

Does virtual reality contribute to the prevention of musculoskeletal disorders at work: a systematic review

Julie Robillard

`julie.robillard@univ-rennes2.fr`

Université Rennes 2

Estelle Chin

Safran Landing system

Nicolas Vignais

Université Rennes 2

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Abstract

Virtual environments are currently used by industrial companies to optimize the design process of future workstations. These immersive experiences also permit to quantify the risk of musculoskeletal disorders that operators may encounter on their future workstation. This systematic review aims to evaluate how virtual reality technologies are used to support proactive ergonomic assessment in order to prevent musculoskeletal disorders. Technical features, ergonomic assessment parameters, and usability testing employed into virtual environments have been examined through the literature ($n = 23$). Outcomes showed that most of the studies did not validate the virtual environment when designing a workstation. However, eight studies assessed virtual reality usability through subjective questionnaires (workload, cybersickness...) and six studies compared behavioral data to real-world data, as well as digital human modelling data. Results of this review confirm the growing interest of virtual environments as a tool for proactive ergonomics, but they also highlight the methodological heterogeneity and the limited statistical support in this field. Future research should adopt standardized protocols and robust validation method to better quantify effectiveness of virtual environments when aiming to reduce the risk of musculoskeletal disorders in industry.

1. Introduction

Ergonomics is an essential component of industrial design processes, with a growing emphasis on placing the user at the center of a system development, as defined by Industry 5.0 principles (Office of the European Union 2021). This human-center design approach aims to improve health, safety, and performance by adapting work environments to human capabilities and limitations (Gregori et al. 2017). This approach has been employed in various professional domains such as engineering, robotics, and computer sciences (de Winter and Eisma 2024). Indeed applying an ergonomic procedure in early stages of the design process should permit to reduce the impact of musculoskeletal disorders (MSDs), which are considered as the most common recognized occupational diseases in the European Union (European Agency of Safety and Health at Work 2019). Musculoskeletal disorders (MSDs) may be defined as soft tissue injuries (muscles, tendons, nerves) that do not result from a sudden or instantaneous event, with a multifactorial origin (Hales and Bernard 1996). Although psychosocial, environmental and individual factors may contribute to the onset of MSDs, biomechanical constraints have been identified as a critical factor in their appearance (European Risk Observatory 2022). MSDs prevention strategies are thus based on the inclusion of human capabilities in early development stages of a workstation design.

According to Chen and Wu (2023), virtual reality (VR) is considered as one of the major technological trends driving the digitalization of various domains of human activity. VR technologies are currently developed by industrial companies to anticipate the risk of MSDs that operator may encounter on their future workstation, and its use has increased over the past decade (Da Silva et al. 2022). VR appears to be a proficient tool, employed for specific milestones in companies: it provides significant added-value for collaborative decision-making, and innovation development (Berg and Vance 2017). For example,

several studies have shown that the use of VR reduced the number of physical prototypes, as well as the cost and time involved in the design process (Peruzzini et al. 2016; Azizi et al. 2019). From a technical point of view, various VR applications already integrate human motion capture systems to enhance experience into the virtual world (Delangle et al. 2017). However, technological constraints (e.g. latency, resolution) as well as aspects related to the standardized design of VR headsets (head circumference adjustment, headset weight, etc.) may induce cybersickness in users (Chen and Wu 2023). These side effects also depend on the task and the type of interaction within the virtual environment (Souchet et al. 2023). These technical constraints reveal a paradoxical issue: while VR is increasingly used for ergonomics purposes, virtual environments are not fully user-center designed. Thus, using VR to prevent MSDs not only depends on technological performance, but also on how users cognitively and perceptually engage within the virtual environment. The sense of presence, defined as the subjective feeling of 'being there' in a virtual environment, is considered a central determinant of the validity of VR experiences, as it implies reacting physically, physiologically, and emotionally as if the virtual scene presented was real (Sanchez-Vive & Slater, 2005; Slater & Wilbur, 1997; Jerald, 2015). Previous works have shown that the sense of presence is positively correlated to task performance, but the occurrence of cybersickness may lead to a decrease in presence (Weech et al. 2019). Indeed, when human attention is no longer focusing on the virtual environment, the sense of presence is consequently reduced. Moreover, users have to perceive the virtual environment as useful and easy to use in order to be fully engaged in their VR experience. This concept, based on the technology Acceptance Model (Davis, 1989), is called acceptance. The perceived consistency of the virtual environment is a key determinant of user acceptance, as engagement is facilitated when the experience is interpreted as coherent and meaningful. This engagement is essential for the emergence of presence, as it corresponds to the allocation of attentional and cognitive resources to the virtual environment (Witmer and Singer 1998; Sagnier et al. 2019).

Therefore, it is essential to test and validate any immersive environment before using it for training in an industrial context. First of all, the performance measured into the virtual environment should accurately represent the real task performance, this refers to 'construct validity' (Harris et al. 2020). Indeed, it is important to verify whether the simulation truly measures the psychological or behavioral phenomenon it claims to measure. In relation to MSDs prevention, a virtual environment employed into a design process should allow the ergonomist to characterize human movement, i.e. assessing biomechanical parameters during the immersive experience.

This review focuses on the technical framework of virtual environments (hardware, software, motion capture systems), the ergonomic assessment methods provided by current virtual environments (RULA, REBA, etc.), and procedures for validating VR scenarios (comparison with real environments, user feedback). The aim of this systematic review is to identify common practices, methodological limitations, and future research prospects in the field of virtual reality-based ergonomic approaches.

