

Critical Success Factors for Virtual Reality Applications in Orthopaedic Surgical Training: A Systematic Literature Review

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ABSTRACT There is an increasing pressure to improve the cost-effectiveness of orthopaedic training, both temporally and financially. Accordingly, virtual reality (VR) has been incorporated into a number of surgical training programs, providing trainees a safe yet realistic environment to practice their craft before going into the operating room. Identification of critical success factors (CSFs) for VR integration in the orthopaedic training program, can be beneficial in guiding the focus of healthcare providers and VR designers during the VR platform development stage. The aim of this study is to identify VR-based training CSFs that encourage orthopaedic surgeons to use VR as a method for acquiring, maintaining, and improving skills. A total of 74 studies conducted between 2011 and 2021 were selected and examined. There were 73 CSFs listed as being essential for VR adoption in orthopaedic surgical training. The CSFs were divided into six general categories: HCI/VR Features, Learning Outcome, Usability, Control and Active Learning, Student and Limitation factors. Subsequently, recommendations were made to guide healthcare professionals, researchers, and designers for optimal adoption of VR in orthopaedic surgical training in the future.

INDEX TERMS Arthroscopy, critical success factors, orthopaedic training, virtual reality.

I. INTRODUCTION

Orthopaedic is a field of medicine concerned with the pathology, physiology, and disease of the musculoskeletal system [1]. Accordingly, an orthopaedic surgeon is a medical professional that specialises in diagnosis and management of diseases related to the musculoskeletal system [2]. Their qualifications include a medical degree, followed by four years of orthopaedic residency training. An orthopaedic surgeon who has undergone extensive preparation is authorized to perform a variety of tasks including examining orthopaedic cases and performing surgery when necessary [2].

The ever-growing elderly population has increased the need for orthopaedic surgeons that can accommodate the resulting healthcare demand, particularly on age-related orthopaedic disease such as osteoarthritis [3]. Additionally, the inevitable retirement of senior orthopaedic surgeons, stresses the importance of training novice clinician into

the orthopaedic field [4]. However, expertise in orthopaedic surgery is a technical skill that grows with experience, and orthopaedic training programs have been cited to be both arduous and demanding [5].

For decades, long hours of training were thought to be necessary in training novice orthopaedic surgeons [6]. The extensive training undergone by orthopaedic surgeons is mainly attributed to the level of complexity involve with the tasks related to this discipline [5]. In particular, orthopaedic surgeries often necessitate a clear understanding of the complex anatomy and physiology of the musculoskeletal system, including changes to it during disease pathology. Often, a great deal of cognitive awareness is required to carefully navigate through parts of the body that are not affected by the disease, to reach the surgery site [5].

In recent years, burnout has been recognised as a crucial factor that has led to deterioration of both cognitive and technical skills among the surgical trainees [7]. Moreover, orthopaedic surgeons are also engaged in academic works on musculoskeletal disorders during their training, in addition

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to working in the operating room [8]. Accordingly, the idea of long workweeks for orthopaedic training is no longer acceptable and many countries have imposed a limit to the working hours of orthopaedic surgical trainee [9].

Aside from these internal challenges, external challenges also exist. Training of orthopaedic surgeon with patient will not only increase the liability towards the patient, but it is also limited in terms of repeatability and inability to simulate the different level of difficulties [10]. Moreover, many of the well established methods of teaching in orthopaedic, require additional resources such as anatomical models or cadavers [11]. These resources come at the cost of finances that may have not be abundant in some institutions. Furthermore, problems with unusable cadaveric tissue, caused by alteration during the specimen preparation process, also hinders the positive outcome of an orthopaedic surgical training [12]. Besides the issues with patient and cadaveric tissues, training delivery can also vary among the surgical trainers. Not only that, even the appraisal of trainee's surgical skills can also be affected by individual trainer's bias [13]. Consequently, current training approaches for orthopaedic interns and residents in most teaching hospitals, have been acknowledged to be inadequate to produce expert level surgeons, without enduring tremendous costs in terms of finance and time [10].

Along with the emergence of the 4th industrial revolution, enduring daily tasks are gradually becoming easier with the aid of so many technological breakthroughs in this age. Among them are the virtual reality (VR) technology, a simulation system that allows users to immerse themselves in and communicate with a 3D, computer-generated world in real time. For decades, VR has been used in a variety of industries and contexts, from consumer applications and manufacturers, to the airlines industry [14]–[16]. In the aviation industry, VR offers great value in flight simulation applications, tremendously improving pilot training, while reducing the financial and temporal burden [17].

Accordingly, records on adaptation of VR technology in the light of medical and surgical education can be traced back to the start of the 21st century [18]. It is an area that is constantly being developed, and continuously gathering interest as its benefits become increasingly clear over the years. Moreover, the maturation of software and hardware related to VR have perpetually expanded the utility of the technology. VR surgical simulation allows the surgical approaches to be rehearsed and refined, allowing trainees to access a range of techniques, with no added liability to the patients [10].

In the field of orthopaedic, the earliest record on VR-based training in orthopaedic surgery can be traced back to the early 2000s [18]. However, since VR is a relatively new technology, research done on this approach of orthopaedic surgical training is still at its infancy stage. Nevertheless, reports on positive real-world effects of its use are available [10], [19], [20]. VR-based training is utilised in two different ways in orthopaedic surgery. First, to improve comprehension

and technical performance of the trainee in comparison to traditional methods [21]–[23], and second, to appraise surgical skills of trained orthopaedic surgeons [24]–[26]. Understanding the critical success factors (CSFs) behind these reports could highlight a research opportunity to further improve the system, particularly at the integration stage of each individual system, into the curriculum of surgeon training.

The term CSFs can be traced back to as early as the 1980s, at a time where competition among businesses was at its peak [27]. The need to understand why some companies were more successful than others has given birth to the study of CSFs [28]. CSFs include every factor that can influence the success of an organisation, whether it is the one that induces or the one that limits it. It is everything that must be done if an organisation is to be competitive.

In the context of VR-based training in orthopaedic surgery, CSFs are factors that determines the success or failure in achieving its goals. These factors can be used as a theoretical framework that guides the development and evaluation of virtual training tools via the design science research methodology [29]. Studies that define CSFs, not only in VR implementation for orthopaedic surgical training, but in any training in the medical field, are practically non-existent. Previously, Benferdia *et al.* (2018) reported the CSFs that have affected VR adoption in the ophthalmology domain [30]. The aim of this study is to identify CSFs that can help healthcare providers, researchers, and designers to design an optimum VR experience in orthopaedic training and learning. Using a systematic literature review, the analysis seeks to categorise VR CSFs and specify the essential factors within each category.

II. REVIEW METHOD

A. RESEARCH IDENTIFICATION

A systematic study of the literature was conducted to identify reports on virtual reality-based training (VRT) in the orthopaedic domain using relevant databases including Medline (PubMed), ACM Digital Library, IEEE Xplore, Science Direct, and Web of Science. The search string was devised from a combination of keywords representing the orthopaedic surgery (“orthop*” OR “surgery” OR “arthrop*”) and the VRT (“simulator” OR “simulation” OR “training” OR “virtual reality” OR “vr”) [10].

B. INCLUSION AND EXCLUSION CRITERIA

Studies published between 2011 and 2021 in the English language that reported the use of VR in any orthopaedic related procedure were considered. Any study that clearly indicated any CSF related to orthopaedic training was prioritised for inclusion into the review. Furthermore, studies that were not in the English language, that focused on VR but not within the healthcare field, that did not use VR as their primary focus, that did not answer the research questions, that were opinion pieces or viewpoints, or that were in the form of

books, editorial notes, editorials, prefaces, poster sessions, panels and tutorial summaries, interviews, or news items were excluded.

C. STUDY SELECTION

Study selection was conducted in five stages. At the first stage, the search result from the keyword search were compiled, before duplicated studies were excluded using the reference manager software, Mendeley. Subsequently, records were screened for relevancy based on the title and abstract. Then, the full text of the remaining studies was evaluated to finalise their inclusion. A manual search was used to supplement the findings of the database search, allowing a broad perspective of the review [31].

