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Immersive Analysis of User Ergonomics in VR-based Training Applications

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Abstract

The evaluation of ergonomics for workplaces has a long history. Many methods and tools have been developed to make the ergonomic evaluation process more effective and efficient. Virtual reality plays a big role in these developments, as the use of virtual prototypes can help to save time and money. Also, immersive applications have been developed as they allow to experience the virtual prototype in a more realistic way. In previous work, the ergonomic evaluation process has been the focus. This thesis focuses on the analysis process and aims to improve it. The goal is to exploit the potential of immersive technologies also for the representation of the evaluation results. To perform the analysis in the same immersive environment where the evaluation was carried out can speed up the whole evaluation process even more, give the user a better understanding of the spatial context and make the result more comprehensible.

An immersive VR application was developed that offers an ergonomic evaluation and analysis process in the same virtual environment. The ergonomic evaluation provides real-time results and the analysis can be started immediately after the evaluation. The immersive analysis gives the user a good first overview of the session and its ergonomic quality. It comprehensibly conveys where, when and how often ergonomic problems are identified and provides information why postures are rated as problematic.

A test scenario was created to simulate an ergonomic test and collect movement data. An exemplary analysis session shows how the implemented analysis tools can be used and their results can be interpreted to make good design decisions.

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1 Introduction

Humans can influence a production system positively thanks to their flexibility, innovation, or problem-solving skills, but they are also at risk to develop so-called work-related musculoskeletal disorders (MSDs) as a result of overloading physical work (Berlin and Adams, 2017). MSDs affect almost all occupations and sectors and do not only bear physical consequences for the worker such as discomfort, pain, recurring injuries and the inability to work, they also bear economic consequences for the business due to productivity losses, compensation and replacement of personnel (Berlin and Adams, 2017; Gómez-Galán et al., 2017).

According to Gómez-Galán et al. (2017) MSDs are the most common labour medical problems among workers in the European union and also in the U.S.A. MSDs were proven to be a problem by causing great losses of working hours. The prevention of MSDs is therefore very important and should be in the interest of companies and governments.

MSDs can be prevented by considering ergonomic principles at the design of workplaces, but these considerations can be difficult and time-consuming. A proactive approach towards ergonomics would be ideal, where ergonomics are considered in the early design phase of a workplace. Unfortunately very often a reactive approach is chosen, where ergonomic issues and risks stay unaddressed until a problem occurs (Berlin and Adams, 2017). Sometimes this approach is paired with a healthcare service offering that takes care of the symptoms but not the root cause of the problems (Berlin and Adams, 2017).

Many applications have already been developed to make the evaluation process less difficult and time-consuming. Very popular applications make use of virtual reality and simulation techniques, where the workplace is created virtually and work tasks are simulated. This kind of applications

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already gained maturity and acceptance in the industry (Jayaram et al., 2006). The problem with purely simulated evaluations is, that the subjective experience later on the real world workplace may differ from the objective result obtained by the simulation (Pang et al., 2018).

Immersive virtual environments have the potential to combine the advantages of a virtual and a physical prototype: money and time can be saved thanks to a virtual model of the workplace and the model can be experienced in a more realistic way than by just seeing it through a computer screen. At the same time, immersive technologies also offer the possibility to train future operators of the workplace. Immersive evaluation methods have not yet gained the maturity and acceptance as the simulation methods but as immersive technologies, like head-mounted displays, become more and more popular and accessible, it is beneficial to analyse and exploit their potential.

As can be seen in previous research, immersive assessment of ergonomics can be beneficial and useful (Aromaa and Väänänen, 2016). Existing ergonomic evaluation systems usually display the result in a traditional two-dimensional way, even when an immersive system is already used for the evaluation. This thesis aims to improve the analysis process by a) giving real-time feedback to the user and by b) exploiting the potential of immersive technologies also for the representation of the evaluation results. Real-time feedback can help to detect ergonomic related problems already during the evaluation. Furthermore, the possibility of analysis in the same immersive environment where the evaluation was carried out may speed up the whole evaluation process even more, give the user a better understanding of the spatial context and make the result more comprehensible. To save even more time and resources, another aim is to ensure that the evaluation can be carried out by a single person and no further assistance, e.g. by an ergonomic expert, is needed.

The following chapter will give an overview of relevant theory and related work, later the concept and implementation of the application will be described. In the end of this document the results and practicality of the application will be discussed, followed by an outlook on future work.

2 Background and Related Work

The scope of this thesis spans over several areas, that are Ergonomics, Virtual Reality and Immersive Analytics. This chapter is going to give an overview of relevant theory and related work.

2.1 Ergonomics

Nowadays many people associate with the word ergonomic the comfort of office chairs or the correct height of computer screens, also advertisements use this term to promote products like computer mice, backpacks or gardening tools (Berlin and Adams, 2017). In fact, ergonomics is a very wide term.

The word ergonomics has its roots in the two greek words ergon (=work) and nomos (=natural laws), so the rough translation is “the science of work” (Berlin and Adams, 2017; IEA 2020). The International Ergonomics association IEA (IEA 2020) defines ergonomics (or human factors) as *“the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance”*.

When the discipline of ergonomics first arose, it exclusively concerned itself with physical work (Berlin and Adams, 2017). As decades passed by, the discipline widened its scope continually as it was realized that many more aspects can affect the workplace. Today ergonomics not only relates to the physical activities or demands of the job, it can also signify how well instructions and interfaces are understood by the human mind or include

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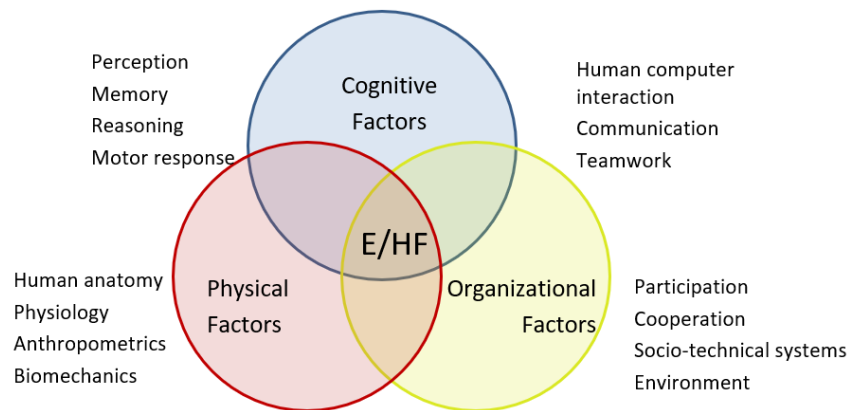


Figure 2.1: Ergonomics or human factors (E/HF) include physical, cognitive and organizational factors. The figure was taken and adapted from *IEA* (2020).

aspects of the environment and teamwork (Berlin and Adams, 2017; *IEA* 2020).

As Berlin and Adams (2017) state, almost any aspect of work that involves human activity can be approached from an ergonomic perspective. The *IEA* (2020) classifies these aspects into 3 categories: physical, cognitive, and organizational ergonomics. While physical ergonomics consider, e.g. the human anatomy and physiology, cognitive ergonomics can include human-computer interaction or communication and teamwork. The organizational side of ergonomics concerns itself, for instance with socio-technical systems and the environment (*IEA* 2020). Figure 2.1 visualizes the three aspects of ergonomics.

In general, all sides of ergonomics, physical, cognitive and organizational, are regarded as equally important and all of them should be considered for the design of inclusive workplaces (Berlin and Adams, 2017). However, this thesis will only consider the physical side of ergonomics and the following section will give an overview of different methods that help to evaluate the physical load.

2.1.1 Evaluation Methods for Physical Load

Over the years many different methods were developed to help to measure the comfort/discomfort of work-spaces and work-tasks (David, 2005). According to Berlin and Adams (2017) these methods can be categorized in three broad categories:

- Posture-based analysis
- Biomechanics-based analysis
- Analysis based on a combination of environmental factors

As the name suggests, posture-based methods evaluate and grade the pose of the body. Usually the further away the body posture is from the neutral standing position, the worse the grade for the working posture is. These methods use a point-based system to rate the different body parts, typically the score is higher the worse the posture is. As Berlin and Adams (2017) state, posture-based evaluation methods often find application as screening tools to obtain a first estimation of risk. In practice, the designers make adjustments if high-risk areas are identified in order to improve the rating and lower the risk but if further evaluations still indicate a high risk, the advice is to do a more in-depth analysis or investigate the problem in more detail by using another analysis method. Some popular examples of posture-based evaluation methods are RULA (Rapid Upper limb Assessment), REBA (Rapid Entire Body Assessment), OWAS (Ovako Working Posture Analysing System) and HARM (Hand Arm Risk-assessment Method) (Berlin and Adams, 2017).

In contrast to posture-based methods, biomechanics-based evaluation methods do not focus on the human body, instead they usually concentrate on work tasks where a load is moved from one place to another by pushing, pulling, carrying, lowering or lifting. This kind of evaluation typically provides a more strictly defined and more numerical result than posture-based analysis methods, but they also tend to be more time-consuming (Berlin and Adams, 2017). Some popular examples of biomechanics-based methods are the NIOSH Lifting Equation and Liberty Mutual manual materials handling tables (Berlin and Adams, 2017).

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The last category combines all methods that use multiple aspects in the analysis. These aspects can be, e.g. the posture, speed of work or working conditions. Popular examples for multi-aspect methods are KIM (Key Indicator Method), JSI (Job Strain Index), EAWS (Ergonomic Assessment Worksheet) or RAMP (Risk Assessment and Management tool for manual handling Proactively) (Berlin and Adams, 2017).

The enormous amount of different evaluation methods can overwhelm and make it difficult to find the most suitable one. As a guideline, Berlin and Adams (2017) and Takala et al. (2010) suggest that the selection should be based on a) the characteristic of the task, for example, is there much carrying and lifting involved b) the objective of the methods or the nature of the problem, e.g. is there already an assumption where problems might occur c) what resources are available to collect and analyse the data, e.g. is it possible to measure joint angles, involved weights and forces and d) the individual(s) who will use the method, e.g. how much does the measurements of the person influence the result.

This thesis focuses primarily on the analysis and not specifically on the task evaluation. Therefore it was not possible to follow the mentioned guideline completely. The only reference point were the available resources for data collection. Consequently, the goal was to choose a method that can be applied to many scenarios, that is observable by a computer system and still offers meaningful results. The decision fell on the Ovako Working posture Analysis System (OWAS) and the next section is going to describe this posture-based method in more detail.

2.1.2 Ovako Working posture Analysis System (OWAS)

The OWAS Method was published 1977 by the Finnish company OVAKO OY, a producer of steel bars and profiles (Gómez-Galán et al., 2017; Gudehus, 2008). First it was just used internally by the company, but over the years it evolved to a widely used and tested method of MSD evaluation (Takala et al., 2010; Gómez-Galán et al., 2017). According to Gómez-Galán et al. (2017) the OWAS method mainly found application in the three sectors: industry, health and agriculture and livestock.

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When the OWAS method was developed, the aim was to create a method that is simple enough to be used by ergonomically untrained people and gives answers that are unambiguous, even if that leads to over-simplification (Karhu, Kansil, and Kuorinka, 1977). Traditionally this method requires an observer who fills out a pre-defined scoring sheet while watching a worker, who performs a task (Grooten and Johansson, 2018). Thanks to its characteristics it is also perfectly suitable to be observed by a computer system.

The OWAS method is an old method and there exist many extensions and adaptations. The following description of the OWAS method is based on the explanations of Gudehus (2008), Karhu, Kansil, and Kuorinka (1977), Grzybowska (2010) and Groborz, Tokarski, and Roman-Liu (2011).

As a posture-based method, OWAS focuses on the human body and its position. In more detail this method considers various positions of the back (4 possibilities), arms (3 possibilities) and the legs (7 possibilities). It also takes the weight of lifted objects into account (3 possibilities). Consequently, there are 84 possibilities in total considering solely the posture. Including the weight, the possible combinations sum up to 252. Figure 2.2 illustrates the distinct possibilities for all the four sections (body parts + weight). Each of the sections gets a grade which results in a four-digit code for the entire body posture. With the help of a table (see Figure 2.3) and the grade of each section, the final class (also called action category) for the body posture is determined. In total, there are four classes (Karhu, Kansil, and Kuorinka, 1977; Grzybowska, 2010):

- Class 1: Regular and normal poses that do not need any special attention. No need for changes at the workstation as the load is optimal or acceptable.
- Class 2: Potentially hazardous poses that may have negative effects. Consideration during the next regular check of working methods is suggested.
- Class 3: Clearly hazardous influence of pose and fairly large static load. Actions should be taken in the near future.
- Class 4: Considerably hazardous pose and large static load. Actions should be taken immediately.

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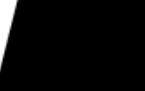
Back	 (1) straight	 (2) bend	 (3) straight and twisted	 (4) bend and twisted
Upper Limbs	 (1) both limbs on or below shoulder level	 (2) one limb on or above shoulder level	 (3) both limbs above shoulder level	An Example:  Back: bend (2) Upper Limbs: both below shoulder level (1) Lower Limbs: loading on one limb, kneeling (5) External Load: Below 10kg (1)
Lower Limbs	 (1) loading on both limbs, straight	 (2) loading on one limb, straight	 (3) loading on both limbs, bend	
	 (4) loading on one limb, bend	 (5) loading on one limb, kneeling	 (6) body is moved by the limbs	
External Load Volume	 (1) below 10 kg	 (2) 10- 20 kg	 (3) above 20 kg	

Figure 2.2: List of poses and weight that are classified by OWAS (the Ovako Working Posture Analysing System). Each category gets a grade, therefore, the entire body posture can be described by a four-digit code. The example on the right side of the figure results in the code 2151. Figure taken and adapted from Karhu, Kansil, and Kuorinka (1977) and Grzybowska (2010).

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Back	Arms	Legs																				
		1			2			3			4			5			6			7		
		Load			Load			Load			Load			Load			Load					
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	1	1	1	1	1
	2	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	1	1	1	1	1
	3	1	1	1	1	1	1	1	1	1	2	2	3	2	2	3	1	1	1	1	1	2
2	1	2	2	3	2	2	3	2	2	3	3	3	3	3	3	3	3	2	2	2	2	3
	2	2	2	3	2	2	3	2	2	3	3	3	4	4	3	4	4	3	3	4	2	3
	3	3	3	4	2	2	3	3	3	3	3	3	4	4	4	4	4	4	4	4	2	3
3	1	1	1	1	1	1	1	1	1	2	3	3	3	4	4	4	4	1	1	1	1	1
	2	2	2	3	1	1	1	1	1	2	4	4	4	4	4	4	4	3	3	3	1	1
	3	2	2	3	1	1	1	2	3	3	4	4	4	4	4	4	4	4	4	4	1	1
4	1	2	3	3	2	2	3	2	2	3	4	4	4	4	4	4	4	4	4	4	2	3
	2	3	3	4	2	3	4	3	3	4	4	4	4	4	4	4	4	4	4	4	2	3
	3	4	4	4	2	3	4	3	3	4	4	4	4	4	4	4	4	4	4	4	2	3

Figure 2.3: With the grade of each body part and the load, a final class for the posture can be determined (table based on Mahachandra, Prastawa, and Susilo (2018))

These classes help to prioritize where adaptations to the workstations should be made to lower the risk of MSDs (Roman-Liu, 2014). Groborz, Tokarski, and Roman-Liu (2011) suggest to further evaluate the risks according to the time that is spent in each category. This thesis will make use of their three-level risk evaluation system, as represented in table 2.1.

In addition, another extension is used: the risk or Lundqvist index I (Lundqvist, 1988). This index is determined with the help of the percentage of observations on each class and is calculated as follows:

$$I = 100(a + 2b + 3c + 4d) \tag{2.1}$$

where a, b, c and d represent the percentage of observation on the OWAS classes 1, 2, 3 and 4.

The risk index will always result in a number between 100 and 400, where 100 (100% class 1 observations) indicates the lowest and 400 (100% class 4 observations) the maximum possible workload/risk. Although Wahyudi, Dania, and Silalahi (2015) give examples where researchers categorized their risk index result as high risk or medium risk, in general the risk index

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OWAS Category	Working Time (%)	Risk/Workload
1	<70	low
	>70	medium
2	<50	low
	50 - 70	medium
	>70	high
3 or 4	<30	medium
	>30	high

Table 2.1: Three-level risk evaluation system as described by Groborz, Tokarski, and Roman-Liu (2011). The risk for each OWAS category is determined by their relative share on the total time.

does not clearly define the level of risk. Nevertheless, the index can be very helpful to get a first overview and it also helps to make different OWAS analyses easily comparable (Gudehus, 2008). As Gudehus (2008) points out, it is important to interpret the result in the right way, e.g. a result of 200 does not mean the work load is double as high as for an index of 100. The right interpretation would be that a result of 200 indicates more workload than a result of 100.

The OWAS method is simple to apply and useful to detect MSD risks (Gómez-Galán et al., 2017; Battini, Persona, and Sgarbossa, 2014). There is no specialized training needed to be able to use this method, and this means people from different fields, e.g. health, engineering or industry can apply this method. A further advantage of the OWAS method is that it is very well documented and unlike other methods OWAS is associated with MSDs in cross-sectional studies (Takala et al., 2010). There are also limitations to this method (Gómez-Galán et al., 2017; Takala et al., 2010): the left and right side of the upper limbs are not differentiated and the neck, elbows and wrists are not considered in the evaluation (there exist some adaptations that optionally consider the position of the head (Stoffert, 1985)). Another downside is that

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repetition or duration of the sequential postures is not considered. Takala et al. (2010) also point out that the posture coding is crude for the shoulders and according to Battini, Persona, and Sgarbossa (2014) some postures are missing in the evaluation like lying on the floor or crawl. Gómez-Galán et al. (2017) also suggest combining the OWAS method with other methods to get more meaningful results.

This method was chosen as the advantages outweigh the disadvantages. First, it supports one important goal of this work: the user does not need specialized training or another supporting person, like an ergonomist, to understand the results of the ergonomic evaluation and to use the implemented application. Furthermore, almost all positions can be unambiguously determined with the available body tracking system that, for example, does not allow a very precise shoulder tracking anyway.

2.2 Virtual Reality (VR)

This section will give a brief overview of Virtual Reality (VR), its definition, relevant hardware and different approaches for motion capturing. It will also mention the use of VR in the industry and its potential for decision making.

