An Efficiency Analysis of Applications of Virtual Reality in the Medical Field

Master's Degree in Management Engineering

Productivity Efficiency Analysis Course

PROJECT - REPORT

Group I

Students:
Alberto Magro 1935939
Alessandro Rossi 1941142
Francesco Sanetti 1933718
Francesco Ventura 1841504

Abstract

Purpose: This project explores the transformative role of Virtual Reality (VR) in healthcare, focusing on applications in medical training, telemedicine, and surgical precision.

Systematic review: We selected a total of 30 articles through a specific query on Scopus, focusing on performance evaluation in healthcare applications of Virtual Reality and then a systematic review was conducted on those. For the bibliographic analysis, we used the Biblioshiny tool, which allowed us to visualize and summarize the data effectively.

Data: We then selected the variables of interest from various datasets available on the Transparency Portal of the Portuguese National Health Service which provided a comprehensive overview of healthcare performance. We performed preliminary evaluations to understand how to properly carry on the analysis and subsequently **a DEA analysis** (bootstrap and order-m). Lastly, we conducted an external factors analysis based on the DEA results.

Results: The study highlights VR's capacity to enhance efficiency, improve education, and redefine clinical practices in healthcare.

Academic Year 2023-2024

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1 Introduction: Virtual Reality in Healthcare

Rapid advancements in virtual reality (VR) technology have opened unprecedented opportunities to transform critical sectors with healthcare emerging as one of the most promising because healthcare systems around the world are facing **growing demands to improve outcomes while managing limited resources**.

This challenge underscores the necessity of adopting innovative approaches, such as VR, to **maximize efficiency and effectiveness**: VR, known for its ability to create **interactive and immersive environments**, has moved beyond its entertainment roots to become a crucial tool in reshaping medial training and patient care.

To understand the real value of VR implementations in the medicine sector it is essential to make a **structured analysis** through a **systematic review** for **evaluating** the **effectiveness** of **integrating VR into healthcare systems**, assess the factors that influence its adoption and performance, identify barriers and opportunities for improvement, providing information on their capacity to **address current challenges in healthcare delivery and innovation**.

Thank to this accurate and scientific analysis we have been able to asses that virtual reality **reshape medial training** due to its ability in **bridging gaps in medical education**. For instance, VR-based simulations provide medical professionals with the ability to **practice and refine their skills in a risk-free, controlled environment**, making it possible to simulate complex and rare scenarios that are otherwise difficult to encounter. These technologies also allow for **highly detailed simulations** of surgical procedures, equipping surgeons with **better tools to prepare for complex operations** and refine their skills.

Moreover, comparisons between **VR-based training methods and traditional approaches highlight its superior ability to improve training effectiveness and clinical performance**.

VR is also playing an increasingly significant role in **remote healthcare solutions**, such as telemedicine, where it bridges the gap between specialists and under-served populations.

Virtual reality is also able to **reshape Patient care** due to **digital twin technologies, reducing errors, optimizing procedural accuracy**, and ultimately ensuring better patient outcomes. In rehabilitation, VR-driven therapies engage patients through **interactive exercises**, improving adherence, and **accelerating recovery processes**.

In order to properly carry out an analysis over the data to find possible correlations in the behavior of the variables tests over **convexity** and **RTS** were conducted to choose the correct method to apply, then a robust **order m** DEA analysis was chosen, as well as a **bootstrap analysis** to obtain an unbiased results.

Finally, all the results were analyzed within the socio-economic context to provide justification and a deeper understanding of the findings.

2 Systematic review

2.1 Framework

To address the research question a PICO framework was utilized, placing a clear focus on healthcare professionals as the **population**. The **intervention** under analysis included innovative technologies such as VR/AR, telemedicine, and remote surgery. These modern approaches have been **compared** with conventional training methods to evaluate their relative effectiveness. The key **outcomes** assessed were skill acquisition, training efficiency, and overall clinical performance. This structured methodology was carefully chosen to provide a comprehensive answer to the **central question**: "How do VR and AR, telemedicine, and remote surgery impact the training effectiveness and clinical performance of healthcare professionals when compared to traditional training methods?"

2.2 Systematic review: query development

Once decided to explore the applications of virtual reality in healthcare, **the first step** of the analysis was a **research based on the existing literature**, the search and selection of proper articles was done with **Scopus**: a scientific article indexing platform that provides abstracts and bibliometric measurements, facilitating scientific research and enabling the evaluation of the impact of publications, authors and journals.

The query, conducted on **November 17, 2024** was designed to capture a comprehensive set of studies focusing on immersive technologies in healthcare, emphasizing surgical training, procedures and remote care, the query is provided in the appendix (A).

The first search on Scopus returned 382 results, which were assessed for relevance through a systematic, staged screening process which followed this order.

Firstly a **Preliminary research** has been done to **exclude** documents that were **not in English**, still under **review**, or contained **irrelevant keywords** for our research (for example, anxiety or empathy, which refer to applications in psychology). After this filtration 382 articles were narrowed to **182**.

Secondly an **Initial screening** was needed to **remove irrelevant studies**, focusing on **Direct applications of VR, AR, or Mixed Reality in medical contexts, Empirical studies** evaluating practical outcomes (e.g., knowledge retention, procedural accuracy). The excluded articles were about **non-medical** applications **or** those focusing on **psychological** impacts unrelated to the scope (e.g., anxiety or empathy), it is also important to mention the exclusion of reviews and overly **outdated** articles. After this second filtration the 182 articles were narrowed to **92** based on their relevance.

Thirdly a **Full-Text Screening** had to be done in order to **manually assess** full-text articles against specific **inclusion and exclusion criteria**. **Inclusion Criteria** were articles strictly addressing the three **key domains of medical training, telemedicine, and surgery**; Studies employing randomized controlled trials, **validated simulations**, or real-world applications were selected; Detailed discussion of **VR's role in medical training, surgery, or telemedicine**; Clear methodological design with **results on effectiveness**, usability, or scalability; Studies focusing on immersive technologies with **use of addicting manufacturing**; Studies focusing on immersive technologies with **haptic feedback** or interactive simulations. **Exclusion Criteria** were **non-empirical** reviews or conceptual frameworks without experimental data. Studies with a primary focus **outside the healthcare** domain; Studies focusing on **overly specific topics** (for example, articles describing a single specific surgical procedure).

Finally a last effort was made to **avoid** articles covering the **same topic**, always favoring the most **recent** article or, if applicable, the most comprehensive or methodologically rigorous one.

Result: By focusing on these criteria, the final selection ensures a high-quality, focused review of VR's role in the specified medical context. Implemented filters can be seen in the PRISMA flow chart diagram in Figure 1

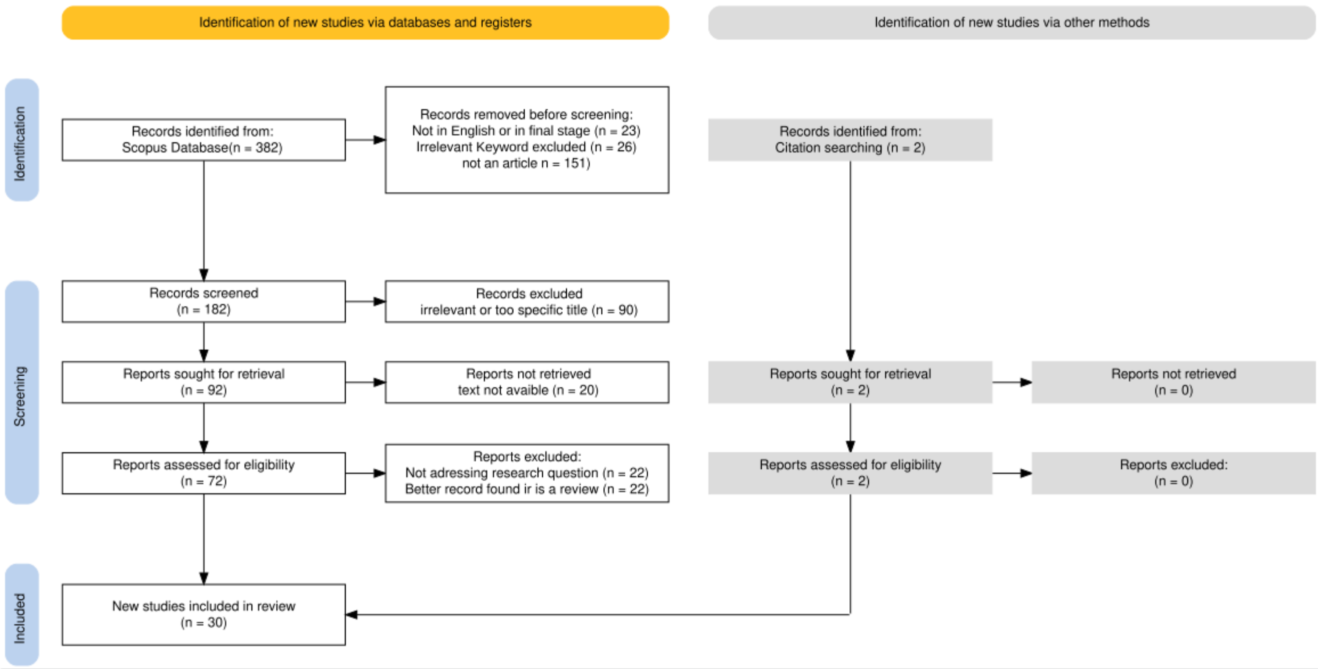


Figure 1: PRISMA flow chart

2.3 Systematic review: Bibliographic analysis

Focusing now on the 30 selected articles, we aimed to highlight further links using Bibliometrix, through these additional analyses it is possible to observe that, following the screening process, a network of connections emerged.

In Figure 2 below it can be seen how the topic of **virtual reality in healthcare** is a **highly emerging theme** that experienced a **significant surge starting in 2015/2016** when VR headsets became commercially available.

