE-certificate.

Two batches of special clothing (PPE) for firefighters were made, on which functional tests were conducted in operational conditions. Both batches were fabricated by the same manufacturer: 1) based on the standard product range of the manufacturer, and the operational procedure of manufacture (research code S); 2) is based on that applied by MOR-ATEX for individual sizes of fireguards, in accordance with the Individualization Procedure (IP) (research code: IP).

Each batch consisted of 12 individualised special clothing for the Fire Service and were submitted to utility tests at the Municipal Headquarters of the State Fire Service in Łódź.

Figures 1 and 2 show the individualised clothing (IP code).

Methods

Individualisation Procedure (IP)

An individualisation procedure (IP) for the design of advanced protective clothing for people working in a highly health and life-threatening environment was developed from biometric data retrieval processes (dimensional data) using 3D scanner support in the course of customer service of group clients of the uniformed services. The procedure covered the operations carried out by both the final consignee and the executing order.

The IP has records on the protection of personal data and on the process of 3D scanning using the results of this process for the development of individualised clothing (IP clothing) available for production in industrial conditions. The individualisation procedure developed:

- provides the protection of personal data during the scanning of persons, in the process of retrieving biometric data (dimensional data) from people using the 3D scanner;

Table 1. Questionnaire – analysis of the qualification tests was carried out via the MORA-TEX questionnaire portal (<http://www.ankietamundurowi.pl/>) using the individually prepared questionnaire:

Dimensional performance		Clothing fit level					
		S cloths			IP cloths		
		Inaccurate	Acceptable	Comfortable	Inaccurate	Acceptable	Comfortable
1.	Matching clothes to user dimensions						
2.	Matching clothes while doing the action:						
a)	Standing						
b)	Sitting						
c)	Walking						
d)	Kneeling						
e)	Creeping						
3.	Fitting clothes while walking on stairs						
4.	Matching clothes while raising both hands over head						
5.	Matching clothes when tilting and raising small items, e.g. pencil						
Dimensional performance of jacket		Jacket fit level					
		S cloths			IP cloths		
		Inaccurate	Acceptable	Comfortable	Inaccurate	Acceptable	Comfortable
1.	Adapting the jacket to the user's dimensions						
2.	Fitting sleeve length of jackets						
3.	Fitting sleeve width of jackets						
4.	Fit on chest circumference line						
5.	Fit the circumference on the hip line						
Dimensional performance of trousers		Trousers fit level					
		S cloths			IP cloths		
		Inaccurate	Acceptable	Comfortable	Inaccurate	Acceptable	Comfortable
1.	Adapting trousers to the user's dimensions						
2.	Fit on waist circumference line						
3.	Fit on hip circumference line						
4.	Matching trouser length						

- describes how to develop dimensional data in order to carry out the individualised design of a garment (IP cloths);
- describes how to prepare dimensional data for the design of a garment tailored for the individual scan participant.

The steps for processing personal data in accordance with the procedure elaborated are graphically illustrated in **Figure 3** (see page 91).

The process of producing individual (tailor-made) special IP clothing for fire brigade officers was carried out according to the scheme presented in **Figure 3** (see page 91) with the preservation of personal data.

Operational qualification (OQ)

The research presented included the selection of the subject of research, the location of the research area, the appointment of an administrator authorised to perform the pseudonymisation¹⁾ of personal data 1 of the test group, the separation of the test group with respect to the procedure for the protection of personal data (GDPR) and ethical considerations, and the laser measurement of the human figure with the use of a 3D scanner (Human Solutions/USA) Results of the measurements of the officer's silhouette using the 3D method were implemented as required by the: clothing template studio for the size of individually scanned silhouettes.

Then, in order to confirm the process qualification of the procedure being developed, a batch of clothes was processed, each of which was adjusted to

Table 2. Measurement results, cm, for silhouettes of 3D scanned persons.