D. ASSESSMENT OF STUDY QUALITY

The quality of studies included in a systematic review is subjective and varies according to the purpose of the review [31]. A list of criteria that determines the quality of a particular study for identification of CSF has been described previously. There are five criteria including whether or not 1) CSF is clearly described in the study, 2) the study is relevant to the topic of the review, 3) the context of the study fits the review, 4) recommendations for overcoming challenges are described in the study, and 5) research gaps for further research are described in the study [30].

The schema included three different values, namely high, medium, and low. As a result, the quality of each study was determined by these scores. Those studies that met a criterion received a two-point score. A score of one indicated that a study only marginally fulfilled a criterion. Finally, if a study failed to meet the criteria, it was given a score of zero. Studies with a score of seven or higher received a high score, while studies with a score of six received a medium score. A low score was defined as anything below six.

E. BIBLIOMETRIC ANALYSIS

The studies included were further evaluated with regards to their impact to the orthopaedic VRT field using bibliometric analysis. Number of citations for each study, annual publication distribution, and geographical distribution of the included studies were noted [30].

F. DATA ANALYSIS

Information on the CSF cited in each study was extracted and categorised into six distinct categories namely hardware-computer interface VR (HCI/VR) features, usability, learning outcomes, student characteristics, control and active learning, and limitation factors. This is in accordance with a previous study done to identify CSF in VR-based ophthalmology surgical training [30]. Categorised factors were then evaluated by judges to verify their validity. The distribution of the factors across the studies included were noted to rank them, giving sense of the importance of each individual factor.

III. RESULTS

A. OUTCOME OF SYSTEMIC LITERATURE SEARCH

The literature search identified 575 potentially relevant records from all the five databases used. A total of 421 duplicate records were excluded before the remaining records were assessed for inclusion or exclusion based on title and abstract. The full texts of the resulting 80 records were perused to further confirm their inclusion. Following discussion with the judges, 66 final studies were included in the data analysis. A flow chart of the selection process, including reasons for exclusion, is shown in Fig. 1.

B. STUDY CHARACTERISTICS

From the 66 studies included, 33 studies investigated the effect of VR-based training on surgical performance of trainees in comparison to traditional training program or no training. Next, 27 studies utilise orthopaedic surgery VR simulators to measure the surgical performance of surgeons at different levels of competences and experiences. An investigation on the effect of VR on learning curve was explored by five studies and the topic of retention of trainee in the surgical training program was explored by one study. The characteristics of the study included were detailed in Table 1. All included studies, satisfy the criteria that determines their quality in terms of CSF identification (Table 2).

The quality of each of the included study was judged by noting their citation rates as illustrated in Fig. 2. Majority of the studies have been cited not more than 20 times. Articles published earlier were cited more than 50 times with one study by Cannon *et al.* 2014, having the most citation with 127 citations. This study was a randomized controlled trial that looks into the improvement in knee arthroscopy technique following training using ArthroSim VR simulator compared to institution-specific conventional training. On the opposite spectrum, the three studies that have zero citation were all published in 2020 and were relatively new.

The distribution of the extracted studies by year is depicted in Fig. 3, demonstrating that the number of published studies on orthopaedic VR training has consistently increase over the last ten years. Since 2011, the publications grew in a linear fashion and peaked at 15 in 2020. Only the year 2012 demonstrated zero publication. The rise in the number of studies since 2011 may have steadily demonstrated VR's effectiveness, which may be a strong indication that VR has been widely accepted by orthopaedic surgeons as a learning and teaching method. Moreover, many of the publications were co-authored by the same author, indicating an increase in the number of experts in orthopaedic VRT. Furthermore, a growing body of literature signifies a deeper understanding of this particular subject with a wealth of evidence to support VRT use in orthopaedic surgical curriculum.

Fig. 4 depicts the geographical distribution of the published studies. Most of the studies were conducted in Europe and North America, with 50 percent and 41 percent of scholars from European and North American institutions, respectively.

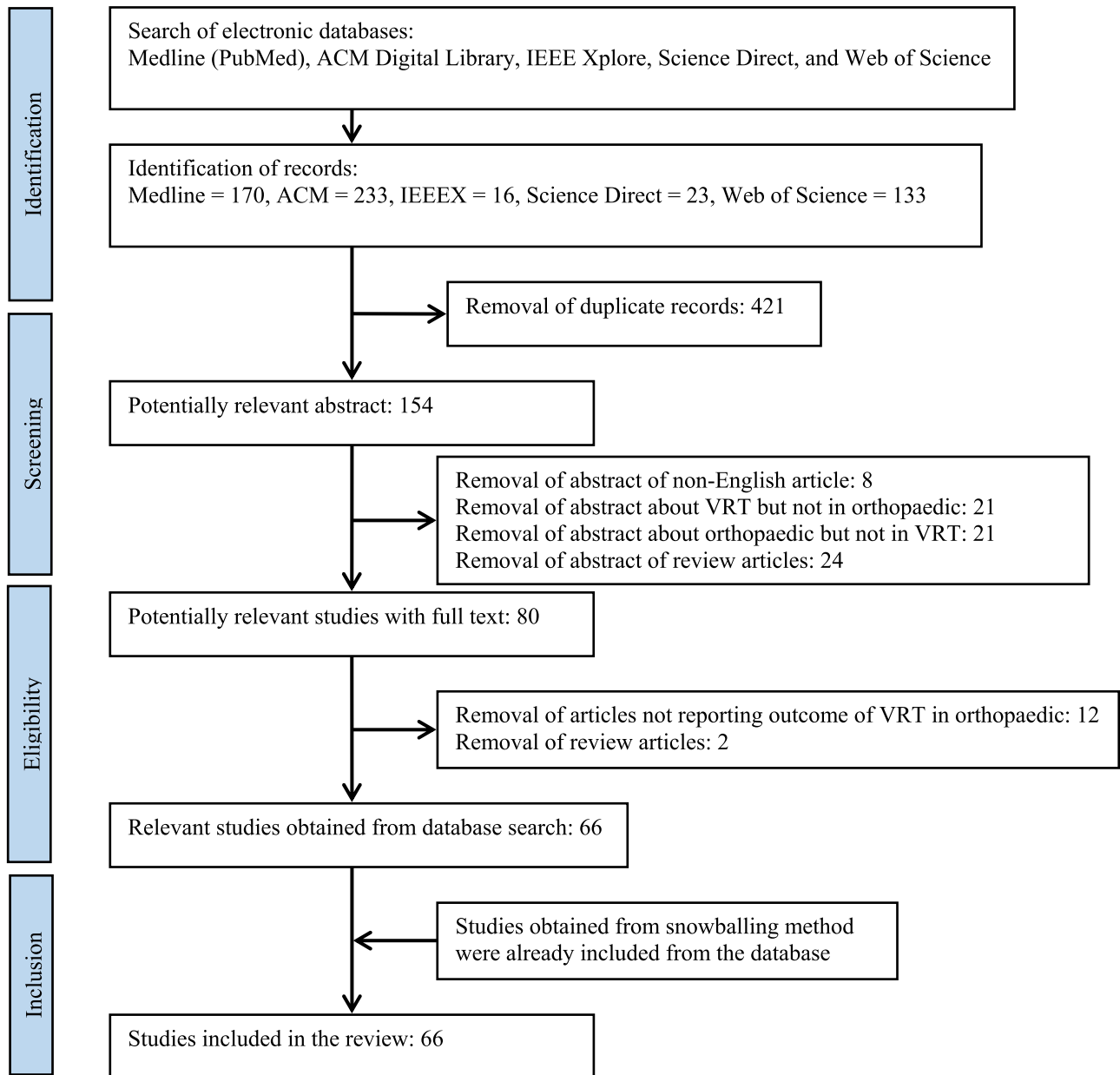


FIGURE 1. Flow chart of study selection procedure.