2. Methods

We use the PRISMA guidelines and PICOS strategy (Page et al. 2021). The methodology for this systematic review is registered on PROSPERO (CRD420251065920).

2.1 Eligibility criteria for considering studies for this review

Studies were included if they:

1. employed VR to analyze postures at a workstation.
2. involved healthy participants aged 18 to 65, with no specific musculoskeletal or neurological conditions.
3. were published in English and French, dating from January 2000 to February 2025.

Studies were excluded if they:

1. involved participants with severe MSDs or individuals outside the specified age range.
2. used technological tools other than VR
3. were not intended to reduce MSDs.
4. were published before 2000.
5. were written in a language other than English and French.

2.2 Search method for identifying studies

We searched Google Scholar, Pubmed, Taylor&Francis and IEEEExplore with keywords. The articles were retrieved using keyword search, for articles matching the query:

("virtual reality" OR "VR") AND ("ergonomics" OR "ergonomic" OR "industrial task" OR "workplace" OR "workstation" OR "industry" OR "musculoskeletal disorders" OR "MSDs").

2.3 Study selection and data collection

Study selection was conducted in two stages: initial screening based on title and abstract, and full-text assessment of potentially eligible articles. The initial screening was performed using Rayyan (Ouzzani et al. 2016). Rayyan is an online tool designed to support systematic reviews by facilitating collaborative and blinded selection of studies. Two reviewers independently screened all records. Data extraction was done in the form of a table to record the authors, year of publication, journal of publication, type of study, hardware, software, whether there was validation of the VR tool (yes/no and how), outcome, description of results, number and profiles of participants and the studied task. The final search was performed on February 07, 2025, for all the databases. Figure 1 represents the flow chart selection of publications for inclusion in this systematic review.

2.4 Risk of bias assessment

The quality of studies was independently evaluated by two reviewers using JBI Critical Appraisal Checklist for Case Reports (2017). The checklist questions were adapted to correspond to the field of ergonomics using virtual environments, and to the methodological characteristics established in this review.

3. Results

3.1 Study characteristics

We identified 527 titles and abstracts through literature search and retrieved 36 articles for full text review. We included 23 studies in this systematic review according to priori criteria. Selected studies were published between 2016 and 2025. All articles were published in the following three scientific fields: Engineering and Manufacturing for the majority (65,2%; $n = 15$) (Peruzzini et al. 2016, 2021; Vosniakos et al. 2017; Michalos et al. 2018; Havard et al. 2019; Ottogalli et al. 2021; Kačerová et al. 2022; Guo et al. 2022; Dias Barkokebas et al. 2022; Buonocore et al. 2023; Garces et al. 2023; Krákora et al. 2023; Lanzoni et al. 2023; Swierski et al. 2023; Ji et al. 2024), followed by Human Factor and Ergonomics (17,4% ; $n = 4$)(Guo et al. 2018; Bernard et al. 2019; Tsuichihara et al. 2022; Sardar et al. 2024) and Computer Science (17,4%%; $n = 4$)(Nguyen et al. 2017; Bruno et al. 2020; Zhong et al. 2022; Fu et al. 2025). The average number of participants for these studies was $8,36 \pm 7,16$.

Regarding the methodological quality of the included studies, most of them provided clear descriptions of the procedures, baseline conditions, and VR interventions, with clear reported results. However, the description of participants' characteristics was largely incomplete, and the validity of the measurement methods was not consistently addressed. These elements suggest that the included studies present a moderate level of methodological quality, with some recurring limitations related to participant reporting and measurement quality.

3.2 Technological framework

3.2.1 Hardware tools

In total, 23 studies, 73,9% ($n = 17$) used virtual reality headset (HTC VIVE, Oculus Rift...)(Vosniakos et al. 2017; Havard et al. 2019; Bruno et al. 2020; Peruzzini et al. 2021; Ottogalli et al. 2021; Kačerová et al. 2022; Tsuichihara et al. 2022; Zhong et al. 2022; Dias Barkokebas et al. 2022; Buonocore et al. 2023; Garces et al. 2023; Krákora et al. 2023; Lanzoni et al. 2023; Swierski et al. 2023; Sardar et al. 2024; Ji et al. 2024; Fu et al. 2025), whereas 26,1% ($n = 6$) studies employed projection-based CAVE systems (Peruzzini et al. 2016; Vosniakos et al. 2017; Nguyen et al. 2017; Michalos et al. 2018; Bernard et al. 2019; Guo et al. 2022). Motion capture was present in 73,9% of the studies included. 34,8% ($n = 7$) studies made use of inertial measurement units (IMUs)(Havard et al. 2019; Peruzzini et al. 2021; Ottogalli et al. 2021; Kačerová et al. 2022; Dias Barkokebas et al. 2022; Swierski et al. 2023; Ji et al. 2024), 30,4% ($n = 7$) employed optical motion capture systems (Peruzzini et al. 2016, 2021; Michalos et al. 2018; Guo et al. 2018, 2022; Bruno et al. 2020; Garces et al. 2023), 13% ($n = 3$) relied on video-based

gesture recognition disposals (Vosniakos et al. 2017; Krákora et al. 2023; Lanzoni et al. 2023) and 21,7% (n = 5) studies did not use motion capture systems (Tsuichihara et al. 2022; Zhong et al. 2022; Dias Barkokebas et al. 2022; Buonocore et al. 2023; Sardar et al. 2024).