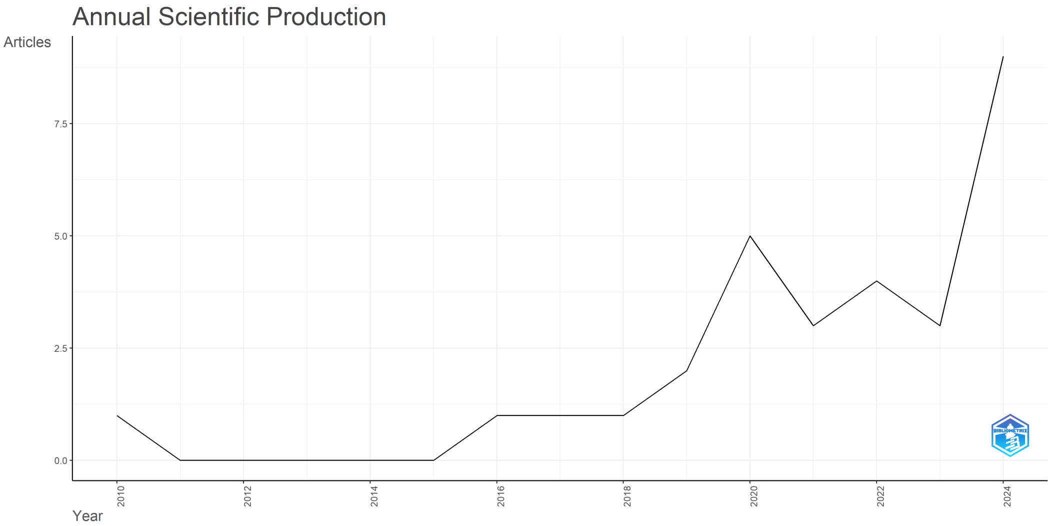


Figure 2: Annual Scientific Production

Once we obtained the first database with the definitive query on Scopus, we constructed the **co-occurrence network** of the keyword using **Biblioshiny**, a tool from Bibliometrix. Through this method, we understood how the various articles were related to each other through keyword analysis (See Figure 3).

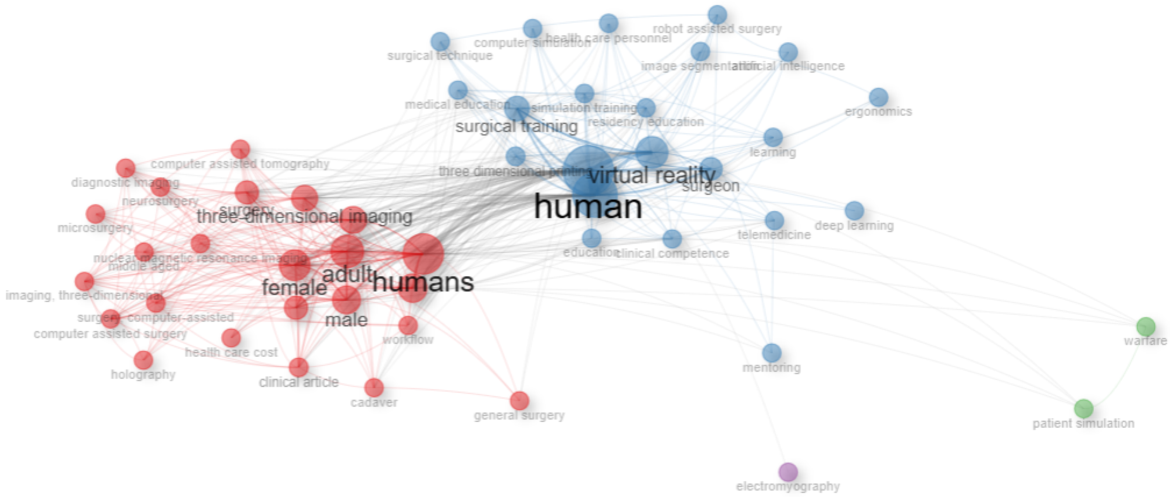


Figure 3: co occurance network

As it can be seen from Figure 3 up above, through this additional analysis, it is possible to observe that a network of connections emerged: our analysis of the co-occurrence network underscores that **virtual reality is a pivotal tool in modern healthcare**, particularly in surgical training, education, and imaging.

Figure 4: recurrent worlds cloud

Of particular relevance is precisely the word-cloud graph that makes the visualization of which keywords are relevant quite easier (Figure 4): the words cloud highlights key recurring themes such as "virtual reality," "augmented reality," "surgical training," "simulation training," and "clinical competence," demonstrating VR's strong relevance to practical and educational aspects of healthcare.
It is also evident that the theme of telemedicine are peripheral both in the network and in our review, while the topic of medical imaging was deliberately omitted as it did not adequately address the research question.

2.4 Systematic review: key findings

2.4.1 VR in medical training

In recent years, the **surgical training of new doctors** has increasingly become a significant **logistical, ethical, and financial challenge** and can no longer rely on the "see one, do one, teach one" approach, which is increasingly perceived as inefficient (Amini et al., 2024, Riddle et al., 2024): the study of Sibomana (Table 1) qualitatively highlights the **advantages of adopting VR in medical training instead of the use of cadavers** (Sibomana, 2024).
The U.S. Department of Defense estimates a need to train annually 100,000 military healthcare personnel and **ineffective medical training** results in at least **50,000 excess deaths** each year (Siu et al., 2016), it is therefore increasingly necessary to **find a more efficient way** both to **train new doctors** and to **maintain the skills** of practicing physicians.
Utilizing VR technologies in synergy with **3D-printed surgical simulators** can certainly **increase patient safety** and **reduce healthcare costs**. However, it is also true that studies on the actual **effectiveness** of these methods are **not yet universally recognized**: Petrone defines them as a valid tool (Petrone et al., 2022), but Amini emphasizes the superiority of phantom simulations, which are noticeably better at conveying surgical skills (Amini et al., 2024).
Beyond training new surgeons, VR technologies are increasingly being used to **enhance procedural learning**: for example, the **VolumetricOR** was developed as a cutting-edge workflow to record and

present **volumetric videos of surgical interventions** in a photorealistic virtual operating room, this innovation allows students to relive the experience of a surgical intervention without the many technical, economic, and regulatory constraints of traditional surgical learning (Queisner et al., 2022). Additionally, the **STAR** (*System for Telementoring with Augmented Reality*) enables **remote mentoring**, allowing expert surgeons to guide less experienced practitioners in real time, particularly in austere or remote environments (Rojas-Muñoz et al., 2020).

We must also consider, beyond teaching, the value that VR can provide in **maintaining the surgical skills of practicing physicians**: Calatayud statistically demonstrated that a **15-minute warm-up in a Virtual Reality Environment improves performance in the operating room** (specifically in laparoscopic surgery) (Calatayud et al., 2010). Similarly, studies on VR-based simulations with haptic feedback, such as the femoral nailing simulator, show how **tactile interactivity enhances skill acquisition** (Almousa et al., 2019). This is particularly relevant for practicing physicians who often need to transition between operating theaters and skill sets, such as combat doctors (Siu et al., 2016).

Lastly, VR offers transformative opportunities in surgical training for resource-constrained settings: studies have shown the feasibility of VR training programs that use affordable equipment to **bring advanced surgical education to underserved areas** (Please et al., 2024). These programs not only reduce training costs but also democratize **access to high-quality medical education, addressing global disparities in healthcare training**.

Table 1: (Sibomana, 2024)VR versus cadavers in surgical trainings

Aspect	**Virtual reality (VR)**	**Cadavers**
Cost	- Low recurring costs.	- High ongoing costs for procurement, preservation, and storage.
Accessibility	- Widely accessible once infrastructure is in place. - Scalable across multiple locations.	- Limited availability, especially in low-resource settings. - Cultural and ethical barriers in some regions.
Repetition & practice	- Unlimited practice opportunities: Procedures can be repeated indefinitely.	- Limited use; once a procedure is performed, repetition is not possible.
Ethical considerations	- No ethical concerns related to use.	- Ethical and cultural concerns in body donation and use.
Educational value	- Highly interactive and customizable learning environment. - Safe environment for making and correcting mistakes.	- Essential for understanding human variation and real-life surgical complexities, but not interactive and customizable. - Unsafe environment for making and correcting mistakes.
Long-term sustainability	- Sustainable with low ongoing costs. - Easily updated and maintained.	- Requires continuous investment in body acquisition and maintenance.
Regulatory and legal issues	- Fewer regulatory barriers compared to cadavers.	- Subject to strict regulations and legal requirements for use.

2.4.2 Applying VR in austere environments

If the issue of surgical training in advanced countries is a matter of increasing input-based efficiency, **in remote areas** this becomes even more critical because the **knowledge of surgical procedures** is often entirely **absent** but Virtual Reality (VR) has the potential to **disseminate surgical knowledge and skill development at low costs**.

So far, we have discussed only on-site training applications, but the growing interest in these technologies has also led to their application in **remote training** as the study (Please et al., 2024) demonstrated the feasibility of a highly scalable **training program at minimal cost**, using limited equipment such as affordable VR headsets and more than half of the participants (in Uganda) found it easy to acquire VR equipment, highlighting its accessibility and potential for widespread use in underserved regions. Despite these successes, **challenges** such as the **availability of stable internet connections** and the **durability of low-cost devices** remain critical issues to address in scaling VR training programs globally.

Another technology, designed specifically for immediate support during procedures, is **STAR** (*System for Telementoring with Augmented Reality*), this system allows an expert surgeon, located remotely, to **guide a less experienced local surgeon** through a surgical procedure in real time: it employs a visual annotation system that appears directly within the local surgeon's field of view through VR devices. The study (Rojas-Muñoz et al., 2020) reported that **STAR participants made fewer errors** when performing the procedure, this is a critical outcome as it identifies and **avoids operative errors that are essential for patient safety and healthcare efficiency**. However, the **success of STAR** and similar systems **heavily depends on** the availability of skilled mentors and **robust technological infrastructure**, which can be **limiting factors in poor regions**. Moreover **STAR** also has applications in combat medicine, where it can be used with a simple tablet (Andersen et al., 2017) as it can be seen in Figure 5.