As a result, almost all of the factors listed in this paper were derived from Europe and North America. This finding might be contributed by the fact that a majority of the included studies use commercially available VR platforms that are manufactured in countries within Europe and North America. Accordingly, this information is useful for candidate orthopaedic surgeons that are seeking for residency at an institution equipped with VR training curriculum. Notably, only 9% of the published studies hail from Asia. This could be due to the limitation in terms of logistic and cost of procuring the hardware required for VR training, particularly considering the location and currency exchange. Interestingly, no published studies were found to affiliated with Australia, South

America, and Africa which may indicate a barrier in adoption of VR in these continents.

From these studies, 73 CSFs were identified and categorised into HCI/VR) features, usability, learning outcomes, student characteristics, control and active learning, and limitation factors. Fig. 5 illustrates the taxonomies of the CSFs identified.

C. HCI/VR FEATURE FACTORS

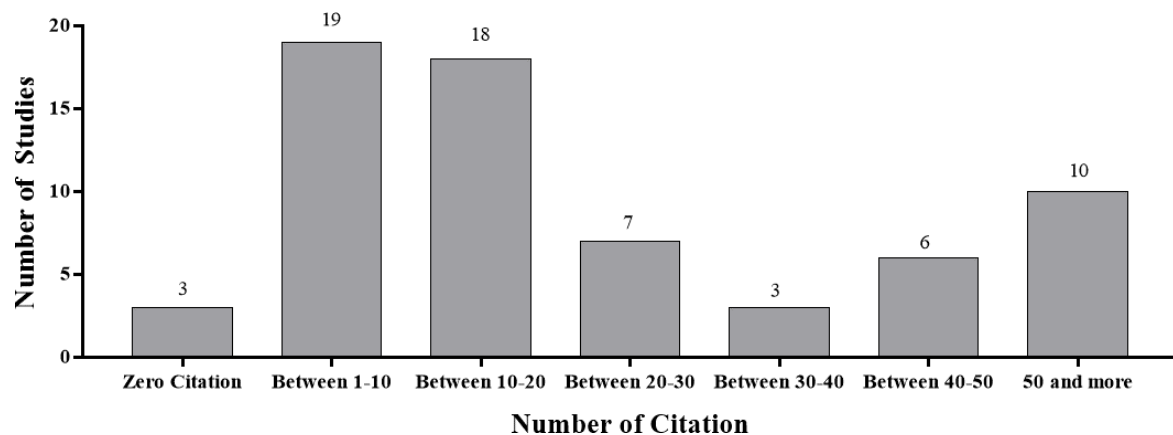
HCI/VR feature factors include technical characteristics of the VR platform used, that can influence the training outcome [32]. Similar to the previous study on VR training in ophthalmology, the CSFs related to HCI/VR can

TABLE 1. Study characteristics.

Ref	Surgical Skills	VR platform	Region
Lohre et al. 2020	Shoulder: Glenoid exposure	PrecisionOS	North America
Lohre et al. 2020	Shoulder: Advanced rotator cuff tear arthroplasty	PrecisionOS	North America
Wilson et al. 2020	Principles of fracture and osteotomy	GoogleCardboard	Europe
Cai et al. 2020	Craniovertebral junction	VR Shinecon	Asia
Orland et al. 2020	Tibia: Intramedullary nailing	OssoVR	North America
Blumstein et al. 2020	Tibia: Intramedullary nailing	OssoVR	North America
Brouwers et al. 2020	Hip: Fracture diagnosis	Meshlab and Simplify 3D	North America
Pietruski et al. 2020	Knee: Fibula free flap osteotomy	Wroclaw University of Technology MentorEye system	North America
Pellicia et al. 2020	Hip: Arthroplasty	Novel haptic VR-based THA surgery simulator	Asia
Mirchi et al. 2020	Spine: Cervical discectomy	Sim-Ortho	North America
Ledwos et al. 2020	Spine: Cervical discectomy	Sim-Ortho	North America
Bouaicha et al. 2020	Knee: Arthroscopy	VirtaMed ArthroS	Europe
Bartlett et al. 2020	Hip: Arthroscopy	Symbionix ArthroMentor	North America
Logishetty et al. 2020	Hip: Total hip arthroplasty	Undisclosed VR for hip arthroplasty	Asia
Rolfing et al. 2020	Hip: Fracture fixation	HipSim	Asia
Wang et al. 2019	Arthroscopy	ArthroVision	Europe
Logishetty et al. 2019	Hip: Total hip arthroplasty	HTC Vive	North America
Bartlett et al. 2019	Hip: Arthroscopy	Symbionix ArthroMentor	Europe
Bartlett et al. 2019	Hip: Arthroscopy	VirtaMed ArthroS	Europe
Homma et al. 2019	Femur: Femoral neck fracture fixation	Swemac Trauma Vision	North America
Bissonnette et al. 2019	Spine: Hemilaminectomy	NueroVR	North America
Koch et al. 2019	Spine: Vertebroplasty	Novel VR for vertebroplasty	North America
Cychosz et al. 2019	Knee: Arthroscopy	VirtaMed ArthroS	Europe
Gustafsson et al. 2019	Femur: Proximal femoral fracture fixation	Swemac Trauma Vision	North America
Rolfing et al. 2019	Hip: Fracture fixation	Swemac Trauma Vision	North America
Xin et al. 2018	Spine: Pedicle screw placement	UG NX8	North America
Cychosz et al. 2018	Knee: Arthroscopy	VirtaMed ArthroS	Europe
Yari et al. 2018	Knee: Arthroscopy	VirtaMed ArthroS	Europe
Courteille et al. 2018	General: history taking and diagnosis	Web-SP	North America
Cecil et al. 2018	Multiple: positioning, screw insertion, fracture reduction	Geomagic Touch	North America
Hou et al. 2018	Spine: Pedicle screw placement	VSTS	North America
Hou et al. 2018	Spine: Pedicle screw placement	VSTS	Europe
Rahm et al. 2018	Knee & Shoulder: Arthroscopy	VirtaMed ArthroS	Europe
Keith et al. 2018	General: Arthroscopy	General VR	Europe
Hendrik et al. 2018	Hip: Screw placement	FluoroSim	Europe
Bhattacharyya et al. 2018	Knee: Arthroscopy	Imperial Knee Arthroscopy Cognitive Task Analysis	North America
Chae et al. 2018	Shoulder: Arthroscopy	Novel haptic VR-based shoulder arthroscopy surgery simulator	North America
Middleton et al. 2017	Knee: Arthroscopy	VirtaMed ArthroS	Europe
Bhattacharyya et al. 2017	Knee: Arthroscopy	Imperial Knee Arthroscopy Cognitive Task Analysis	Europe
Demirel et al. 2017	Shoulder: Arthroscopy	Virtual Arthroscopic Tear Diagnosis Evaluation Platform	Asia
Amer et al. 2017	Carpal tunnel release	TouchSurgery	North America
Roberts et al. 2017	Knee & Shoulder: Arthroscopy	VirtaMed ArthroS	Europe
Khanduja et al. 2017	Hip: Arthroscopy	Symbionix ArthroMentor	Europe
Martin et al. 2016	Knee & Shoulder: Arthroscopy	Symbionix ARTHRO Mentor, VirtaMed ArthroS, Toltech ArthroSim	Europe
Akhtar et al. 2016	Knee: Arthroscopy	Symbionix ArthroMentor	Asia
Camp et al. 2016	Knee: Arthroscopy	Toltech ArthroSim	Europe
Martin et al. 2016	Knee: Arthroscopy	Symbionix ArthroMentor	Europe

TABLE 1. (Continued.) Study characteristics.