3.2.2 Software tools

Concerning software, more than half of studies (60,9%, n = 14) used Unity 3D (Unity Technology, San Francisco, CA, USA)(Bruno et al. 2020; Fu et al. 2025; Havard et al. 2019; Ji et al. 2024; Kačerová et al. 2022; Lanzoni et al. 2023; Michalos et al. 2018; Ottogalli et al. 2021; Peruzzini et al. 2021; Swierski et al. 2023; Tsuichihara et al. 2022; Vosniakos et al. 2017; Krákora et al. 2023; Zhong et al. 2022), followed by 26,1% of studies (n = 6) which used 3DEXPERIENCE (Dassault Systems, Vélizy-Villacoublay, France) (Peruzzini et al. 2016; Vosniakos et al. 2017; Guo et al. 2018, 2022; Havard et al. 2019; Buonocore et al. 2023), and then Unreal Engine (Epic Games, Cary, NC, USA) for 8,7% (n = 2)(Dias Barkokebas et al. 2022; Garces et al. 2023). Other studies used software like IC.IDO (Keysight Technologies, Santa Rosa, CA, USA)(Peruzzini et al. 2017; Buonocore et al. 2023), or they did not specify (Nguyen et al. 2017).

3.3 VR in design process

Based on Tosi's model (2020), inspired by the ISO 9241 – 210 standard, humans needs to be placed at the center of the design process. In this context, the use of VR serves as an additional tool to simulate the future human work and then identify constraints related to ergonomic requirements under future real-world conditions. Because of the immersive nature of VR, users can validate the modifications made to the virtual workspace at a 1:1 scale, allowing early detection of risks or malfunctions in the iterative design process (Guo et al. 2018, 2022; Havard et al. 2019; Kačerová et al. 2022; Manghisi et al. 2022; Buonocore et al. 2023; Fu et al. 2025). As highlighted by Nguyen et al., (2017), the design process is inherently collaborative, involving operators, designers, and ergonomists in working together to address both industrial issues (productivity, cost, available time, etc.) and human–system interaction challenges. This VR-based approach has several potential benefits, such as reducing the risk of MSDs, limiting the need for physical prototypes (Ottogalli et al. 2021; Dias Ferreira Barkokébas 2022), and decreasing costs and time (Peruzzini et al. 2016) throughout the iterative design process (see Fig. 2).

Nevertheless, to be truly beneficial in simulating a work situation, VR digital environment must reproduce the real situation (Bernard et al. 2019; Ji et al. 2024). It should be noted, however, that the value of a virtual environment is not judged by the visual realism, but by the ability to reproduce behaviors comparable to those observed in the real task (Harris et al. 2020). The concept of fidelity is also an important factor in validating a virtual reality environment, insofar as certain forms of fidelity, particularly biomechanical, psychological, and emotional fidelity, determine the validity of the simulation and its potential for transferring to the real task (Harris et al. 2020). For example, in proactive workplace ergonomics, the validity of a virtual environment would be reflected by its ability to reproduce real biomechanical constraints that would be found in a real environment (Personieni & Savescu, 2023).

3.3.1 Virtual reality validity

Majority of the included studies (n = 15) (Peruzzini et al. 2016; Vosniakos et al. 2017; Michalos et al. 2018; Guo et al. 2018; Havard et al. 2019; Bruno et al. 2020; Ottogalli et al. 2021; Tsuichihara et al. 2022; Zhong et al. 2022; Buonocore et al. 2023; Garces et al. 2023; Krákora et al. 2023; Lanzoni et al. 2023; Swierski et al. 2023; Sardar et al. 2024) did not assess the validity of the virtual environment, i.e. how accurately reproduced is the working situation. These previous studies primarily focused on identifying high-risk postures in order to influence future workstation design. Thus, ergonomic assessments computed within VR environments were not compared to real-world assessments, nor digital human models evaluation. Although several protocols involved small samples, number of participants varied substantially across studies. Table 1 shows the distribution of studies based on assessment of virtual reality.

3.3.2 Behavioral comparative studies

Six studies compared their outcomes obtained with a VR system to the results from an existing workstation (Bernard et al. 2019; Peruzzini et al. 2021; Dias Ferreira Barkokébas 2022; Kačerová et al. 2022; Guo et al. 2022; Ji et al. 2024), or a digital human model (DHM)(Peruzzini et al. 2021; Guo et al. 2022). Most studies reported differences in postural analysis between real and virtual environments. However, it should be noted that different calculation methods have been employed through research to assess the reliability of the real environment compared to the virtual environment. For example, when comparisons included a digital mannikin, the ergonomic analysis performed into the virtual environment aligned more closely with the analysis from the real environment than with that obtained using a DHM (Peruzzini et al. 2021; Guo et al. 2022). The study by Kacerova et.al (2022) focused on the time spent in risky postures in real vs virtual environments. Results showed that for certain joints (head and right arm especially), exposure time to these postures was longer in VR than in reality. In the article by Barkokebas et al (2022), a correlation test was performed between RULA and REBA scores in real vs VR conditions. The correlation reached 85% for RULA and 80% for REBA, with most joint angle values being overestimated. In the study from Ji and colleagues (2024)(Ji et al. 2024), the assessment of VR validity was based on shoulder, hip and knee joint angles, L4/L5 compressive forces, and anteroposterior shear force for specific postures. Regarding the kinematic reliability of users, the study did not show any significant difference between real and virtual environments, except for the left shoulder abduction. In Bernard et. al.(2019), a real vs. virtual comparison was performed using the total RULA score and the percentage of time spent in risky postures (EN 1005-4) for several helicopter maintenance subtasks. Results did not demonstrate any significant difference in RULA ratings between the two conditions. However, the time spent in risky postures was significantly higher in a virtual environment than in a real environment. Moreover, for the Nordic questionnaire, symptoms in the neck were higher in VR than in reality. For the back, the pain felt was greater in a real-world environment.