Also other low-cost VR-based simulations have been explored in field hospitals and mobile clinics, showcasing their adaptability to diverse medical challenges. Such innovations underscore the **versatility of VR technologies in addressing critical gaps in healthcare training and delivery, particularly in underserved and resource-constrained environments**.

Figure 5: (Andersen et al., 2017) A remote surgeon provides guidance using STAR to provide telementored guidance to a local surgeon. Annotations (dark arrows) were drawn by the remote user and transmitted to the local surgeon's view of the operating field.

2.4.3 Introduction of Haptic Feedback to VR

Current VR systems **cannot** effectively **simulate physical touch**, which is of **immense importance** to surgeons. This issue can be addressed through the **introduction of Haptic Feedback**, which enhances the realism of simulations and bridges the gap between theoretical learning and practical application: by combining AR's ability to overlay real-world environments with virtual tactile sensations, surgeons could practice procedures in **highly realistic and context-aware settings**. This approach is already being explored in preliminary studies, highlighting its potential to further revolutionize medical training (Gießer et al., 2024 Figure 6, Figure 7)

Figure 6: (Gießer et al., 2024) SenseGlove Nova—tracking system

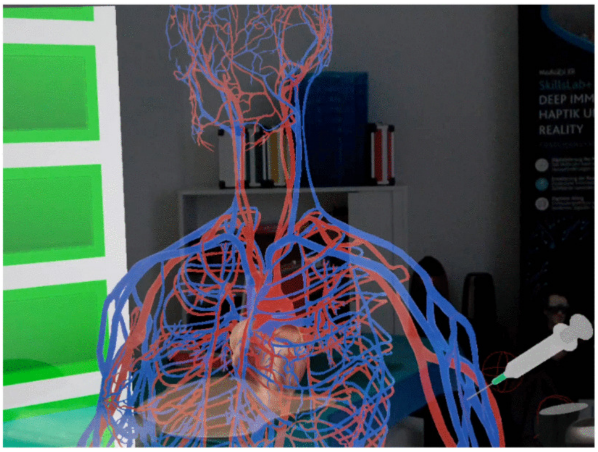


Figure 7: (Gießer et al., 2024) View through AR glasses—Arm injection in the SkillsLab+

Both studies of (Racy et al., 2021) and (Almousa et al., 2019) describe **simple and accessible devices** capable of simulating straightforward scenarios, such as Femoral Nailing and Cardiopulmonary Resuscitation. These simulations allow trainees to gain hands-on **experience in controlled environments**, significantly improving their procedural confidence.

More general devices, such as **smart gloves**, are also being developed, for instance (Zhu et al., 2020) demonstrated the potential of smart gloves in simulating **precise tactile interactions**, making them invaluable for delicate surgical procedures: these gloves incorporate sensors to provide tactile feedback that **simulates a wide range of situations encountered in the medical field**, from feeling tissue resistance during surgery to practicing intricate suturing techniques. In addition to gloves, advanced systems are now **integrating haptic feedback with visual simulations** to create **highly immersive training platforms**: studies on the use of VR simulators in laparoscopic surgery have shown that devices combining haptic feedback and realistic visual environments improve accuracy and reduce errors during training (Almousa et al., 2019). However, despite these advancements, **challenges remain**, current haptic devices can be **cost-prohibitive**, and their **technological complexity** limits scalability, especially in resource-constrained environments. Additionally, many systems **lack the ability to replicate the full range of tactile sensations** experienced during real surgeries, which is a critical area for future research and development.

Haptic feedback is also finding applications **beyond surgical training**: **rehabilitation devices** that employ haptic feedback are helping patients regain mobility by **simulating natural movements** and **providing resistance-based exercises** tailored to individual recovery needs (Zhu et al., 2020). These innovations underscore the versatility of haptic technologies in addressing diverse challenges across the medical field.

2.5 VR and MR applications in surgery

Virtual Reality (VR) and Mixed Reality (MR) technologies have already found **applications in surgical planning and anatomical visualization**, significantly aiding operations (Caglar et al., 2024; Cho et al., 2021; Kenngott et al., 2022). These technologies enable **detailed preoperative visualization** and foster enhanced understanding of complex anatomical structures, thereby **improving surgical outcomes**. Notably, MR has been used effectively for pre-surgical planning in minimally invasive and robotic-assisted surgeries, as highlighted by (Casas-Yrurzum et al., 2023 Figure 8).

The most transformative use of VR and MR lies in **supporting surgeon navigation during intricate procedures**: (Carl et al., 2019; Liu et al., 2024) demonstrated how augmented Reality (AR) headsets provide real-time anatomical overlays that assist surgeons in better understanding the operative field, similarly (Caglar et al., 2024) emphasized the benefits of MR-assisted navigation in improving accuracy and **reducing intraoperative error**. (Lu et al., 2022) further illustrated the integration of AR in **microsurgical procedures**, showcasing its potential in enhancing the surgeon's field of view. Additionally, MR-guided simulations are being developed to provide **real-time tissue interaction feedback** (Kenngott et al., 2022).

However, AR adoption in the operating room is hindered by significant **challenges**: the **limitations of current hardware** such as head-mounted devices, pose issues with **comfort**, including headaches and dizziness during prolonged usage (Ghaednia et al., 2021). Furthermore, the **lack of standardized interfaces and consistent training protocols** adds to the steep learning curve associated with VR and AR systems, necessitating substantial training time before widespread implementation. Studies like those by (Casas-Yrurzum et al., 2023) underline the importance of **refining these technologies** to improve their usability and adaptability in diverse surgical environments.

Robotic-assisted surgeries are also benefiting from advancements in MR and AR technologies, noteworthy developments include the application of real-time AI-driven deocclusion algorithms which enhance visibility during robotic procedures and this innovation has been instrumental in **addressing critical visual obstructions**, thereby improving surgical precision(Hofman et al., 2024). Despite these advancements, **achieving seamless usability and improving hardware ergonomics remain critical goals**. Continued research into **more intuitive interfaces and lighter, more comfortable devices** will be essential to fully realize the potential of VR and MR in surgery. Emerging systems, such as lightweight AR glasses and wearable sensors, are showing promise in addressing these challenges (Gießer et al., 2024; Zhu et al., 2020). As AR technology progresses, its transformative impact on surgical procedures is likely to expand, making surgeries safer and more efficient.

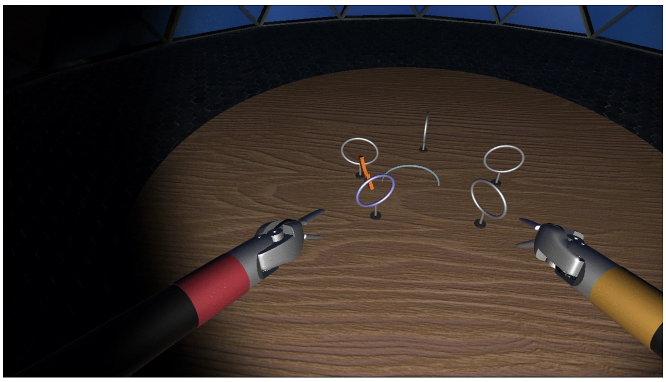


Figure 8: (Casas-Yrurzum et al., 2023) AS simulator used for skill training, developed for the ViPRAS project (virtual planning for robotic-assisted surgery) (see acknowledgment section). The simulator is utilized to master the use of the different tools available in robotic-assisted operating rooms

2.6 VR and telemedicine

A case study highlighted the effectiveness of telemedicine-based collaboration for preoperative discussions, doctor-patient communication, and real-time surgical guidance.
This innovation **reduced barriers** and improved the efficiency of remote medical consultations by enabling **real-time interaction with advanced visualization tools, such as 3D patient models** (Zhang et al., 2023). These tools allowed surgeons to access high-fidelity patient information and **communicate effectively across regions**, showcasing the potential for telemedicine in **bridging global healthcare gaps**.
In addition, integrating digital twin technology with virtual reality has facilitated immersive and interactive **virtual health consultations**: as described by (Sai et al., 2024), digital twin technology has been synergized with VR to create **realistic digital replicas of patients**, enabling accurate health visualization and personalized treatment plans (Figure 9). These advancements improve the quality of remote consultations by providing clinicians with tools to simulate and predict health outcomes in real-time.
Despite these advancements, **challenges persist**: telemedicine-based consultations often require **high-speed internet and advanced hardware**, which may not be readily available in rural or underdeveloped regions. Additionally, there is a **need for standardization in the implementation of digital twin** systems to ensure interoperability between healthcare providers (Sai et al., 2024).