Waterman et al. 2016	Shoulder: Arthroscopy	Symbionix Arthro VR	Europe
Rahm et al. 2016	Shoulder: Arthroscopy	VirtaMed ArthroS	Europe
Stunt et al. 2016	Knee: Arthroscopy	Practice Arthroscopic Surgical Skills for Perfect Operative Real-life Treatment V2	Europe
Rahm et al. 2016	Knee: Arthroscopy	VirtaMed ArthroS	Europe
Sugand et al. 2015	Hip: Screw placement	SimBones AB TraumaVision VR	North America
Rebolledo et al. 2015	Knee & Shoulder: Arthroscopy	Insight Arthro VR	Europe
Gandhi et al. 2015	Shoulder: Arthroscopy	GMV Insight Arthro	Europe
Akhtar et al. 2015	Hip: Screw placement	SimBones AB TraumaVision VR	Europe
Koehler et al. 2015	General: Arthroscopy	General VR	North America
Jacobsen et al. 2015	Knee: Arthroscopy	Symbionix ArthroMentor	Europe
Cannon et al. 2014	Knee: Arthroscopy	Toltech ArthroSim	North America
Stunt et al. 2014	Knee: Arthroscopy	VirtaMed ArthroS	Europe
Fucentese et al. 2014	Knee: Arthroscopy	VirtaMed ArthroS	North America
Cannon et al. 2014	Knee: Arthroscopy	Toltech ArthroSim	Europe
Pedersen et al. 2014	Femur: Femoral neck fracture fixation	Swemac Trauma Vision	Europe
Henn et al. 2013	Shoulder: Arthroscopy	Procedicus arthroscopy simulator	North America
LeBlanc et al. 2013	Ulnar: Fracture fixation	Novel VR for fixation of ulnar fractures	Europe
Andersen et al. 2011	Shoulder: Arthroscopy	GMV insightMIST	Europe
Tuijthof et al. 2011	Knee & Shoulder: Arthroscopy	Toltech ArthroSim, GMV Insight Arthro	Europe

**FIGURE 2. Citation rate of the included studies.**

be categorized into hardware, software, control and realism features [30]. Successful performance by the surgeons undergoing VR training is mostly attributed to having VR hardware that simulates real surgical equipment, utility of the head mounted display (HMD), valuable visual input, and the practicality of the 3D morphology of the surgical model.

Alternatively, in terms of the VR platform software, successful outcome is attributed to the immersive environment simulated, particularly in the haptic and technical aspects of the simulated environment, in addition to the graphics simulated. Regarding control features, CSFs identified include the function to import personalised patient data that allows customisation of the training context, as well as the force and

tactile feedbacks that allow the trainee to interact with the simulated environment.

Finally, realism features describe the realism of the platform as rated by the participants, including features like surgical team interaction, patient interaction, coarse movements such as the wrist movements, and fine movements such as the finger sensations and movements.

D. USABILITY FACTORS

The second cluster of CSFs that influence VR-based orthopaedic outcome is the usability factors. These CSFs comprise two sub-clusters, perceived usefulness, and perceived ease of use. Perceived usefulness factors consider

TABLE 2. Study quality assessment.

Ref	CSF clearly described	Relevant to review topic	Context fit the review	Recommendation to overcome challenges	Describe research gap	Total
Lohre et al. 2020	2	2	2	2	2	10
Lohre et al. 2020	2	2	2	2	2	10
Wilson et al. 2020	2	2	2	2	2	10
Cai et al. 2020	2	2	2	2	2	10
Orland et al. 2020	2	2	2	2	2	10
Blumstein et al. 2020	2	2	2	2	2	10
Brouwers et al. 2020	2	2	2	2	2	10
Pietruski et al. 2020	2	2	2	2	2	10
Pellicia et al. 2020	2	2	2	2	2	10
Mirchi et al. 2020	2	2	2	2	2	10
Ledwos et al. 2020	2	2	2	2	2	10
Bouaicha et al. 2020	2	2	2	2	2	10
Bartlett et al. 2020	2	2	2	2	2	10
Logishetty et al. 2020	2	2	2	2	2	10
Rolfing et al. 2020	2	2	2	2	2	10
Wang et al. 2019	2	2	2	2	2	10
Logishetty et al. 2019	2	2	2	2	2	10
Bartlett et al. 2019	2	2	2	2	2	10
Bartlett et al. 2019	2	2	2	2	2	10
Homma et al. 2019	2	2	2	2	2	10
Bissonnette et al. 2019	2	2	2	2	2	10
Koch et al. 2019	2	2	2	2	2	10
Cychosz et al. 2019	2	2	2	2	2	10
Gustafsson et al. 2019	2	2	2	2	2	10
Rolfing et al. 2019	2	2	2	2	2	10
Xin et al. 2018	2	2	2	2	2	10
Cychosz et al. 2018	2	2	2	2	2	10
Yari et al. 2018	2	2	2	2	2	10
Courteille et al. 2018	2	2	2	2	2	10
Cecil et al. 2018	2	2	2	2	2	10
Hou et al. 2018	2	2	2	2	2	10
Hou et al. 2018	2	2	2	2	2	10
Rahm et al. 2018	2	2	2	2	2	10
Keith et al. 2018	2	2	2	2	2	10
Hendrik et al. 2018	2	2	2	2	2	10
Bhattacharyya et al. 2018	2	2	2	2	2	10
Chae et al. 2018	2	2	2	2	2	10
Middleton et al. 2017	2	2	2	2	2	10
Bhattacharyya et al. 2017	2	2	2	2	2	10
Demirel et al. 2017	2	2	2	2	2	10
Amer et al. 2017	2	2	2	2	2	10
Roberts et al. 2017	2	2	2	2	2	10
Khanduja et al. 2017	2	2	2	2	2	10
Martin et al. 2016	2	2	2	2	2	10
Akhtar et al. 2016	2	2	2	2	2	10
Camp et al. 2016	2	2	2	2	2	10
Martin et al. 2016	2	2	2	2	2	10
Waterman et al. 2016	2	2	2	2	2	10
Rahm et al. 2016	2	2	2	2	2	10
Stunt et al. 2016	2	2	2	2	2	10
Rahm et al. 2016	2	2	2	2	2	10
Sugand et al. 2015	2	2	2	2	2	10
Rebolledo et al. 2015	2	2	2	2	2	10
Gandhi et al. 2015	2	2	2	2	2	10
Akhtar et al. 2015	2	2	2	2	2	10
Koehler et al. 2015	2	2	2	2	2	10
Jacobsen et al. 2015	2	2	2	2	2	10
Cannon et al. 2014	2	2	2	2	2	10
Stunt et al. 2014	2	2	2	2	2	10
Fucentese et al. 2014	2	2	2	2	2	10
Cannon et al. 2014	2	2	2	2	2	10
Pedersen et al. 2014	2	2	2	2	2	10
Henn et al. 2013	2	2	2	2	2	10
LeBlanc et al. 2013	2	2	2	2	2	10
Andersen et al. 2011	2	2	2	2	2	10
Tuijthof et al. 2011	2	2	2	2	2	10

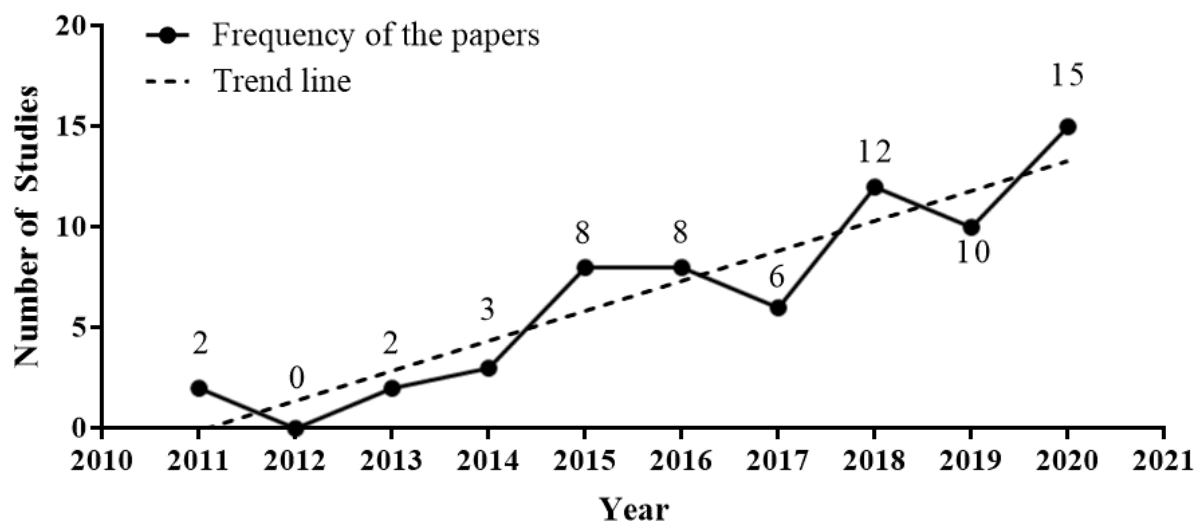


FIGURE 3. Trend in publication by year.

