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Workstations for people with disabilities: an example of a virtual reality approach

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This article describes a method of adapting workstations for workers with motion disability using computer simulation and virtual reality (VR) techniques. A workstation for grinding spring faces was used as an example. It was adjusted for two people with a disabled right upper extremity. The study had two stages. In the first, a computer human model with a visualization of maximal arm reach and preferred workspace was used to develop a preliminary modification of a virtual workstation. In the second stage, an immersive VR environment was used to assess the virtual workstation and to add further modifications. All modifications were assessed by measuring the efficiency of work and the number of movements involved. The results of the study showed that a computer simulation could be used to determine whether a worker with a disability could access all important areas of a workstation and to propose necessary modifications.

Keywords: virtual reality; people with disabilities; adaptation of workstation

1. Introduction

Employment of people with disabilities is a very important problem. In 2012, only ~450,000 out of the 2 million working-age people with disabilities in Poland actually worked (Economic Activity Survey, Poland's Central Statistical Office [GUS]). People with disabilities constitute nearly 10% of the working-age population; however, their share in total employment is less than 4%. [1] This is so mainly because of their greater-than-average difficulties in finding a job, or less willingness or capacity to enter the labour market. [1] According to some estimates, the odds of finding work by an occupationally active disabled person are 20–40% lower than those of a healthy person. [1] Therefore, it is very important to support people with disabilities in finding employment, and employers in preparing workstations suitable for their needs.

Various tools and methods can be used to assist designing and adapting workstations for workers with disabilities. Computer simulation and virtual reality (VR) are the most advanced of those. Various studies indicate that VR can be used for training purposes. [2,3]

Computer simulation and VR can also be used successfully in designing workstations in terms of ergonomics and safety, [4,5] and in solving problems in production systems. [6] Advanced research is carried out in using virtual modelling and simulation in analysing accidents in the mining industry, [7] in analysing and assessing ergonomics and occupational risk in mines, [8] in studying ergonomics of operating machinery [5] and in identifying hazards and simulating accidents to improve the efficiency of

decision-making. [9] Grajewski et al. [10] proposed an interesting application of immersive VR and haptic technologies in designing and virtual prototyping of manufacturing workstations. As concluded, VR makes it possible to perform a thorough analysis and optimization of solutions without the need to build physical prototypes of workstations. Possibility of testing the human–machine system in the virtual environment limits the costs of such studies and is much safer to perform. Also Luquetti dos Santos et al. [11] indicated that VR can be successfully used in designing a nuclear control desk. According to Luquetti dos Santos et al., human factor issues in designing nuclear control desks can be verified by experts using virtual models. There are various examples of VR applications for persons with disabilities. In most cases VR is used for rehabilitation purposes (e.g., [12–14]). The use of VR benefits especially in telerehabilitation applications. [15] However, computer simulation and VR tools can also be used to adjust a workstation to the needs of a person with a disability. In this context, VR has several advantages over a real workstation:

- Building a workstation or its model to perform an analysis is not necessary. This is especially important when a workstation is being designed. However, it is still possible to adjust existing working environments.
- A virtual workstation is easy to modify. In the virtual environment, moving or changing control elements or even whole machines can be done with a few

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clicks of the mouse. Such modifications are possible while a worker is immersed in this environment, so changes can be assessed immediately.

- Recording movements of workers or of individual objects in the virtual environment is a built-in feature of VR research; it can be used to evaluate the efficiency of work and to assess any modification or versions of a workstation.

This article describes a method of adapting workstations for workers with motion disability with computer simulation and VR techniques. Adaptation of a real workstation for two workers with disabled upper extremities is used as an example.

2. Materials and methods

A VR environment is used in the proposed method of adapting workstations for people with disabilities. While the worker simulates work, the researcher assesses the worker's capability to work and comfort of work, and suggests modifications. In this study the workstation was preliminarily modified by placing a computer human model of a disabled worker in the virtual workstation. Thus it was possible to eliminate the most obvious problems where objects that had to be reached were out of the maximal arm reach area. Thus, VR exposure could be shorter.