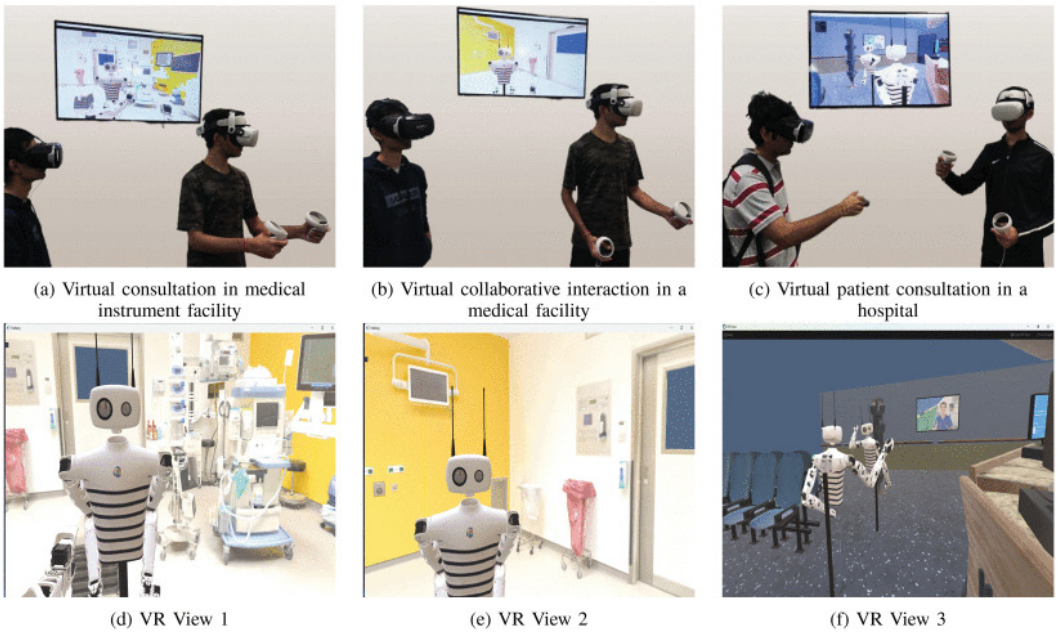


Figure 9: (Sai et al., 2024) Virtual medical consultation in interactive Metaverse consumer health environment

3 Data overview

The primary objective was to evaluate the impact of implementing new digital technologies based on virtual reality on the overall efficiency of healthcare systems. Additionally, the aim was to identify the key areas within these systems where such technologies could drive significant improvements, thereby enhancing operational performance and further optimizing efficiency. By understanding these impacts and opportunities, the study sought to provide insights into how virtual reality can contribute to the improvement of healthcare systems'performances.

3.1 Data generating process

The data utilized for the efficiency analysis were sourced from the **Plataforma de Transparência do SNS**, a Portuguese platform that offers comprehensive information on healthcare performance; The data, collected **from January 2015 to December 2023**, are recent and well-suited for the analysis, particularly in the context of new and emerging technologies such as virtual reality. Given the absence of specific data directly related to the adoption of virtual reality (VR) technologies in healthcare, the **number of telemedicine consultations** was chosen as a **proxy** variable for the analysis. This metric serves as an indicator of hospitals' integration of digital solutions for remote care, providing insight into their utilization of innovative technologies to enhance efficiency and accessibility in healthcare services. It's been decided to remove all the hospitals that didn't have at least one observation per year, in order to have the possibility to observe the evolution of data throughout the years. A second source of data was the official **Eurostat dataset**, which includes information on the **population of the region** of interest. This **variable** was treated as **exogenous** input for the model.
A table summary of the inputs/outputs selected is provided in the appendix (see Table 4).

3.2 Statistical Analysis

This subsection examines the input and output data used in the analysis, both before and after normalization. **Normalization** was essential to ensure that variables on different scales could be effectively compared.

3.2.1 Introductory analysis

The temporal analysis of the variable $y4$, stratified by region and aggregated by year, reveals an overall consistent increase in telemedicine adoption over time, with a notable acceleration after the beginning of the COVID-19 pandemic. A pronounced peak is observed in the Algarve region, which is subsequently followed by a complete cessation of the initiative. This disruption is likely attributable to the conclusion of experimental efforts led by the National Health Center (CNTS) and a regional reorganization of healthcare services. A comparable peak is noted in the Alentejo region shortly before the end of the pandemic.
These findings underscore the pivotal role of telemedicine during the pandemic, highlighting its capacity to address healthcare challenges in times of crisis. Furthermore, the observed trends emphasize the significant impetus provided by the pandemic for the adoption of telemedicine and related technologies, such as virtual reality, in healthcare systems. Regarding the overall trend in in-person consultations, the implementation of telemedicine has contributed to a notable decline in the number of in-person consultations in the Lisboa e Vale do Tejo (LVT) region, following a peak observed in previous years. Conversely, the observed decrease in the Algarve region is attributed to the recent severe challenges faced by the regional healthcare system, which resulted in a significant reduction in the number of consultations being delivered (total consultation trend 23).

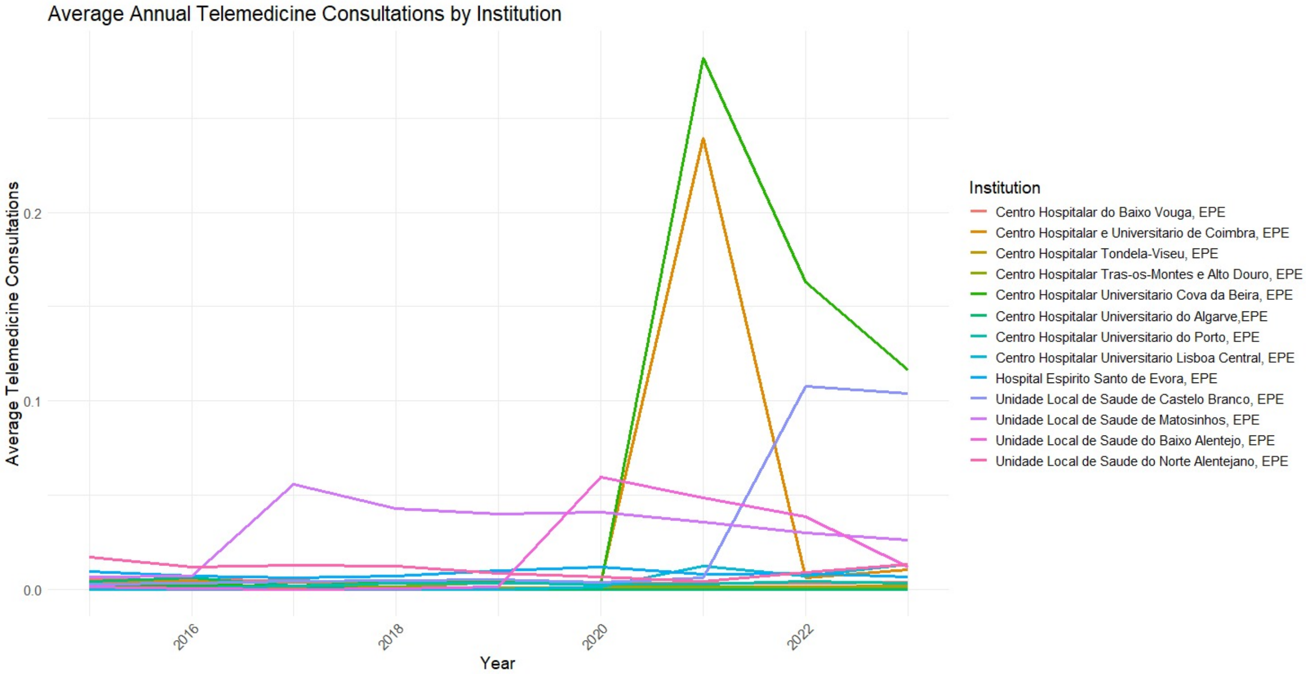


Figure 10: Evolution of telemedicine-total consultants ratio over time

3.2.2 Distribution of the data

The input and output data show substantial **variability in scale** before normalization, as illustrated in the plot below, with some variables exhibiting significantly larger ranges than others. To ensure reliable and consistent analysis results, it was necessary to preprocess the data, which was accomplished in two steps.

Normalization was applied using the **standard deviation (SD) normalization method** to ensure that different features (variables) have comparable scales. After normalization, as it can be observed from Figures 21 and 22 (check Appendix), the data distribution remains highly right-skewed, with a long tail extending towards higher values (**asymmetric data**). To address this, a **logarithmic transformation** was applied to reduce skewness and achieve a more symmetric distribution.

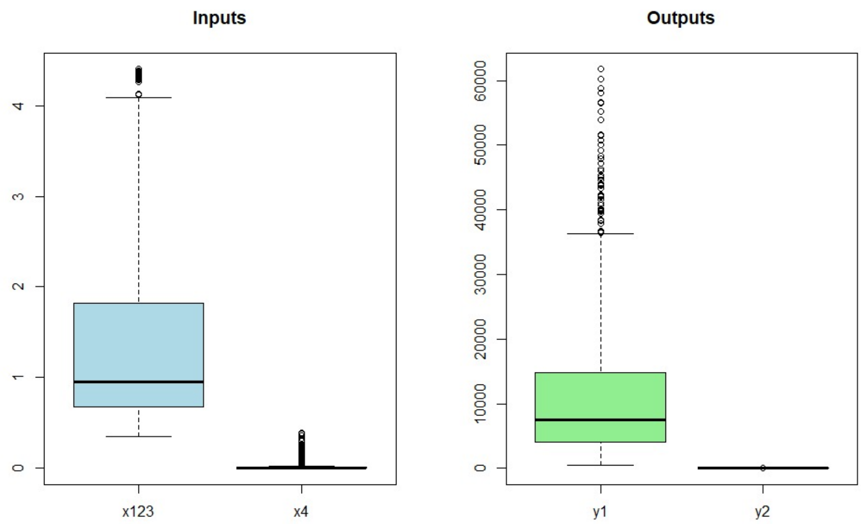


Figure 11: Distribution of data before normalization and log-scaling

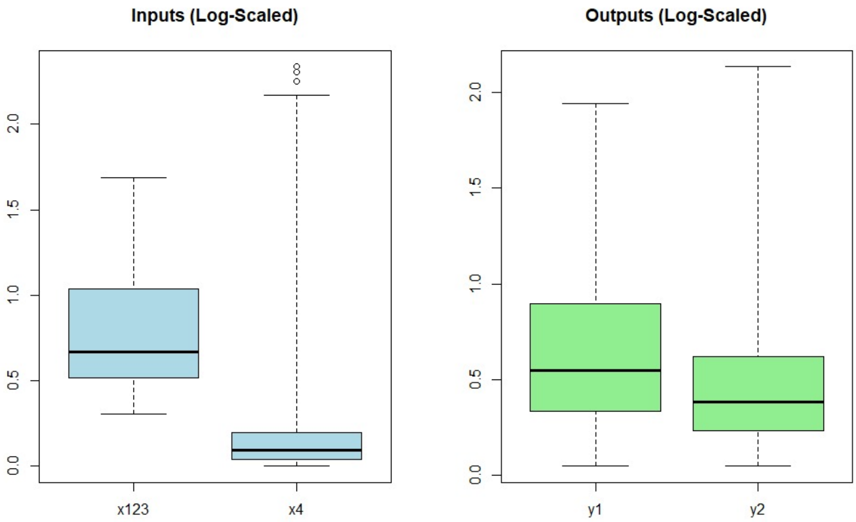


Figure 12: Distribution of data after normalization and log-scaling

3.2.3 Correlation Analysis

The correlation analysis revealed strong associations among specific variables, particularly $x1$, $x2$, and $x3$. These correlations are intuitive from a practical perspective: the operational capacity of a medical facility ($x1$) is closely tied to the availability of doctors ($x3$) and nurses ($x2$). To improve efficiency and **reduce dimensionality**, these **highly correlated variables** were **aggregated**, ensuring that key information is retained while minimizing the number of inputs for subsequent analyzes.