User code	Height	Chest circumference	Waist circumference	Hip circumference	Back width on shoulder lines	Length to waist	Length from crotch to ground (leg length to crotch)	Length from waist to ground (leg length to hip)	Sleeve length	Thigh circumference	Hand circumference in bicep
KM14	168.3	104.4	89.1	97.7	41.0	57.9	66.5	97.6	61.1	53.5	30.3
KM4	177.0	101.8	85.2	101.3	39.0	61.1	73.5	105.8	63.0	57.5	34.0
KM9	177.0	120.7	94.6	105.7	44.7	60.9	71.9	101.6	62.5	60.0	34.4
KM1	179.6	110.9	96.0	103.4	45.0	60.3	75.0	108.3	67.8	57.0	31.7
KM5	181.7	110.3	90.7	101.2	37.0	60.0	76.8	109.7	70.9	56.1	31.9
KM2	182.8	106.0	92.6	102.4	43.4	61.2	79.3	110.0	65.8	59.4	34.0
KM10	182.8	126.0	98.2	106.6	47.0	61.2	72.8	106.5	68.0	58.7	39.5
KM11	185.7	119.8	100.3	108.4	42.7	66.6	73.7	104.9	65.0	65.5	34.3
KM7	186.8	96.7	84.7	93.5	40.2	64.6	76.3	108.2	65.5	51.3	28.9
KM8	186.8	128.7	106.4	113.0	45.4	64.9	74.5	106.3	68.0	62.5	36.3
KM3	187.5	100.5	88.5	100.4	41.7	68.3	75.9	109.0	71.2	55.5	31.5
KM12	193.6	118.1	103.1	111.8	44.7	64.1	80.6	115.5	69.0	64.5	35.0



Figure 4. Match of clothes during standing activities.



Figure 5. Match of clothes during seating activities.



Figure 6. Match of clothes during walking activities.

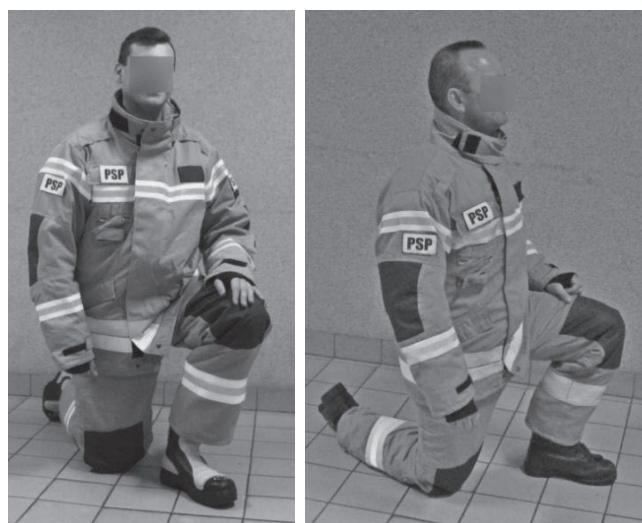


Figure 7. Match of clothes during kneeling activities.

the individual size of 6 scanned persons from the test group. The batch of clothes was used in real conditions. The number of clothes made was selected on the basis of the analysis of documents containing the number of the crew of the fire engine, given as 3-6 persons, and the number of combat trucks going to the incident at the same time – 3-4 [17-18].

The purpose of the OQ is to demonstrate the technical feasibility of carrying out the IP. Data collected during the implementation of this validation verify whether the IP is compliant with the assumptions and accompanying, practically unverified documentation.

Results and discussion

3D scanning results

After the 3D scanning process and correction of the operations performed, the dimensions necessary to complete the

planned assortment of IP clothes are included in a readable table containing the dimension names – their location and value in units measured for all scan participants by code.

Table 2 contains the results of 12 officers' scans at eleven measurement points for the IP clothing design. To fabricate the IP clothes under individual dimensions, we only need to use output **Table 2** without sorting. The completed dimensions of 12 scanned participants were transferred to the manufacturer of special clothes for firefighters, where 12 individual IP clothes adapted to the individual dimensions of the 3D scanned officers were produced.

Simultaneously, typical clothes using the manufacturer's product range dimensions were fabricated for each officer participating in the research. These clothes were used as references for the validation.

Performance test

The performance of the individualised batches (IP and reference) of clothes for firefighters was assessed by users in a survey after 5 months of use of the clothes in real conditions of work activities.

Preliminary functional tests

At the Municipal Headquarters of the State Fire Service in Łódź /Poland, during the ongoing use of individualised clothes, an initial assessment of size functionality was carried out by checking (**Figures 4-11**):

- 1) the match of the clothes to the user's dimensions;
- 2) the match of the clothes while performing activities:

Figures 12-14 presents the test results of the performance of IP clothes and reference – S clothes. One of the twelve users participating in the study did not score the clothing tested.