2.1. Computer human model

A computer human model was created for this task. It visualized maximal arm reach and preferred workspace (Figure 1). [16,17] The model had two basic versions: a female one and a male one. Their geometry was based on the 50th percentile of the population. [16,18] To analyse an individual worker's capability for work, this model could

be modified to reflect the measurements of any person and the constraints caused by their disability. All segments of the human body were modelled as rigid bodies connected with joints with applied constraints. Visualizations of maximal arm reach and preferred workspace were calculated according to those constraints and the length of the body segments. The modified model could reflect the needs not only of a specific person, but also of a model person representing a group of people with disabilities.

A human model like this can be placed in a virtual environment that reflects the workstation and can be freely moved to each working area. In this way, all areas out of a workers' reach can be identified and suitable modifications can be suggested.

2.2. Virtual reality analysis

The concept of using an immersive VR environment in research involves creating a virtual environment that reflects a real workstation and 'placing' a subject in it with dedicated VR equipment. In its most advanced form, this equipment consists of a head-mounted display that provides an image of the VR environment, a pair of data gloves that allow interaction with objects and a tracking system to capture the position and rotation of the person and the segments of their body. Because the image generated by the head-mounted display is always in front of the subject's eyes, no matter how their head is rotated and, also, the image is updated according to those rotations, the subject feels immersed in the virtual world.

In this study, this method was used to analyse the capability to work of a person with disabilities and to propose modifications of the workstation. A virtual environment reflecting a real workstation (i.e., a virtual working environment) was created, and a disabled worker was

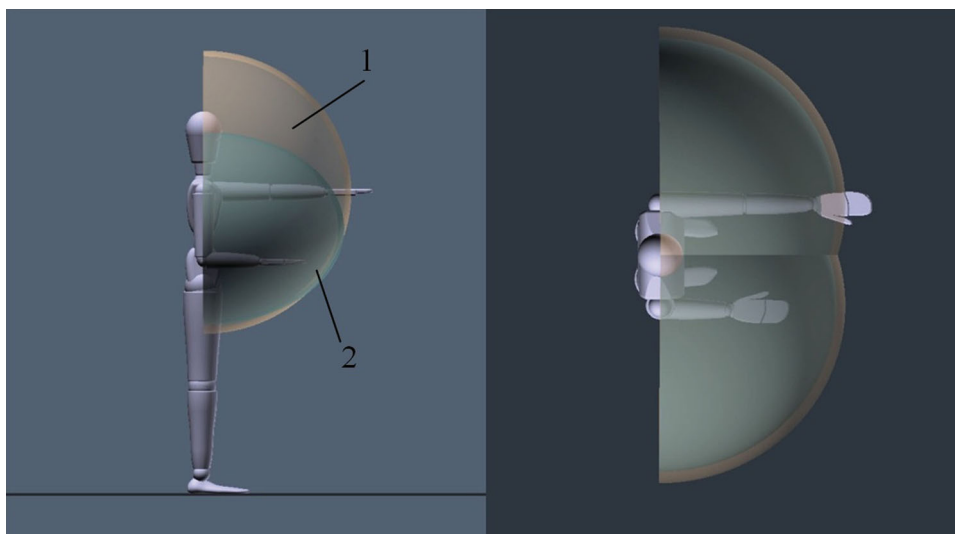


Figure 1. A computer human model.

Note: 1 = maximal arm reach; 2 = preferred workspace.

immersed in it and performed simulated work. The worker then assessed the capability to work and proposed necessary modifications. As the worker's movements were recorded, it was possible to compare the duration and the number of movements in individual work tasks and in the whole work cycle in various versions of the working environment.

2.3. Equipment

The following equipment was used to access the VR environment:

- an eMagin (USA) Z800 3D Visor head-mounted display to visualize three-dimensional images – it is small and lightweight, so it hardly restricts movement;
- a pair of 5DT (USA) Data Gloves 14 Ultra with 14 sensors to move objects in the VR environment; and
- Polhemus (USA) Liberty magnetic tracking with a long-range transmitter to move around the environment. Three sensors captured and recorded positions and rotations of the hands and the head. An additional sensor was attached to the belt to visualize body movement and check for collisions with objects in the virtual workstation.