Table 2: Correlation table 1

Variable1	Variable2	Correlation	P-Value
x1	x2	0.9248	<0.05
x1	x3	0.8759	<0.05
x1	x4	-0.0637	<0.05
x2	x3	0.9589	<0.05
x2	x4	0.4576	>0.05
x3	x4	-0.0446	>0.05

Table 3: Correlation table 2

Variable1	Variable2	Correlation	P-Value
y1	y2	0.1793	<0.05

4 Model and methods

4.1 Model

The model was developed to **evaluate the efficiency** of the healthcare system in relation to virtual reality technologies, with decision-making units (**DMUs**) identified within **hospital structures** across various healthcare regions, known as Região de Saúde. These DMUs represent entities responsible for transforming inputs into outputs. After excluding units with non-conforming data, such as null or invalid values, a **total of 13 DMUs** were included in the analysis..

The **selection of the model** is a crucial aspect of the analysis, and multiple tests were conducted to identify the most suitable approach for this specific purpose. Ultimately, an **output-oriented model** was chosen as the most appropriate for the analysis.

4.1.1 Model description

- **Inputs:** x123 (Effective Service Capacity), x4 (Ratio between telemedicine and total consultations)
- **Outputs:** y1 (Discharged patients), y2 (The inverse of the operating expenses)

The input variable x4 works as a **usage coefficient** relative to telemedicine conslutations. In the output variable y2, the operating expenses were **inverted** to align with the output-oriented approach chosen for the analysis. This transformation ensures that lower expenses correspond to higher values of the variable, thereby indicating a more efficient situation.

4.2 Data envelopment analysis

4.2.1 Efficiency Tests

Three efficiency-related tests were performed to analyze the properties of production technology: **Return to Scale** (RTS), **Convexity**, and **Separability**. The RTS test examines whether the production process exhibits constant or variable returns to scale. The Convexity test evaluates if the production possibility set satisfies convexity, while the Separability test determines whether inputs and outputs are separable under specific conditions. Each test was carried out using the input orientation (ORIENTATION = 2) as a direction for the production frontier analysis and an euclidean metric (METRIC=1). Finally the number of times that the bootstrap test is repeated (NREP) is set to 5000, this will increase the estimate accuracy and stability. Efforts were made to strike an optimal balance between the **accuracy** of the tests and their **computational running time**. The results of the tests are summarized in the table below, showing the τ statistic and the corresponding P-value for each test.

Metric	Return to Scale	Convexity
τ	-29.0494	2.4738
P-value	1	0.0066

Observations:

- **Return to Scale:** The τ value is different from 0, meaning that the **RTS are variable**; but the P-value is very high (1) so the result of the **test is not so significant**.
- **Convexity:** The τ value indicates convexity in the dataset and the P-value suggests us that this result is **strongly significant** and this ensures that the **dataset is convex**.

4.2.2 Frontier estimation

Following the assessment of the convexity of the data, an initial frontier estimation was performed using the **Data Envelopment Analysis** (DEA) model. This approach is a non-parametric method characterized by a **deterministic frontier.** The resulting estimation is depicted in the plot below:

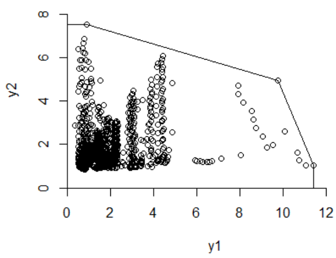


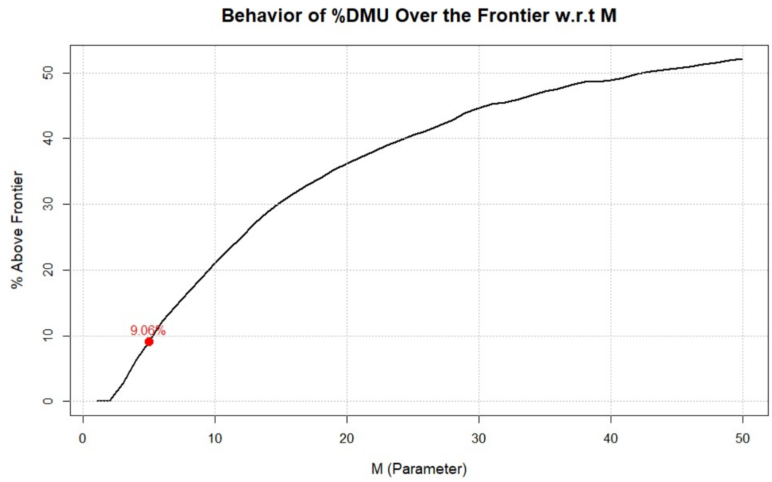
Figure 13: Efficient frontier computed using DEA

The area with the highest sample density is noticeably distant from the estimated frontier, and the estimation is affected by the **large number of outliers in the dataset**. To improve the accuracy of the frontier estimation, a new model was implemented that adjusts the frontier by shifting it below the outermost points and **excluding a fixed percentage of outliers**.
To implement this, a r**obust analysis of order-M** was conducted (Dario, 2019). A **trial-and-error approach** was employed to define and optimize the parameter M, ensuring that approximately **10%** of the outliers were positioned above the efficient frontier. The computed efficiency was then **aggregated** using the mean value w.r.t. year and hospital; in this way a larger set of observations was preserved while making the results **more meaningful**. Once the optimal value of M was determined, the analysis proceeded with the following main results:

Intervals	DMUs	Percentage
[0.65, 0.7)	2	15.4
[0.7, 0.75)	1	7.7
[0.75, 0.8)	3	23.1
[0.8, 0.85)	4	30.8
[0.85, 0.9)	3	23.0

Figure 14: Efficiency table

There are **no DMUs** on the efficient frontier, which may be due to data aggregation. The mean efficiency value is 0.8015.
As shown in the table, the majority of DMUs (76.9%) tend to have a level of **efficiency above 0.75**.



The identified value of M that maintained 10% of the observations above the efficient frontier is **M=5**.

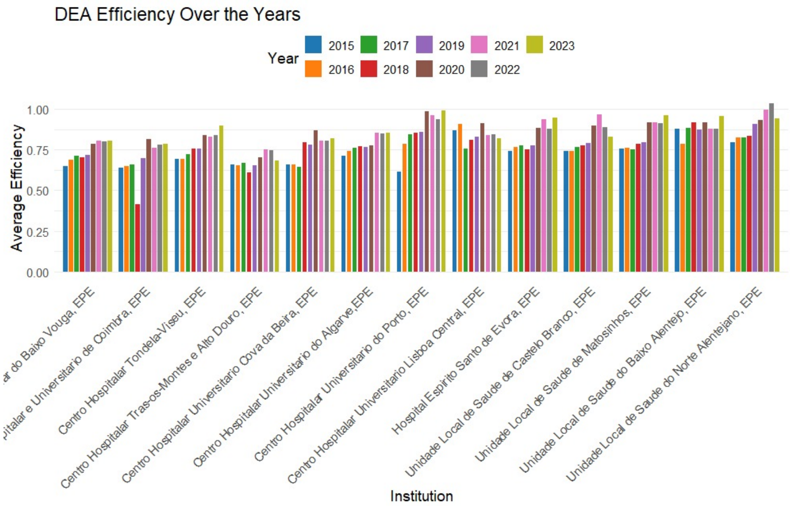


Figure 15: Levels of efficiency for every year

In the histogram above, obtained through the order M analysis, the distribution of efficiency for each hospital across each year is displayed. This type of analysis results in a **"soft" frontier** (non-deterministic) taking into account **noise in the data**, which means that it may be easier for a DMU to be classified as efficient. The analysis shows that almost all DMUs have an efficiency score **significantly lower than 1** and indeed even by excluding the 10 % of outliers hospitals are **far away from the efficient frontier**.

4.2.3 Bootstrap analysis

A **bootstrap** analysis was performed with the aim to either **build confidence intervals** by estimating the quantiles of the sampling distribution and estimating the **bias of the DEA estimator** that it is biased by construction.

Figure 16 illustrates the distribution of confidence intervals for the **Farrell efficiency** resulting from the bootstrapping procedure. As mentioned earlier, a narrower confidence interval indicates a more precise estimate, while a wider interval suggests greater uncertainty or variability in the estimates. It can be observed that **DMUs with lower efficiency** tend to have, on average, **narrower confidence intervals**.