Jerald (2016) defines Virtual Reality as *'a computer-generated digital environment that can be experienced and interacted with as if that environment were real'*. When thinking about VR, most people probably have an image in their mind about someone with an eye-covering device on the head, performing strange actions as they interact with a world that nobody but them can see. It is important to note here that VR systems can also include visualization systems that do not offer a sense of immersion to the user (Grajewski et al., 2013). Mujber, Szecsi, and Hashmi (2004) categorize VR systems into non-immersive (e.g. standard monitor), semi-immersive (e.g. large screen monitor, multiple television projection systems) and fully immersive systems (e.g. head mounted display, CAVE). All the hardware mentioned below refers to fully immersive VR systems as they are used for this thesis.

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Figure 2.4: The pictures show a HMD (left) and a hand held-controller (middle) (*HTC Vive* 2020). A glove from *Manus Gloves* (2021) is shown on the right.

The eyes-covering device mentioned before is called a head-mounted display (HMD). These displays were getting more and more popular and affordable in recent times e.g. *Oculus* (2020), *Sony Playstation VR* (2020) and the *HTC Vive* (2020). According to Jerald (2016) HMDs are able to provide the greatest amount of immersion compared to other forms of visual displays like world-fixed (e.g. CAVEs) and hand-held displays (e.g. smartphones, tablets), when they are implemented well.

Input devices are required to interact with the virtual world and in VR they can take many forms (Jerald, 2016). At the moment, the most common input device are tracked hand-held controllers, and they are used by the common VR headsets mentioned before. According to Jerald (2016) they are currently the best option for a majority of interactive VR applications and they are also easy to use and have a natural, direct mapping to hand motion. Another kind of input devices are hand-worn devices that include for example gloves, muscle-tension sensors and rings (Jerald, 2016). Figure 2.4 shows some examples of VR hardware.

HMDs and tracked hand-held controllers can track the position of the head and hands of the user, while full-body tracking requires more complex solutions. Besides providing necessary data, e.g. for an ergonomic evaluation, full-body tracking can also have a significant positive effect on the illusion of self-embodiment and social presence in the immersive virtual environment (Jerald, 2016). A typical approach is to use a motion capture suit as it finds application in the film industry. Other solutions include electro-magnetic

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sensors, retro-reflective markers, and inertial sensors (Jerald, 2016). Depth cameras can also be applied to track the full body. Ray and Teizer (2012) for instance, use the Microsoft Kinect to automate posture estimation and classification for ergonomic purposes, but as Jerald (2016) states it can be challenging to capture the entire body unless multiple cameras are used.

2.2.1 VR Applications

VR (non-immersive to fully immersive) is a very versatile technology and finds application in many fields, from industry to education/training and entertainment (Choi, Jung, and Noh, 2015; Mujber, Szecsi, and Hashmi, 2004). Mujber, Szecsi, and Hashmi (2004) even state that there are hundreds if not thousands of diverse scenarios where VR has been applied.

Alone in manufacturing, VR has a lot of application possibilities, e.g. in design, prototyping, machining, assembly, inspection, planning, training and simulation (Mujber, Szecsi, and Hashmi, 2004). Mujber, Szecsi, and Hashmi (2004) underline the great potential of decreasing the time to market and product costs and to increase profitability and worker safety. Whole manufacturing processes and designs can be defined, modelled and verified before they are implemented physically. Mujber, Szecsi, and Hashmi (2004) also point out it is not only the visualization of the problems but also the possibility to interact with the environment to solve the problems that makes VR so effective. VR can be a great tool to improve decision-making capabilities and therefore improve the quality of new products and decrease their development time (Mujber, Szecsi, and Hashmi, 2004).

According to Grajewski et al. (2013) a thoroughly explorable virtual building was the first registered use of an immersive virtual environment for industrial design. The virtual environment made it possible to detect design errors and correct them before the building was physically constructed. In the last years VR technologies have become more available and affordable and their use increased accordingly (Choi, Jung, and Noh, 2015; Aromaa and Väänänen, 2016). Today the walk-through or 'fly-over' of engineering or architectural designs are very popular uses of immersive display technologies (Chandler et al., 2015). Choi, Jung, and Noh (2015) also underline the

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potential of immersive VR for manufacturing companies and that nowadays it is undisputed that investments in VR are valuable.

This thesis focuses on VR and its use for ergonomic evaluation, the next section will give more detailed information about related work in this field.

2.3 VR and Ergonomics

As mentioned in chapter 1, ergonomic evaluation in the early design phase of a workplace is in great interest of companies and governments. This section will give an overview of how VR can support an early evaluation and give examples of existing evaluation applications.

To support the ideal proactive evaluation process in the early design phase of a workplace, a prototype is required. Obviously, there is the possibility of a physical prototype which provides the same or a very similar experience for the operator as the actual end product. Unfortunately, the downside of this kind of prototype is that the production cycle is long, manufacturing is expensive, and modifications can be difficult to implement (Pang et al., 2018).

On the other side are virtual prototypes that allow a much faster and easier creation and change implementation (Pang et al., 2018; Aromaa and Väänänen, 2016). Commonly, these virtual prototypes are combined with simulated human models, which makes it possible to reduce errors of subjective judgment and to receive uniform evaluation results (Pang et al., 2018). The uniform results make it easier to compare the results of different design models to get an optimized design (Pang et al., 2018). Virtual prototypes are confirmed to be a powerful solution to overcome the shortcomings of conventional prototyping methods (Aromaa and Väänänen, 2016; Pontonnier, Dumont, and Duval, 2014; Grajewski et al., 2013).

There are many commercial software applications available that make use of virtual models for the ergonomic evaluation process and these applications already gained maturity and acceptance in the industry (Jayaram et al., 2006). Examples of such applications are *DELMIA* (2020), *JACK* (2020) and *Ramsis*

2 Background and Related Work

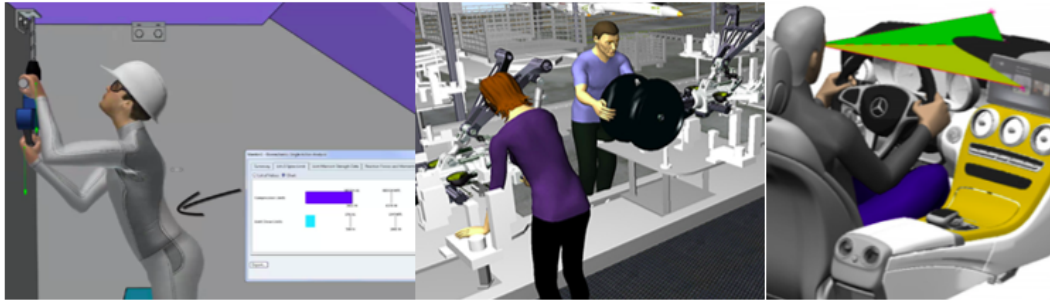


Figure 2.5: Examples of commercial software applications that evaluate ergonomics on virtual models are *DELMIA* (2020), *JACK* (2020) and *Ramsis* (2020) (from left to right).

(2020) (Figure 2.5). Already in 2000, Hanson (2000) compared this kind of software and showed that these applications had an excellent potential to evaluate ergonomics in the early design phase.

As Pang et al. (2018) point out, these kinds of virtual prototypes also have disadvantages: for example, the design plan can only be looked at through the computer screen and it is not possible to support the operator to make an accurate subjective evaluation. Therefore, there exists the risk that the objective evaluation results obtained from the virtual analysis are not consistent with the subjective experience that would be gained with the physical model.

Using immersive VR technology has the potential to combine the advantages of physical and virtual prototypes and to avoid their shortcomings (Pang et al., 2018). The operator can experience the prototype model in a more realistic way and this supports the subjective evaluation. Also, the virtual model reduces costs and effort. Another advantage mentioned by Pang et al. (2018) is that different sensors can be integrated to the immersive VR technology and the evaluation can be done automatically.

The idea to use immersive VR for an early ergonomic analysis is not new. Already in 1999, Wilson (1999) analysed the potential value of virtual environments for ergonomic analysis, but the technology was limited and therefore such applications were restricted. Later in 2004 Whitman et al. (2004) also evaluated the usefulness of immersive VR for ergonomic analysis

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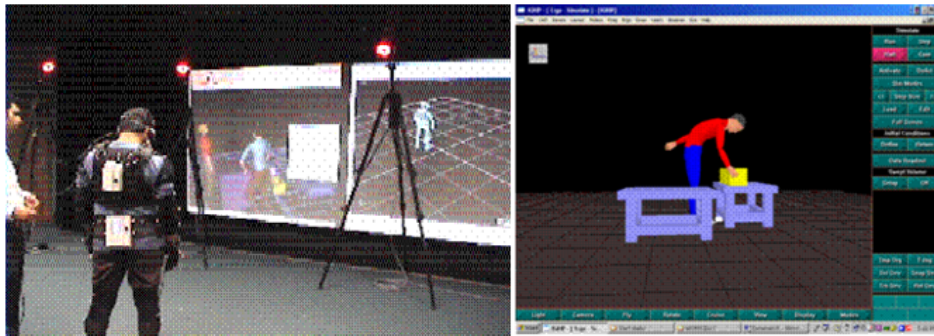


Figure 2.6: Already in 2004 Whitman et al. (2004) evaluated the usefulness of immersive VR for ergonomic assessments. The picture on the left shows the test person suited up for the evaluation. The right picture shows one of the virtual test scenarios.

(Figure 2.6) but again due to technical limitations (monographic HMD, high latency) the results showed that their data collected in VR was only partly comparable to the data gained from their real world experiment. Over the years the technology advanced and HMDs overcame their limiting factors of the past. Nowadays HMDs are still the preferred immersive VR technology for this kind of applications (Jayaram et al., 2006; Pontonnier, Dumont, and Duval, 2014; Pang et al., 2018; Grajewski et al., 2013). In 2016 Aromaa and Väänänen (2016) confirmed that virtual environment (VE) prototypes are suitable to support ergonomics evaluation during the design, and also state that VE prototypes have advantages over Augmented Reality (AR) prototypes.

In previous work usually a fully virtual model was used (Jayaram et al., 2006), other researchers took a hybrid approach and combined a virtual and a physical prototype (Pang et al., 2018; Grajewski et al., 2013). The mentioned examples use different ways to evaluate the data: while Pontonnier, Dumont, and Duval (2014) still rely on an ergonomist for the evaluation, Jayaram et al. (2006) examine two different approaches, one where they included an external evaluation software and another where they implemented their own evaluation system into the existing VR application. Pang et al. (2018) also did the evaluation calculation on their own, but the calculations were very domain specific (Figure 2.7). All mentioned examples do not give real-time feedback to the user of the VR system and present the result of

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Figure 2.7: Pang et al. (2018) evaluated cockpit operation efficiency with VR.

the evaluation (if at all) in traditional two-dimensional ways.

A commercial software that makes use of VR technology is *Nawo* (2020). They offer a solution that makes use of immersive VR and motion tracking to do an ergonomic evaluation. Similar to the mentioned examples NAWO only offers traditional analysis possibilities.

As mentioned in the introduction in chapter 1, the integration of data visualisation and analytics into the immersive ergonomic evaluation process is a core feature of this thesis. The concept of using immersive VR systems to support data understanding and decision making is called Immersive Analytics (IA) and the next section is going to describe this research area in more detail.

2.4 Immersive Analytics

Immersive Analytics is a multi-disciplinary research initiative and involves researchers from different fields, such as data visualisation, visual analytics, virtual reality, computer graphics, and human-computer interaction (Dwyer et al., 2018; Chandler et al., 2015). Dwyer et al. (2018) define it as '*the use of engaging, embodied analysis tools to support data understanding and decision making*'. The aim of IA is to remove barriers between people, their data and the tools that are used for analysis and decision making. The vision is also

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to support the possibility for data understanding and decision making by everyone and everywhere (Dwyer et al., 2018).

The idea is to move away from traditional desktop applications and instead use immersive techniques, e. g. tabletop interfaces or CAVEs (Chandler et al., 2015). This thesis focuses on VR but as Dwyer et al. (2018) state, IA is not tied to any specific kind of technology and can include any immersive environment.

It is still an ongoing discussion if immersive analytics techniques actually offer a benefit over traditional 2D desktop visualisations (Dwyer et al., 2018). Studies show that it cannot generally be said that 3D representations are better than 2D representations, nor the other way round - it depends on the task (Marriott et al., 2018). Marriott et al. (2018) mentions studies that show that 3D representations can be more suitable to show 3D shapes, terrain, structures, multidimensional data or networks while 2D representation show to be more useful for precise manipulation, accurate data value measurement or comparison.

To measure the effectiveness and to decide what is 'better', data visualisation researchers traditionally focus on task performance, accuracy and speed (Dwyer et al., 2018). Dwyer et al. (2018) point out that there are also other factors that can be equally important, like emotional engagement or recall. According to Marriott et al. (2018), studies showed that users preferred 3D representations even though they did not improve task performance. Immersion can create feelings of presence (sense of "being there") and increase engagement in the user (Büschel et al., 2018). According to Makowski et al. (2017) presence and emotional engagement can improve recall. Therefore IA researchers argue that effectiveness should be understood in a wider sense by also including other factors of the users experience (Marriott et al., 2018). If these new factors are considered when measuring the effectiveness, the question of when IA applications offer a benefit over traditional visualisations may be answered more accurately.

The discussion on whether to use 2D, 3D or a combination of the two is just one of many research questions IA is dealing with. The new kinds of devices and environments require very different models and techniques for interaction and visualisation than traditional visual analytics (Chandler et al., 2015). Chandler et al. (2015) also emphasize the fact that IA has the

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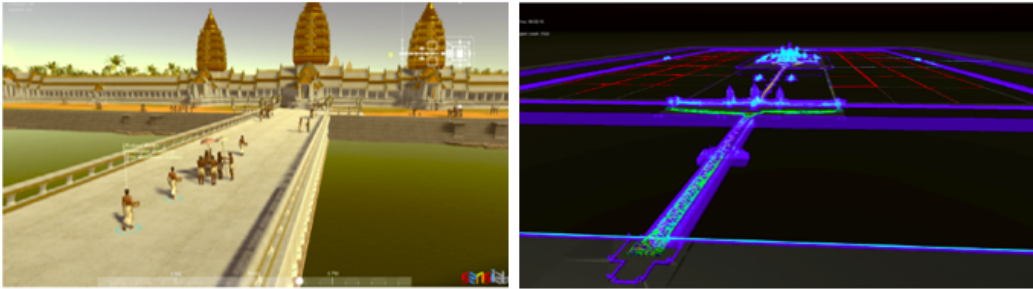


Figure 2.8: Isenberg et al. (2018) virtually reconstructed the ancient Angkor Wat complex. To visualize how the complex might have operated almost a millennium ago, additional data is visualized.

significant possibility to address not only our vision but all our senses. Sound and touch can also be powerful ways to understand the world. Using audio and haptic presentation devices could give blind or visually impaired people access to information, which would be a huge social benefit. An example of such an application is GRAVVITAS (Goncu and Marriott, 2011), which makes use of touchscreen devices and sonic and haptic feedback to enable blind people to interact with information.

Various types of data can be visualized for immersive analytics. According to Fonnet and Prie (2021) these data can be categorized into five categories: spatial, temporal, spatio-temporal, multi-dimensional and graphs and trees. Fonnet and Prie (2021) provided an overview of how these data is typically represented in IA applications. They mention that spatio-temporal data can, for example, be visualized with a heatmap or by lines to represent trajectories. 3D Scatterplots are suited to visualize temporal or multi-dimensional data. 3D Models or 3D Glyphs can, for example, convey spatial information and textures can be used to represent spatial or multi-dimensional data. As mentioned before, IA can address all senses. Sound and haptics can also be used to represent data. Surface force feedback or a simple tone can, for example, convey spatial data (Fonnet and Prie, 2021).

As mentioned in section 2.2.1, immersive displays allow walk-through or ‘fly-over’ of, for example, architectural or engineering designs, but this technology can be used for more than just visualisation. An example is a research project of the Monash University, where the ancient Angkor

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Wat complex was virtually reconstructed (Figure 2.8). Additionally, it also showed the activity in and around the site to visualize how the complex might have operated almost a millennium ago (Isenberg et al., 2018). IA for built environments is just a small application example, according to Czauderna et al. (2018) a key application area for IA is life and health sciences, like medicine, pharmacology or biology. In fact, it can be said that IA has the potential to improve all areas of our lives (Dwyer et al., 2018) and as immersive technologies become more and more common, it makes sense to use the great potential they offer also for analytical purposes.

The following chapters will show the concept of the application and how it is implemented, the analysis specifically will be discussed in section 4.4.

3 Concept

This chapter will provide information about the application concept. It will point out the goals and the requirements that the application needs to fulfill.

3.1 Goals

The main goal of this thesis is to introduce an improved analysis process for immersive ergonomic evaluations. Therefore, an immersive application was developed that gives the user real-time feedback about the ergonomic results and exploits the potential of immersive technologies also for the representation of the evaluation results. Real-time feedback can help to detect ergonomic related problems already during the evaluation. Furthermore, the possibility of analysis in the same immersive environment where the evaluation was carried out may speed up the whole evaluation process even more, give the user a better understanding of the spatial context and make the result more comprehensible. More precisely, the intended immersive analysis aims to first, give the user a good first impression (overview) of the session and its ergonomic quality. Second, to comprehensibly convey where, when and how often an ergonomic problem was identified and third, to provide information why postures are rated as problematic.

Although this thesis focuses on the analysis, the implementation of the application also included the ergonomic evaluation itself. The developed application aims to be a standalone solution to evaluate ergonomics of workplaces in the early design phase, where data integration is tightly coupled and no additional solutions are needed. Besides achieving the main goal of an improved analysis process, the application as a whole aims to

3 Concept

be versatile and easy to integrate into the workplace design process. This means the application can be used for a variety of scenarios, requires no additional solution (evaluation and analysis process are combined in one application) and can be used alone and by anybody (no special education or specialist needed). It should also offer an automated evaluation that can provide meaningful results in real-time and use hardware that is easy to use, accessible and affordable.

3.2 System Overview

This section provides an overview of the application. It will explain what the supported workflow looks like and how the system was designed to implement all requirements.