3.3.3 User experience

The questionnaires administered in studies were primarily designed to elicit user feedback concerning experience through the virtual reality system (Guo et al. 2018; Bernard et al. 2019; Dias Ferreira Barkokébas 2022; Fu et al. 2025). The items predominantly assessed the perceived realism of the virtual

environment, the extent of immersion experienced, the level of cognitive load, the perceived effort associated with task execution, and the perceived usefulness of the technology. From a technical perspective, results indicated that users demonstrated a realistic perception of their virtual environment (Guo et al. 2018; Fu et al. 2025) and considered their movements to be equivalent to those performed in the real environment (Dias Ferreira Barkokébas 2022; Fu et al. 2025). However, two studies reported results in mental workload: the study by Bernard et al.(2019) showed an increase in mental workload in VR, whereas Fu et. al (2025) did not observe any increase between the two conditions, real and virtual, as well as the perceived effort which did not change.

3.3.4 Other assessments

Other means of evaluating the VR tool were used, such as completion time and productivity (Bernard et al. 2019; Peruzzini et al. 2021; Guo et al. 2022). The results showed that the completion time was longer in VR compared to the real environment (Bernard et al. 2019). Conversely, the study from Peruzzini et al. (2021), and Guo et al. (2022) showed that the completion time was shorter compared to the method using a DHM. However, in the study from Guo et al. (2022), VR required higher designer's skills than DHM developments.

Table 1

Type of validity assessment across included studies. Summary of approaches used to assess VR validity: no explicit assessment, behavioral comparisons with real tasks, user experience evaluation, or performance indicators.

No explicit VR validity assessment (n = 15)	Behavioral comparative (n = 6)	User experience (n = 4)	Performance indicator (n = 3)
Bruno (2020), Buonocore (2023), Garces (2024), Havard (2019), Lanzoni (2022), Michalos (2018), Ottogali (2021), Peruzzini (2016), Sardar (2024), Swierski (2023), Tsuichinara (2022), Vosniako (2017), Krakora (2023), Zhong (2022), Guo (2018)	Dias Barkokebas (2022) - VR vs real – score RULA/REBA	Dias Barkokebas (2022) – realism, usability, user feedback	Peruzzini (2021) – VR vs DHM - realization time
	Ji (2024) – VR vs real - angles, L4/L5 forces	Bernard (2019) – NASA TLX, borg scale	Guo (2022) - VR vs DHM - realization time and necessary skills
	Kacerova (2022) – VR vs real - exposure time	Fu (2025) – NASA TLX, sense of trust	Bernard (2019) – VR vs real - realization time
	Guo (2022) – VR vs DHM vs expert ergonomist – RULA global score	Guo (2018) – realism, usability	
	Peruzzini (2021) – VR vs real vs DHM – OWAS/REBA global score		
	Bernard (2019) – VR vs real – exposure time to unacceptable posture, RULA score and Standard EN 1005-4:2008		

3.4 Ergonomic assessment approaches

As discussed in the previous section, existing studies indicate that virtual reality constitutes a potentially reliable tool for workstation design, with the aim of anticipating the risk of musculoskeletal disorders. However, particular attention must be paid to differences reported across studies, whether related to the ergonomic assessment methods employed or the tasks assigned to operators. The following section focuses on the uses of virtual reality: which tasks have been evaluated, and which ergonomic analyses have been used to assess workstations. Table 2 illustrates a summary of studies in that perspective, by classifying them according to the ergonomic assessment method, the type of task, and the obtained results.

3.4.1 Type of simulated tasks

The majority of the tasks represented through the reviewed studies involved assembling or disassembling industrial parts (60,9%; n = 14) (Vosniakos et al. 2017; Michalos et al. 2018; Guo et al. 2018, 2022; Bernard et al. 2019; Havard et al. 2019; Bruno et al. 2020; Peruzzini et al. 2021; Ottogalli et al. 2021; Dias Ferreira Barkokébas 2022; Kačerová et al. 2022; Garces et al. 2023; Krákora et al. 2023; Sardar et al. 2024). These studies focused mainly on automotive assembly (Bruno et al. 2020; Peruzzini et al. 2021; Kačerová et al. 2022; Krákora et al. 2023; Sardar et al. 2024), aeronautical assembly (Vosniakos et al. 2017; Bernard et al. 2019; Ottogalli et al. 2021), electrical assembly (Garces et al. 2023), and industrial mechanical assembly (Dias Ferreira Barkokébas 2022). Although these assembly tasks required mostly gross motor skills, five studies focused on finer motor skills, small industrial components (Michalos et al. 2018; Havard et al. 2019), or positioning a screw on an aircraft APU or satellite (Guo et al. 2018, 2022). Other tasks (39,1%; n = 9) were more specific to each industrial context like grinding task (Peruzzini et al. 2016), pull and push trolleys (Swierski et al. 2023), object displacement (Nguyen et al. 2017), cardboard handling (Zhong et al. 2022; Ji et al. 2024), door installation with robot collaboration (Fu et al. 2025), shelving (Tsuichihara et al. 2022), flange control (Lanzoni et al. 2023) and piloting (checking the aircraft console)(Buonocore et al. 2023).