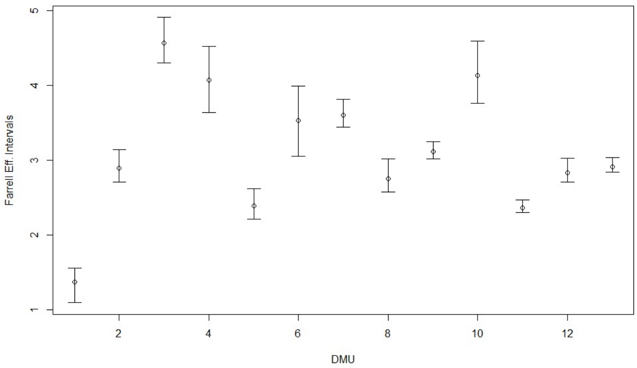


Figure 16: distribution of confidence intervals

Then a new DEA efficiency estimation was computed over the **bias corrected distribution**. The results show that this **efficiency is lower** than the one obtained through the order M analysis. This difference is due to the presence of a **large number of outliers** in the dataset, which push the efficient frontier much further away from the data points. As a result, the average efficiency values for all DMUs are lower. The **mean efficiency** across all DMUs is 0.3568, indicating that there is **significant room for improvement** to get closer to the efficient frontier.

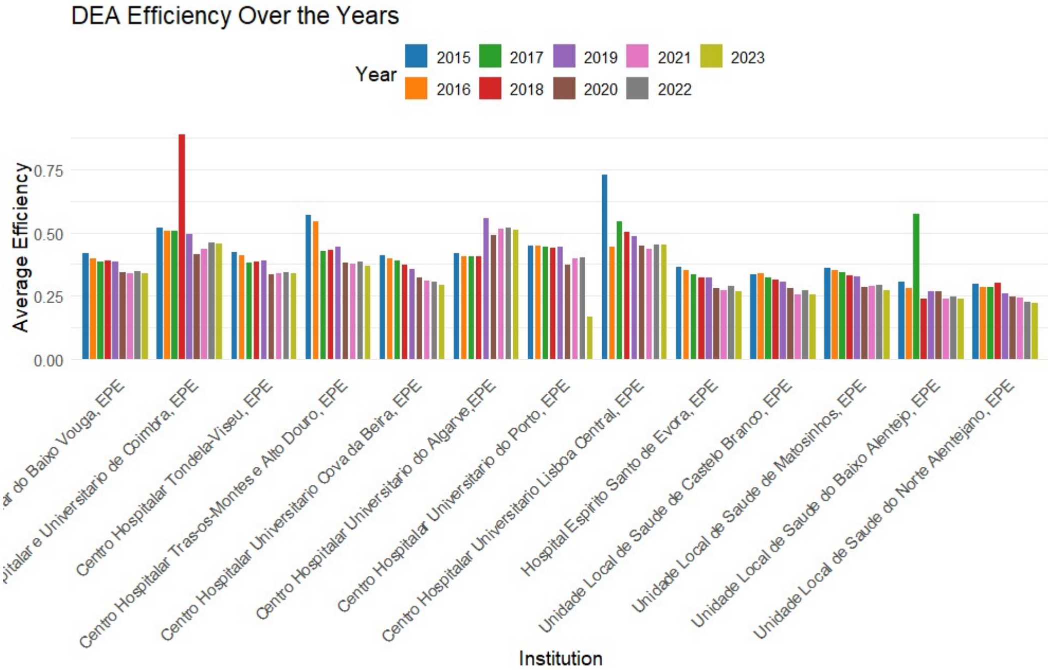


Figure 17: Levels of efficiency for every year computed with unbiased DEA

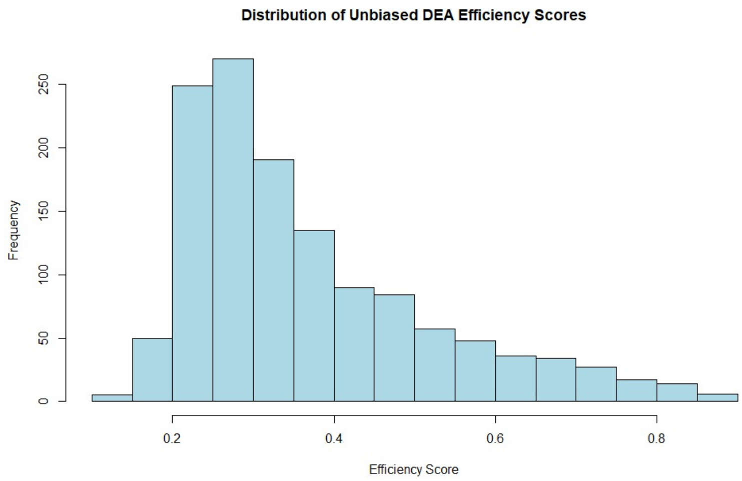


Figure 18: Distribution of efficiency scores

4.3 Results

The analysis of the results obtained in the order M model and in the bootstrapped one compared with the **trend of the telemedicine consultations** (figure 10) shows that there is **no significant impact of telemedicine over the efficiency** in the considered hospitals however it also suggests that **huge improvements can be made in that area**.
These findings align with the recent report by **EIT Health** (EIT, 2020), which highlights that, despite **higher rates of Portugal's telemedicine adoption** compared to other European countries, its utilization is hindered by a **notable lack of expertise and inadequate IT infrastructure**. Additionally, **limited motivation among healthcare professionals** further impedes the potential of telemedicine to enhance efficiency. Emerging technologies in the **VR** and **digital twin** framework have the potential to **significantly improve the efficiency benefits** of telemedicine consultations (Sai et al., 2024) since they enable hospitals to reduce the number of patients **physically present** in the hospital by effectively monitoring and managing their health from **home**, thereby **optimizing hospital capacity and resource allocation**.

4.3.1 Conditional measures of efficiency and results

External environmental variables play a crucial role in comparative efficiency analysis, as they can significantly influence the performance of decision-making units (DMUs). The selection of these variables should be carefully performed on a case-by-case basis, relying on expert knowledge and a thorough understanding of the specific study context.
To assess their impact, external variables it must first be **incorporated into the frontier estimation** model. It is then necessary to analyze whether these variables **affect the production process** and, consequently, **the efficiency scores** of the DMUs. This approach allows for a systematic evaluation of the extent and nature of their influence.

- **Separability:** The results for separability are obtained by testing a **subset of 600** observations using 4 splits and a high number of repetitions to increase statistical significance. Given the large dimension of the dataset, a **medium-high value** of NSPLIT has been used in order to increase the **robustness without compromising the stability of the test.** This parameter determines the number of subsets in which the dataset is split, each one being locally analyzed, by leading to a clearer search of evidence for the test in consideration. These values of τ represent respectively a **strong assumption of non separability of data and a not significant one** with respect to 2 different components. The test is actually **penalized** by the use of a reduced subset of 600 observations, but it is essential in order to obtain an **acceptable running time**.

Metric	Separability
τ	$1.7260, 0.5999$
P-value	$0.0497, 0.3606$

Therefore the examination of the chosen external factor (population) size revealed only **small differences** in efficiency levels across differently populated regions , as illustrated in Figure 19 and 20 with the **Alentejo** region standing out the **highest overall efficiency**. This demonstrates an efficiency trend that is **independent of the population** and region served, indicating an almost uniform distribution of efficiency across regions with different levels of population.

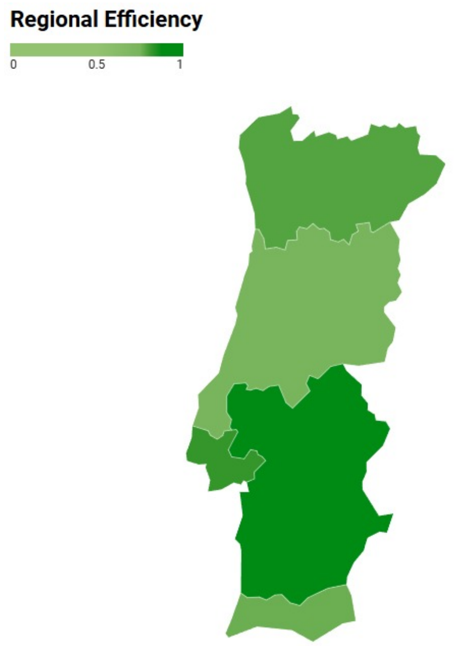


Figure 19: Regional Efficiency

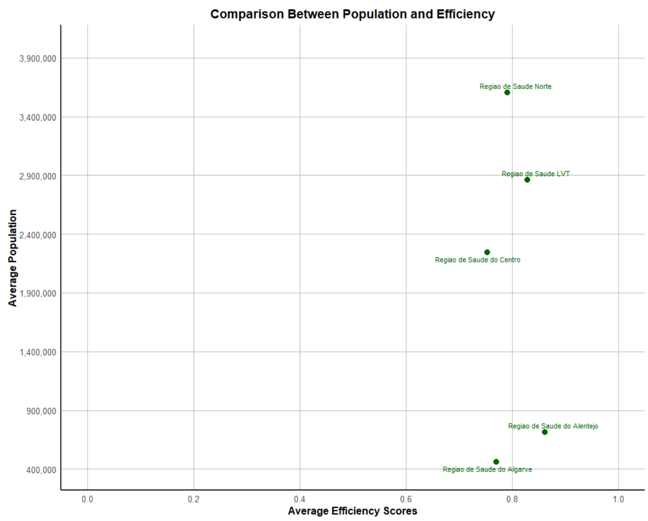


Figure 20: Comparison Between Population and Efficiency

5 Conclusions

This study has explored the **transformative role** of Virtual Reality (VR) technologies in the healthcare sector, particularly in medical training, telemedicine and surgical applications through a systematic review of existing literature and a robust efficiency analysis. The findings highlight VR significant potential to **revolutionize healthcare practices**.

The research demonstrates that VR-based training of professionals provides **superior educational outcomes** compared to traditional methods, offering interactive, risk-free, and repeatable simulations that enhance medical skill acquisition and procedural accuracy. Additionally, the integration of haptic feedback and digital twins promises to further **bridge the gap** between theoretical learning and hands-on practice.