3.2.1 Workflow Overview

The developed application aims to be a standalone solution to evaluate ergonomics of workplaces in the early design phase. This means the solution covers not only the analysis but also the ergonomic evaluation and the creation/modification of the virtual workplace. Figure 3.1 visualizes the ideal workflow that is provided by the application.

The used game engine provides the workplace creation and modification and therefore offers the possibility to rebuild any scenario. An ergonomic evaluation happens automatically and in real-time and requires no specialist to understand the result. The real-time feedback can motivate the user to perform immediate adjustments to the workplace. Otherwise, a more thorough analysis can be carried out directly after the evaluation. This analysis takes place in the same immersive environment where the evaluation was carried out. This analysis can again encourage the user to perform modifications on the workplace and start the ergonomic evaluation once more. If the user is satisfied with the outcome of the analysis, the workplace design is finished.

3 Concept

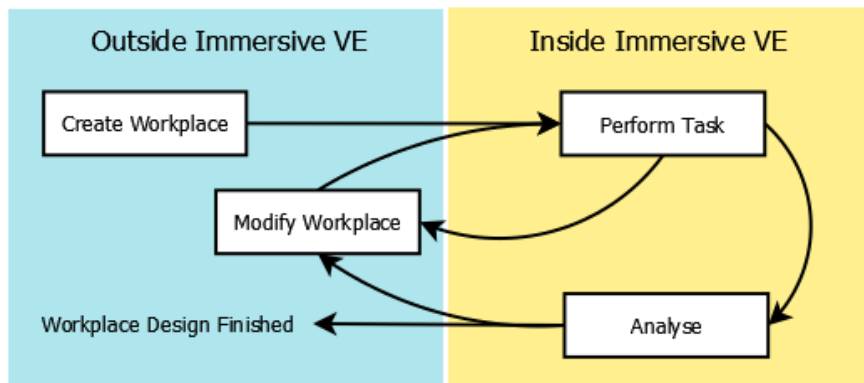


Figure 3.1: The ergonomic evaluation process supported by the application: At the beginning, the virtual workplace is created. Then, the user performs the task while an ergonomic assessment is running. Real-time feedback of the evaluation can immediately encourage the user to perform modification on the workplace. Last, the completed evaluation can be analysed in more detail. This is done in the same immersive environment. This analysis can again encourage the user to perform modification on the workplace and start the ergonomic evaluation once more. If the user is satisfied with the outcome of the analysis, the workplace design is finished.

In the following, this entire process of evaluation and analysis will be called a session. The part of the task execution and ergonomic evaluation will be called an evaluation session. The execution of the analysis will be referred to as the analysis process.

3.2.2 Requirements

To provide an application that supports the workflow mentioned above, more factors had to be considered than just the evaluation and analysis. Also other aspects, like user interactions, that build the base for the application, had to be implemented. In more detail, the application required:

A virtual representation of the user in the VE The user representation determines how the user looks in the virtual environment and how the user can interact with the virtual world. A virtual avatar, that moves according

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to the user in the real world, can increase the feeling of presence (Jerald, 2016). This feeling of presence is desired as it encourages the user to move naturally as he or she would in real life. This natural movement is essential for a meaningful ergonomic evaluation.

Interaction possibilities with the VE and a locomotion system Furthermore, interaction possibilities need to be implemented. They are required to enable the user to perform tasks in the virtual environment at all. These interactions have again an impact on the meaningfulness of the evaluation results. The more realistic and intuitive these interactions feel, the more natural are the user's movements. Interaction possibilities are also needed later to control the visualizations of the analysis. Also, the provided space to perform VR applications is usually limited. If the user is restricted in his or her movement in the real-world, the possible application cases in the virtual environment are limited. Therefore, a locomotion system was implemented that enables the user to move unrestricted.

An automated ergonomic evaluation, that gives real-time feedback The application requires an ergonomic evaluation method that is able to provide meaningful results with the available motion tracking system and can also provide results in real-time. A method that is able to achieve these requirements is the OWAS method. The OWAS method evaluates the physical load. It is also a posture based method, which means the method assesses the pose of the entire body in specific time intervals. Traditionally, this method usually requires an observer who fills out a pre-defined scoring sheet while looking at the worker directly or at a video. Thanks to the characteristics of OWAS, its simplicity and unambiguity, it is also perfectly suitable to be observed by a computer system.

An analysis that is able to extract relevant information of the ergonomic evaluation The analysis and its visualisation are the heart of the application. The analysis needs to be able to provide information that can give the user a good first overview of the evaluation session. Furthermore, it should reliably detect ergonomically problematic sequences and provide enough

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information that explain the assessment comprehensibly. The user should have the possibility of viewing further detail information if required. In general, the data provided by the analysis should focus to give the user enough information so that he or she can make a decision but while avoiding to overwhelm the user with unnecessary information.

A meaningful and comprehensible analysis visualization The visualization aims to present the provided data in a meaningful and comprehensible way. It should intuitively drag the user's attention to problematic areas and convey why they are problematic. The right visualizations should be chosen to represent different kinds of data optimally, e.g. spatial or temporal data. The potential of the virtual environment should be used and exploited to represent the results of the analysis. Furthermore, tools need to be provided to enable the user to control the visualization and to gain more information if necessary.

3.2.3 System Design

The application needs to consider all the mentioned requirements. Figure 3.2 shows a rough overview of the implemented system that considers all these requirements.

The user representation determines how the user looks and how the user can interact with the virtual world. This virtual representation imitates the movement of the user. The ergonomic evaluation uses this movement imitation as a base for its calculations. The results of the ergonomic evaluation are presented to the user in real-time and are saved to a file. The file management ensures that the results are stored correctly and loads the required file when an analysis is started. The analysis component processes the loaded file and provides the data for the analysis visualization. The analysis visualization presents the provided data in a meaningful and comprehensible way. The application manager is the brain of the application and ensures the communication between the different parts of the application. User interfaces enable the user to interact with the system, e.g. to control the analysis visualization.

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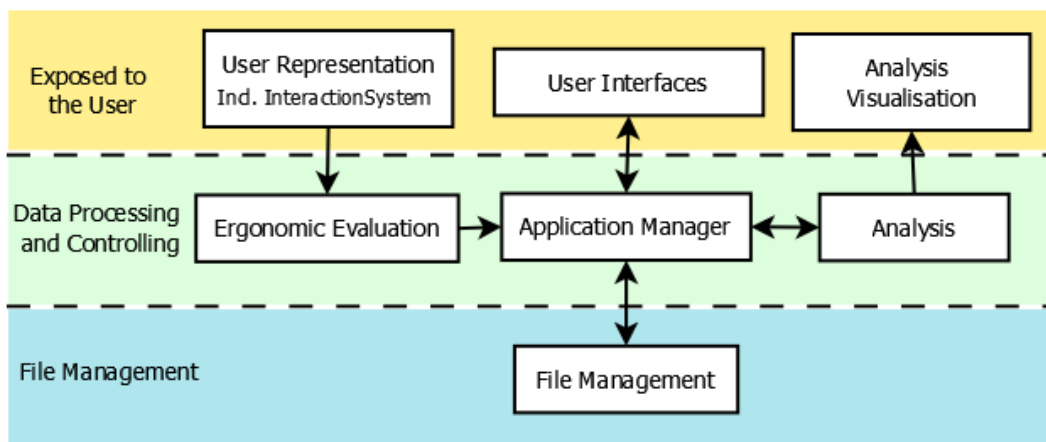


Figure 3.2: A rough overview of the system: A virtual representation of the user determines what the user looks like in the virtual environment and how the user can interact with the virtual world. This virtual avatar imitates the movement of the user of the real world and builds the base for the ergonomic evaluation. The evaluation offers real-time results that are presented to the user and also saved for a later analysis. After the evaluation is completed, the evaluation session can be loaded and analysed. The user can control the visualization of the analysis.

4 Implementation

This chapter is going to describe the implementation of the application in more detail. It will explain the provided functions and visualizations.

4.1 User Representation

The user representation determines not only how the user looks but also how the user can interact with the VE. A convincing virtual avatar, that moves according to the user in the real world, is essential to increase the user's feeling of presence. Additionally, the virtual avatar can be used as a base for the ergonomic evaluation. Currently, the application offers one full-body avatar as shown in Figure 4.1. This avatar is provided from *Renderpeople* (2021). The next sections will describe in more detail how the avatar was animated and how interactions are enabled.

4.1.1 Avatar Animation

To animate a full-body mesh, some reference points from the real world are required. Many tracking points enable a precise tracking, but it can also make the usage more complicated. For this application, the goal was to find a balance between precise tracking and laborious usage. To obtain a realistic full-body tracking with as less reference points as possible inverse kinematics (IK) is used. IK allows to animate the whole body without a full-body tracking. It is necessary to provide the orientation and position of few body parts and the data for the rest of the body can then be estimated by IK calculations. To enable a decent full-body animation with IK at least the following body parts must be tracked: the head, the hands, the feet

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Figure 4.1: The application provides this avatar. It represents the user in the VE and imitates the user's movements. Although the avatar might differ from the user in appearance, skin color and gender, research has shown that this does not affect the user's feeling of presence (Jerald, 2016). According to Jerald (2016) the convincing imitation of the user's movements is more important. If the visual and actual physical motion does not correlate, the user's feeling of presence is damaged.

and the pelvis. Therefore, these six tracking points are considered in this application. They can already provide a decent full-body tracking and the setup is not too laborious and time-consuming for the user.

The six tracking points are assigned to the corresponding bones of the virtual avatar's skeleton. These bones then rotate and translate according to these reference tracking points. Offsets are considered to make the result more precise, e.g. the tracked reference point of the right wrist does not sit exactly at the bone but some centimeter above it. The position and rotation of the remaining bones of the skeleton are determined with inverse kinematics (IK). The used game engine already provides support for IK. Only the corresponding joint target locations needed to be evaluated, e.g. the elbow for the wrists and the knees for the ankles. The order of the calculations had to be considered to ensure a realistic animation, e.g. calculating the IK for the head and torso before the arms. Figure 4.2 visualizes the concept of the full-body animation.

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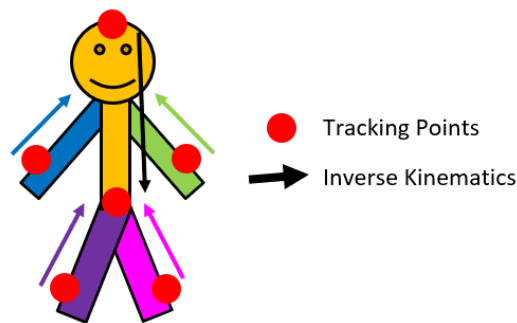


Figure 4.2: Six points on the user's body are tracked: head, left wrist, right wrist, pelvis, right ankle and left ankle. The pelvis determines the pivot position and rotation of the avatar. All other tracking points determine the position and rotation of the closest bones. The location and rotation of the remaining bones are calculated with inverse kinematics (IK).

4.1.2 Avatar Calibration

For a realistic and accurate avatar animation and a less complicated setup, two problems needed to be solved: Different user sizes and changing tracker IDs. These problems will be explained in the next paragraphs.

Different user sizes For an as realistic avatar animation as possible, it is important that the avatar's size fits the user's size. In extreme cases, a size deviation of the user and the virtual avatar can lead to an inaccurate animation and pose estimation. This means the ergonomic evaluation is not meaningful. Additionally, the user's feeling of immersion can be destroyed when the virtual body does not move as expected. This can also change the user's behaviour, e.g. that the user does not move as he or she would in real life due to the mismatching body sizes. It also distorts the ergonomic evaluation result. That is why it is necessary to adjust the virtual avatar's size to the user's size.

Changing tracker IDs The second problem is the changing tracker IDs. The IDs of the trackers can vary in each session depending on the time they are turned on and registered. This is a problem as they are specifically assigned

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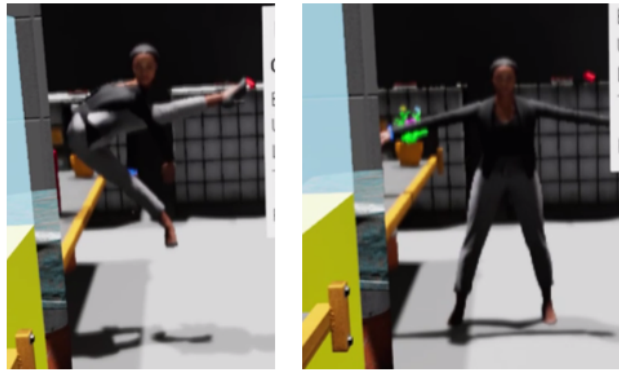


Figure 4.3: At the beginning of each session, the user needs to calibrate the avatar. This is necessary to adjust the avatar's size to the user's size and to set the right ID for each tracker. The user can look into a mirror and observe the process. The pictures show the avatar before (left picture) and after the calibration (right picture).

to a bone, e.g. tracker 1 to the right wrist. If the IDs switch the avatar does not move as expected, e.g. the tracker on the right wrist animates the right ankle. A solution would be to check the IDs of the tracker every session and put them manually to their right position. To reduce the effort and to make the setup less laborious, tracker IDs are assigned automatically.

These two problems are tackled together by an avatar calibration. This calibration considers the user's body size and corrects the tracker IDs. The calibration needs to be carried out at the beginning of each session. To ensure precise calculations, the user needs to stand in a T-Pose. While the user is in this position, the right IDs are evaluated and assigned to each tracker. Also, the size of the virtual avatar is adjusted to the user's size. Figure 4.3 shows the avatar before and after a calibration.

4.2 Interaction and Locomotion System

For a realistic experience and to be able to perform tasks, users must be able to interact with the virtual world. In this application, they need to be able to perform at least the following actions:

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Start the avatar calibration The avatar calibration is a very important step at the beginning of each session, to adjust the virtual avatar to the user's size and to correct the tracker IDs. During the calibration, the user needs to stand in a T-Pose. Therefore, it would be ideal that the user can start the calibration process while he or she is already in that position. In this case, the calibration can start immediately after the activation.

Move around in the virtual world For VR applications, the movement area in the real world is usually limited. To be able to still move around in the virtual world unrestricted, other solutions are required. A typical solution to enable movement in VR is teleportation. It is a fast and effective movement option and avoids motion sickness (Jerald, 2016). To teleport, the user simply selects a destination point in the world where he or she wishes to be and then executes the teleportation to teleport to this place. Ideally, the selection of the destination place and the execution of the teleportation can be carried out in close succession.

Pick up and carry objects To make the ergonomic evaluation as meaningful as possible, it is important that the user can actually carry out the tasks in a realistic way. This makes it necessary to enable interaction possibilities with the virtual scene. For this application it was sufficient to enable the user to pick up and carry objects. This action already allows testing of most scenarios.

Start and stop the ergonomic evaluation For a targeted and efficient ergonomic evaluation, it is necessary that the user can control when the ergonomic evaluation starts and stops. Also, that he or she can choose to start a new evaluation to be able to perform multiple evaluations in one session.

Load completed evaluations Completed evaluations can be analysed in more detail. To do so, the user needs to be able to select and load the desired session.

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Gestures	UIs
<ul style="list-style-type: none">• start avatar calibration• enable movement (teleportation)• hold and carry objects	<ul style="list-style-type: none">• start and stop ergonomic evaluation• load completed evaluations• control the visualization of the analysis

Figure 4.4: The user needs to be able to perform at least the listed interactions. They are either enabled by gestures or by the use of UIs.

Control the visualization of the analysis Once a session is loaded, the system will offer different visualization options. Therefore, the user needs to be able to control these visualizations to gain a better understanding of the analysis.

Usually a HMD is used in combination with tracked hand held controllers to enable interaction with the virtual environment. With controllers, actions can simply be mapped to buttons. In this application, gloves are used to increase the feeling of immersion and to enable a more realistic movement. Gloves do not have buttons that can be mapped to actions. Therefore, another solution was required. As the gloves allow a decent tracking of the hand and fingers, it was decided to make use of gestures. Gestures can feel very intuitive and natural but they can easily lead to fatigue (gorilla-arm effect) (Büschel et al., 2018). Furthermore, Jerald (2016) recommends to limit the number of gestures to keep interactions simple and learnable. To minimize the gestures that the user needs to learn, users should be able to also interact with user interfaces (UIs) like menus.

Gestures can be used much faster therefore they were used to enable actions that are performed more often and where a fast and uncomplicated usage is advantageous, e.g. for actions that need to be performed during the ergonomic evaluation. Using an UI is slower but it can provide more information, therefore this option was used for actions that are not used that often and outside the ergonomic evaluation or where additional information is beneficial.

Figure 4.4 shows which interaction was mapped to which solution.

4.2.1 Gestures

The criteria for the chosen gestures were that they are simple and easy to learn and to recognize. They should also be unambiguous and unique. This ensures that the system only recognizes the gestures when they are actually performed and are not mistaken for any other gesture the user might use during the evaluation. It was also considered how well the gesture fits the task, e.g. for the teleportation a gesture is needed that makes it easy to select a point on the floor.

The next paragraphs will further examine how the gestures were chosen for each action.

Teleport To teleport the user needs to first, select a destination point and then second, execute the teleportation. Therefore, there are two gestures required to perform this action. For the destination selection, a gesture is required that allows a comprehensible selection of a point on the floor. The teleport execution requires a gesture that is similar to the first gesture. The user should be able to perform the second gesture within a minimal time frame after the first gesture and without much movement involved. This allows the user to keep the destination point focused.

For the destination point selection, a gun gesture is used. Once this gesture is recognized, the teleporter gets activated. The teleporter is a mesh that visualizes the destination point and the distance from the user to it. It is based on the VR example of Unreal Engine. As long as the user performs the gun gesture, this teleporter is visible. To actually execute the teleportation, the user needs to move from the gun gesture to the gun trigger gesture. To do so, the user moves the thumb by about 90 degrees. If the gun trigger gesture is recognized within a certain time frame after the gun gesture, the teleportation is executed. Figure 4.5 shows how to activate and how to execute the teleport.