Figure 8. Match of clothes during crawling activities.



Figure 9. Match of clothes while climbing stairs.

The performance test of the IP clothing fit level showed an increase in acceptable and comfortable results of the answers in the whole range of the questionnaire. A comfortable feeling of users wearing IP clothes was stated by 36.4% of users in the following criterion: match of clothes while performing the action of standing (vs 27.3% found for S clothes). The criteria of the match of clothes to user dimensions, as well as the match of clothes while performing the actions of: walking and creeping also indicated

more fitting benefits as compared with S clothes (27.3% vs 9.1-18.2%). A shift of the positive score for IP clothes from an acceptable to a comfortable feeling, in comparison to S clothes, was found in the study. An acceptable score for IP clothes was given by more than 50% of the users testing both S and IP clothes.

Figure 13 shows results of the performance of the jackets tested, both reference (S cloths) and fabricated by the individualisation procedure (IP clothes).

The jacket performance results indicated comfortable scoring in a population of more than 25% of IP users in the majority of the criteria tested, whereas the most negative score was found for S clothes in all criteria estimated. A significant negative estimation of jacket performance was pronouncedly identified in the group of S clothes users (54.5% vs 36.4% IP clothes), confirming the benefit of the individualisation procedure of firefighter clothes fabrication in the area of jacket design. A significant increase in the acceptable and comfortable scoring of IP clothes was found during the operational qualification in real conditions of use.

The clothes tested belong to the most individual personal protection equipment with an acceptable reduction in ergonomic behaviour due to the necessity to provide high safety due to the risks of the activities. Taking into account the above, the resultant benefits of the individualisation of personal protection equipment should be underlined.

Figure 14 presents the test score of IP and S trousers.

Estimation of the following criteria: fit on hip circumference line and match of trouser length yielded a maximal level of scoring for the IP clothes (27.3% vs 18.2% for S trousers). Moreover, an increase in the positive estimation in the comfort scoring for IP trousers as compared to S clothes was obtained. However, an increase in negative score of IP trousers was indicated as compared with S clothes.



Figure 10. Match of clothes while raising both hands above the head.

The IP trousers showed a comfort benefit in the aspect of fitting in the majority of criteria tested during the real condition operational qualification as compared with the reference (S trousers).

Conclusions

Validation of the IP Procedure was carried out under the following real conditions : 1) the manufacture of the firefighter clothes (PPE), and 2) their use in real conditions (operational qualification).

The obtained and developed 3D scanning results allowed to create a batch of individualised special clothing tailored to the dimensions of individual silhouettes of officers participating in the 3D scanning process.

The clothing fabricated was tested for performance and fitting in real conditions of use by the users and scored in a wide range of fitting criteria. A significant majority of the scoring criteria showed the benefit of the use of the individualised clothing (IP clothes), especially due to its maximal score level for comfort. The above confirmed the advantages of personalisation of the PPE as conducted in this study.

The procedure for the individualisation of advanced protective clothing for people working in environments with a high risk to life and health will be validated during real-world functional tests (performance qualification test). After completion of the functional tests, the procedure will be made available through training conducted in production plants.

The research presented (as described in the aim) is the first stage of qualification validation that confirms the possibility to manufacture an individualised product that fulfills the requirements of users in real conditions. The second step – processing qualification allows to confirm the reproducibility of the IP procedure in real conditions (manufacture and use).

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Figure 11. Match of clothes when performing the activities of leaning and lifting small objects, e.g. a pencil.