3. The study

A workstation for grinding spring faces was selected as an example of how a workstation can be adapted for people with disabilities (Figure 2). This workstation was located in a company that employed people with disabilities. This method is most useful for workstations that are still being designed; however, it is possible to consider existing workstations, too. The workstation for grinding spring faces was selected because the comfort of work was strictly related to the placement of all objects that had to be reached. Although this particular workstation could be adapted to the needs of disabled people without using a virtual environment, this workstation was suitable to test the method. The workstation was to be adapted for two people with disabled right upper extremities.

3.1. Workstation and subjects

Figure 3 illustrates a grinding machine (1), which is the main equipment at the workstation for grinding spring faces. It is equipped with a rotating horizontal wheel (2) with a few rings of holes. The worker's task is to place springs in those holes. The wheel slowly rotates during the task. When all holes have been filled in, the machine is turned on. The grinding process automatically stops after a predefined time. Ready springs drop from the machine to an output box (3), leaving empty holes for the next set of springs.



Figure 2. An overall view of the workstation for grinding spring faces.

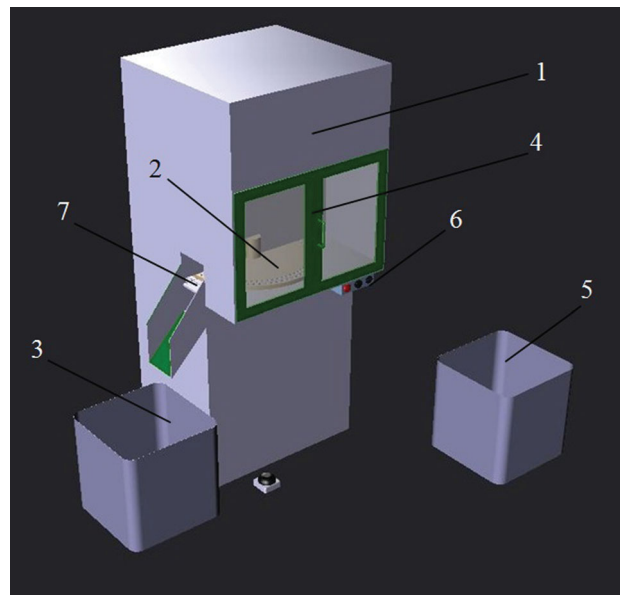


Figure 3. Important elements of the workstation for grinding spring faces.

Note: 1 = grinding machine; 2 = wheel with holes for the springs; 3 = output box; 4 = door of the grinding compartment; 5 = input box; 6 = control panel; 7 = output door.

The wheel and the grinding mechanism are located in a compartment behind a see-through door (4). For safety reasons, grinding can take place only if that door is closed. There is also another safety mechanism: a sensor that stops the rotation of the wheel if there is a hand close to the grinding mechanism.

Table 1. Subjects.

Characteristic	Person 1	Person 2
Gender	Male	Female
Age (years)	31	39
Body mass (kg)	100	70
Body height (cm)	180	165

Work is done in a standing posture. However, there is a chair where the worker can sit while waiting for the grinding process to end.

Work consists of five stages:

- (1) The worker opens the door of the grinding machine (4 in Figure 3).
- (2) The worker takes springs from the input box (5) and puts them into the holes of the wheel (2).
- (3) When all holes in the wheel have been filled in, the worker closes the door (4) and turns on grinding with a button on the control panel (6).
- (4) After the end of grinding, the worker opens the output door (7) by lifting it. This can be done both from the outside and from the inside, by reaching above the wheel (2). The springs fall into the output box (3).
- (5) The worker opens the door of the machine (4) and fills the holes with springs in the next cycle of work.

This workstation was adapted for two people with disabled right upper extremities. Both were stroke victims. Table 1 presents their basic characteristics.

Both workers could work with their left upper extremities only, which in both cases was fully operational. A sitting posture was medically advised for both of them.