3.4.2 Posture assessment tools

Ergonomic assessment was performed using a variety of established tools for scoring MSD risk. The most common tool was the RULA quotation (65,2%; n = 15) (Peruzzini et al. 2016; Vosniakos et al. 2017; Nguyen et al. 2017; Michalos et al. 2018; Guo et al. 2018, 2022; Bernard et al. 2019; Havard et al. 2019; Bruno et al. 2020; Dias Ferreira Barkokébas 2022; Buonocore et al. 2023; Garces et al. 2023; Lanzoni et al. 2023; Sardar et al. 2024; Fu et al. 2025), followed by REBA (21,7%; n = 5) (Peruzzini et al. 2016, 2021; Tsuichihara et al. 2022; Sardar et al. 2024; Fu et al. 2025), national norms (17,4%; n = 4) (Guo et al. 2018; Bernard et al. 2019; Kačerová et al. 2022; Krákora et al. 2023), OWAS (8,7%; n = 2) (Peruzzini et al. 2021; Ottogalli et al. 2021) and NIOSH (8,7%; n = 2) (Nguyen et al. 2017; Bruno et al. 2020). Others specific tools like compressive strength (Ji et al. 2024), scope and reach (Peruzzini et al. 2016; Buonocore et al. 2023), EAWS (Garces et al. 2023), displacement (Michalos et al. 2018), Nordic questionnaire (Bernard et al. 2019), center of gravity (Sardar et al. 2024) and pain perception questionnaire (Vosniakos et al. 2017) have been also employed.

3.4.3 Ergonomic assessment results

Five studies reported a reduction in ergonomic risk scores after using VR environments, typically presented through descriptive statistics or qualitative indicators. These results included score changes (5 to 4) (Peruzzini et al. 2016; Kačerová et al. 2022; Guo et al. 2022; Fu et al. 2025), risk ranges (RULA levels, from red to yellow) (Guo et al. 2022), or reduction in time spent in constrained postures (Kačerová et al. 2022). However, it must be noted that none of the studies employed inferential statistics to support a significant change through these ergonomic risk scores.

Table 2
representation of ergonomic assessment results and type of tasks

Ergonomic tool	Studies	Simulated tasks	Ergonomic assessment results
RULA	Peruzzini et al. 2016; Vosniakos et al. 2017; Nguyen et al. 2017; Michalos et al. 2018; Guo et al. 2018, 2022; Bernard et al. 2019; Havard et al. 2019; Bruno et al. 2020; Dias Ferreira Barkokébas 2022; Buonocore et al. 2023; Garces et al. 2023; Lanzoni et al. 2023; Sardar et al. 2024; Fu et al. 2025	Assembly task, collaboration with robot, grinding and control, riveting tasks, object displacement	Barkokebas (2022): low to moderate RULA score after modifications. Fu (2025) : moderate to low RULA and REBA score. Guo (2022) : RULA score decrease after workstation modifications.
REBA	Peruzzini et al. 2017, 2021; Tsuichihara et al. 2022; Sardar et al. 2024; Fu et al. 2025	Assembly task, collaboration with robot,	Peruzzini (2016) RULA score decrease after workstation modifications.
Natinal norms	Guo et al. 2018; Bernard et al. 2019; Kačerová et al. 2022; Krákora et al. 2023	Assembly task	Kacerova (2022) : Reduction in exposure time to risky postures.
OWAS	Peruzzini et al. 2021; Ottogalli et al. 2021	Assembly task	
NIOSH	Nguyen et al. 2017; Bruno et al. 2020	Assembly task, object displacement	
Others (strength, scope and reach, EAWS, displacement, Nordic questionnaire, center of gravity, pain perception questionnaire...)	Ji et al. 2024; Peruzzini et al. 2016; Buonocore et al. 2023; Garces et al. 2023; Michalos et al. 2018; Bernard et al. 2019; Sardar et al. 2024; Vosniakos et al. 2017	Assembly task, handling task, service trolleys pulling, grinding and control task, lifting task	Peruzzini (2016): RULA score decrease after workstation modifications. Peruzzini (2021): EAWS score decrease after workstation modifications.

4. Discussion

This review aimed to examine the impact of virtual environments as a strategy to prevent occupational injuries. Most of the reviewed studies focused on use cases involving industrial assembly tasks, and they have been published in the fields of engineering and manufacturing. The use of head-mounted displays (HMDs) combined with motion capture technologies emerged as the preferred approach, often implemented through game-oriented software (Unity 3D) or industrial software (3DEXPERIENCE). The primary objective of these studies was to prevent the risk of MSDs during the iterative design process of workstations. This section examines and discusses the different methods used to ensure the validity of virtual environments in this context, while also analyzing the ergonomic assessments conducted through these VR use cases.

In this review, most studies apply VR directly to an industrial case study without a structured validation framework to ensure the validity of the environment ($n = 15$). This may be due to the multidisciplinary aspect of ergonomic research studies based on virtual environments. Indeed, De Winter et Eisma underscored that the adoption of ergonomic principles by other scientific disciplines tend to overshadow the scientific field of ergonomics and human factors (de Winter and Eisma 2024). While this integration may favor innovation, it also contributes to the marginalization of ergonomics as an independent academic field, and to the redefinition of its boundaries by adjacent disciplines. In the current review, most selected studies were published in manufacturing/engineering or computer science domains, and this disciplinary orientation may explain the emphasis on field applications, with many studies conducted directly in industrial contexts or based on simulated industrial tasks.