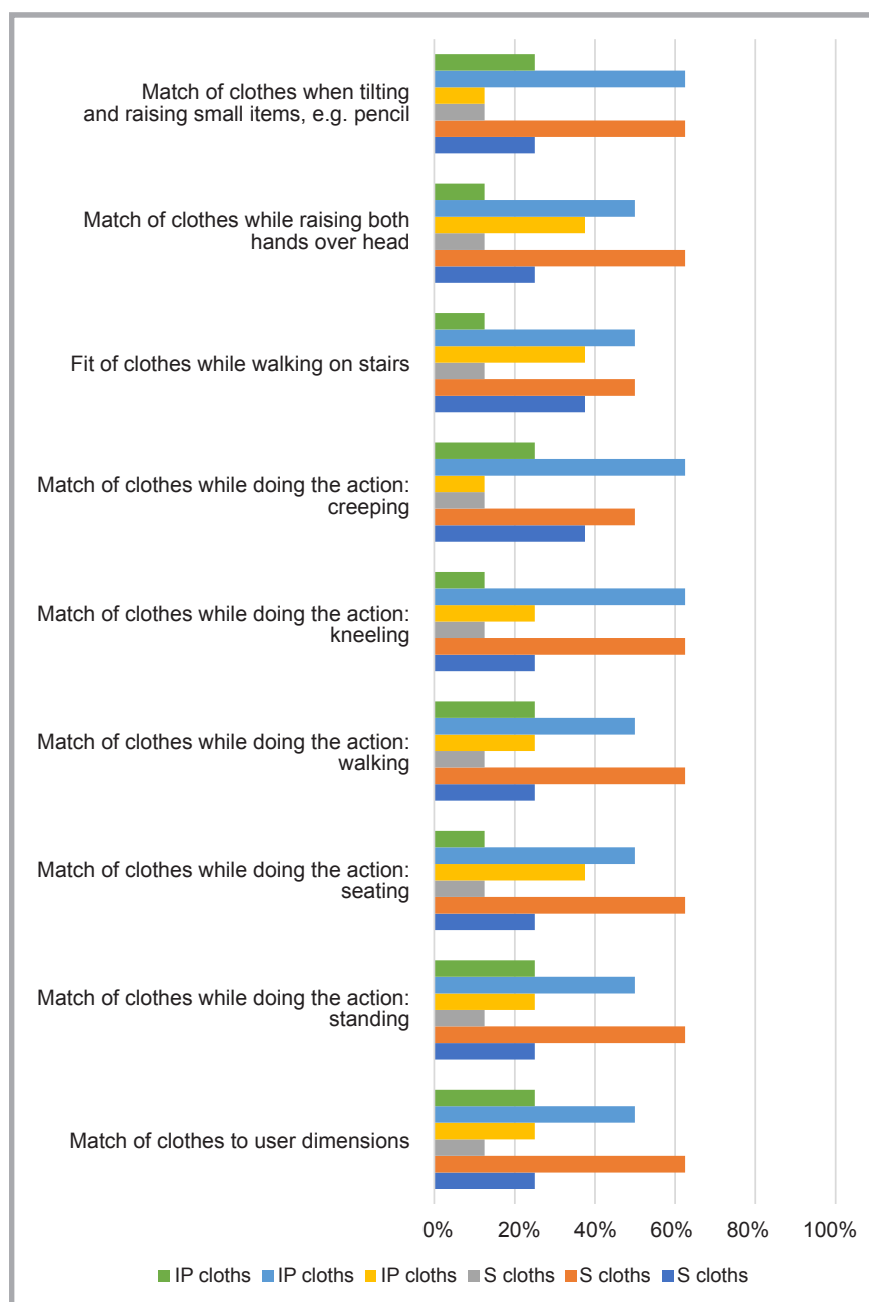


Figure 12. Results of the performance test of S and IP clothing in real condition of use (only 11 answers of 12 users tested for PPE were obtained during the test. One of the users did not complete the survey).