In resource-constrained environments, VR offers s**calable and cost-effective solutions** to address disparities in medical education, while systems like STAR showcase the potential for remote surgical guidance, improving access to expertise in austere settings. However, limitations such as technological costs, infrastructure requirements, and scalability challenges remain **critical barriers** to widespread adoption. From a telemedicine perspective, the study reveals that while digital technologies like VR enhance remote care efficiency, their **full impact is hindered** by inadequate IT infrastructure and a lack of training among healthcare professionals. At the current stage, as shown in the analysis there is **no direct link** between efficiency and the number of telemedicine consultation, however the study of these data helps to **identify areas in which improvements can be made** to be able to fully exploit the advantages of this new technology. The study assessed the potential of virtual reality, particularly digital twin technology, to make telemedicine consultations a **key driver** in improving hospital efficiency. Overall, this research underscores that VR technologies hold **great promise for enhancing healthcare outcomes**.

Ongoing investment in technology development, infrastructure, and professional training will be essential to fully realize the potential of virtual reality, ensuring its integration as a **core component of modern healthcare systems** worldwide.

A Appendix

Filtered Scopus Query:

```
(TITLE-ABS-KEY (healthcare OR "Health Care" OR "simulated operating room" OR
"telemedicine") AND
TITLE ("virtual reality" OR "Simulated reality" OR "Mixed Reality" OR "digital twin"
OR "augmented reality")
AND TITLE-ABS-KEY ("haptic feedback" OR "surgical education" OR "surgical training" OR
"surgery" OR
"Simulation Training" OR "distance healthcare" OR "Medical Skills")) AND PUBYEAR >
2014 AND
PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) AND
(LIMIT-TO (PUBSTAGE, "final")) AND (EXCLUDE (EXACTKEYWORD, "Anxiety") OR EXCLUDE
(EXACTKEYWORD, "Systematic Review") OR EXCLUDE (EXACTKEYWORD, "Empathy")).
```

Non Filtered Scopus Query:

```
(TITLE-ABS-KEY (healthcare OR "Health Care" OR "simulated operating room" OR
"telemedicine") AND
TITLE ("virtual reality" OR "Simulated reality" OR "Mixed Reality" OR "digital twin"
OR "augmented reality")
AND TITLE-ABS-KEY ("haptic feedback" OR "surgical education" OR "surgical training" OR
"surgery" OR
"Simulation Training" OR "distance healthcare" OR "Medical Skills")) AND PUBYEAR >
2014 AND
PUBYEAR < 2025.
```

Distribution of data:

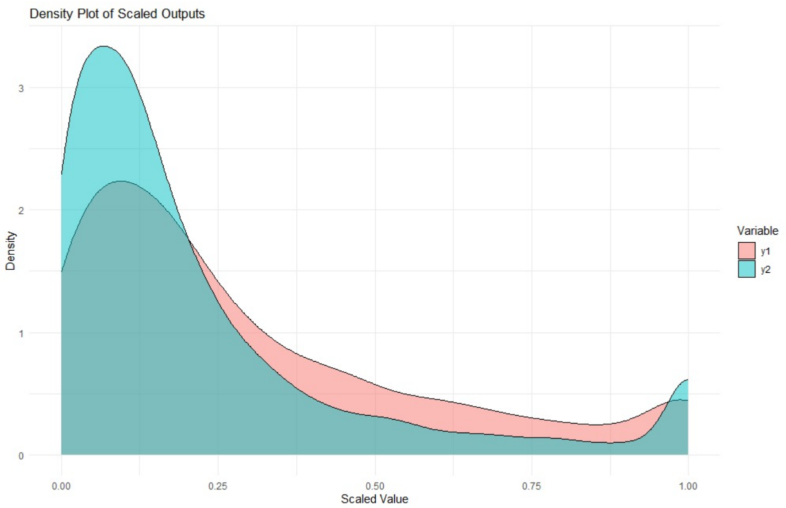


Figure 21: Distribution of outputs

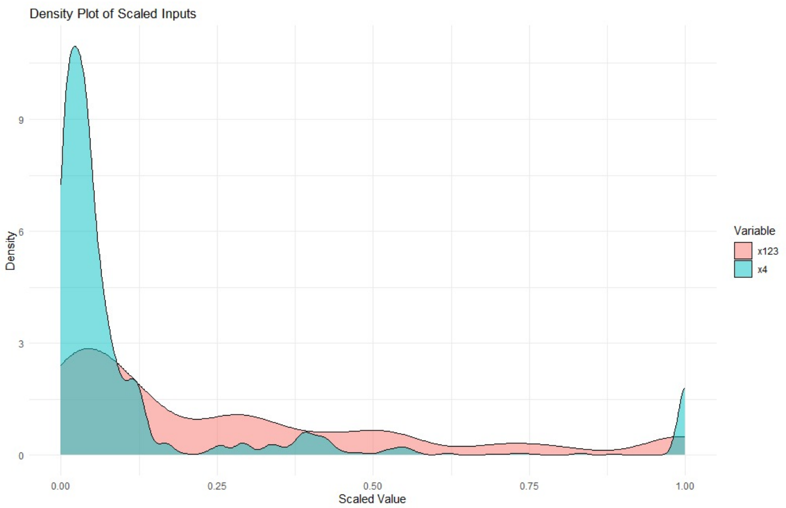


Figure 22: Distribution of input

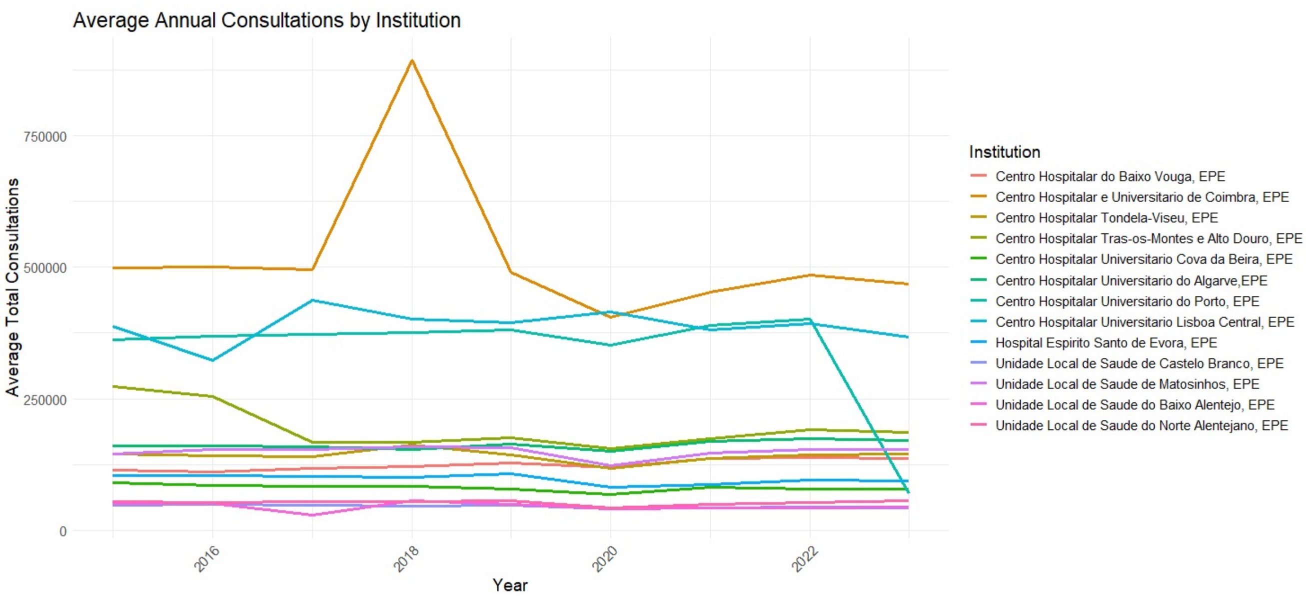


Figure 23: Evolution of total consultants over time

Table 4: Inputs and Outputs, Indicators for Efficiency Analysis

Type	**Indicator**	**Reference**	**Justification**
Input	Number of Doctors	Trabalhadores por Grupo Profissional SNS dataset	Essential for effective healthcare delivery.
Input	Number of Nurses	Trabalhadores por Grupo Profissional SNS dataset	Nurses support patient management and consultations.
Input	Practical capacity	Taxa de Ocupação Hospitalar SNS dataset.	Refers to the number of patients that a hospital can effectively serve within its current operational constraints.
Input	Total in-person Consultations Performed	Consultas Médicas Hospitalares SNS dataset	Serves as an indicator of in-person services delivery capacity and utilization.
Input	Total telemedicine Consultations Performed	Consultas em Telemedicina dataset	Serves as an indicator of telemedicine services delivery capacity and utilization.
Output	Total Hospital Expenditure	RAgregados Económico Financeiros SNS dataset	assesses the hospital's efficiency in managing economic resources and controlling cost.
Output	Number of Patients Treated	Lotação Hospitalar para Doentes SNS dataset	Reflects the hospital's capacity to handle treatments.

Table 5: Exogenous variables considered in the efficiency analysis.

Exogenous Variables	**Reference**	**Description**
Regional Population	Eurostat Population Dataset	Could affect efficiency due to varying demands on services and infrastructure availability.