Six studies included in this review showed significant differences between the real-world (or DHM) and VR conditions regarding kinematics and the resulting ergonomic analysis, although these differences were not observed for all joints. These specific differences can be firstly explained by the immersion rate of the virtual environment. For example, in the study by Kacerova et al. (2022), the authors explained that the two main differences observed (longer exposure times to risky postures for the head and right arm in the virtual environment compared to the real environment) are due to immersion rates that are probably insufficient for users (Kačerová et al. 2022). Peripheral vision limited by the headset would also require more rotation of the head in order to explore the environment as in real life. Moreover, the non-simulation of a 1.5 kg weight might have caused the user to keep their arm flexed for a longer period of time during the simulated task. The same observation applies to Bernard et al.'s study (2019), who explained the differences observed due to the lack of realism in the scene (pauses between each task, limited movement in the virtual environment, graphical quality into the headset, etc.). In the study by Guo et al. (2022), it was suggested that adding haptic feedbacks would improve users' interactions with the virtual environment. These issues are related to the concept of 'affordance', which refers to what the environment offers and makes possible for a person, based on their capability for action (Gibson, 2014). More precisely, it corresponds to a relationship between the characteristics of the environment and the capabilities of the person. To evaluate a workstation using VR, it seems important that the environment would afford the same actions as their real-world equivalents (Steffen et al. 2019). Another study from the scientific literature showed that increasing realism could help reduce behavioral differences between the two conditions, using a fire scenario as an example (Ahmed et al. 2019). More precisely, the inclusion

of realistic elements such as smoke simulation led to behaviors that were closer to those observed in real situations. Thus, using appropriate affordances in the virtual environment could provide 'invitations' that convey the same properties of an object or situation as in the real world (Tosi 2020). This comparative approach between real and virtual world is also used in other scientific fields to study the validity of virtual reality. It ensured that the results obtained in virtual environments were consistent with those obtained in real conditions. For example, in Bideau et. al.'s (2003) study, a real vs virtual comparison of key performance parameters in handball validated a VR tool for analyzing visual information uptake (Bideau et al. 2003). Thus, comparing the human behavior observed in a real and a virtual environment represents a first step in the validation process of a VR tool.

Moreover, the user's perception into a virtual environment may also appear critical to ensure user's engagement into the virtual experience. In the current review, only five studies analyzed users' perception in VR. The first dimension of subjective feedback concerned the sense of presence: since VR aims to convey sensory information such as touch, vision, and hearing (Berg and Vance 2017), it is essential to verify that these cues enable an accurate perception of the virtual environment. To simulate user's behavior that is as close to reality as possible, it is essential that the user's sensory modalities are congruent, meaning that the stimuli presented in the virtual environment behave in the same way as they would in the real world (Jerald 2015). However, when the virtual environment reaches a simulation limit, it is sometimes possible to circumvent these limitations through other sensory feedback. For example, one study demonstrated that the use of multiple sensory stimuli (auditory and olfactory) could induce user reorientation during walking, allowing them to remain within the designated virtual area without requiring manual reorientation (Lee et al. 2024). Consequently, the sense of presence and realism appears to be crucial for the development of a reliable and effective virtual environment. A second dimension concerns the potential side effects of VR on users. Studies assessed factors such as mental workload, perceived effort, stress, frustration and safety, to ensure that using the tool does not generate negative effects in the context of a virtual intervention. This assessment appears relevant for all studies which used HMDs as it has already been demonstrated that these headsets can cause undesirable side effects during VR sessions (Chen and Wu 2023). Evaluating users' subjective experiences in VR therefore provides insights into the applicability and usability of the tool for the individuals who will eventually use it. This issue is also highlighted in several studies, emphasizing the importance of placing the human factor at the core of VR system design in order to enhance the user experience (Personeni and Savescu 2023; Chen and Wu 2023).

Moreover, two studies grounded the validation of their VR tools in operational criteria such as task completion time, cost and economic added-value. This approach reflected the requirements from an industrial context, for which cost optimization and profitability may be seen as priorities. A VR tool should therefore not only contribute to the prevention of MSDs from an ergonomics perspective, but also meet these operational criteria to be fully integrated into the industrial design process. However, using VR requires technical expertise, which can be costly in terms of both time and materials. This is also the case for DHM applications, which explains why some studies intended to determine whether the use of VR provided a real added value compared to their initial DHM simulation (Guo et al. 2022; Peruzzini et al.

2021). This cost optimization logic also applies to the increase in HMDs compared to CAVE, highlighted in Da Silva et. al (2022) review. This finding illustrates the challenges of the industry 5.0 era, in which technology is expected to serve as an effective means of achieving social and environmental objectives with reasonable affordable costs (Xu et al. 2021).

After discussing the various validation methods for virtual environments through the design process, the methods used to assess the risk of MSDs into these virtual environments may be reviewed. These methods are usually based on the user's professional activity. Indeed, a variety of industrial tasks were represented, although nearly half involved assembly operations. This may be explained by the fact that assembly tasks involved relatively simple interactions to simulate (snapping parts together for example). It is also possible to quickly identify when an assembly operation is complete in a virtual environment (for example, when two parts are assembled). The same applies to more specific tasks ($n = 9$), which involve interactions such as pushing, pulling, or carrying an object. It is more difficult to simulate complex tasks such as cutting, painting, pouring, filling, welding, etc., as these actions often require sensory feedback (visual, auditory, haptic) to inform the user about the progress of the task (changing colors, informative sounds, etc.).