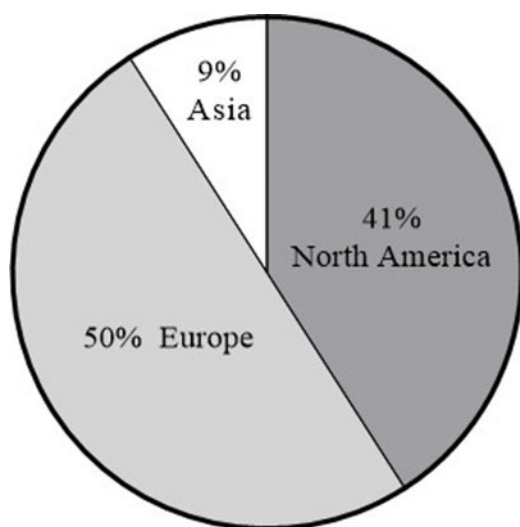


FIGURE 4. Geographic distribution of the published studies on VR-based orthopaedic training.

the potential utility of VR training such as increasing productivity, reducing cost, or ability to teach several surgeries [30].

Perceived usefulness factors identified from the studies revolve around the potential of VR in developing many skills required by the trainee. This includes fine psychomotor skills for open surgery, making sense of the spatial connections between the various anatomical structures, and mastering the rotational and translational dimension of the skeletomuscular system. Furthermore, the validity, reliability, and efficacy of VR training in measuring different levels of surgical skills were also included in the perceived usefulness factors category.

On the other hand, perceived ease of use factors, are factors that prompt the user to choose VR over conventional training

on a basis of simplicity, controllability, or ease. In the context of orthopaedic surgical training, VR was preferred due to the safe simulated environment that allows for reduction of the stress involve in operating. The safe environment also allows proper identification of the surgical pathology, which significantly reduces the complexity of the procedure.

Learning Outcome Factors: The learning outcomes factors that influence the use of VR as a surgical orthopaedic teaching tool are those relevant to the trainee's action and performance [30]. The learning outcome factors can be divided into performance achievement and perceived learning effectiveness, where the former describes the skills improvement displayed by the trainee, while the latter describes other achievements such as improved patient safety and decreased complication.

The most commonly reported performance achievement CSFs are increased accuracy of critical steps, reduction of time to complete the procedure, reduction of camera path length, improved knowledge on arthroscopy, skill transfer validity on cadaver test, and validation of surgical skills according to experience. The remaining performance achievements were less cited due to the available studies being mostly on arthroscopy. They include improved performance and knowledge on glenoid positioning, guide pin orientation, fracture fixation and osteotomy.

In terms of perceived learning effectiveness, a reduced rate of complication, reduced duration of training, long-term retention of surgical skills, reduced amount of resected bone and reduced amount of implant exhaustion were amongst the advantages realised. One study included in the review demonstrated that VR-based orthopaedic training may prevented trainees from dropping out of the surgical training program.

E. STUDENT CHARACTERISTIC FACTORS

Student characteristic factors describe the innate or acquired characteristics of the surgical novices that influence their

HCI/VR Feature Factors				Control and Active Learning Factors
Hardware	Software	Control	Realism	<ul style="list-style-type: none">• Repetition until confidence• Interactive learning• Enjoyable learning• Active learning• Immediate evaluations and feedbacks• Higher student engagement• Sense of purpose• Focused on skill acquisition
<ul style="list-style-type: none">• Simulate real surgical instruments• Head mounted display• 3D morphology• Visual feedback	<ul style="list-style-type: none">• Immersive environment• Haptic aspects of environment• Technical aspects of environment• Graphics	<ul style="list-style-type: none">• Tactile feedback• Context of training• Import function for personalized data• Environment simulation• Force feedback	<ul style="list-style-type: none">• Realistic surgical team interaction• Realistic patient interaction• Simulate wrist movements• Simulate finger sensations and movements	
Usability Factors				
Limitation Factors	Usability Factors			Student Characteristics Factors <ul style="list-style-type: none">• Prior surgical experience• Motivation for self-learning• Confidence• Prior knowledge on assessment• Feedback to identify weakness• Gender difference• Adaptive learner• Interest• Talent• Independence• Opportunities for repetition to improve recall
Structure and Content	Perceived Usefulness	Perceived Ease of Use		
<ul style="list-style-type: none">• Expensive but cost-effective• Multiple learning style• Reduced cost of complications• Reduced dependence of cadaver• Reduced dependence of space	<ul style="list-style-type: none">• Efficacy• Validity• Reliability• Spatial relationship between various anatomical structures• Fine psychomotor skills for open surgery• Rotational and translational dimensions	<ul style="list-style-type: none">• Safe simulated environment• Stress of operating reduced• Objective evaluation• Better identification of surgical pathology		
Technical Skills	Learning Outcome Factors			
<ul style="list-style-type: none">• Exclusively arthroscopy• Bias in evaluation of skills• Skill ceiling (Additional training will not improve skills)• Certain individuals are not meant for VR training	Performance Achievement	Perceived Learning Effectiveness		
	<ul style="list-style-type: none">• Validation of surgery skills according to experience• Skill transfer validity: using cadaver• Reduction of time to complete the procedure• Improved accuracy of critical steps• Reduction of caution path length• Improved knowledge on arthroscopy• Improved glenoid positioning• Improved guide pin orientation• Improved knowledge on fracture fixation• Improved knowledge on osteotomy	<ul style="list-style-type: none">• Reduction in learning time• Retention of surgical skills over time• Reduced rate of complications• Reduced amount of resected bone• Reduced implant exhaustion• Prevent drop out from surgical training program		
	Non-Technical Skills			
<ul style="list-style-type: none">• Regulated working hours• Concern of burn out• Not enough case during residency				

FIGURE 5. Taxonomies of the CSFs in VR-based orthopaedic training.

intention to use VR training, which may subsequently impact the learning outcome. These factors include listening skills, learning styles, problem-solving styles, attitudes toward technology, cognitive challenges, machine anxiety, and technology experience [30]. Performance achievements following VR-based training in orthopaedic surgery were attributed to a variety of student characteristic factors. These include being an adaptive learner, motivation for self-learning, innate interest in the surgical procedure, talent, confidence, independence, prior surgical experience, prior knowledge on assessment, feedback to identify weakness, opportunities for repetition to improve recall, and gender difference.

F. CONTROL AND ACTIVE LEARNING FACTORS

The control and active learning factors refer to the instructional design that determines learner control. Having learner control means that the learner can make choices about their learning journey or instructional activities. Learner control could cover a wide range of items, including learning pace, instructional material, and amount of practice in a learning atmosphere [30]. CSFs attributed to control and active learning factors include that VR learning is enjoyable, involves active learning, allows repetition until confidence is achieved, permits interactive learning via immediate evaluation and feedback, encourages higher student engagement, and has a clear purpose of training that focused on skill acquisition.

G. LIMITATION FACTORS

In this cluster, factors that could become limitation towards achieving the VR training objective were listed. The limitation factors are separated into limitations in overall structure and content, overall technical skills, and non-technical skills.