3.2. Virtual working environment

In the first part of the study, a virtual environment reflecting the real workstation was created. Because there was no detailed technical documentation, all relevant dimensions were measured in the field. The workstation and its environment were photographed in detail and a video of a worker performing a complete work cycle was recorded. These data were used to create CAD models of all objects; CATIA V5R16 (Dassault Systèmes, France) CAD software was used. Next, all models were imported into Blender 2.49 (www.blender.org), where textures and materials were created according to the photographic documentation, and a complete workstation was assembled. To operate that virtual workstation, custom software based on the Ogre Rendering Engine (www.ogre3d.org) was used.

Next, all areas of the workstation that the worker had to reach during a work cycle were selected. These areas were marked for further analysis.

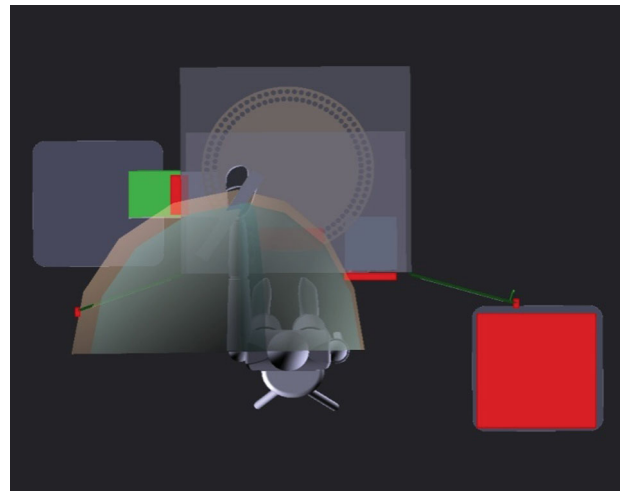


Figure 4. A computer model of a disabled person placed in the virtual working environment.

3.3. Computer human model

Two human models were created by scaling all segments of the basic computer human model to reflect each subject. The movement of the right upper extremity was disabled. Then, a visualization of maximal arm reach and preferred workspace was generated on the basis of the geometry and the constraints of the model. Both computer models were placed in the virtual working environment and located in front of the grinding machine. It was thus possible to analyse which areas of work were inside the human models' maximal arm reach or preferred workspace (Figure 4).

As both workers had to work in a sitting posture, during this analysis the computer human models were not moved around the workstation, only rotated in a range suitable for a sitting person. The results for both models were very similar. The wheel of the grinding machine, where most activities took place, was located in the preferred workspace. The control panel was located outside that space, but inside the maximal arm reach area, so the worker could reach it. Opening the output door was only possible by reaching above the wheel inside the machine; however, that door was within the maximal arm reach area, too. The input box was located outside the maximal arm reach area, so the worker had to stand up to take out springs. There were also problems with opening the door of the machine, which was a swinging door. A worker was sitting in the front could not open it. Moreover, when sitting, the worker could not reach the left sash of the open door.

As a result of the analyses, modifications of the workstation that would allow the subjects to work were selected and implemented into the virtual working environment. Both people had similar problems. Modifications were made for person 2, because of her shorter stature. Those modifications were also suitable for person 1, who had a