References

Almousa, O., Prates, J., Yeslam, N., Mac Gregor, D., Zhang, J., Phan, V., Nielsen, M., Smith, R., & Qayumi, K. (2019). Virtual reality simulation technology for cardiopulmonary resuscitation training: An innovative hybrid system with haptic feedback. *Simulation and Gaming*, *50*(1), 6–22. https://doi.org/10.1177/1046878118820905

Amini, A., Allgaier, M., Saalfeld, S., Stein, K.-P., Rashidi, A., Swiatek, V., Sandalcioglu, I., & Neyazi, B. (2024). Virtual reality vs phantom model: Benefits and drawbacks of simulation training in neurosurgery. *Operative Neurosurgery*, *27*(5), 618–631. https://doi.org/10.1227/ons.0000000000001167

Andersen, D., Popescu, V., Cabrera, M., Shanghavi, A., Mullis, B., Marley, S., Gomez, G., & Wachs, J. (2017). An augmented reality-based approach for surgical telementoring in austere environments. *Military Medicine*, *182*, 310–315. https://doi.org/10.7205/MILMED-D-16-00051

Barber, S., Jain, S., Son, Y.-J., & Chang, E. (2018). Virtual functional endoscopic sinus surgery simulation with 3d-printed models for mixed-reality nasal endoscopy. *Otolaryngology - Head and Neck Surgery (United States)*, *159*(5), 933–937. https://doi.org/10.1177/0194599818797586

Caglar, Y., Zaimoglu, M., Ozgural, O., Erdin, E., Alpergin, B., Mete, E., & Dogan, I. (2024). Mixed reality assisted navigation guided microsurgical removal of cranial lesions. *Turkish Neurosurgery*, *34*(5), 926–938. https://doi.org/10.5137/1019-5149.JTN.44974-23.2

Calatayud, D., Arora, S., Aggarwal, R., Kruglikova, I., Schulze, S., Funch-Jensen, P., & Grantcharov, T. (2010). Warm-up in a virtual reality environment improves performance in the operating room. *Annals of Surgery*, *251*(6), 1181–1185. https://doi.org/10.1097/SLA.0b013e3181deb630

Carl, B., Bopp, M., Saß, B., Voellger, B., & Nimsky, C. (2019). Implementation of augmented reality support in spine surgery. *European Spine Journal*, *28*(7), 1697–1711. https://doi.org/10.1007/s00586-019-05969-4

Casas-Yrurzum, S., Gimeno, J., Casanova-Salas, P., García-Pereira, I., García del Olmo, E., Salvador, A., Guijarro, R., Zaragoza, C., & Fernández, M. (2023). A new mixed reality tool for training in minimally invasive robotic-assisted surgery. *Health Information Science and Systems*, *11*(1). https://doi.org/10.1007/s13755-023-00238-7

Cho, K.-H., Papay, F., Yanof, J., West, K., Gharb, B., Rampazzo, A., Gastman, B., & Schwarz, G. (2021). Mixed reality and 3d printed models for planning and execution of face transplantation. *Annals of Surgery*, *274*(6), E1238–E1246. https://doi.org/10.1097/SLA.0000000000003794

Dario, W., Simar. (2019). Fast and efficient computation of directional distance estimators. https://link.springer.com/article/10.1007/s10479-019-03163-9?

Desselle, M., Brown, R., James, A., Midwinter, M., Powell, S., & Woodruff, M. (2020). Augmented and virtual reality in surgery. *Computing in Science and Engineering*, *22*(3), 18–26. https://doi.org/10.1109/MCSE.2020.2972822

EIT. (2020). Portugal in the e-health path. https://eithealth.eu/news-article/portugal-launches-its-national-telehealth-as-the-first-country-in-the-world/

Elsakka, A., Park, B., Marinelli, B., Swinburne, N., & Schefflein, J. (2023). Virtual and augmented reality in interventional radiology: Current applications, challenges, and future directions. *Techniques in Vascular and Interventional Radiology*, *26*(3). https://doi.org/10.1016/j.tvir.2023.100919

Ghaednia, H., Fourman, M., Lans, A., Detels, K., Dijkstra, H., Lloyd, S., Sweeney, A., Oosterhoff, J., & Schwab, J. (2021). Augmented and virtual reality in spine surgery, current applications and future potentials. *Spine Journal*, *21*(10), 1617–1625. https://doi.org/10.1016/j.spinee.2021.03.018

Gießer, C., Schmitt, J., Lowenstein, E., Weber, C., Braun, V., & Bruck, R. (2024). Skillslab+ - a new way to teach practical medical skills in an augmented reality application with haptic feedback. *IEEE Transactions on Learning Technologies*, *17*, 2034–2047. https://doi.org/10.1109/TLT.2024.3435979

Hofman, J., De Backer, P., Manghi, I., Simoens, J., De Groote, R., Van Den Bossche, H., D'Hondt, M., Oosterlinck, T., Lippens, J., Van Praet, C., Ferraguti, F., Debbaut, C., Li, Z., Kutter, O., Mottrie, A., & Decaestecker, K. (2024). First-in-human real-time ai-assisted instrument deocclusion during augmented reality robotic surgery. *Healthcare Technology Letters*, *11*(2-3), 33–39. https://doi.org/10.1049/htl2.12056

Kenngott, H., Pfeiffer, M., Preukschas, A., Bettscheider, L., Wise, P., Wagner, M., Speidel, S., Huber, M., Nickel, F., Mehrabi, A., & Müller-Stich, B. (2022). Imhotep: Cross-professional evaluation of a three-dimensional virtual reality system for interactive surgical operation planning, tumor board discussion and immersive training for complex liver surgery in a head-mounted display. *Surgical Endoscopy*, *36*(1), 126–134. https://doi.org/10.1007/s00464-020-08246-4

Liu, K., Chen, S., Wang, X., Ma, Z., & Shen, S. (2024). Utilization of facial fat grafting augmented reality guidance system in facial soft tissue defect reconstruction. *Head and Face Medicine*, *20*(1). https://doi.org/10.1186/s13005-024-00445-x

Lu, L., Wang, H., Liu, P., Liu, R., Zhang, J., Xie, Y., Liu, S., Huo, T., Xie, M., Wu, X., & Ye, Z. (2022). Applications of mixed reality technology in orthopedics surgery: A pilot study. *Frontiers in Bioengineering and Biotechnology*, *10*. https://doi.org/10.3389/fbioe.2022.740507

Neupane, A., Alsadoon, A., Prasad, P., Ali, R., & Haddad, S. (2020). A novel modified chaotic simplified advanced encryption system (mcs-aes): Mixed reality for a secure surgical tele-presence. *Multimedia Tools and Applications*, *79*(39-40), 29043–29067. https://doi.org/10.1007/s11042-020-09478-1

Petrone, S., Cofano, F., Nicolosi, F., Spena, G., Moschino, M., Di Perna, G., Lavorato, A., Lanotte, M., & Garbossa, D. (2022). Virtual-augmented reality and life-like neurosurgical simulator for training: First evaluation of a hands-on experience for residents. *Frontiers in Surgery*, *9*. https://doi.org/10.3389/fsurg.2022.862948

Please, H., Narang, K., Bolton, W., Nsubuga, M., Luweesi, H., Richards, N., Dalton, J., Tendo, C., Khan, M., Jjingo, D., Bhutta, M., Petrakaki, D., & Dhanda, J. (2024). Virtual reality technology for surgical learning: Qualitative outcomes of the first virtual reality training course for emergency and essential surgery delivered by a uk–uganda partnership. *BMJ Open Quality*, *13*(1). https://doi.org/10.1136/bmjoq-2023-002477

Pollock, A., & Berge, E. (2018). How to do a systematic review [PMID: 29148960]. *International Journal of Stroke*, *13*(2), 138–156. https://doi.org/10.1177/1747493017743796

Queisner, M., Pogorzhelskiy, M., Remde, C., Pratschke, J., & Sauer, I. (2022). Volumetricor: A new approach to simulate surgical interventions in virtual reality for training and education. *Surgical Innovation*, *29*(3), 406–415. https://doi.org/10.1177/15533506211054240

Racy, M., Barrow, A., Tomlinson, J., & Bello, F. (2021). Development and validation of a virtual reality haptic femoral nailing simulator. *Journal of Surgical Education*, *78*(3), 1013–1023. https://doi.org/10.1016/j.jsurg.2020.10.004

Riddle, E., Kewalramani, D., Narayan, M., & Jones, D. (2024). Surgical simulation: Virtual reality to artificial intelligence. *Current Problems in Surgery*, *61*(11). https://doi.org/10.1016/j.cpsurg.2024.101625

Rojas-Muñoz, E., Cabrera, M., Lin, C., Andersen, D., Popescu, V., Anderson, K., Zarzaur, B., Mullis, B., & Wachs, J. (2020). The system for telementoring with augmented reality (star): A head-mounted display to improve surgical coaching and confidence in remote areas. *Surgery (United States)*, *167*(4), 724–731. https://doi.org/10.1016/j.surg.2019.11.008

Sai, S., Prasad, M., Garg, A., & Chamola, V. (2024). Synergizing digital twins and metaverse for consumer health: A case study approach. *IEEE Transactions on Consumer Electronics*, *70*(1), 2137–2144. https://doi.org/10.1109/TCE.2024.3367929

Sibomana, O. (2024). Could virtual reality be a solution in surgical trainings in resource-restricted settings? a perspective. *Surgery Open Science*, *21*, 14–16. https://doi.org/10.1016/j.sopen.2024.08.004

Siu, K.-C., Best, B., Kim, J., Oleynikov, D., & Ritter, F. (2016). Adaptive virtual reality training to optimize military medical skills acquisition and retention. *Military Medicine*, *181*(5), 214–220. https://doi.org/10.7205/MILMED-D-15-00164

Vashishth, T., Kumar, B., Panwar, R., Sharma, K., Chaudhary, S., & Sharma, M. V. (2023, October). Virtual reality (vr) and augmented reality (ar) transforming medical applications. https://doi.org/10.4018/979-8-3693-0876-9.ch020

Zhang, J., Gao, F., & Ye, Z. (2020). Remote consultation based on mixed reality technology. *Global Health Journal*, *4*(1), 31–32. https://doi.org/10.1016/j.glohj.2020.01.001

Zhang, J., Zhao, Y., Shone, F., Li, Z., Frangi, A., Xie, S., & Zhang, Z.-Q. (2023). Physics-informed deep learning for musculoskeletal modeling: Predicting muscle forces and joint kinematics from surface emg. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *31*, 484–493. https://doi.org/10.1109/TNSRE.2022.3226860

Zhu, M., Sun, Z., Zhang, Z., Shi, Q., He, T., Liu, H., Chen, T., & Lee, C. (2020). Haptic-feedback smart glove as a creative human-machine interface (hmi) for virtual/augmented reality applications. *Science Advances*, *6*(19). https://doi.org/10.1126/sciadv.aaz8693