Structure and content limitations include obstacle within the design of the training curriculum such as a lack of an integrated comprehensive training curriculum or cost limitation. Technical skill limitations include obstacles related to learning outcomes that are specific to orthopaedics such as complexity of the surgery or unrealistic simulation of the anatomical structures. Finally, non-technical limitations deal with obstacles related to the learning outcomes that are not specific to orthopaedics such as decision making, communication, and teamwork [30].

The most frequently cited CSFs for structure and content limitations that have been overcome by VR training are ability to adapt to multiple learning style, VR equipment cost-effectiveness, reduced cost of complications, reduced dependency on cadavers, and reduced dependency on training space. In terms of technical skills, limitations identified include many studies that are exclusively on arthroscopy, some studies demonstrated that at a certain point, additional VR training will not add any more benefit in surgical skills, the fact that certain individuals will never be competent with VR training, and finally, existence of bias in the evaluation of VR training success. This was followed by regulated working hours, and cautions surgeon on the risk of burn out that might jeopardise the amount of cases that a surgeon had during residency within the non-technical skills category.

IV. DISCUSSIONS

A. EFFECTIVENESS OF VR IN ORTHOPAEDIC TRAINING

Identification of the critical success factors (CSFs) for the use of VR in orthopaedics, draws special attention to the research opportunity to improve VR design, to obtain the best outcome. Although CSFs research has been essential in

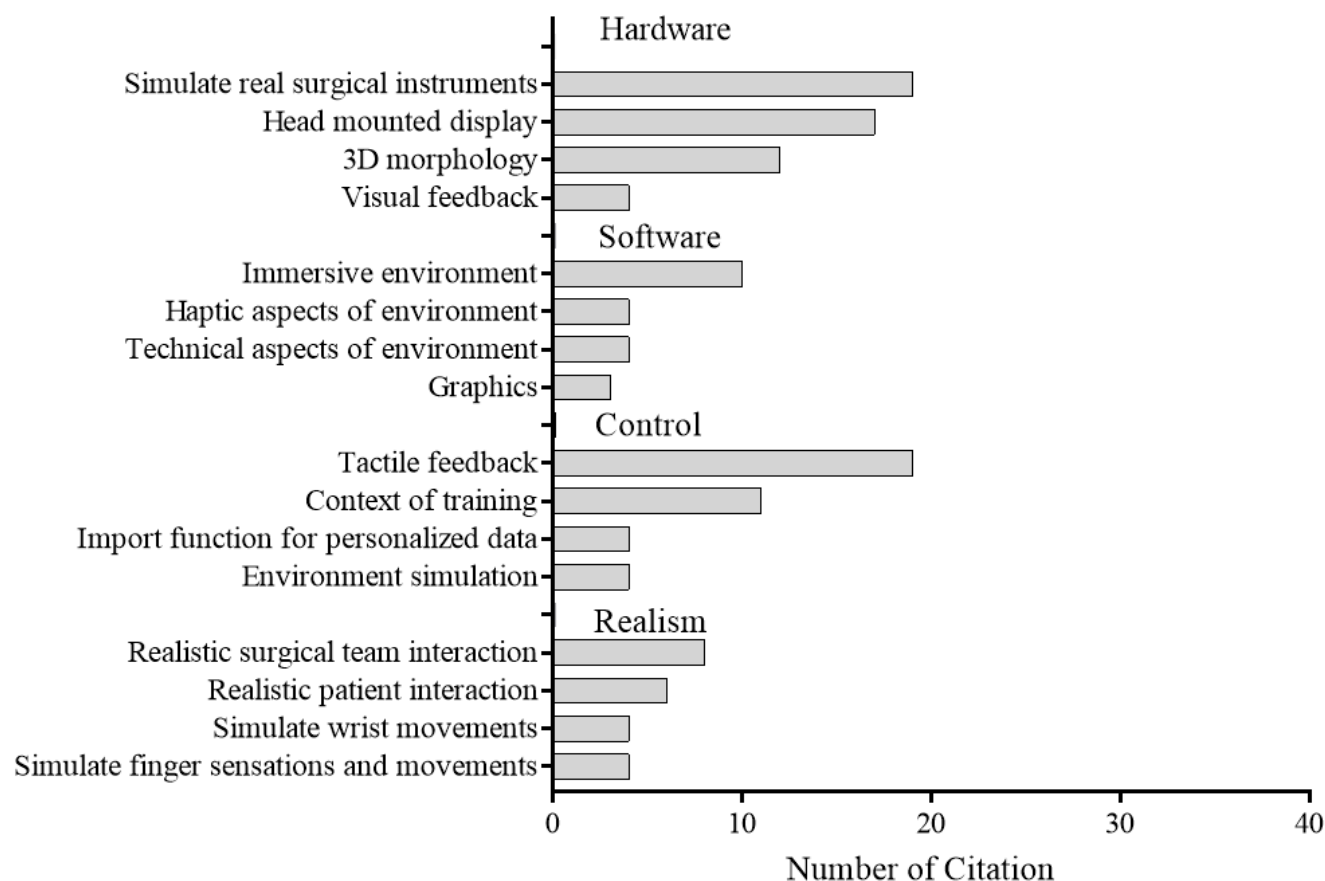


FIGURE 6. Citation distribution for CSFs related to HCI/VR features.

developing theoretical frameworks that guide improvement of many systems, it has been noted that virtually no studies have looked into the CSFs in the application of VR in orthopaedic education. Not only that, to our knowledge, in terms of VR application in medical education, only one study has identified the CSFs of success in implementing VR in ophthalmology surgical education.

Nevertheless, systematic reviews and meta-analyses for the effectiveness of VR training in orthopaedic domain were available [10], [19], [20]. There are two forms of efficacy measured related to VR in orthopaedic. In the first type, VR is used as an alternate teaching device in orthopaedic surgery, with higher efficacy indicated by improved surgical skills and reduction of surgical complications [21]–[23]. The second form occurs as VR is used as an appraisal instrument to predict and quantify the abilities of residents [24]–[26].

The published research found a strong association between surgical practice and VR success. A 2016 systematic review by Aim *et al.*, concluded that although VR was promising, evidence was limited, with only 10 studies were included in the study [19]. Virtual reality, according to Clarke *et al.*, is an immersive emerging simulation tool that has been embraced by many fields but is underutilised in orthopaedics. Numerous RCTs have shown that it is more effective in

teaching orthopaedic surgical techniques, with improved participant outcomes than current low-fidelity simulators. However, there are still some inconsistencies in the data [10].

Thus, taking together the importance of CSFs and the scarcity of evidence within this domain, conducting a systematic review is of utmost importance to establish the CSFs that can lead to the best outcome in VR based orthopaedic training. This outcome can be the result of using VR as a teaching or appraisal method in the workplace.

The suggested taxonomy in this analysis can also be interpreted in terms of matching external and internal variables for the purpose of using VR. Most users clearly want to use VR in the workplace for internal variables that can benefit them, such as skill conversion, accelerated surgical preparation and learning, and improved orthopaedic surgical efficiency.

