Development of an ergonomic protective suit for physiotherapists during the COVID-19

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Abstract
During the COVID-19 pandemic, the provision of appropriate protective clothing for medical staff who must continue to perform their duties at this period is of particular importance. Physiotherapists are not allowed to suspend working during this time either, and the specifics of their work is close contact with the patient within various movements during the therapy process. Inadequate (intended for general use) protective clothing affects work capacity in the aspects of movement restriction, thermal comfort and thereby increasing energy consumption. For the design and supply of personal protective equipment (PPE) and protective clothing of the best possible quality, PPE should be explored in a systemic approach (holistics) to assess anthropometric fit and ergonomics, material properties and thermal performance. This study investigated anthropometric characteristics of target group representatives; sizing, fit and design flaws of protective suits for physiotherapists; provision of mobility in the protective clothing of physiotherapists; the protective suit fabric layer interaction with the human body and the importance of subjective evaluation of fit and ergonomics of PPE (made by specialists and wearers). The results of the study promote the usage of objective knowledge of anthropometry and ergonomics as well as subjective assessment findings in the development of protective suits for physiotherapists.

Keywords
PPE for physiotherapists, anthropometric fit, ergonomics, sizing, evaluation

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Introduction
It is impossible to prepare for an unexpected crisis, including a pandemic! Solutions that have been sufficient in everyday work can, in unusual circumstances, prove to be inappropriate and even harmful. This situation arises because there has been no need for specific resources in the current work. For example, a coverall that protects medical personnel from infectious diseases has so far only been used in those treatment facilities where they face
infectious diseases. However, with the spread of the Covid-19 virus, it turned out that such a suit should be worn by any medical professional in contact with patients. Rehabilitation is an integral part of health care, and professionals (doctors, physiotherapists, occupational therapists, etc.) continue to work in such hazardous conditions, therefore provision with appropriate PPE and protective clothing is required. The risk to physiotherapists is increased due to close contact with the patient and the duration of the therapy session (between 15 and 45 min).  

The job responsibilities of the specialists include assisting/supporting the patient to perform various specific, purposeful postural manoeuvres according to the therapy methodology. It requires physical effort from a specialist and numerous active, wide-range body movements. The coverall used to control infectious diseases is a one-piece, wide cut, usually surrounds the body freely, and is not designed to perform large-scale movements. Hence, the work capacity of a physiotherapist can be directly affected by the design solutions, material selection and quality of the worn coveralls, protective clothing and PPE. With the above considered, the universal protective clothing available on the market is not always suitable for rehabilitation work specifics, because of restricted movements, contributed fatigue due to thermal discomfort, and thus increased energy consumption in general.

Due to the specificity of the virus and risk of contamination, the areas of the human body most considered to be at risk of infection are identified (see schematic Figure 1). The most exposed is the respiratory system and palms as a transport area to the airways. Therefore, protective masks/respirators are a significant PPE. Also, the infection risk through the eyes is increased due to internal connections to the airways and possible transmission from the palms. The ears and genitals are the least risky area, and the risk of infection through the skin is low (unless there are injuries). Therefore, a protective coverall/suit mostly is necessary for the hygienic function and serves as a means of the barrier and eliminator of contaminated surfaces.

To protect themselves, patients and other medical staff (nurses, assistants and other personnel working in a medical institution), physiotherapists choose to wear various PPE configurations, including respirators, goggles, overalls and gloves (this choice varies also from the government to government – at the beginning of pandemics various suggestions raised).

The recommendations and studies state that PPE (including protective clothing), simultaneously with protective properties, must be appropriate to the wearer’s morphology (fit), functional and not affecting wearers work capacities during various routine and work movements – ergonomic. Regarding the ergonomics of PPE, the Regulation (2016/425) of the European Parliament and the Council require that they must be designed and manufactured in such a way that the user can perform the risk-related activity normally under the intended conditions of use. And some of the general requirements applicable to all PEE include such design principles as ergonomics, highest level of protection possible, suitable constituent materials, maximum permissible user impediment, adaptation of PPE to user morphology, lightness and design strength and compatibility of different classes or types of PPE designed for simultaneous use. In terms of wearer comfort, it is affected by the thermoregulatory properties of the garment, including heat exchange and vapour permeability. Though, they depend not only on the properties of clothing materials but also on the design and size of the garment – the air gap size, the contact area and interaction processes between the garment layer and the human body.