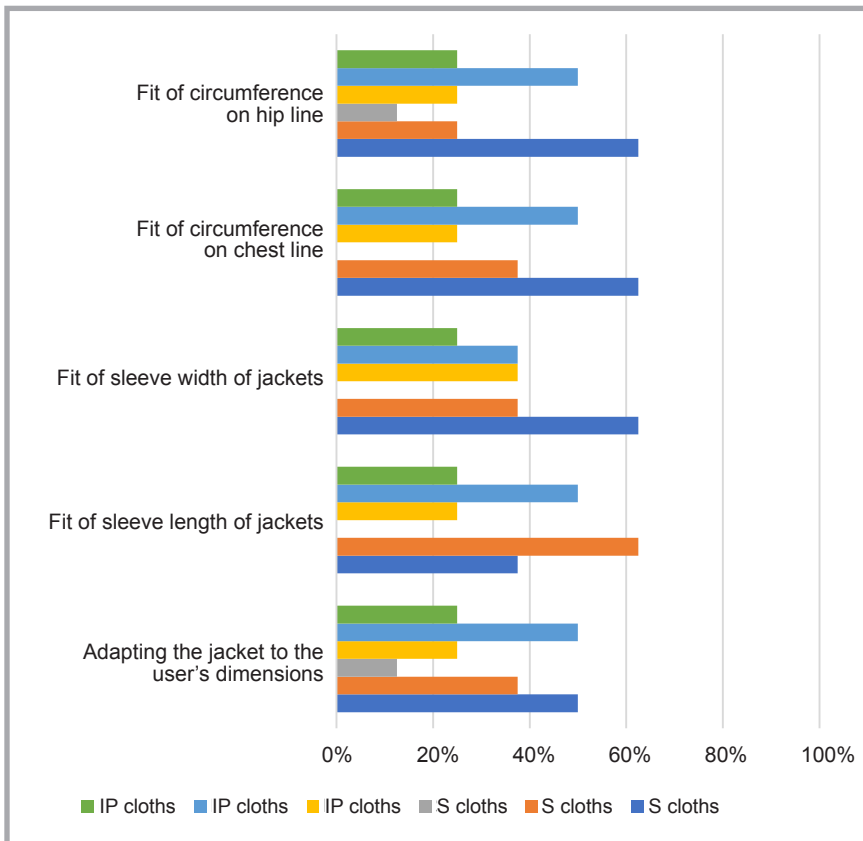


Figure 13. Results of performance tests of IP and S jackets in real condition of use (only 11 answers of 12 users tested for PPE were obtained during the test. One of the users did not complete the survey).

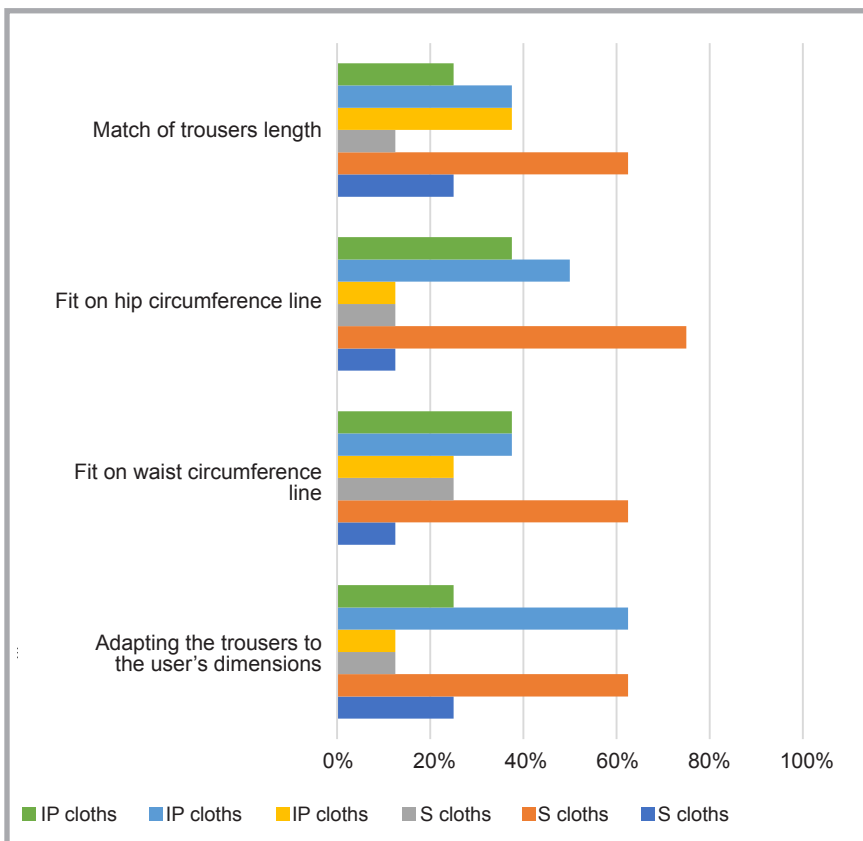


Figure 14. Results of the performance test of IP and S trousers in real conditions of use (only 11 answers of 12 users tested for PPE were obtained during the test. One of the users did not complete the survey).

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Editorial notes:

1) Pseudonymization – means the processing of personal data in such a way that it can no longer be attributed to a specific data subject without the use of additional information, provided that such additional information is stored separately and is subject to technical and organizational measures that make it impossible to attribute it to an identified or identifiable natural person (Article 4(5), RODO).

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