In ophthalmologic domain, ophthalmology trainees are cited to be limited in taking chances with VR as a teaching tool due to external factors such as a lack of an integrated and standardised VR training programme, an abundance of realism and difficulty levels, a lack of instruction and monitoring, a lack of instructor's encouragement and input, higher costs, and a lack of cognitive skills emphasis [30]. Interestingly, in orthopaedic domain, these external limitations were

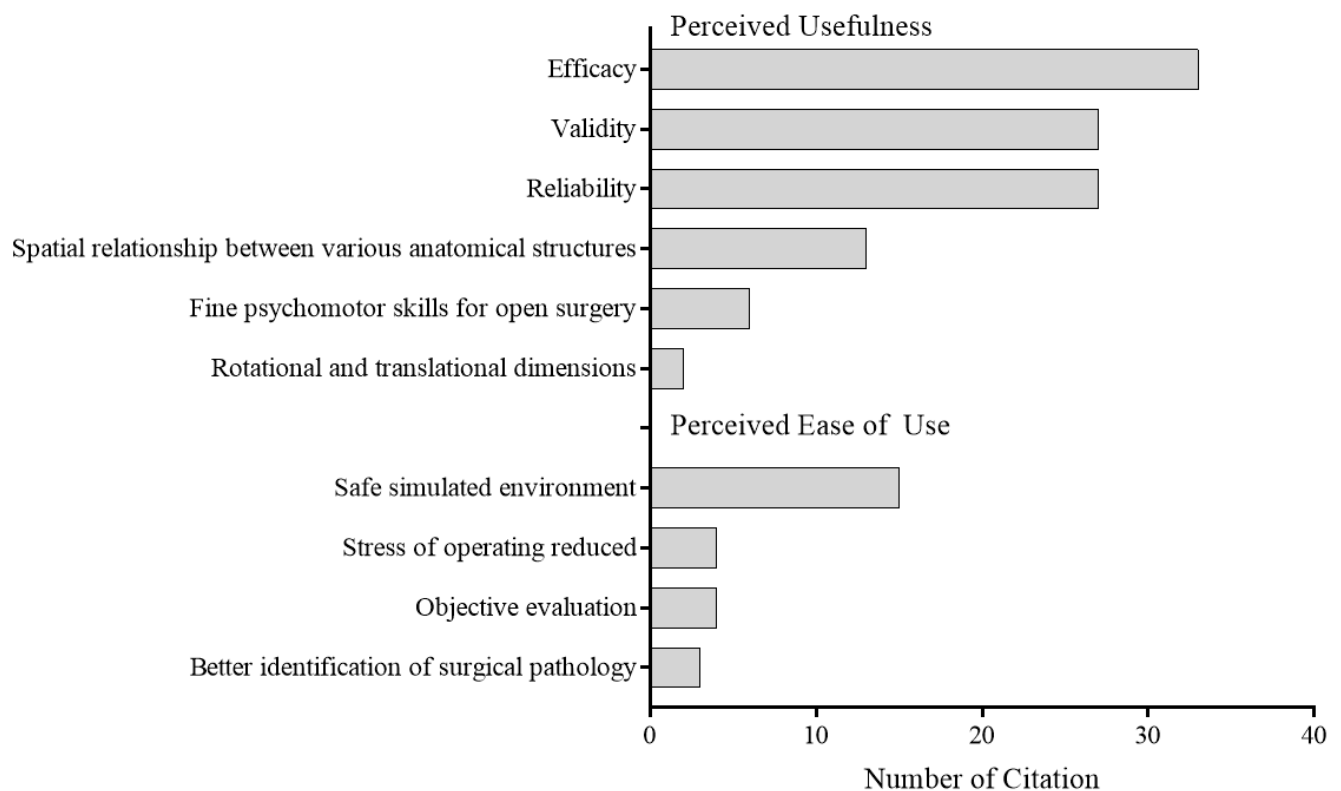


FIGURE 7. Citation distribution for CSFs related to usability.

not cited. This may indicate an easier path for orthopaedic surgeons to adopt VR in their training curriculum.

B. RECOMMENDED ELEMENTS IN DESIGNING FUTURE VRT

HCI/VR features, learning outcomes, control and active learning, and usability, all have functional consequences for embracing VR as a means to acquire, improve, maintain and measure skills. As such, considerations could, at best, contribute to a learning atmosphere that is tolerable for orthopaedic residents, such as a safe learning environment, decreased trainee anxiety, reduced complexity, and transferable skills. The distribution of the frequently cited HCI/VR features are shown in Fig. 6. Within the included articles, these are the ones that have been mentioned by at least two articles.

There are 12 CSFs attributed to HCI/VR features, with each feature attributed to four CSFs. With 19 citations, authors of many of the studies included credited the use of real or close to real surgical equipment as VR controller for its efficacy. However, this is mostly hypothesised by the authors following informal information obtained from the participants during their study, particularly among senior surgeons who participated in validation study of using VR as performance measure [33]. Next, 17 authors supported the crucial role of head mounted display (HMD) in ensuring the

immersive experience of the operation room. A VR system that does not use HMD might be perceived as unrealistic, leading to the lack of interest to use the system [34]. The model to which the surgical procedure is done, also plays an important role in adaptation of VR into training in medical field. Where cadaver or 3D printed model are involved, their 3D morphology is noted as an important CSFs in 12 studies. This provides the necessary tactile feedback for the surgeon to anticipate the next steps in the procedure. Finally, quality of the visual feedback is also important in ensuring the success of VR-based training in orthopaedic surgery. Surgical procedures in orthopaedics are typically hindered by unfavourable visual field, due to many factors such as excessive bleeding or obstruction by anatomical structures [35]. Accordingly, these visual cues need to be translated accurately so that the trainee can anticipate them in the real surgery.

There are also few CSFs related to the software design of the VR system, as mentioned by authors in the studies included. Immersive environment was the one quoted the most in terms of software design with 10 citations. A non-immersive VR experience not only leads to a lack of interest to participate, but can also affect focus during the course of the training. Some of the authors even specify the importance of different aspects of the immersive experience, namely the haptic and technical aspects of the immersive environment. Both are important in preparing the surgeon for the real surgery, where interaction with the environment is

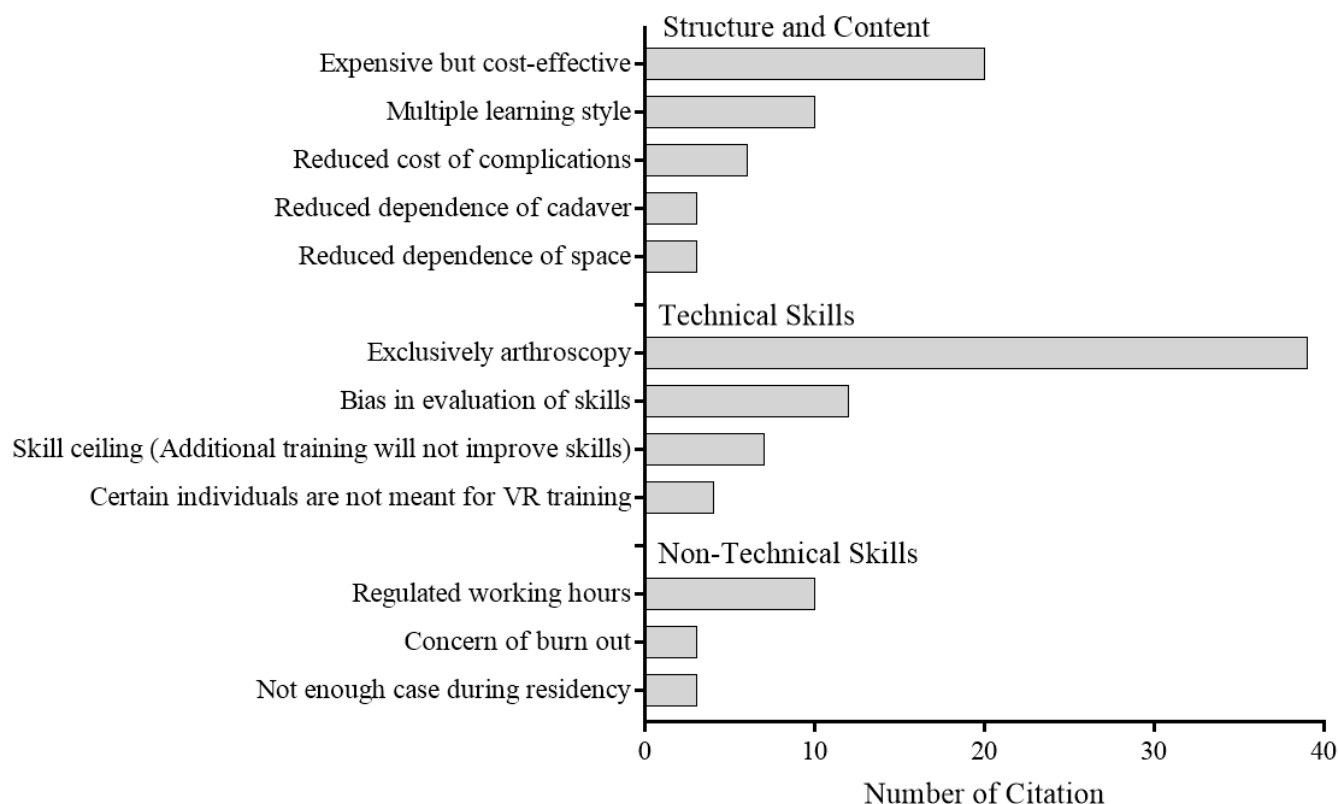


FIGURE 8. Citation distribution for CSFs related to limitations.