The object of this study is the anthropometric fit of protective clothing (protective suit in this case), which is defined as the correspondence of its size and shape to the size and shape of the human body. And ergonomics refers to product solutions for human needs – the ability of wearers to perform daily duties and/or tactical tasks, such as work movements or other activities. The research aims to determine the characteristics of anthropometric fit and ergonomics of protective suits worn by physiotherapists, to clarify the deficiencies by using objective and subjective study methods and draw conclusions about potential problem solutions.

**Materials and methods**

In total, ten (10) representatives of the target group (practising physiotherapists) participated in the study. The data were obtained for a small group of participants to test the hypotheses about the uselessness of existing coveralls and to make preliminary recommendations.

A non-contact method (3D scanning) was applied to obtain anthropometric data using the human body 3D scanning device VitusSmart XXL® (Human Solutions Group...

Figure 1. Human body areas at risk of infection.
GmbH) with the AnthroScan data processing system. The main advantages of the applied non-contact method are the relatively fast and simultaneous acquisition of a large number of measurements; re-availability of the obtained 3D body models for additional research; lack of physical contact between the person to be measured and the anthropometrist; availability of various system tools for in-depth research (additional measurements, cross-sections especially for non-standard positions). Anthropometric data were used to analyse the conformity of protective suit (available to the target-group) sizing systems for the wearer population.

Software tools were used for the acquisition of images for further processing and analysis of clothing anthropometric fit and interaction with the human body in 3D scanning software and vector graphic systems. This part of the study included a definition of axes for body position characterisation and quantification; visual identification of defect folds and fabric tension of suits using scanning images; the analysis of the garment layer interaction with a human body using transverse cross-sections (superimposition of the body in underwear and body in a protective suit).

Subjective assessment was used as one of the methods for the evaluation of protective suits. They included expert (with knowledge of clothing, anthropometry and ergonomics) conclusions by visual evaluation of defects in protective clothing (folds and fabric tension), as well as wearer feedback (in the form of direct interviews) on movement restrictions and effects of different garment parts when moving.

The research methodology in the aspect of method combinations was partially based on Lapkovska’s Doctoral Thesis ‘Improvement of methods for evaluation of anthropometric fit and ergonomics of clothing’, which is expected to be published in the first quarter of 2022. The subject of the Thesis is a method – an algorithm (system of principles), which allows combining the objective and subjective evaluation methods of clothing to focus on the practical principles for determining the anthropometric sizing and ergonomics of clothing.

### Results and discussions

#### Anthropometric characteristics, fit and sizing

The provision of anthropometric fit is based on a definite distribution of sizes of the target population. It can be ensured by an anthropometric survey and favourably the acquisition of anthropometric data of the entire target group and annual surveys. Then it is followed by the classification of body sizes and the distribution of morphotypes according to the group of product wearers. The use of anthropometric data through effective measurement of the human body is considered to be the most effective solution for the development of appropriate fit clothing and adequate sizing systems.

In this study in total, 10 test persons participated in the experiments using the 3D scanning method and anthropometric characteristics are summarised in Table 1.

Size labelling of protective clothing available on the market commonly is a combination of key measurement intervals, including body height and chest circumference. Available protective clothing items on the market (protective clothing that was most available and actively used by health care specialists in Latvia) were selected as options for participants. Test persons had access to three (3) sizes of suits (see Table 2) with a theoretical option to choose the suitable one.

As a result, six (6) out of ten (10) participants by their body characteristics fall within the specified size ranges (four (4) ‘M’, one (1) ‘S’ and one (1) ‘L’ size), but despite the theoretical correspondence, it was indicated that the fabric tension and body limitations are still felt during the movements. The remaining four (4) participants do not fall within the existing sizing system, so when choosing clothes according to body height, the chest circumference of a person is larger or smaller than indicated on the label, and vice versa. Thus, the selected protective garments may be inappropriate in circumferences or length. Furthermore, it is concluded that the lack of clarification on the meaning of the clothing label creates difficulties and confusion for the wearer to understand and choose clothing that matches the body characteristics. Even more, the wearer knowledge

| Characteristic        | Data                      |
|-----------------------|---------------------------|
| Gender (t/f/m)        | 6 female, 4 male          |
| Age (year)            | 30 ± 3                    |
| Body height (cm)      | 174 ± 5                   |
| Bust/chest girth (horizontal) (cm) | 96 ± 5                   |
| Waist girth (cm)      | 78 ± 5                    |
| Buttock girth (cm)    | 100 ± 4                   |
| Body weight (kg)      | 68 ± 6                    |