Start avatar calibration The avatar calibration only happens once and only at the beginning of a session. Ideally, the calibration can be activated when the user is already in the required T-Pose. This requirement is already

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Figure 4.5: The picture on the left shows the user performing the gun gesture. This gesture activates the teleporter. The teleporter visualizes the destination point and its distance to the user. The user can control this destination point with the index finger. The right picture shows the user performing the gun trigger gesture. This gesture needs to be performed within a short time frame after the gun gesture to execute the teleport. After the gun trigger gesture is performed, the user teleports to the chosen destination point.

provided by any gesture, and no further additional gesture characteristics are required for this action. Due to these reasons and to minimize the gestures that the user needs to learn, the gun gesture is reused to enable this action. To ensure that the calibration cannot be activated per accident during the session, the calibration only starts the first time the gun gesture is used.

Pick up and carry objects To enable these actions, it was decided to use a gesture that is intuitive and can be easily connected to the task. Therefore, it was decided to use a grab gesture. This gesture can be easily connected to the action of picking up and carrying objects. As long as the user performs the grab gesture, objects can be picked up and carried. The user can only perform this action on objects that were specifically defined as pick up objects. Figure 4.6 shows the user performing the grab gesture.

In total, there are three gestures that the user needs to learn to use the application properly. Figure 4.7 visualizes these three chosen gestures.

4.2.2 User Interfaces

User Interfaces are enabling the remaining actions. The first two actions ('start/stop ergonomic evaluation' and 'load evaluation session') can be

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Figure 4.6: The user can pick up objects by performing a grab gesture. As long as the user uses this gesture, objects can be carried.

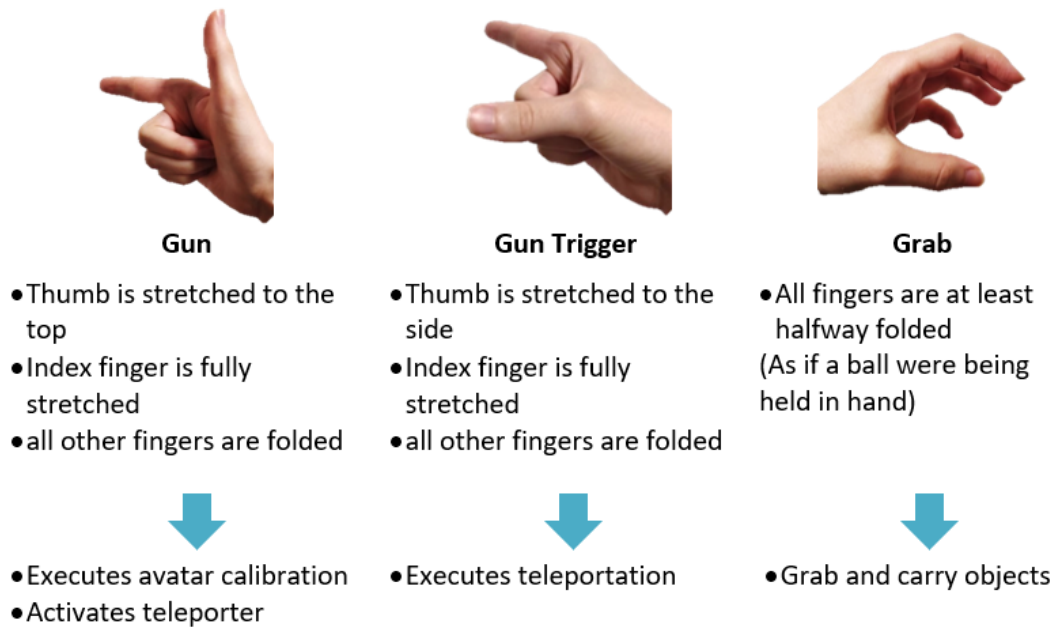


Figure 4.7: The user needs to learn three gestures to use the application properly. The figure shows and explains these three gestures.

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performed quickly and do not require a lot of information. Therefore, it was decided to use one single menu for both actions. The last action (control analysis visualization) requires more information and detail. Therefore, it was decided to use a separate control panel for this action.

The two used UIs will be described in the following.

Watch Menu

The first two actions ('start/stop ergonomic evaluation' and 'load evaluation session') are covered by a single menu.

The user may start/stop and pause an ergonomic evaluation several times during a session. Therefore, a solution was needed that makes it possible to do this in a fast and uncomplicated way. The user may not load an completed evaluation that often during a session, but this action can also be performed in a fast way as it only requires the selection and confirmation of the required evaluation session. Additionally, it also needs to be considered how the menu will be opened as no controllers are used and additional gestures need to be avoided.

Because of these considerations, it was decided to use a watch menu. A menu on the wrist can be accessed easily and fast, e.g. by looking at it, and therefore fits the criteria for our actions. It can bear the risk to tire the user (gorilla arm) but as the actions do not require a lot of time, the advantages (easy and fast to access) outweigh this disadvantage.

To remind the user that there exists a watch menu, a big blue watch is placed on the avatar's left wrist. This blue watch aims to catch the user's attention. As mentioned above, the original idea was that the menu opens once the user looks at it. Unfortunately, this can lead to the problem that the menu opens unintentionally and distracts the user while he or she performs a task. Ideally, the user acts as much as possible as in real life to gain a precise and meaningful ergonomic assessment. That is why it is important to reduce such unnecessary distractions as much as possible. To prevent the user to open the menu unintentionally there are in total two constraints that need to be fulfilled to open the watch menu: First, the user is looking at the menu and second, the menu is tilted towards the user's face. The

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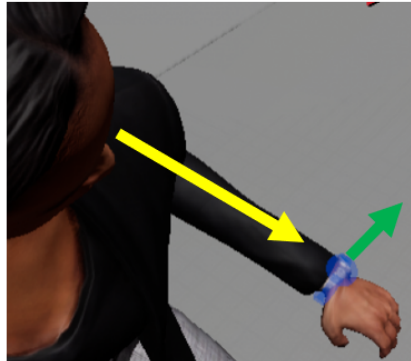


Figure 4.8: A blue watch on the left wrist of the avatar draws the attention of the user. It should remind him or her of the watch menu. Only if two constraints are fulfilled the watch menu opens. These constraints are: The user is looking at the watch and the watch is facing the user. In the figures example, the user looks at the menu, but the watch is not facing the user. Therefore, the menu does not open. This prevents the menu to open unintentionally.

menu will disappear two seconds after these two constraints are not fulfilled anymore. The two constraints are visualized in Figure 4.8. Figure 4.9 shows and explains the different screens of the menu.

Analysis Panel

The UI to control the analysis visualizations is only needed when the analysis is taking place. And then it is used in a high frequency. Therefore, it was decided that this UI, called the analysis panel, does not need to be hidden. The analysis panel appears when the user loads an evaluation session and stays as long as the user analyses it. Also, this UI offers more information, and the user requires more time to interact with it. Because of that reason, the position of the analysis panel needed be considered more thoroughly. It was decided to place the UI on a pleasant height for the user, to avoid to tire the user. After an evaluation session is loaded for further analysis, the analysis panel appears in front of him or her, about on pelvis height and slightly tilted towards the user. The tool moves with the user and is always positioned in front of him or her. Figure 4.10 shows the control panel. It will be further described in the analysis section 4.4.

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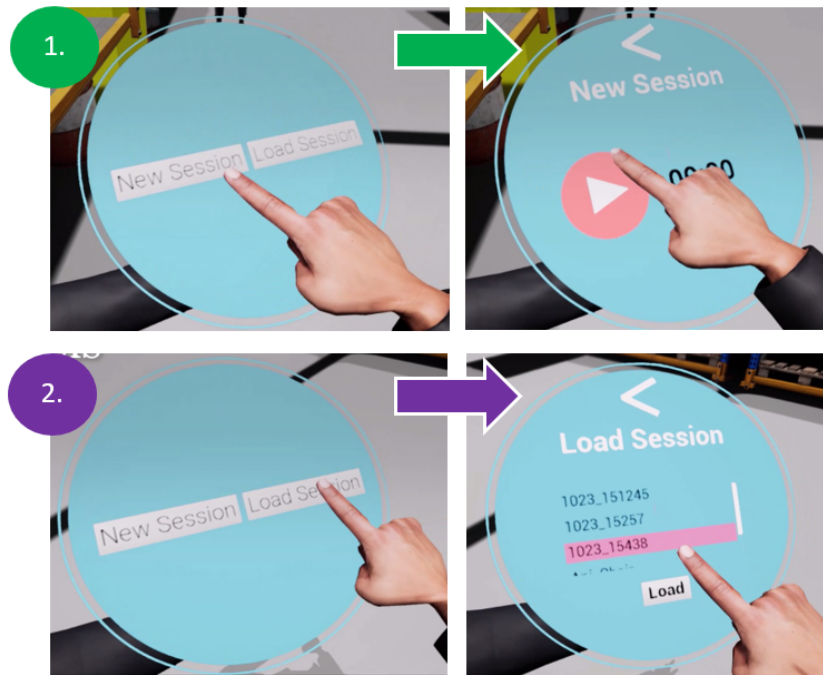


Figure 4.9: The pictures in the first row show how a new evaluation session can be created and started. On the title screen, the user needs to select 'New Session'. This creates a new evaluation session and the screen changes. By clicking on the play button, the user can start the evaluation. Another click pauses the evaluation. The arrow on top of the screen allows the user to stop the evaluation and to return to the title screen. The second row shows how the user can load an evaluation session. On the title screen, the user selects 'Load Session'. The screen changes and the new screen offers a list of completed evaluation sessions. The user needs to select the desired evaluation and click on the 'Load' button. The arrow on top of the screen allows the user to stop the analysis and return to the title screen.

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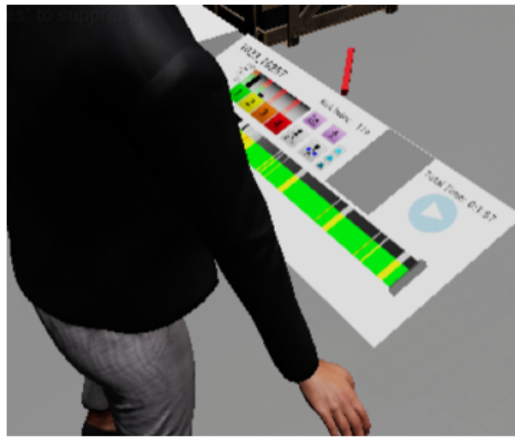


Figure 4.10: After the user loaded an evaluation session, the analysis panel appears in front of him or her. This panel allows the user to control the analysis visualization. It is positioned around pelvis height and is slightly tilted towards the user. It stays visible during the whole analysis process.

4.3 Ergonomic Evaluation

To evaluate the physical load of the user, the OWAS method is used. This method is described in more detail in section 2.1.2. This section will describe how the OWAS method was applied in this application and mention necessary adaptations. Furthermore, this section will show how the real-time results are presented to the user and how the results are stored for the following analysis.

4.3.1 OWAS

OWAS is a posture based method, this means the method assesses the pose of the entire body in specific time intervals. Traditionally, this method usually requires an observer who fills out a pre-defined scoring sheet while looking at the worker directly or by looking at a video. Thanks to the characteristics of OWAS, its simplicity and unambiguity, it is also perfectly suitable to be observed by a computer system.

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In this application, the user's virtual avatar is animated to simulate the user's movement from the real world. Therefore, the OWAS method can use this virtual avatar as a base for the ergonomic calculations. The automated observation gives the possibility to evaluate the postures in a higher frequency and improve the accuracy of the result. To guarantee a uniform behaviour and to make results comparable, the frequency of observations are limited. In this application the default frequency is set to 30 observations per second, but this value can be adjusted to fit different needs and resources.

Posture Evaluation

Before the whole body posture is assigned to an OWAS class (see section 2.1.2), three separate body parts (back, lower limbs, upper limbs) and the carried weight are evaluated. The virtual avatar forms the basis for the calculations. Bone locations and rotations can simply be measured and compared. The following will describe how this categorization is carried out and point out adaptations that had to be made.

The back can be classified into four categories. The given motion capturing resources do not allow a precise determination of the torso's twist. Therefore, the last two categories were adapted as it was also done, e.g. by Iqbal et al. (2021). Instead of determining a twist of the torso, it is checked if the torso is bend to the side.

OWAS considers three variations of upper limb positions. No adjustments had to be performed for this body part.

There are seven classification possibilities for the legs. Because of the limited space in the real world, the user cannot walk around much and needs to teleport to move around in the virtual world. Therefore, the sixth category for the legs (body moved by legs) is registered when an unnaturally big change in the pelvis position is recorded. This 'unnatural big change' was determined by trial, so that also a short teleportation is recognized but false recognition are avoided. The current application does not consider sitting positions, that is why the seventh category (both legs hanging free/sitting) is not completely considered in the ergonomic evaluation. The application

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does recognize when both feet are off the floor. The current test scenarios do not consider this position as well, but it is used to detect if the trackers are positioned correctly. An example: if the pelvis tracker is rotated too much towards the floor, due to a loose attachment of the pelvis tracker, the feet of the virtual avatar get lifted from the ground and the detection of the positions is not accurate anymore. To detect this error as soon as possible, this possibility for the legs is recognized.

At last, the carried weight needs to be classified. Here, there are three possibilities and none of them had to be adapted. When movable objects are created for the scene, their weight needs to be defined by the user. The weight will then be forwarded to the OWAS calculations.

After every body part and the weight is categorized, the final class for the entire posture is determined. This information is simply looked up in a table. This table is shown in section 2.1.2 (Figure 2.3).

Table 4.1 shows the OWAS grades for each body part and the grade with all adaptations.

Time Related Risk Evaluation and Risk Index

As mentioned in section 2.1.2 a time related risk evaluation is carried out. Also, the risk index is calculated. Both calculations can give the user important information about the evaluation already during the assessment. Therefore, both calculations, the time related risk evaluation and the risk index, are determined together with the other observations in each evaluation cycle and not only at the end of the evaluation.

The time related evaluation can assess almost every pose like in real life. Most actions need the same time in the virtual as in the real world. Special considerations are needed for the walking poses. In the virtual environment, teleportation can be used to move from one place to another within an instant. In the real world, the user would need more time to move around. The application still aims to make the result as realistic as possible. Therefore, calculations are performed to compensate this time difference. As described by Carey (2005), walking speed ranges around 1.26 m/s and 1.52 m/s. In this application it was decided to use an average value of 1.4 m/s.

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Body part	OWAS grade	Description
Back	1	Back straight
	2	Back bend forward
	3	Back bend to the side*
	4	Back bend forward and to the side*
Arms	1	Both hands below shoulder level
	2	One hand above shoulder level
	3	Both hands above shoulder level
Legs	1	Load on two legs straight
	2	Load on one leg straight
	3	Load on two legs bend
	4	Load on one leg bend
	5	Load on one or both legs kneeling
	6	Body moved by legs (walking)
	7	Both legs hanging free*
Load	1	Less than 10 kg
	2	Between 10 and 20 kg
	3	Above 20 kg

* adapted

Table 4.1: The table shows the OWAS grades for each body part and the load. Some adaptations were made to the original method to adjust to the available motion capturing system, and the planned scenarios. The original classification for each category is described by Karhu, Kansilinen, and Kuorinka (1977) and Grzybowski (2010) and can be seen in Figure 2.2.

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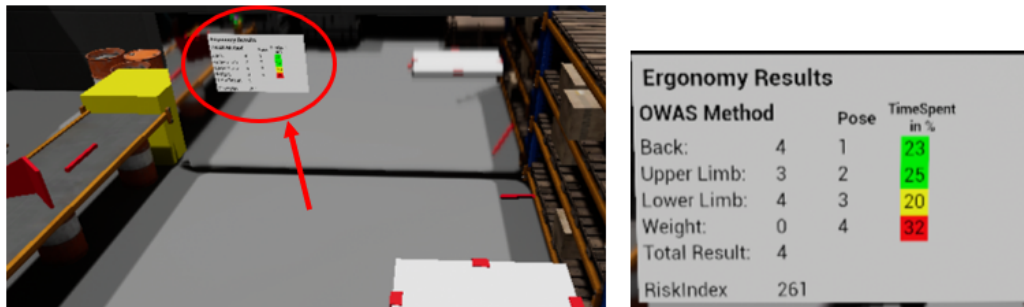


Figure 4.11: The result panel shows the OWAS classes for each body part and the whole body. Also, the risk index and the time related risk evaluation is shown. The panel is placed at a central place in the scene and the user can look at it whenever it is needed (left picture). The right picture shows the panel in more detail.

Considering the teleportation distance and this walking speed, the estimated time consumption is calculated. This makes the time related evaluation more realistic.

4.3.2 Real-Time Result Visualization

To enable the user to detect possible ergonomic problems early on, the evaluation results are presented to the user in real-time. It had to be considered how the result is presented to the user. One solution would be to attach the result to the user's view. In this case, the user can see the result permanently while the evaluation is running. This solution allows the user to immediately detect ergonomically problematic poses, but it can also distract the user from the task. In the worst case, the constant reminder of the evaluation also influences the user's behaviour. Therefore, it was decided to use an information panel instead. This panel is positioned in a central position in the scene, and the user can look at it whenever it is needed. Figure 4.11 shows this panel and explains its content.

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Avatars Scale Value		
Timestamp	Tracking Points	OWAS Result
Timestamp	Tracking Points	OWAS Result
...

Figure 4.12: This figure shows how the evaluation data is saved into a file. Once the file is created, the scale value of the avatar is saved. Each evaluation cycle the following information is saved: the timestamp of the observation, the location and rotation data of all six tracking points and the OWAS result.

4.3.3 Result Storage

The results are not only visualized in real-time, but also saved to a file. This file can be loaded later for a more thorough analysis.

The file is created once the user starts an evaluation. For simplicity, the filename is by default defined by the day and time of execution.

The application saves every data that can be interesting later on in the analysis. The first information that is saved is the scale value for the avatar. It gives information about the user's height. Then, each evaluation cycle the following information is saved: the timestamp of the observation, the tracking point information (location and rotation of each of the six tracking points), The main OWAS results (body part grades and whole body grade) and the additional calculations (time related result, risk index). This is visualized in Figure 4.12.

The saved timestamps already consider the special case of the walking postures. As mentioned in section 4.3.1 calculations are performed to compensate the time difference of the teleportation in the VE and walking in real life.

4.4 Analysis and Visualization

The main goal of this thesis is to introduce an improved analysis process for immersive ergonomic evaluations.