Ergonomic assessment methods applied in VR were mainly represented by RULA, followed by REBA. This distribution reflects practices commonly observed in the industrial sector when conducting ergonomic evaluations in real context (Joshi and Deshpande, 2019). The RULA method is a scientifically validated ergonomic rating system that may be easily automatized into a virtual environment (Halek et al. 2025). Moreover, a RULA evaluation is mainly based on joint angles, biomechanical parameters that may be obtained through motion capture systems, disposals employed in most of the reviewed studies. Thus, the use of motion capture systems for ergonomic analysis is particularly prevalent to offer a high degree of objectivity (Rybníkář et al. 2023). It is therefore not surprising to see motion capture coupled with VR to perform ergonomic analyses on virtual workstations (Da Silva et al. 2022). For most studies, the use of ergonomic evaluations (scoring, standards, accessibility, reach, biomechanical parameters, etc.) helped identify high-risk postures during the design process. These evaluations then allowed for modifications applied to the workstation design based on the recommendations. A few studies ($n = 5$) went as far as repeating their ergonomic evaluation on the modified version of the workstation. For these studies, results showed a decrease in high-risk postures on the modified version. However, these reductions were not statistically significant, as the studies reported their results mainly in a descriptive manner, which greatly limited their generalizability. This may be explained by the fact that most of these studies were identified as case studies.

Future research should place a particular emphasis on the use of inferential statistical tests to rigorously evaluate the effects of using VR into the iterative design process of workstations aiming at reducing the risk of MSDs. The adoption of a structured methodology that integrates both objective measures (joint angle analysis derived from motion capture) and subjective measures (user perceptions of realism, usability) would strengthen the validity of the findings and thus gain a dual understanding of the behavior of immersed users. Moreover, increasing the sample size and including a more diverse group of

participants, particularly operators, is essential, as they gained professional expertise and their preferences are directly relevant to workstation design. Future studies could also focus on optimizing virtual environments to reduce kinematic differences between real and virtual settings, by testing different haptic feedback, combining multiple sensory feedback modalities, or even designing the virtual environment itself to provide specific affordances for the workstation. Such an approach would provide a more comprehensive understanding of the impact of VR-based ergonomic analyses on the prevention of MSDs.

5. Conclusion

This systematic review highlighted the current use of VR for the assessment and prevention of MSDs in industrial settings. Many studies applied VR mainly during the design process, without formal validation of the tool, relying on its field of application as proof of concept. This empirical approach limited the generalizability of the results. For studies evaluating the validity of VR, comparisons have been made between real, virtual, and DHM situations. Tools related to this question were subjective questionnaires on presence, immersion, realism, mental load, and/or effort. These results highlighted the importance of combining objective and subjective indicators in order to achieve a complete validation of VR. The use of inferential statistics is also crucial for obtaining robust results, yet only two studies in this review made use of them. Regarding ergonomic scores, studies incorporating workstation redesign showed a decrease in risk scores, illustrating the potential of VR to simulate operator workstations and postures. However, these results remain descriptive and do not allow statistical conclusions to be drawn about the actual reduction of risky postures. The methodological heterogeneity observed between studies, whether in terms of technical configurations or validation approaches, limits the direct comparisons and the generalization of obtained results. Future research should standardize protocols, combine objective and subjective data, and rigorously evaluate whether VR-based recommendations reduce MSDs in real-world situations, while keeping human factors and ergonomics at the center of the MSDs prevention strategy.

Declarations

Competing interest

The authors declare that they have no conflicts of interest.

Informed consent

Not applicable. This study is a systematic review of previously published studies and did not involve human participants

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Author Contribution

JR: Conceptualization, Methodology, writing original draft; Funding acquisition, Writing- review & editing
EC: Supervision, Validation, Writing- review & editing.
NV: Methodology, Funding acquisition, Supervision, Validation, Writing- review & editing