Continuous variables are presented as mean ± standard deviation.

| Size   | Body height interval (cm) | Chest/bust girth interval (cm) | Corresponding test-persons (number) |
|--------|---------------------------|--------------------------------|-----------------------------------|
| S      | 164–170                   | 84–92                          | 1                                 |
| M      | 170–176                   | 92–100                         | 4                                 |
| L      | 176–182                   | 100–108                        | 1                                 |

Letter sizes (designation for clothing): S: small; M: medium; L: large.
of their body characteristics, even easy-to-obtain key measurements, is limited in their choice of appropriate clothing. This poses a common problem – the size designations of clothes are so fuzzy that it is impossible for the user to understand which size to choose. The key measurement system with a pictogram recommended by EN 13402 would be more useful here.

**Ergonomics**

Ergonomics research involves the ability of a person to perform certain movements in clothing by detecting limitations with amplitude measurements or by obtaining a subjective assessment of mobility in garments from the wearers themselves. The daily work dynamics of rehabilitation specialists include many different and combined movements that are constantly changing. Along with the movements, there is forceful physical contact with the patient, so the coverall must not affect the amplitude of the movements and also the ability to perform actions that require force. To achieve the best results in supplying the target groups with ergonomically appropriate clothing, a rational set of measures is obtaining the information on the specifics of the job (work movements, conditions, habits) followed by the identification of shortcomings and recommendations from real wearers (interviews, surveys) and real ergonomics tests.

The study was conducted for anthropometric research of the target group to determine the interaction of the protective suit (coverall) with the human body. 3D scanatars were used to obtain body measurements, perform a visual assessment of the body composition and evaluate the fit of the protective suit.

First, the scans were performed by the test subjects wearing underwear (as provided under the conditions of the method to obtain adequate body measurements) and taking six (6) body positions: stand; ‘Hug yourself’; rise arms; kneel; bend forward; and squat (see Table 3). Specific body positions/postures were chosen (agreed with the representatives of the target group) to simulate the maximum possible amplitude movements that may occur in the daily work of physiotherapists. Standard standing position (stand) scans were used for basic body measurements, and dynamic posture images were processed to identify changes in body shape during movements and to compare the ability of test subjects to perform such movements.

The axes were chosen to characterise the body position for the quantitative characterisation (by angles) of the movement range, and a comparison of the participant physical abilities was performed by superimposing scan contours. For example, posture ‘Bending forward’ with axes: Cervical vertebrae 7CV through Gluteus maximus; Lumbar Vertebrae L5 through the medial axis of Medial malleolus (Figures 2 and 3). And posture ‘Raised arms’ with axes: Lumbar Vertebrae L5 to Olecranon (elbow) in relation to the medial axis of the body; Lumbar Vertebrae L5 to Acromion in relation to the medial axis of the body (Figures 4 and 5).

Within the experimental set differences in movement ranges were determined, indicating disparities in the ability to perform specified postures even without wearing the protective suit (see Table 4). Values in the bending position indicate different abilities to reach hands towards the floor by bending forward torso, and in the raised arm position to raise arms at the shoulder and elbow joints.
In both cases, even at similar length values, the differences occur in the shape of the back, shoulders and arms, potentially causing dissimilar interaction of the garment layer with different bodies and thereby diverse tension zones.

With the above considered, knowledge and real data on body movement ranges must be interpreted for usage in the design process of clothing intended to perform dynamic work.\textsuperscript{23}

Afterwards, the scanning was performed by each subject wearing a protective suit in two cases (examples in Table 5): standing in a protective suit; taking the posture subjectively most restricted by the suit (chosen from six (6) previously taken without a suit).\textsuperscript{24} Protective suits were selected based on the size label information to theoretically choose the most appropriate size according to body characteristics. Previously summarised movements were performed wearing a protective suit for evaluation of the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image1.png}
\caption{Movement range in bending forward posture.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image2.png}
\caption{Movement range in bending forward posture (10 test person results).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image3.png}
\caption{Movement range in bending forward posture.}
\end{figure}
In the protective suit scan images, defect folds and fabric tension areas were visually identified. This approach makes it possible to identify areas of garments where defects occur as a result of body movements, in particular fabric tensions that affect the comfort of the wearer by compressing parts of the body or even causing skin abrasion.