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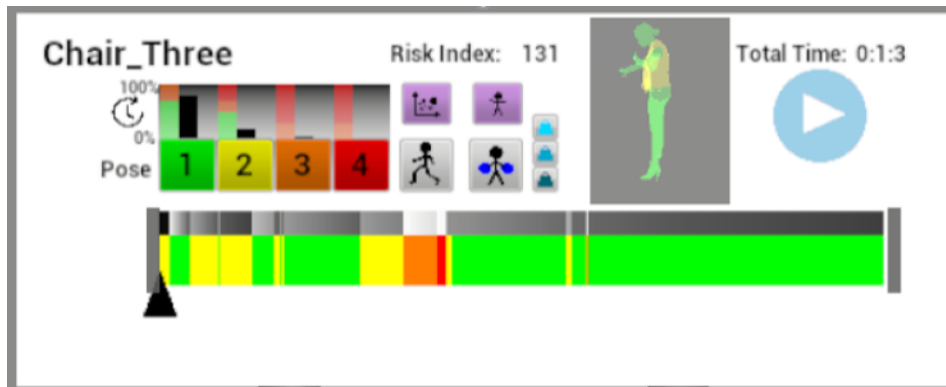


Figure 4.13: The analysis panels appears once the user loaded an evaluation session. This picture shows the panel in more detail.

To achieve this goal, an immersive application was developed that not only gives the user real-time feedback about the ergonomic results but also exploits the potential of immersive technologies for the representation of the ergonomic evaluation results. The analysis aims to first, give the user a good first impression (overview) of the session and its ergonomic quality. Second, to comprehensibly convey where, when and how often an ergonomic problem was identified and third, to provide information why poses are rated as problematic.

Section 4.3.2 already described how the real-time results are presented to the user. This section will explain in more detail how the immersive technology is exploited for the analysis.

The ergonomic evaluation can be analysed immediately after the evaluation is performed. The user can stay in the same immersive environment without any further adjustments. To analyse an evaluation, the user simply needs to load the desired file, as described in section 4.2.2. Once a completed evaluation is loaded, a panel appears in front of the user. This panel, called the analysis panel, is shown in Figure 4.13. The analysis panel and its functions will be described in the following.

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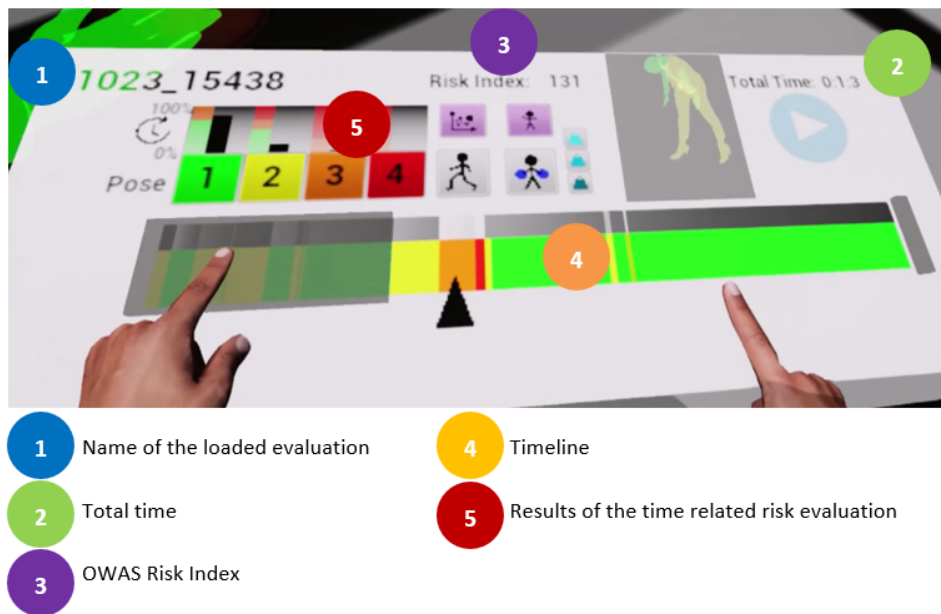


Figure 4.14: The analysis displays basic information, like the name and length of the loaded evaluation. Furthermore, it provides an overview by displaying the OWAS risk index, a timeline that represents the temporal sequence of OWAS poses and the time related risk evaluation result.

4.4.1 Overview

First, the analysis tool displays basic information, that is the name and length of the loaded ergonomic evaluation. Second, the tool aims to give an overview of the loaded evaluation. This overview should give the user a good first impression (overview) of the session and its ergonomic quality. Additionally, it should convey if an ergonomic problem was identified and also how often and about how long this problem occurred.

This first overview is provided by the OWAS risk index and a timeline. The risk index is simply a number, but it can already give the user a first impression of the ergonomic quality of the evaluation. Additionally, the user can immediately see if changes to the workplace were effective by comparing the risk index of the evaluation before and after the change. The risk index is more thoroughly described in section 2.1.2.

The timeline aims to give the user an overview of how the ergonomic quality evolved over time. It also shows how often and about how long an ergonomically risky position occurred. This is provided by giving information about the temporal sequence of OWAS poses. The color green indicates posture class one (lowest risk), yellow indicates posture class two, orange indicates class three, and red indicates posture class four (highest risk). The red color is interesting to the user as this pose category bears the highest risk to cause MSDs.

Additionally, the timeline also visualizes how the time share of each pose evolved over time. This is interesting for the time related risk evaluation. The time share is visualized by the smaller gray-scale stripe on top of the timeline. The white color indicates 0% and black 100%. The definite time share of each pose category is more precisely visualized on the left, where the final time share is shown for each pose separately. Additionally, a colored bar on the right helps to identify the risk level according to the time related risk evaluation.

Both the classical OWAS classification and the time related risk evaluation help to identify possible problematic pose classes. The timeline helps furthermore to identify how often and about how long the problematic poses

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occurred. Figure 4.14 shows where these overview tools are located on the analysis panel.

4.4.2 Filter

After the user gains an overview of the loaded session, the user might want to obtain more information. The timeline offers information about the general pose category and how often and about how long these pose category occurred. Further information about where the poses happened and how the poses actually look like is missing. OWAS class four is of special interest or any other class that indicates a high risk according to the time related evaluation. Therefore, a pose related filter was included. This filter aims to give the user information about where the pose class occurred, and what the pose actually looks like.

This filter can also point out transitional poses. Transitional poses often cannot be visualized by the timeline, because they occur in a brief time span between two bigger pose sequences. These poses could easily be avoided, e.g. by training and therefore it is important to detect them.

In addition to the pose class, also other aspects can be interesting to the user. Sometimes a task involves a lot of carrying and lifting or walking. If walking distances are known, especially where objects need to be carried, they can be adapted and optimized. For these reasons, the analysis panel offers two more filter options: a 'walking' and 'carrying' filter. The 'carrying' filter offers an additional option to select the weight grade of the carried load.

Figure 4.15 shows the filter tools on the analysis panel. The next two section are going to describe how these pose and spatial related filters are visualized.

4.4.3 Static Pose Avatar

This section is going to describe how the pose related filter is visualized. As described in the previous section, the analysis tool offers the possibility

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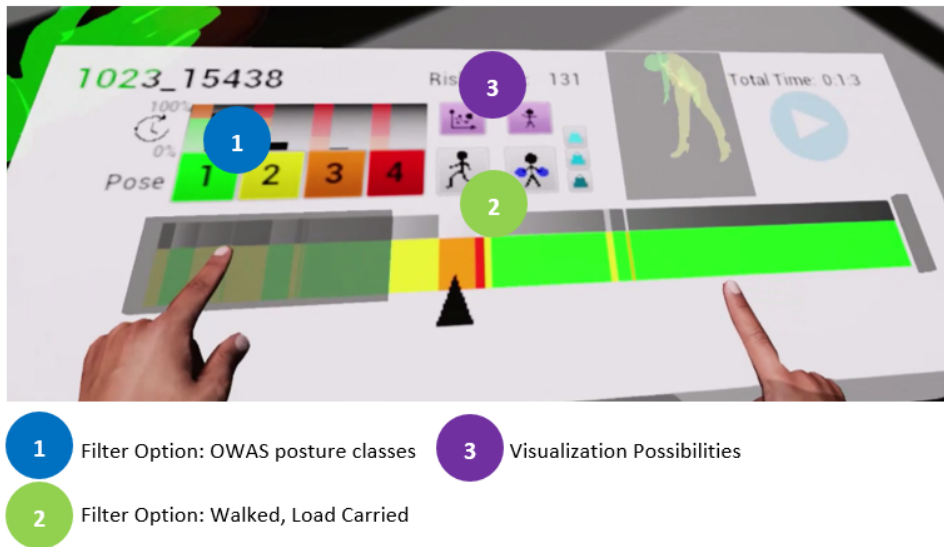


Figure 4.15: The user can filter for OWAS pose categories or for areas that were used for walking or carrying objects. There are two visualization possibilities for these filters. The pose visualization is optimized to visualize the pose categories, whereas the heatmap visualization is optimized to display the spatial-temporal information of the 'walking' and 'carrying' filter.

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to filter by OWAS pose category. This filter should give the user information about where these poses happened and how these poses are actually composed. The following will describe how the poses are actually visualized, how the right pose to present is chosen and which further details are displayed.

Pose Creation

To point out the place where the poses occurred is simple. To actually visualize the pose and give information about its composition is more challenging. The user's avatar is reused to visualize this information. The avatar can simply be recreated as the evaluation file includes the avatar's scale factor. Additionally, the file contains the location and rotation of all six tracking points for each evaluation cycle. With the help of this information and the known rules of the avatar animation, the poses can be recreated precisely.

A special treatment is required for 'walking' poses. As teleportation is used as a locomotion system, no tracking point information is provided for this pose. In special cases, this pose might need to be represented. To still be able to represent a walking pose, a 'fake' pose can be created by considering the direction of the teleportation. This pose can then be displayed between the start and end point of the teleportation.

Pose Details

The pure recreation of the desired pose still does not give enough information to the user, e.g. why the pose is now critical or not. To give the user more details about this decision, not only the pose is represented but also information about all separate OWAS grades is given. The total OWAS class is determined by the grade of the back, upper limbs, lower limbs and the carried weight. Knowledge of this information can make the overall pose classification more comprehensible. This information is visualized by coloring the corresponding parts of the pose avatar. In that way the grade

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for the body parts can be visualized easily. More challenging is the visualization of the grade for the carried weight. To visualize the carried weight, two spheres are added to the avatar's mesh. The spheres are placed at the avatar's hands to symbolize the carried object. These spheres can then be colored accordingly. To offer the complete results, also the result of the total OWAS class is visualized. To represent the overall result, a visualization was required that intuitively conveys that it concerns the whole body posture. To convey this information, a circle on the floor is used that surrounds the pose avatar. This prominent circle is easy to notice for the user and can convey that it concerns the overall posture.

The body parts, the spheres and the circle are colored according to their grades. To avoid confusion, the same color grading scheme is used as for the OWAS classes in the timeline (green, yellow, orange, red). Usually the higher the grade, the worse the grade is. Therefore green is chosen for low grades, red for high grades and yellow and orange for the grades in-between. The circle is colored according to the OWAS classes and corresponds with the colors used in the timeline. Figure 4.16 shows how such an analysis pose avatar looks like. The figure also explains the color grading.

Pose Clustering

The application visualizes information about the pose with the help of the pose avatar, that was described before. To offer a meaningful filter, not all postures of a certain type can be visualized. This would crowd the scene and overwhelm the user. The application aims to give the user exactly as much information as he or she needs to make a decision, but avoids to overwhelm the user. Therefore, one representative pose is chosen for each pose category sequence. The goal was to choose a pose that has a high probability to represent the pose sequence in a meaningful way, e.g. if the sequence contains the motion of picking something from the floor, the best pose would be that shows the user the closest to the floor. The assumption was made that the beginning of the sequence contains the transition into the pose and the end of the sequence the transitioning out of the pose. Therefore the pose in the temporal middle of the sequence is picked as a representation of the whole sequence. An example is shown in figure 4.17.

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Body part	Grade	Description
Back	1	Back straight
	2	Back bend forward
	3	Back bend to the side
	4	Back bend forward and to the side
Arms	1	Both hands below shoulder level
	2	One hand above shoulder level
	3	Both hands above shoulder level
Legs	1	Load on two legs straight
	2	Load on one leg straight
	3	Load on two legs bend
	4	Load on one leg bend
	5	Load on one or both legs kneeling
	6	Body moved by legs (teleport)
	7	Both legs hanging free
Load	1	Less than 10 kg
	2	Between 10 and 20 kg
	3	Above 20 kg



Figure 4.16: An avatar visualizes the pose filter. This avatar is a copy of the user's avatar and precisely reconstructs the user's pose in the evaluation. The partial OWAS results are visualized by coloring the corresponding body parts. The carried object is symbolized by two spheres that are located at the user's hands. The circle on the floor, that surrounds the avatar, represents the grade for the overall pose. The table on the right shows the color grading system.

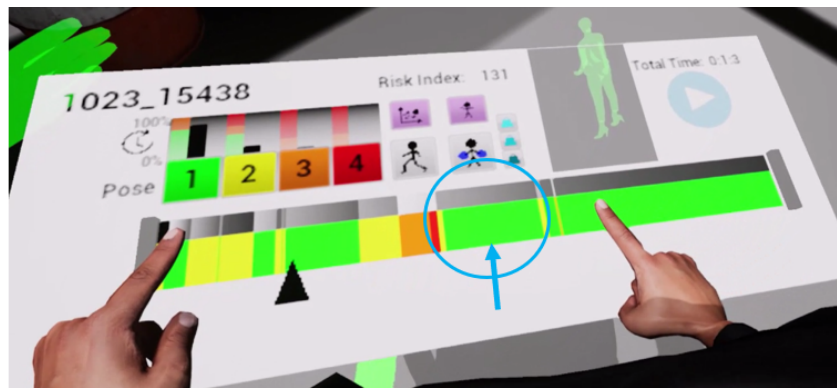


Figure 4.17: From one pose class sequence, only one pose is chosen and visualized. It was decided to use the pose in the temporal middle of the sequence as a representation of the whole sequence. An example is shown in the figure. The marked sequence of OWAS class 1 is represented by one pose, that is the one in the middle of the sequence.

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Furthermore, it had to be considered that the same pose may appear at the same place multiple times. For example, the user might return to a shelf several times during a task and pick up a tool. This would lead to the unwanted result that multiple similar poses are created and shown at the same place. This, again, would unnecessarily crowd the scene and distract the user. To avoid this scenario, poses are not created if a pose of the same class already exists very close to it. This avoids that an area gets crowded by similar poses.

Time Details

The user can identify problematic poses and filter for them. A representative pose for each pose class sequence is reconstructed and then placed at the location where it actually happened. The pose and the location give the user information about where the pose category happened and what the pose actually looks like. Furthermore, details about the OWAS classification is provided. Thanks to the timeline, the user obtains information about the problematic poses, when and about how long they occurred. Nevertheless, the user cannot connect the information provided by the static pose avatar and the timeline. To solve this problem, the pose avatar needs to offer more details. This is done by reusing the timeline and placing it over the pose avatar. A time indicator helps to connect the pose with the corresponding sequence in the timeline. This makes it easy to connect the pose avatar and timeline information. The additional information above the pose can crowd the scene and overwhelm the user. Therefore, this information is hidden and as soon as the user looks at the pose it is inserted. With this technique, the user is provided with the necessary information as soon as he or she needs it. If the same pose category occurred multiple times at the same place, also multiple time indicators are used for the timeline. The timeline also rotates according to the user's position. This ensures that the timeline is clearly visible to the user, no matter from what position the user looks at the pose avatar. An example is shown in figure 4.18.

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Figure 4.18: The static pose gives the user information about the pose composition, but the user cannot connect this information with the timeline and when this pose occurred. Therefore, the timeline is also visualized above the static pose. This timeline is hidden by default and is visible as soon as the user looks at the pose. The timeline as rotates towards the user. This ensures that the timeline is clearly visible wherever the user is located.

4.4.4 Heatmap

The pose avatar is a good visualization form to convey information about the pose composition. It also gives spatial information, but is not very accurate. As just one pose of a sequence is chosen and visualized, spatial information can be missing. Also, the filter offers more options than just the OWAS classes. The application also includes a 'walking' and 'carrying' filter. These two filters do not need to provide information about the pose. The interesting information is, where did the user walk and where did he or she carry objects. Especially the carrying of heavy objects can be interesting. Additionally, temporal details can be beneficial to identify how long or rather how often an area was used by walking and/or carrying. Hence, to improve the spatio-temporal information given by the filter, an additional visualisation is needed.

A visualization that can convey spatio-temporal data is a heatmap. It can visualize information for the carry and movement filter meaningfully and

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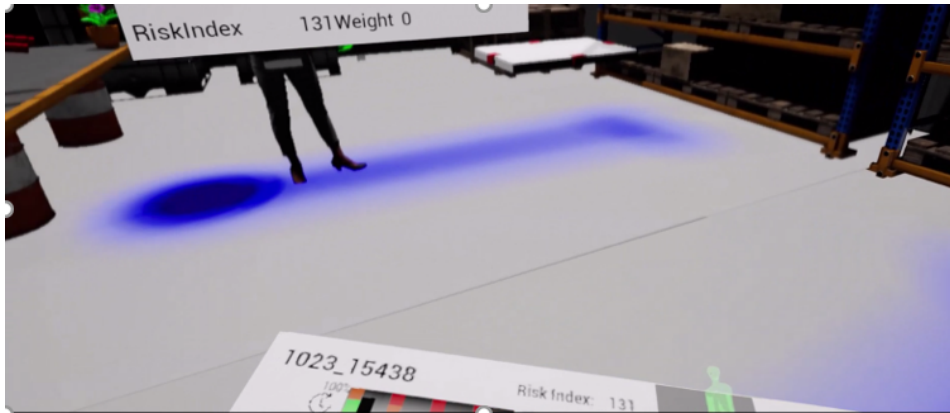


Figure 4.19: The heatmap visualizes spatial-temporal information. In this example, the heatmap visualizes the area where the user carried objects. The darker the blue, the longer the user stayed at this place.

also compensate the disadvantages of the pose avatar for the OWAS classes. The heatmap is shown on the floor and can visualize where and about how long/often the user was present at a certain place. Usually a heatmap uses a color range from cool shades (e.g. blue) to warm shades (e.g. red). The application already uses colors for the timeline and the coloring of the avatar. Therefore, a color scale is chosen that does not interfere with the already used colors to avoid misunderstandings. The only primary color that is not used for the OWAS grades is blue. Therefore, it was decided to use gradations of blue for the heatmap. The darker the color of blue, the longer or the more often this area was passed by walking or carrying. An example of the heatmap is shown in figure 4.19.