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Figures

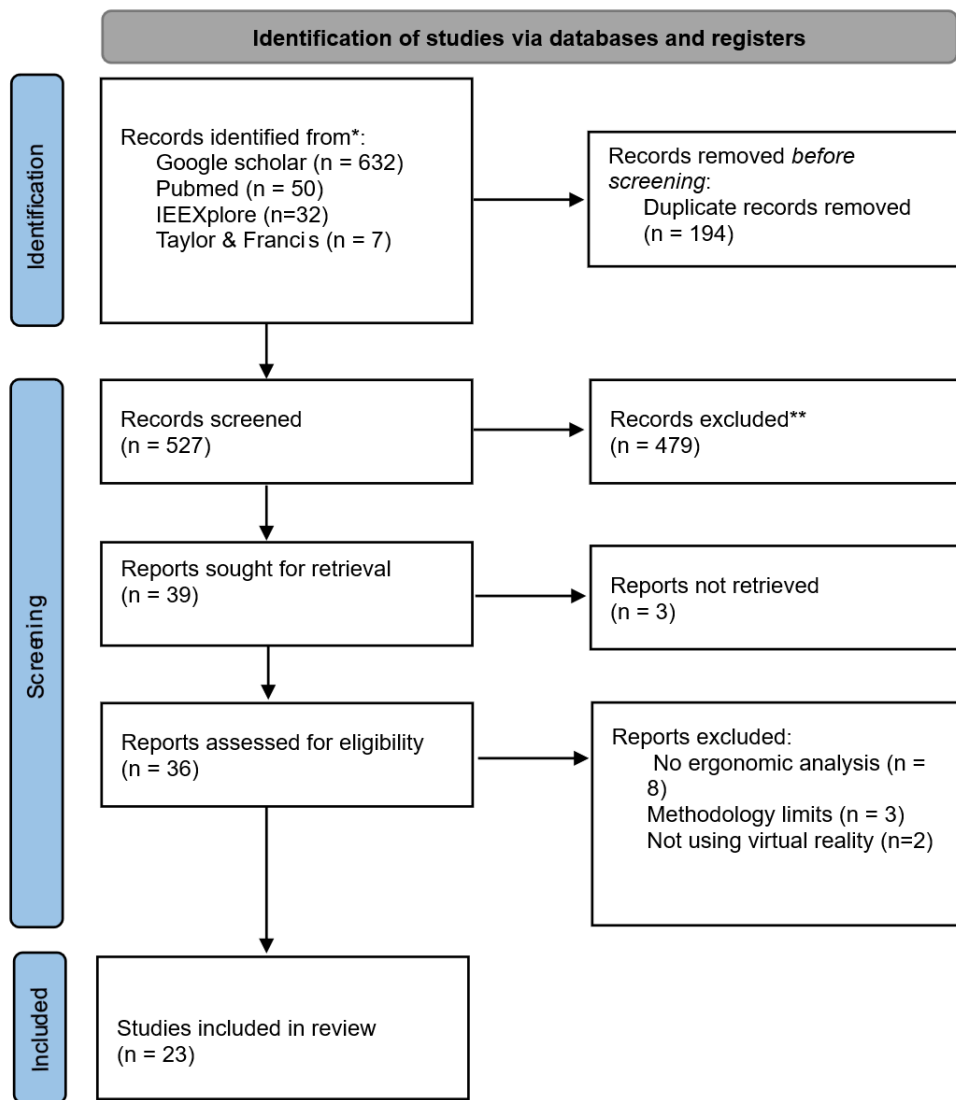


Figure 1

PRISMA flow diagram

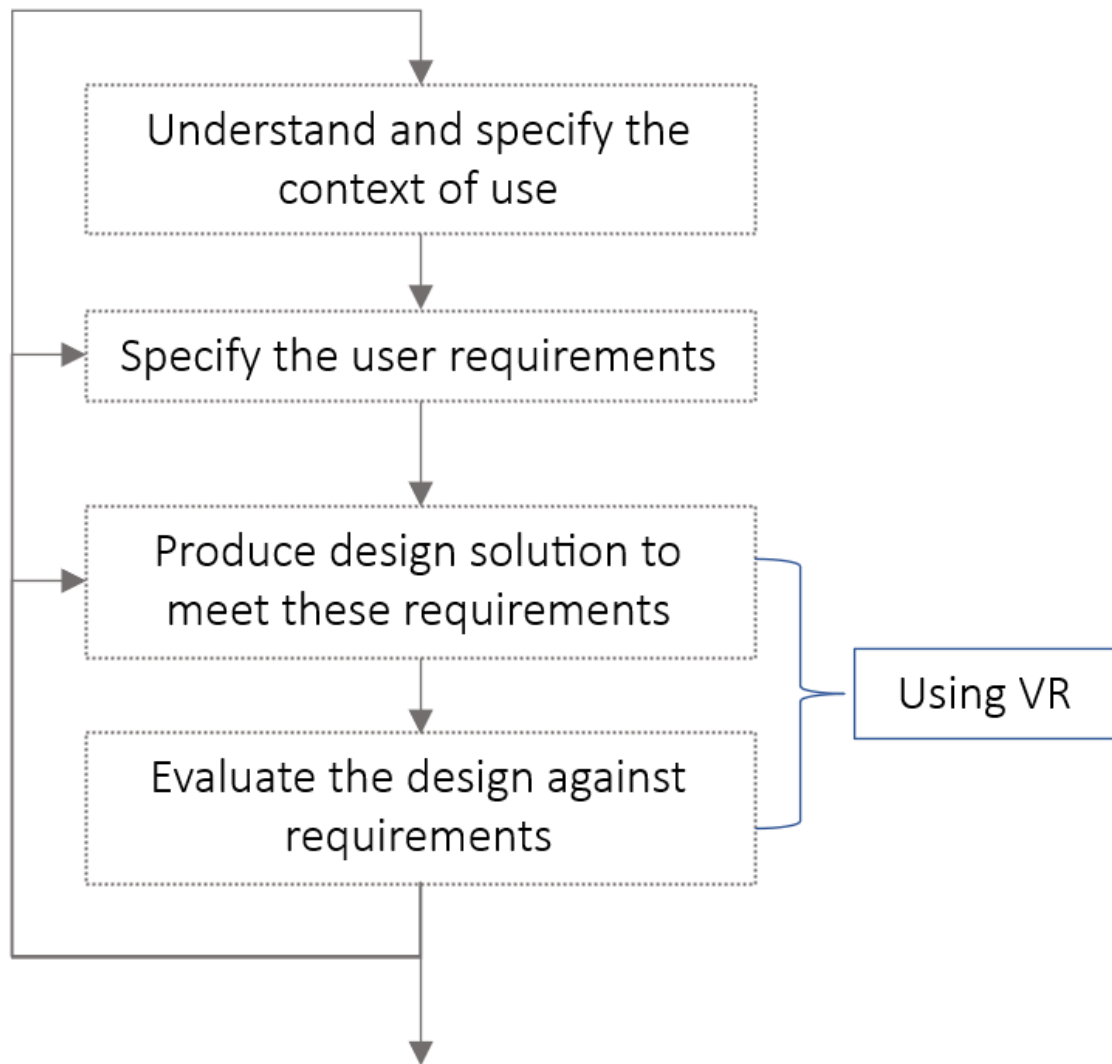


Figure 2

Design process according to Tosi (2020), based on the ISO 9241-210 standard. VR is employed during the last two stages in order to define constraints related to ergonomic requirements and to support the evaluation of design choices.