The subjective assessment of the ergonomics of the protective garments was performed during the experiments by receiving feedback from the wearers. The feedback was obtained on the freedom of movements and effects of different garment parts when moving. The assessment of the ease of movement was performed on the Likert scale, where all the assessments were only in the negative range. For example, most wearers first pull up the thigh section of the trouser leg to be able to perform squat or kneel movements. Also, after making these movements, the trouser leg parts remain puckered and do not return to the starting position (anklet (cuff or band) required). It was concluded that in a squat and kneel position the top of the fastener makes pressure on the neck in the under-chin zone if garments do not have a sufficient ease-allowance for the length at the back, as well it causes a tight feeling in the knee area. When bending forward, the wearers feel the tension in the seat seam and the buttock area in general, as well as tightness in the thigh area. For most of the participants, tension is felt in the crotch part when lifting arms. Analysing data about functional positions in which the level of comfort was lower, it was concluded that more attention in a process of making protective clothing should be paid to the sections of the back, pelvic zone and knees, more specifically by increasing the ability of the material to stretch in these areas.

**Clothing layering**

Using 3D scanning, changes in the human body configuration (compression, tissue movement) and the space between
the body and the layers of clothing are studied, displayed and analysed with linear (girth and cross-section dimensions), area and volume measurements.

For the analysis of the garment layer interaction with a human body, transverse cross-sections were obtained superimposing the scans of the body clothed in underwear and body clothed in a protective suit. Transverse cross-section at the chest/bust level of ‘M’ size coverall (body height 170–176, chest/bust circumference 92–100) on four different wearers (Figure 6) indicated an increased volume of the fabric at the back and tight fit at the chest/bust part in front.

The extra volume (ease-allowance for freedom of movement) ensures that the wearer is not restricted during movements; however, the excess volume can also be a distraction. Especially for material used in antiviral protection coverall. The material has a low tangential resistance, excess folds stick together, slip poorly and interfere with the necessary actions. Therefore, solutions such as elastic material (if meets protective requirements) or folds of different extent may be more appropriate for protective garment design to adapt the garment to changes in body shape.

Conclusion

In general, there is a need to think more broadly about the revision and improvement of protective clothing sizing systems and grading principles, as well as the choice of materials and garment design solutions that ensure the most appropriate product creation and distribution to the target audience.

It has been found that not always the implemented protective clothing sizing system allows the wearer to choose a product that fits because of the lack of a clear, user-friendly sizing system. Besides, wearers with similar total morphological features may have a different range of movements, so it is necessary to study their limit values and find appropriate pattern-making solutions for the improvement of clothing fit. Though, to introduce adequate ease-allowances in critical areas, it is necessary to obtain extensive and reliable data on changes in body size and shape.

The advantages of 3D scanning technology in obtaining fast and reliable anthropometric data can be used to determine body characteristics of different groups of wearers so that the data can be used to design suitable clothing and develop or review sizing systems. Moreover, 3D scanning can be used for in-depth analysis of the human body movement features and the interactions between the layers of clothing and the human body surface.

By combining quantitative data with expert judgements and the wearer’s subjective assessment of protective clothing, the design processes can be improved by moving towards the creation of an end-user-friendly and ergonomic product.

Principles to be considered in the design of advanced PPE (protective clothing) includes that it allows free movements required during the working hours of medical staff; the fabric of the suit does not cause increased skin irritation and damage due to severe friction during movement; it does not cause body overheating and increased sweating; it does not cause subjective discomfort.

Further research requires the expansion of the research set (representatives of the target group, suit types), the exact definition of work-specific poses and ergonomic requirements, the objective testing of thermal comfort indicators (air and water vapour permeability tests), as well as the introduction of improved design solutions and the development of a prototype for testing in real working conditions.
The approach used in the study: end-user survey, physical anthropometry, anthropometric kinematics, motion research, sizing and motion amplitude analysis – allows the PPE to be developed when professionals are faced with a new situation – one in which PPE was not needed so far. It is clear that at the beginning of the COVID-19 pandemic, it was not possible to make such improvements and enhancements but getting to know the hitherto unknown form of the virus and its behaviour can also improve the wellbeing of medical staff.