4.4.5 Pose Preview

The pose filters are a good technique to gain more knowledge about the composition of the poses. Nevertheless, the filter action and the subsequent connection with the timeline information takes time. To also introduce a way that allows the user to gain a quick overview of the pose composition in context with the timeline, the analysis panel provides another tool. This tool is called the pose preview. Figure 4.20 shows this tool on the analysis

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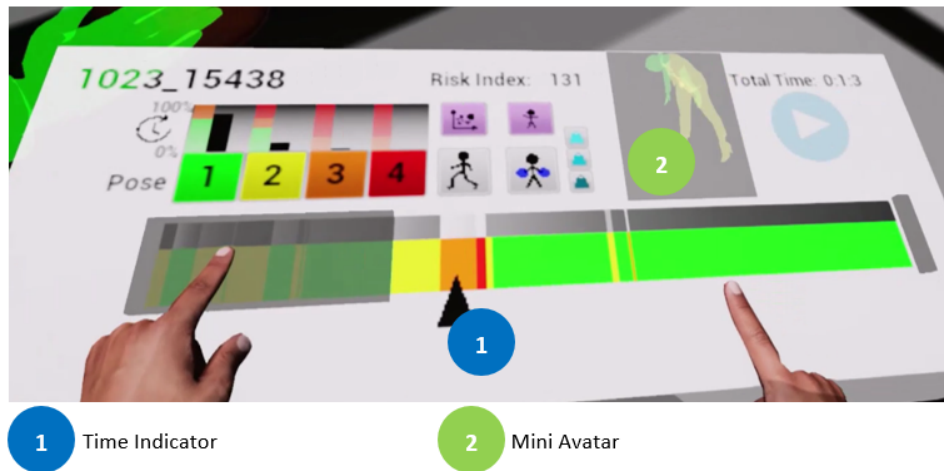


Figure 4.20: To allow the user to gain a fast overview of the session and its poses a pose preview function was implemented. The user can move the time indicator at the bottom of the timeline and the panel shows a mini-avatar of the pose. This avatar is a miniature version of the static pose avatar.

panel. The time indicator on the bottom of the timeline can be moved on the horizontal axis of the timeline. A mini avatar on the top right visualizes the pose at the chosen time. This mini avatar is a miniature version of the static pose avatar and represents the exact same poses as the pose filter. With the help of this tool the user can get information about the poses without spatial context to quickly gain an overview of the evaluation session.

4.4.6 Replay

The tools presented so far already enable the user to gain important information about the evaluation session. The user can make out areas and poses that need further investigation. Still, the static pose filter only visualizes a moment in the pose sequence. Although the application aims to provide the most representative pose of the sequence, more information about the sequence can be beneficial and required to make a more determined decision. To enable the user to gain more details about the pose sequences, users can use a replay function. This replay function allows the user to replay

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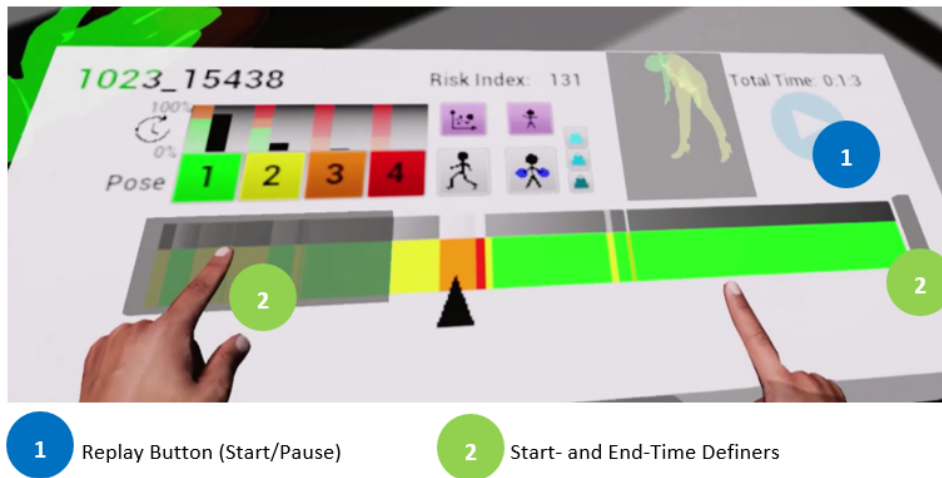


Figure 4.21: To investigate the evaluation session or parts of it in more detail, a replay function is offered. The user can define the start and end time of the replay in the timeline. The replay button starts and pauses the replay.

a certain time frame or even the whole ergonomic session, which enables the user to experience the whole evaluation session without any gaps and loss of information. Figure 4.21 shows this tool on the analysis panel. The user can define the end and start time of the replay, for example, to look more closely at problematic areas. The replay button starts and pauses the replay. The time indicator at the bottom of the timeline moves accordingly to the replay. This enables the user to keep track of the current status of the replay.

The quality and smoothness of the replay will be determined by the evaluations per second (eps) that the user specified for the ergonomic evaluation. As described in section 4.3.1 the default value is set to 30 eps. The replay will check the timestamp and replay the evaluation session in the right speed.

The next section is going to describe how the replay is visualized.

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Figure 4.22: The replay visualization uses the same avatar as the pose visualization. In contrast to the static pose avatar, the avatar for the replay is dynamic and can represent motion sequences. In this example, the user started the replay to look closer at a problematic area. The avatar on the right is in the beginning of this sequence and about to pick something from the floor.

4.4.7 Dynamic Replay Avatar

To visualize the replay, a similar version of the static avatar is used (section 4.4.3). The dynamic replay avatar is animated and can visualize movement sequences. This is in fact the only difference between these two avatars. The dynamic replay avatar is created according to the same rules as the static avatar: the user's avatar is taken and scaled according to the saved scale value, the saved tracking point data and the known animation rules are applied to reconstruct the motion sequences precisely. Also the mesh is colored according to the same rules as the static avatar. This means the user can observe the individual results for each body part also during the replay. Figure 4.22 shows the dynamic replay avatar.

4.5 Technical Details

This section will give more information about the technical details, like the used soft- and hardware and system specifications.

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Figure 4.23: A user with the full setup: HTC Vive Pro, Manus Gloves and five Vive trackers, placed on the pelvis, each wrist and each ankle.

4.5.1 Soft- and Hardware Resources

The application was implemented with the game engine Unreal Engine from Epic Games (*Unreal Engine* 2021). The engine uses the programming language C++ and a visual scripting system called Blueprints. As a VR system, the HTC Vive Pro (*HTC Vive* 2020) is used. The full-body tracking and avatar animation is enabled by five Vive trackers and intuitive user interactions are provided by using Manus Gloves (*Manus Gloves* 2021).

The trackers are placed on the pelvis, each wrist and each ankle. Figure 4.23 shows a user with the full setup.

4.5.2 Timing of Algorithms and System Specification

The most demanding process of the application is the loading and processing of an evaluation session for the analysis. The performance here depends on the length and eps of the evaluation, these factors determine the number of entries in the evaluation file. Furthermore, it also depends on the number of poses that need to be created, and this can vary from session to session regardless of the length of the evaluation. The algorithm has a linear runtime that depends on the entries in the evaluation file and the number of

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poses. The eps of the evaluation can be adjusted before a session is started, and it allows the user to affect the performance of the application and the accuracy of the evaluation if necessary.

The application was developed and tested on a computer with an AMD FX-8350 processor, 16GB RAM and an NVIDIA GeForce GTX 1080 Ti graphics card. Evaluation sessions of a length between 1 minute and 3 minutes were recorded and analysed and they did not affect the fps and visualisation stability.

5 Application Evaluation

To test the implementation, a sample scene was created that would allow to perform a variety of scenarios. One example scenario is the box-scenario. This scenario will be explained in the following. The sample scene was created with assets from *SilverTm* (2021).

5.1 Scenario Description

The box-scenario was inspired by an Ikea shopping experience. It includes boxes of different weight, that have to be moved and carried. Figure 5.1 shows the scene and the stations of the box-scenario.

Different workflows can be performed in this scenario. The workflow presented in this example is as follows: The user walks to a shelf and selects two boxes, one at the lowest level and one at the top level. Then, the user picks up these boxes and puts them on a board right next to the shelf. This board represents a shopping cart. Then, the user sends the board towards a table by pushing one of the red buttons on the board. The table represents a checkout. The user follows the board to the table. There, the user picks up the boxes from the board and puts them on the table. Then the scenario is finished.

This scenario includes boxes of different weight, that are not placed optimally. One box is placed on the lower level of the shelf, one box at the third level. It will be interesting how the ergonomic evaluation assesses this positioning and if the weight affects the results. Furthermore, it is to be clarified if the analysis and its visualization are able to convey all necessary information to the user.

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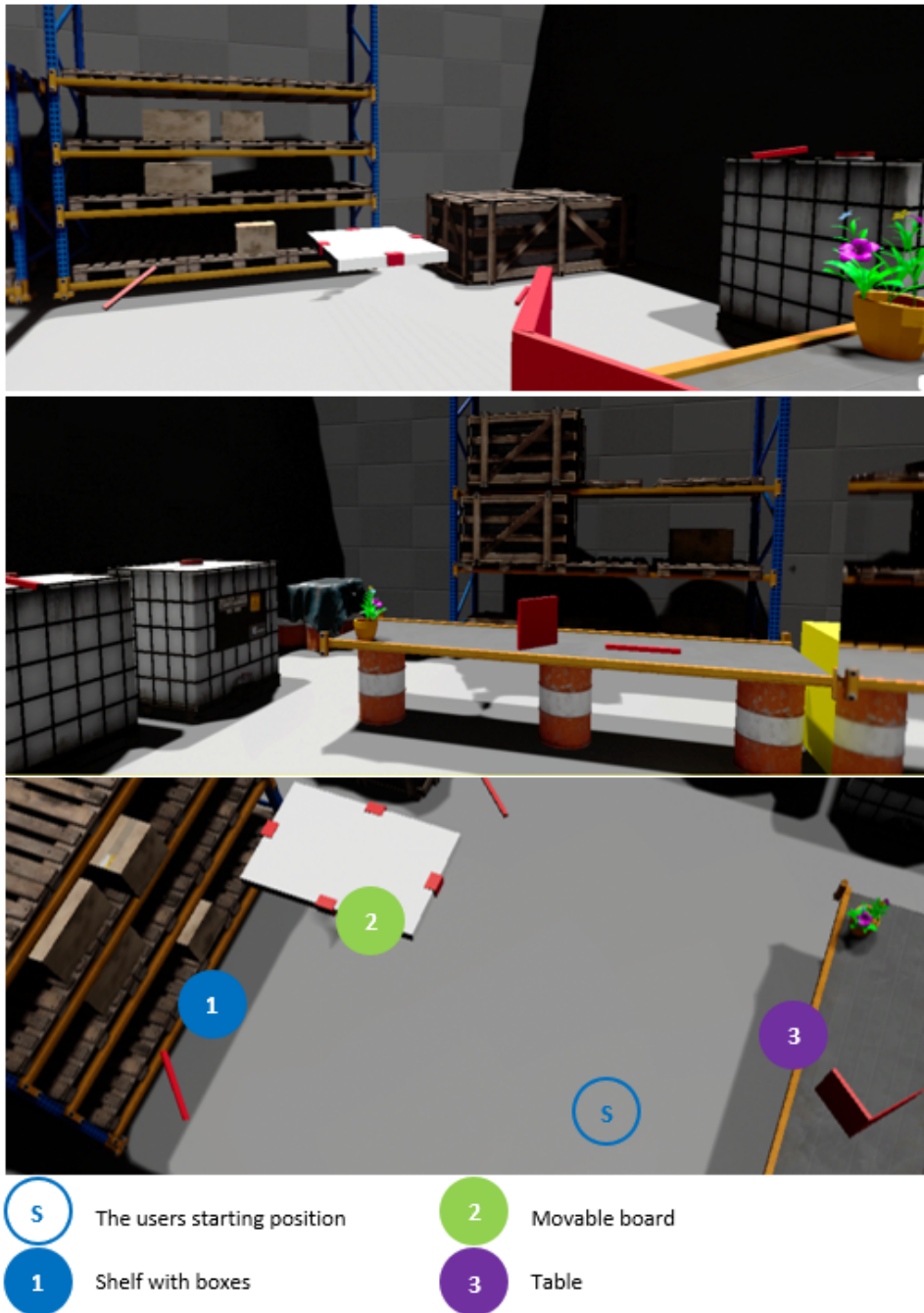


Figure 5.1: The box-scenario includes a shelf filled with boxes, a movable board and a table. The workflow is as follows: The user walks to the shelf, picks two boxes and puts them on the board. The user sends the board to the table. The user follows the board and puts the boxes from the board onto the table.

5.2 Scenario Simulation and Data Collection

To obtain meaningful data for an example analysis process, some test evaluations were performed. Two test users were chosen to go through the ergonomic evaluation. They got an introduction into the system and the test scenario. Also, support for the hardware setup was provided. For both test subjects, it was the first time they used a VR technology. Therefore, some more time was taken into account to let them get used to the system. As soon as the users felt ready, they started the ergonomic evaluation and performed the box-scenario as it was described before.

Both test users were close contacts of the thesis author and all Corona safety measures were strictly followed.

5.3 Example Analysis Process

This section is going to describe an example analysis process that a user might have. It shows how the analysis tools can be used and how their results can be interpreted to make good design decisions. In this case, an ergonomic evaluation was analysed that was not performed by the analyst. One of the evaluation sessions from the two test users was used for the following analysis process.

After the evaluation session of the box-scenario is loaded, the analysis panel appears in front of the user. This panel is shown in Figure 5.2.

The evaluation session is named 'Boxes2'. Evaluation sessions are named automatically, but they can be renamed later, outside the VE, by changing the file name. The displayed time shows that the loaded evaluation session lasted exactly one minute.

5.3.1 Identify Risky Areas

Besides basic information about the loaded ergonomic evaluation, the analysis panel also displays information that aids in gaining an overview. The

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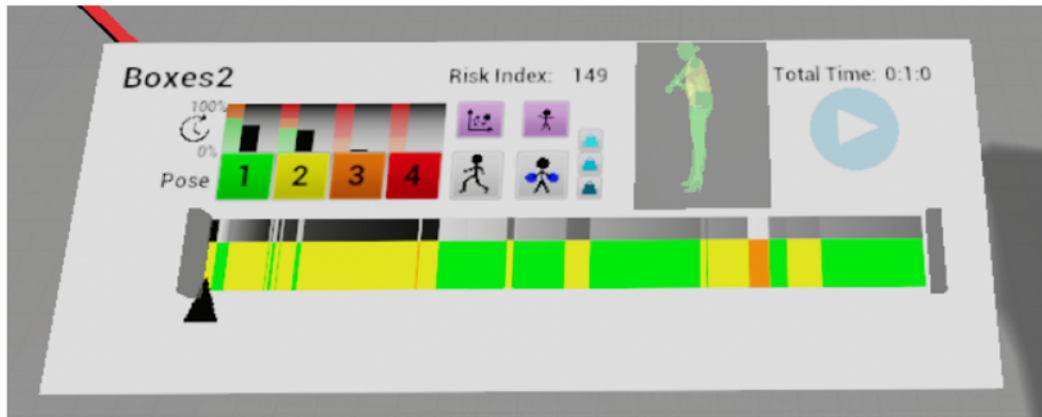


Figure 5.2: The user loaded an evaluation session of the box-scenario. This analysis panel appears in front of the user.

risk index shows a value of 149 (out of 400). This is in general a good result. A result close to 100 indicates that high-risk poses did not take over a lot of time.

The timeline conveys that the session mainly consisted of OWAS class 1 and class 2 pose sequences. This aligns with the risk index. There are also class 3 pose sequences visible, but only two in total. Class 4 poses are not visible in the timeline.

The time related risk evaluation also does not show that a class 4 pose occurred. Nevertheless, it might be that a class 4 pose was performed, but just for too little time to be visible. According to the time related risk evaluation, the poses of class 1 and 2 would not need further investigation as they stay in a percentage range that still state a low risk. The class 3 pose indicates a medium risk. This pose class occurred for little time, but the class is in general a higher risk class.

Due to the obtained overview and the result that is presented on the analysis panel, occurrences of pose class 3 need to be investigated more closely. It seems that pose class 4 never occurred. Nevertheless, it is suggested to make sure if this pose class was really never detected. It might be that a pose class 4 occurred for a very short time, e.g. as a transitional pose.

The next sections show how more information about the pose class occurrences can be retrieved.

5.3.2 Investigate Pose Class 4 Occurrences

The timeline and the time related risk evaluation did not show the occurrence of a class 4 pose. Nevertheless, it still might be that a pose of this class was performed, but did not consume enough time to be visible on the analysis panel. To definitely find out if a class 4 pose occurred, the pose 4 filter is activated.

Although the timeline does not show the occurrence of a class 4 pose, the filter shows that a high-risk pose was performed. Figure 5.3 shows a picture of the filter. It seems that the pose occurred while the user was bending down to pick up a box from the lowest level of the shelf. The static pose avatar shows that the main issue is the posture of the back: it is bend forward and to the side. The timeline on top of the static pose avatar shows that the pose occurred just right before a pose 3 sequence.

The pose class filter gives information about the composition of the pose. It is also known that the pose happened for a very short time. Still, it is necessary to gain more context about the movement sequence to make a more accurate assessment. To gain more insight about the whole movement sequence, a replay is started. The replay (Figure 5.4) of the problematic sequence shows that the user did not bend down right in front of the box. First, the user shifted the weight to the right leg. This movement was not enough to reach the box. Therefore, the test user also had to bend the torso more to the right to grab the box. This would still have been okay, but then the system detected for a split second that the loaded leg is bend. This was then the decisive factor that the pose was classified as a high-risk pose. A close look at the static pose avatar shows that the leg is not really bend much. Because of the little time the pose was detected and the indistinct bend of the leg, it can be decided to not attach much importance to the class 4 pose. Nevertheless, the analysis process so far showed that there is in general potential to improve this specific movement sequence. Further ergonomic evaluations can be performed to make a more meaningful decision.