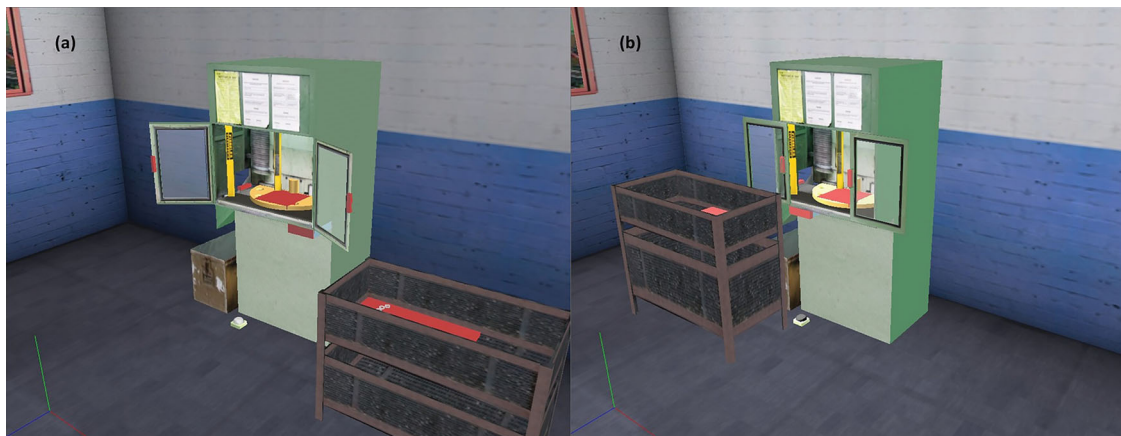


Figure 5. A computer model of (a) the unmodified workstation and; (b) the workstation with modifications resulting from an analysis with the computer human model.

longer arm range. They made it possible for both people to work:

- the input box was moved to the left-hand side of the workstation, so the springs were in the maximal arm reach area of both people;
- the swinging door was replaced with a sliding one, so a sitting worker could open and close it without any problem. Also, the handles of the sashes were in the maximal arm reach area both when the door was closed and when it was fully open (Figure 5).

3.4. Immersive virtual reality environment

During this part of the study, the workers were immersed in the VR environment and simulated work. Appropriate algorithms were used. They were responsible for the operation of the grinding machine, for moving springs and for placing them in the wheel.

When the workers were familiar with their task, they suggested modifications of the workstation that reflected their needs. Both suggested modifications independently of each other. Person 1 suggested the following modifications:

- moving the control panel from the right-hand side of the machine to the middle, just under the handles of the closed door;
- moving the input box so that it was closer to him;
- moving down the door handles.

Person 2's suggestions were as follows:

- sitting on a higher seat. Even though this workstation was initially modified for her needs (she was shorter than person 1), she decided that everything at the workstation was too high;
- moving the control panel. Like person 1, this person decided that the right-hand side was not suitable.

However, unlike person 1, she moved it to the left-hand side of the machine;

- moving the input box. This person decided it should be placed in front of her (between her legs and the machine);
- moving the door handles. Like person 1, she moved them down.

Additionally, both people complained about the mechanism of opening the output door. To open the door, it was necessary to reach far inside the machine. They suggested introducing some kind of automatic system for operating this door. So, a mechanism was designed with a button on the control panel opening and closing this door.

After the changes were introduced, both people performed a few cycles of work on two variants of the workstation: initially modified with the use of the computer human model and modified in accordance with that person's opinion. Each cycle took 15 min with a 15-min break in-between. Tests took place over 2 days, work on each variant of the workstation was done four times. During these tests, movements of the worker's head, hand and body were recorded as functions of time. The following events were also recorded:

- contact between the worker's hand or body and objects in the virtual environment (in particular, springs and buttons on the control panel and door);
- contact between the springs and other objects (in particular the wheel);
- beginning and end of machine cycle;
- whether the door of the machine was open or closed.

An analysis of those parameters made it possible to compare several activities in different variants of the workstation:

- moving a spring from the input box to the wheel (counted between the last contact between the spring

and the box and the first contact between that spring and the wheel). This measurement was important for assessing the location of the input box;

- closing the door of the grinder door after placing the last spring in the wheel (counted between the last contact of the hand and the wheel and the moment when the door was fully closed). This measurement was important for assessing the location of the door handles;
- starting the machine after closing the door (counted between the moment the door was closed and the moment the grinding machine started). This measurement was important for assessing the location of the control panel;
- opening the output door after the machine stops (counted between the moment the machine automatically stops and the moment the output door is open). This measurement was important for assessing the way the output door was opened.

In all those activities, their duration and the number of movements of the hand and the body were considered. Those parameters were recorded for all occurrences of the described activities in all cycles of work. The median was then calculated. It was used instead of the mean to eliminate outliers. Those outliers were caused by incidents such as dropping a spring when moving it.

3.5. Results

For all activities, parameters of work for two variants of the workstation were compared: the workstation initially modified by researchers and the workstation with implemented modifications proposed by the workers. The results follow.