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**References**

1. Wang X, Zhang X and He J. Challenges to the system of reserve medical supplies for public health emergencies: reflections on the outbreak of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) epidemic in China. *Biosci Trends* 2020; 14(1): 3–8.  
2. Harrod M, Petersen L, Weston LE, et al. Understanding workflow and personal protective equipment challenges across different healthcare personnel roles. *Clin Infect Dis* 2019; 69: S185–S191.  
3. Loibner M, Hagauer S, Schwantzer G, et al. Limiting factors for wearing personal protective equipment (PPE) in a health care environment evaluated in a randomised study. *PloS One* 2019; 14(1): e0210775.  
4. Project “Integration of reliable technologies for protection against Covid-19 in healthcare and high-risk areas”, Project No. VPP-COVID-2020/1-000. Guidelines For the Manufacture of Protective Clothing. https://lzp.gov.lv/wp-content/uploads/2021/04/WP-2.1._3-Vadlinijas.pdf (accessed 25 February 2021).  
5. ISO 13688:2013. Protective clothing—general requirements. Geneva: ISO.  
6. ASTM F1154-99a. Standard practices for qualitatively evaluating the comfort, fit, function, and integrity of chemical-protective suit ensembles. West Conshohocken, PA: ASTM.  
7. Tejeme Y, Malengier B, Tesfaye T, et al. A review of contemporary techniques for measuring ergonomic wear comfort of protective and sport clothing. *Autex Res J* 2021; 21(1): 32–44.  
8. Loercher C, Morlock S and Schenk A. Design of a motion-oriented size system for optimizing professional clothing and personal protective equipment. *J Fashion Technol Textil Eng* 2018; s4(4): 1–4.  
9. Regulation (EU) 2016/425 of the European Parliament and of the Council of 9 March 2016 on personal protective equipment and repealing Council Directive 89/686/EEC (Text with EEA relevance). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32016R0425# (accessed 28 May 2021).  
10. Song G (ed.). *Improving comfort in clothing*. 1st ed. Cambridge: Woodhead Publishing, 2011, p.496.  
11. Boorady LM. Functional clothing—principles of fit. *Indian J Fibre Text Res* 2011; 36:344–347.  
12. Zöller S. *Mapping individual subjective values to product design: an attitudes-based approach for user centered design*. PhD Thesis, FAU University, DE, 2019.  
13. Lapkovska E. *Improvement of methods for evaluation of anthropometric fit and ergonomics of clothing*. Unpublished PhD Thesis, Riga Technical University, LV, 2022 (expected to be published in May 2022).  
14. Bogović S, Stepanović Z, Cupar A, et al. The use of new technologies for the development of protective clothing: comparative analysis of body dimensions of static and dynamic postures and its application. *Autex Res J* 2019; 19(4): 301–311.  
15. Ashdown SP (ed.). *Sizing in clothing*. Developing effective sizing systems for ready-to-wear clothing. Boca Raton, FL: CRC Press LLC, 2007, p.384.  
16. Otieno RB. Improving apparel sizing and fit. In: Fairhurst C (ed.) *Advances in apparel production*. Cambridge: Woodhead Publishing, 2008, pp.73–93.  
17. Watkins SM and Dunne LE. *Functional clothing design: from sportswear to spacesuits*. 1st ed. New York, NY: Fairchild Books, 2015, p.448.  
18. EN 13402-3:2017. *Size labelling based on body measurements and intervals*. Brussels: European Committee for Standardization.  
19. Teyeme Y, Malengier B, Tesfaye T, et al. A review of contemporary techniques for measuring ergonomic wear comfort of protective and sport clothing. *Autex Res J* 2021; 21(1): 32–44.  
20. Lu Y, Song G and Li J. A novel approach for fit analysis of thermal protective clothing using three-dimensional body scanning. *Appl Ergon* 2014; 45(6): 1439–1446.  
21. ISO 20685-1:2018. 3-D scanning methodologies for internationally compatible anthropometric databases - part 1: evaluation protocol for body dimensions extracted from 3-D body scans. Geneva: ISO.  
22. Adams PS and Keyserling WM. Three methods for measuring range of motion while wearing protective clothing: a comparative study. *Int J Ind Ergon* 1993; 12(3): 177–191.  
23. Gupta D and Zakaria N. *Functional clothing design: an attitudes-based approach for user centered design*. West Conshohocken, PA: ASTM.  
24. ASTM F3031-17. *Standard practice for range of motion evaluation of first responder’s protective ensembles*. West Conshohocken, PA: ASTM.  
25. Coca A, Williams WJ, Roberge RJ, et al. Effects of fire fighter protective ensembles on mobility and performance. *Appl Ergon* 2010; 41(4): 636–641.