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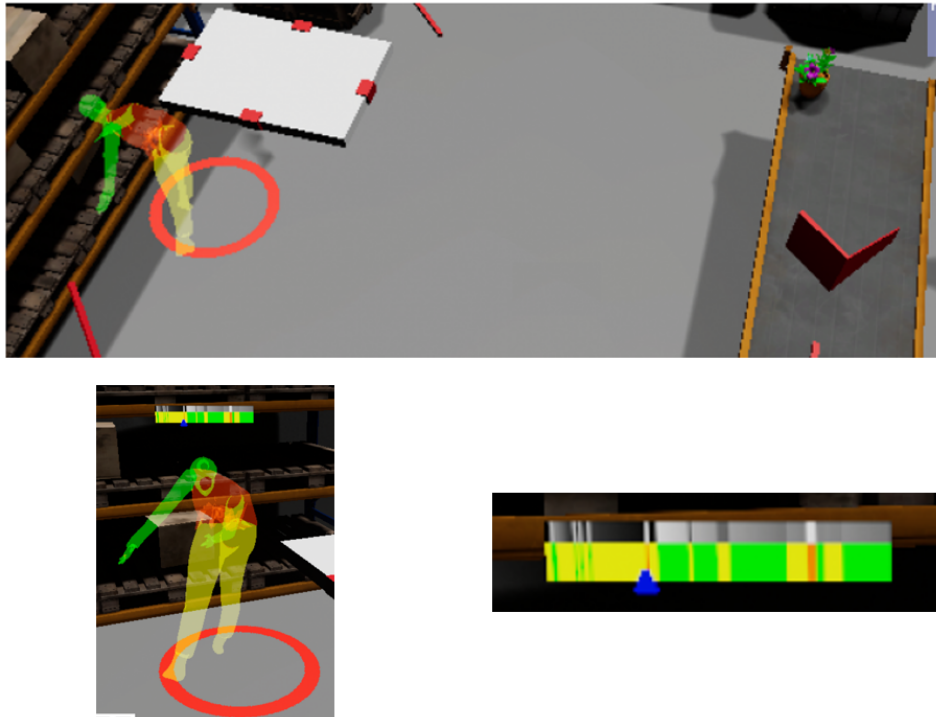


Figure 5.3: The user filtered for pose class 4. The system visualizes a pose next to the box shelf. The top picture gives an overview of the scene, while the lower left picture shows the pose from the users view. The picture on the right enlarges the timeline for a better visibility.

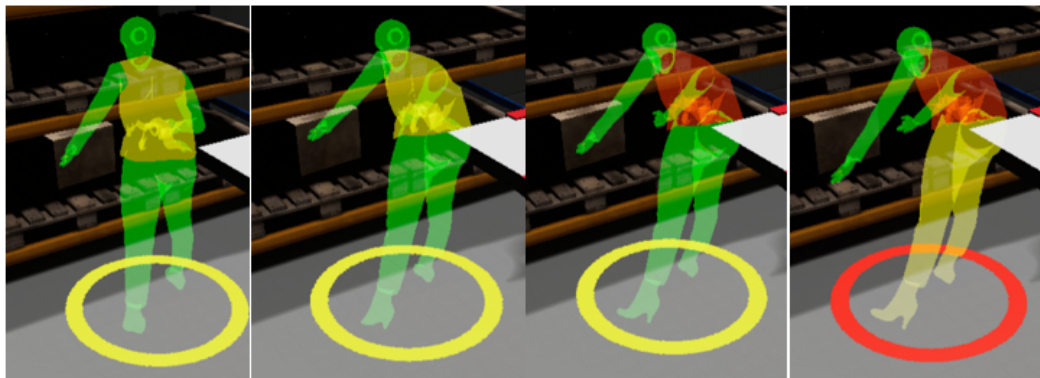


Figure 5.4: To gain more context information about the pose class 4 occurrence, a replay of the specific sequence is started. The figure shows some frames of the replay.

5.3.3 Investigate Pose Class 3 Occurrences

The analysis panel showed two occurrences of the third OWAS pose class. The filter is used and it shows two poses. They are visualized in Figure 5.5. The first occurrence of this pose class is situated at the shelf and shows a pose that is bend down to the lowest level of the shelf. It also shows that the user already picked up a box. The box has a weight that is classified between 10 and 20 kg (load grade 2). Due to the position and pose of the static avatar, it can already be assumed that the pose happened right after the already investigated pose 4 class. The timeline confirms this assumption. This time, the back is also bend forward and to the side. In combination with the heavy carried weight, the system classified the pose as OWAS class 3.

Another occurrence of pose class 3 is shown near the table. The static pose avatar shows that the back is bend forward and a very heavy load is carried (load grade 3). The pose probably happened while the user moved a box from the board onto the table.

To gain more insights about the movement sequences, the replay function is used again. The first occurrence of pose class 3 is investigated first. The replay shows that the system detected class 3 right after the user picked up the box. As soon as the user shifts the load from one straight leg to both legs the assessed pose class changes to class 2. Figure 5.6 visualizes the replay. Although it turned out that the previously investigated pose class 4 occurrence could be ignored, the posture class 3 occurrence now shows that the whole movement sequence is problematic and should be reconsidered. This pose class could easily be avoided. The box could be positioned somewhere else, e.g. at a higher level of the shelf. Another solution would be to train the user to bend over in the right way, to distribute the load on both legs and to avoid the stressful position for the back.

After investigating the first class 3 pose, the replay is used to learn more about the second occurrence of the pose 3 class. Figure 5.7 shows frames from the replay. The replay shows that the user starts to bend down to pick up the box. When the user picks up the heavy box, pose class 3 is detected. As soon as the back is straight, the pose class even changes to pose class 1. It is clear that the pose class is caused by the heavy weight and the position

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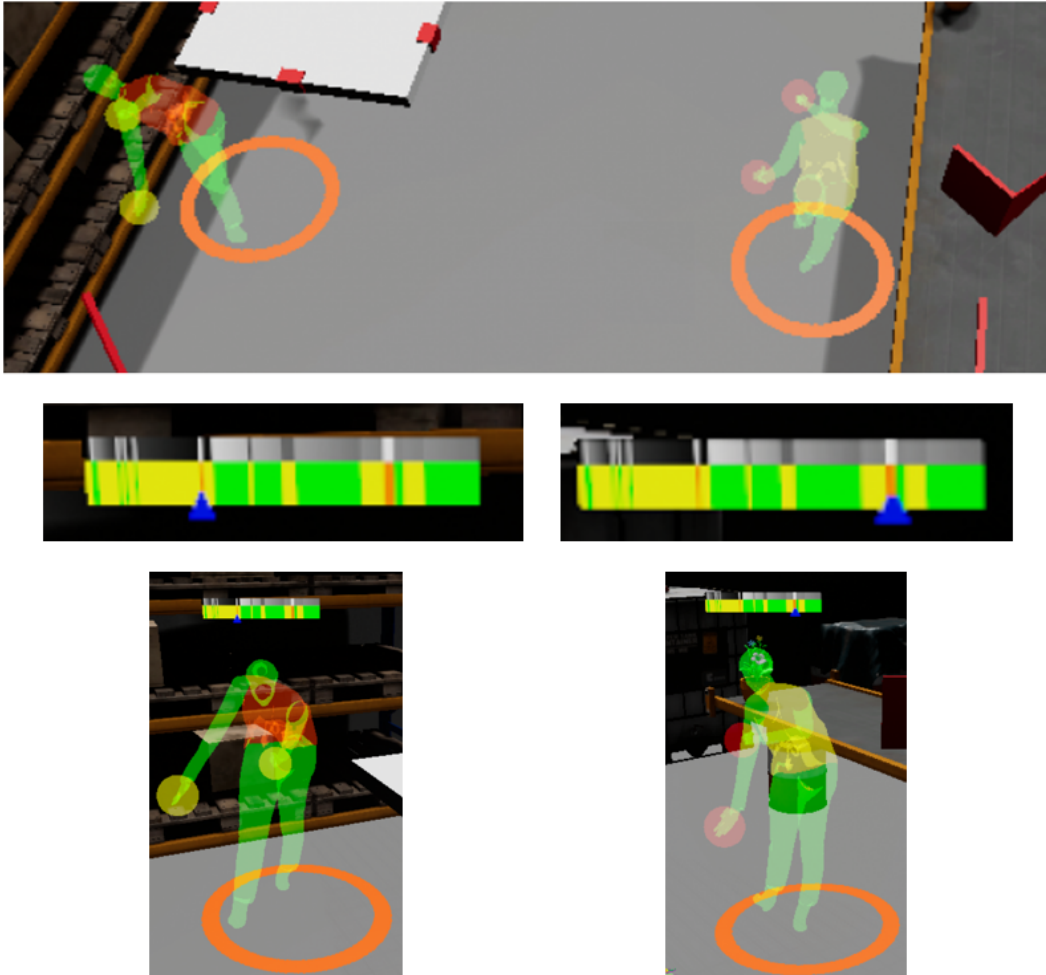


Figure 5.5: The user filtered for pose class 3. The system visualizes two poses at different locations. The top picture provides an overview of the scene. The bottom pictures show the poses from the users view. The pictures in the middle enlarge the timelines for a better visibility.

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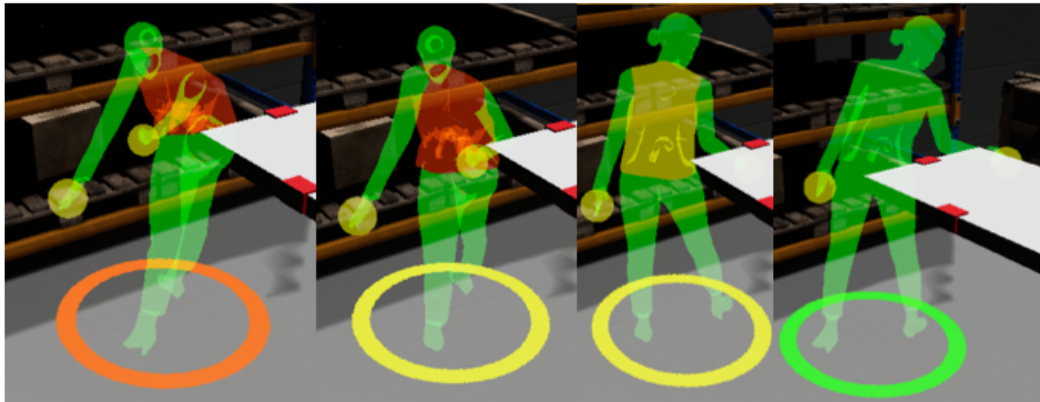


Figure 5.6: To gain more context information about the first pose class 3 occurrence, the replay tool is used. The figure shows some frames of the replay.

of the back. This posture probably cannot be avoided that easily. The box on the board is positioned at a lower level and the board's height cannot be adjusted as it should represent a shopping cart. In this case, the user should train to pick up heavy objects by bending the legs to keep a straight back.

5.3.4 Investigate Carried Load

The scenario includes a lot of carrying and lifting. Although the scenario lets assume where loads were carried (e.g. at the shelf), the user cannot make out clearly where loads were carried. Furthermore, the user has no chance to easily identify the weight class of the carried objects. The OWAS pose filters already provided information about two occurrences of heavy lifting and carrying, but a general overview is not provided. To gain an overview about the performed carrying and lifting, the user can use the 'carrying' filter with the heatmap visualization.

To find out more about where objects were carried in general, the main 'carrying' filter is used. It shows that objects were carried at the shelf and then next to the table. The weight differentiated filters show that the user moved objects of load class 2 and 3. Load class 1 never occurred. Figure 5.8 shows the visualization of the carried load filters. The heatmaps show that grade 3 loads consumed a little more time than the grade 2 loads. This

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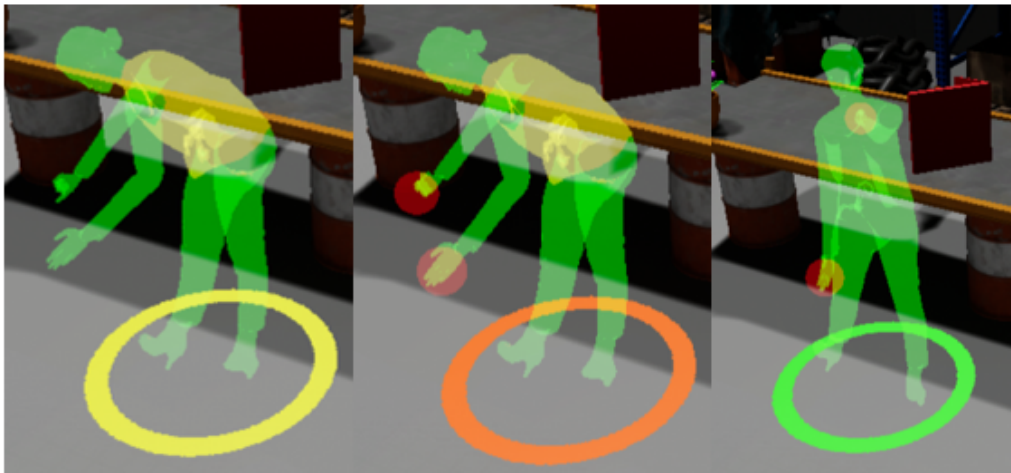


Figure 5.7: The replay tool is also used to investigate the second pose class 3 occurrence in more detail. The figure shows some frames of the replay.

might be related to the positioning of the boxes. For example, to pick up a box from a higher shelf might consume more time than to pick a box from a lower shelf.

The second investigation of the pose class 3 sequence showed that a very heavy load (load grade 3) caused a problematic assessment. A heavy box was moved onto the table. No problematic pose was pointed out on the shelf. To make sure that the heavy load really did not cause problematic poses, more investigations are performed. The 'carrying' filter pointed out where the heavy load was carried but is not known when exactly the load was carried. To find out in a fast and efficient way when the load was carried, the pose preview tool is used. The time indicator at the bottom of the timeline is moved and the visualized mini avatar is checked. A pose is found where the mini avatar carries a heavy weight. With the help of the replay tool, the movement sequence is then investigated in more detail. The replay indeed shows that the heavy weight did not cause a problematic pose. Only once, and only for a short time, the pose class changed to class 2. It seems that, as long as a straight back is maintained while carrying very heavy loads, the ergonomic assessment does not point out a higher risk. Figure 5.9 shows the use of the posture preview tool and visualizes the replay.

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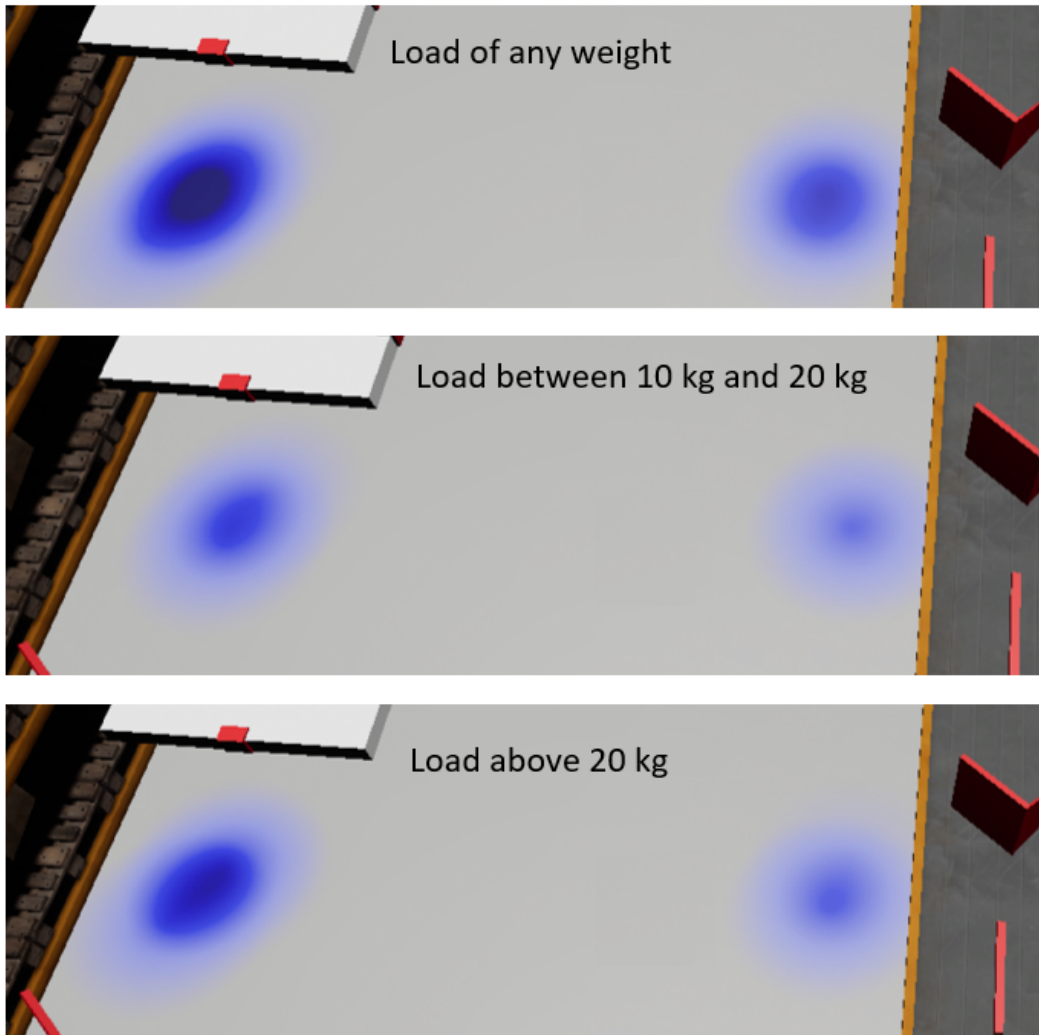


Figure 5.8: The 'carrying' filter is used to find out more about where objects were carried. The pictures of the visualized heatmap show the result for the general 'carrying' filter, but also for loads of grade 2 and 3. The filter for grade 1 loads did not show any results. To provide a better overview, the pictures were taken outside the VE, in the Unreal Editor.