3.5.1. Moving a spring from the input box to the wheel

For person 1 there was no significant difference in the time necessary for this task or in the number of movements of the hand. However, this task involved 35% less movements of the whole body at the workstation modified by this person. For person 2 there was no significant difference in the duration of the movement; however, there was a 41% improvement in the movements of the hand and almost 90% in the movement of the body. This activity was strictly related to the location of the input box. The modification proposed by person 1 was very small, which explains small (or not significant) differences in results. person 2 placed the input box closer to the machine, immediately in front of herself. The main improvement can be seen in the number of movements of the whole body, which did not have to rotate to reach the box. Although this task was rather short (usually less than 3 s to move one spring from the input box to the wheel of the machine), it involved lifting the hand up to 1 m (in the initially modified version of the workstation) and was repeated 20 times per work

cycle. It is interesting that the time required for this activity did not change after the modifications for either person. The modification influenced the number of movements, and thus work comfort, but did not increase work efficiency (measured as the number of work cycles per time).

3.5.2. Closing the door of the grinder after the last spring is put in the wheel

Both people relocated door handles. For person 1 all parameters significantly improved. Time was 22% shorter, the number of movements of the hand improved by 27% and that of the body by 40%. Person 2's results were even better: 51%, 50% and 36%, respectively. Both people needed less than 10 s to open or close the door of the machine. Although this activity was done only twice per cycle, improvement in the parameters can influence both total efficiency and comfort of work. At the same time this modification is relatively easy to implement.

3.5.3. Starting the machine after the door closes

For person 1, time (25%) and movements of the hand (47%) significantly improved. For person 2, time and movement of the hand improved, too (40% and 25%, respectively). This improvement resulted from both people's relocation of the control panel. Changes in these parameters are significant; however, these tasks were done only once per work cycle and were relatively short (starting the machine took less than 1 s). Moreover, this task involved much less movement than all the others. Improvement in these parameters had minor impact on the overall efficiency of work; however, it was important in terms of comfort.

3.5.4. Opening the output door after the machine stops

In this particular task, improvement in all parameters was the highest. For person 1, this improvement was 66% (time), 81% (movement of hand) and 74% (movement of body). For person 2, it was 72% (time), 83% (movement of hand) and 84% (movement of body). This task was repeated twice per work cycle; however, in the initially modified version of the workstation it involved a lot of movement (up to 4 m of hand movement) and time (almost 10 s). Replacing manual opening with a button-activated mechanism significantly reduced those values. Although this modification was the most complicated, it was reasonable to implement it.

4. Discussion and conclusion

The results showed that computer simulation and VR could be successfully used to determine whether a worker with a disability could access all important areas of a workstation and to propose necessary modifications. This can be done without a need to build physical prototypes or workstations, as it is done in a traditional way, which is

the main advantage of VR. A virtual environment makes simple, one-step modifications possible. Modifications can be assessed almost immediately by measuring work efficiency and the number of movements during individual work tasks. Thus, the process of designing adaptations of workstations for workers with motion disability can be done in a relatively short time. The use of immersive VR benefits over projection VR or augmented reality [10] in less physical space being needed for the study – there is no need for a projector and screen or any physical objects. At the same time, as proposed in previous research using computer simulation and the computer human model, the VR study allows one to preliminarily prepare the workstation by eliminating the most obvious problems. This allows one to shorten the VR exposure and is the advantage of the proposed methodology over research involving only VR.[10,11]

The main disadvantage of VR-based research is that the computer model of the workstation has to be created. This is a labour-consuming task, especially if all of the models have to be created from scratch. This task is much easier if CAD models of the workstation are available, e.g., when a workstation is being designed. The described methodology is therefore mostly suitable for such workstations. Another disadvantage of the proposed solution is a lack of haptic feedback. The task of picking objects or operating controls is less natural when the worker is not able to actually touch these objects. One of the solutions is to use physical objects corresponding to these virtual objects.[3,10] There is, however, a problem with this solution: the position and rotation of such physical objects have to be traced, which may be very hard or even impossible when considering large amounts of small objects (like springs in the grinding machine described in this article). Another solution is to use devices simulating haptic feedback, such as haptic gloves. The use of such devices needs further studies, however, which are planned in the near future.

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