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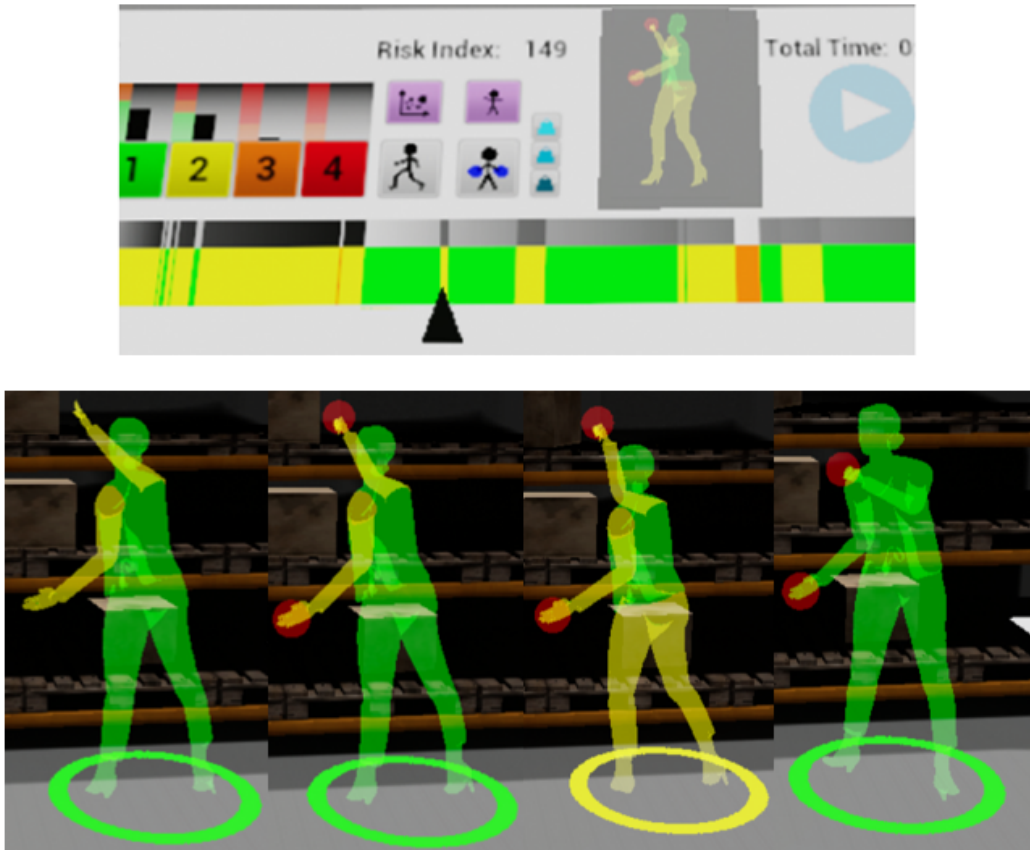


Figure 5.9: The pose preview tool, shown in the top picture, helped to detect when the load of grade 3 was carried. The replay of the sequence is visualized in the lower picture.

5.3.5 Further Investigations

The OWAS class 2 pose occurred often, especially in the beginning of the session. The time related risk evaluation stated a low risk for this pose class, but the classification was very close. Almost a medium risk level would have been detected. The beginning of the scenario does not require any demanding actions from the user. Therefore, it is interesting to find out what exactly caused the class 2 pose sequences.

The filter for class 2 poses is used and four pose avatars appear in the room. They are visualized in figure 5.10. Two of these poses are situated close to the shelf. They show the user picking up boxes. The poses near the table show the avatar with a slight bend back. The pose closer to the table probably happened while the user was picking up boxes from the board. The other pose might show the user in the beginning of the session looking at the watch menu. A view on the timeline confirms this assumption. The timeline above the right avatar also shows that this pose represents multiple pose sequences at the beginning of the session. Figure 5.11 shares a closer look at these poses. The assumption can be made that the bend back caused all these pose 2 sequences. Maybe the pelvis tracker was not positioned correctly and that caused the bend back. To be sure about this, the replay tool is used. Figure 5.12 shows the essential frames of the replay. The replay shows that the bend back indeed caused all pose 2 sequences at the beginning of the session. The possibility of an incorrect attachment of the pelvis tracker can be excluded. Instead, the user probably tested the ergonomic evaluation by raising the legs one after another. These movements caused a slight bend back. Also, the user maintained a bend back when performing the teleportation. The system considers the time that is needed to move from one place to another, and additionally it assumes that the bend back is maintained during this movement process. This and the following down bending to grab the first box caused the longest pose class 2 sequence.

The frequent occurrence of pose class 2 in the beginning of the session is not worrying and no further actions are required.

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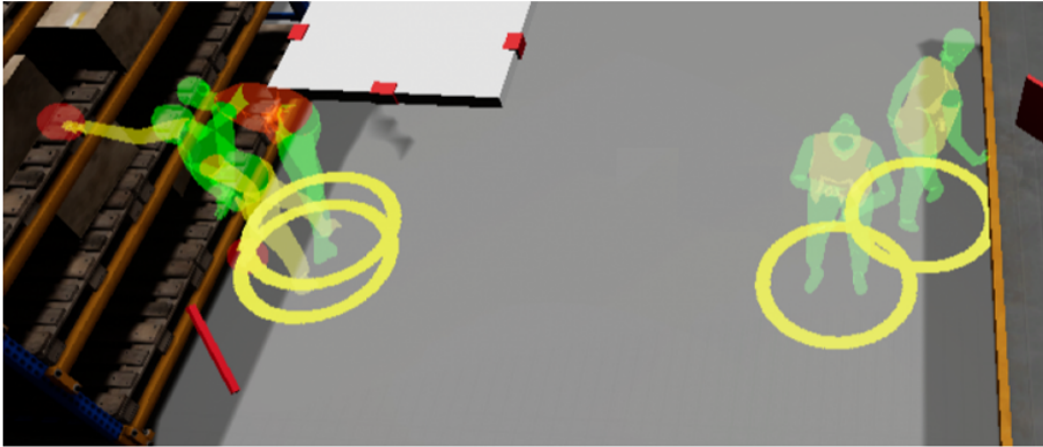


Figure 5.10: The filter for pose class 2 visualizes four pose avatars. The picture shows an overview of the scene, where these pose avatars are displayed.

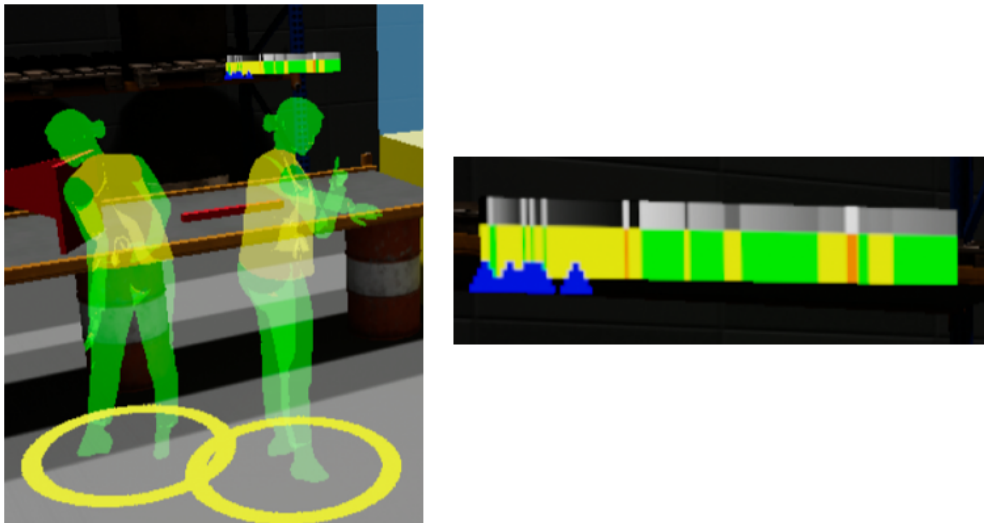


Figure 5.11: The pose class 2 filter visualized two poses near the table. The left pose shows the user while picking up a box from the board. The right pose shows the user in the beginning of the session. The timeline (enlarged in the right picture) shows that this pose represents multiple pose sequences in the beginning of the session.

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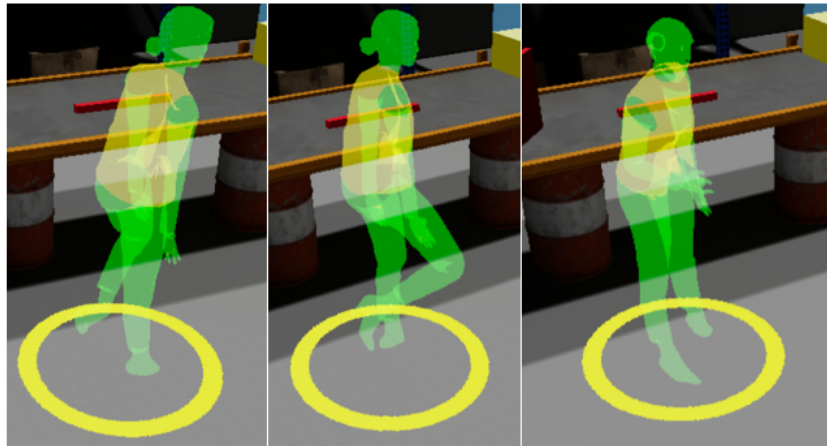


Figure 5.12: The replay shows that the bent back caused the pose class 2 occurrences. The user probably tested the ergonomic evaluation and performed unnecessary movements. The teleportation was also executed with a bent back.

5.3.6 Analysis Conclusion

After finishing the analysis process, adaptations to the virtual scene can be made. Some areas were found that caused problematic postures. After performing some adjustments on the virtual scene, a further ergonomic evaluation can be carried out to check if the changes were effective.

According to the analysis results, the following conclusions were made: The Box of load grade 2 on the lower level of the shelf caused the user to bend down in a problematic way. The box could be positioned on a higher level of the shelf to avoid this problem. The user could also be trained to bend down in the right way.

A further problem was pointed out when the user was lifting a box of load grade 3 from the board onto the table. The problem here was the position of the back. Here, too, a training can be beneficial to teach the user to pick up objects in the right way, e.g. by bending the legs and by keeping a straight back.

The box above 20 kg on the third level of the shelf did not cause an ergonomic problem. Nevertheless, the virtual simulation in that regard may not be realistic enough. Weight cannot be experienced in the VE, therefore

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the user's behaviour in the real world could be different. For example, the user would probably pick up a box of that weight with both hands. Therefore, it could be suggested to position the box on a lower level of the shelf.

The user can change the position of one or both boxes and start the ergonomic evaluation once more. This time the user can also try to bend down in another way or to grab the heavy box with both hands. Afterwards, the analysis process can be started once more to see how the changes affected the ergonomic assessment.

6 Discussion and Future Work

The analysis of the example scenario showed that the system is able to point out problematic postures in an uncomplicated and comprehensible way. The system can convey where, when and how often problematic postures occurred. Besides, it can provide a good overview of the evaluation session and show how its ergonomic quality evolves over time.

The analysis panel provides tools that enable the user to find out more about the problematic postures. The OWAS pose filters allow to investigate the postures in more detail and enable the user to gain information about the poses composition and answer the question why they were rated as problematic.

Furthermore, the provided tools allow to investigate the evaluation session more thoroughly. This enables the user to gain more information about problematic pose sequences. Additionally, the user is also able to check other pose sequences that do not indicate a high risk according to the ergonomic evaluation. This allows the user to not only experience the results of the objective assessment, but to also perform a subjective analysis. This enables the user to also form their own opinion about the evaluation session. This can be helpful, especially in the current state of the application, where only one evaluation method is used.

The integration of the analysis process into the same VE turned out to be convenient and time saving. An analysis can be started right after an ergonomic evaluation was carried out. No adjustments need to be performed. Also, after the analysis another ergonomic evaluation can be started to retry the same scenario or to evaluate another one. More time could be saved by also including the workplace modification process into the same VE. Currently, only the position of pick-up objects can be changed in the scene.

6 Discussion and Future Work

To perform bigger adjustments, e.g. to change the height of a shelf, a scene modification mode could be added.

The application evaluation showed a satisfactory result. Nevertheless, potential for further improvements were detected. These improvement possibilities will be discussed in the following and concern the interaction system, the ergonomic evaluation, the used hardware and the analysis process.

In the current state of the application, it is possible to pick up objects with one hand, no matter how heavy they are. Weight cannot be experienced easily in VEs and therefore nothing forces the user to use both hands to lift heavy objects. This case could be experienced in the example scenario, where a more than 20 kg heavy box was picked up with one hand. Future improvements of the system should include constraints for pick up objects. These constraints could state whether the object can be picked up by one hand or if both hands are required. This would make the ergonomic assessment more realistic. If two handed pick ups are enabled, also another locomotion system is needed. If both hands are unavailable, the gun gesture cannot be used to perform the teleportation. A possible solution would be to implement walking in place as an additional locomotion possibility.

The carrying and lifting interaction can also be improved in other ways. Currently, the user can use the grab gesture to pick up objects. Future improvements could include a more physical realistic behaviour of the pick up objects without the need of gestures. In general, the interaction possibilities with the scene could also be extended, e.g. by including possibilities to push or pull objects.

Currently, the application only uses the OWAS method to evaluate ergonomics. OWAS is a quite rough evaluation method and it is suggested to combine it with other methods. The analysis of the example scenario showed that OWAS has a weakness regarding carried loads. The system did not detect a problem when the user was picking up a more than 20 kg heavy box from a top level of the shelf. Furthermore, the classification scheme for the weight does not distinguish if the user is a man or a woman. A combination with a biomechanics-based method, that also considers gender differences, could show more precise results. In general, future improvements could include more evaluation methods. The user could then choose

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the methods according to the characteristics of the scenario. This would make the application more versatile.

The used hardware has proven itself. The trackers enabled a sufficient full-body motion tracking and the finger tracking of the gloves was satisfactory. Nevertheless, potential for improvement was detected. The full-body tracking was sufficient, but it could be more precise. Currently, the position of the elbows and the shoulders cannot be clearly determined. Therefore, the OWAS method had to be adapted, as the torsos twist could not be detected. It has to be considered though, that more tracking points would lead to a more laborious usage. Furthermore, the position of the trackers should be checked precisely. The trackers have to be attached to the body manually. If one tracker is placed wrongly, especially the pelvis tracker, the body tracking is inaccurate. The finger tracking of the gloves was sufficient, but showed weaknesses when used with smaller hands. At least one bigger and one smaller glove size should be offered. Furthermore, the wire of the headset was sometimes distracting and caused a break-in-presence (the feeling of presence was destroyed (Jerald, 2016)). A headset without wire could solve this problem.

The analysis process showed a good performance, but also here potential for improvement was detected. The static pose representation is intuitive and comprehensible. It also displays further information regarding the OWAS classification. To represent the grade for each body part, the same colors were used as for the OWAS classes. This was done to avoid confusion, but it does not allow a precise assessment. Especially for the legs, were 4 colors are used to represent 7 possibilities. Although the right grade can be guesses by looking at the pose avatar, a more precise color grading can be beneficial. To make the assessment even more clear, the analysis panel could provide a tool that allows the user to look up the OWAS assessment rules during the analysis process. Furthermore, instead of visualizing spheres to symbolize a carried object, a precise imitation of the carried object could be visualized. This would give the user more information and context about the loaded evaluation session.

The analysis of the example scenario also showed a weakness of the pose clustering. The pose preview tool was used to detect where the heavy box was picked up at the shelf. The pose could be detected, but the replay

6 Discussion and Future Work

showed that the pose classification changed only for a short time, when the user was slightly bending the legs. If the user would not have done that, the whole sequence would have consisted of class 1 postures. In that case, the pose might not have been detected so easily. To avoid this, a solution is needed that distinguishes more aspects of the pose than just the OWAS class.

The heatmap helped to identify where objects were carried and to compare the time consumption. The heatmap does provide a precise spatial information. The information regarding the time is not precise and it does not convey information when or exactly how often the carrying exactly happened. This can be beneficial though, e.g. to check the sequence with the replay tool. Sequences where objects were lifted could for example, be marked in the timeline. The 'carrying' and 'walking' filter could include more accurate information, like concrete numbers (e.g. distance traveled, number of objects that were picked up, ...).

As mentioned before, future improvements could include more evaluation methods. This would also require adaptations for the analysis process. The analysis process could then also include the possibility to compare the results of different evaluation methods. Also, a possibility to compare different evaluation sessions could be implemented.

Besides including more ergonomic evaluation methods, the application could also make use of more sensors. For example, the user's eyes could be tracked and the heart rate could be measured to identify when the user experiences stress. Furthermore, the noise of the workplace could be simulated. Ergonomics is a very broad term and also includes other aspects than just the physical load. Nevertheless, in the end it is sufficient that the virtual workplace prototype offers just enough details and information to make a good design decision. This is also stated by Aromaa and Väänänen (2016).

Finally, a more thorough evaluation and testing of the approach is needed to further improve the application.

7 Conclusion

This work has shown how the potential of immersive technologies can be exploited for the analysis of ergonomic evaluations. Although some areas for improvement were detected, the overall performance of the implemented application was satisfactory. The analysis system provides a good overview of the evaluation session and answers questions about the location and duration of problematic posture sequences. Furthermore, tools are offered to investigate the evaluation session in more detail and give the user more information about the ergonomic assessment. The example evaluation showed that the system provided enough information to enable the user to make good design decisions.

The OWAS method was used to evaluate ergonomics, but the application could be extended for other methods. The application offers a tight data integration that enables an ergonomic assessment in real-time and a targeted analysis in the VE. Furthermore, the analysis process can be started right after the ergonomic assessment in the same VE. This can accelerate the whole evaluation and analysis process.

The use of VR enables the user to perform a subjective evaluation of the virtual workplace. Furthermore, this application also allows the user to form their own opinion about the analysis. Even if the system does not detect a problem, the user can identify areas and movement sequences that could be improved. Especially, the replay tool has proven itself to be a very effective tool to evaluate and reflect on certain movement sequences. This is especially beneficial in the current state of the application, where only one ergonomic evaluation method is offered.

Overall, this work showed that the immersive evaluation of ergonomics is useful and offers advantages over traditional, non-immersive, evaluation processes. Especially the integration of ergonomic evaluation and analysis in

7 Conclusion

the same VE has proven to be beneficial. This work showed how ergonomic data can be presented in a meaningful way and how the potential of the immersive environment can be exploited for an improved information understanding. Further work and research can help to improve the process even more.

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