paramount. For example, a surgeon has to be prepared to react to a multitude of complications during the surgery [5]. This can be a serious issue if he or she has never experienced those complications when training with a technically imperfect VR scenario. This potential problem also applies to VR experience with imperfect haptic aspects. The user's ability to control the VR experience is an important factor contributing to interest in its use. In the orthopaedic surgical training, VR is favoured when the VR applications are equipped with sufficient tactile feedback that allows the surgeon to interact with their environment. This was mentioned the most in terms of controllability of VR. Second place falls to the context of the training. Due to its arduous nature, training in orthopaedic surgery requires commitment, which can be easily incited with a clear context or purpose of the training. Few authors mentioned the import function of certain system, that allows uploading of personalised data into the system. This enables customisation of the simulation, allowing the context of the training to be set by the trainer. Furthermore, agreeing to the immersive VR experience role, several authors mentioned the importance of environment simulation compared to partially immersive VR for training. Finally, element of realism was also cited in studies included, covering from the interaction with other members of the surgical team, interaction with the patient, and movement of the wrist and fingers.

The perception on the usability of VR influences the decision to adopt it. The citation rate of usability as a CSF by the authors of the included studies is illustrated in Fig. 7. Ten CSFs were mentioned to be related to the perception of usability of VR. The perception can be divided into two, the perception of usefulness and the perception of ease of use. Usefulness is related to the benefit that can be obtained from VR, particularly in the context of orthopaedic surgical training. Directly due to the fact that most of the studies included aims to measure efficacy of VR implementation in orthopaedic surgical training, efficacy is the most cited CSF in this context.

Alternatively, VR was also used to validate surgical skills among senior and trainee surgeons alike. As a result, validity and reliability of VR are also cited in most of study in this context. Other CSFs cited are considered as advantages of VR compared to traditional cadaveric or non-fidelity training, namely, better understanding of spatial relationships between the various anatomical structures, attainment of fine psychomotor skills needed for open surgery, and better comprehension of rotational and translational dimensions needed in navigating orthopaedic procedures. A strong driver towards adoption of a particular technology into activity of daily living is the perception of ease of use. VR need to be perceived as a solution for it to be adopted in orthopaedic surgical training. The most cited perceived ease of use attributed to

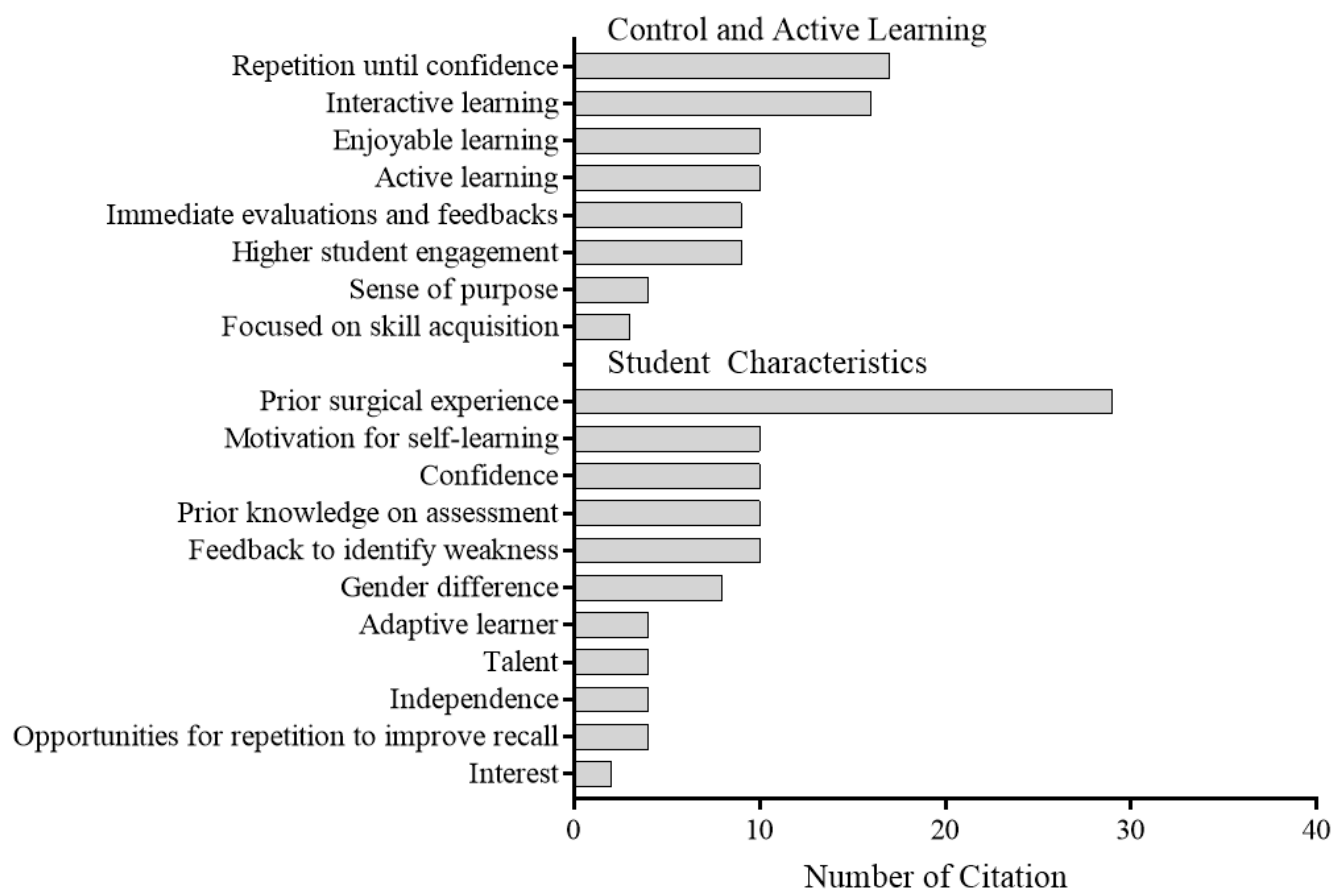


FIGURE 9. Citation distribution for CSFs related to student characteristics and control and active learning.

VR adoption in orthopaedic surgery is the provision of a safe, simulated environment for trainee surgeons to practice their craft. With operation room training, the stress exerted by the unpredictable scenario, may hinder the learning process. Hence, VR was also cited to reduce the stress of operating, leading to a more successful outcome of the surgical training. Furthermore, most of the VR simulators have the capacity to provide objective assessment of the training progress, allowing trainees to identify areas they need to improve on. Together, the factors mentioned above, it allows for ample preparation for the surgical trainee, which is attributed to the better identification of the surgical pathology during surgery.

Because of the functional importance of this topic for training new surgeons, this review looked at the CSFs of VRT in the orthopaedic domain. The outcome of this review can guide designers and healthcare professionals. To begin, the authors will suggest ways to make VRT a better platform for passing skills to residents. Furthermore, many CSFs influence VRT acceptance in surgical results, so identifying and addressing these issues are critical for those healthcare providers. Second, these suggestions will help classify the rigorous training curriculums that are most likely to be combined with VR.

This article aims to provide perspectives for healthcare practitioners and designers into why orthopaedic trainees want to use VRT for learning, in terms of how high-value skills can be translated, and how obstacles can be addressed to reduce surgical risks. Accordingly, precaution has to be taken upon limitations that can hinder the aim of VR implementation. Fig. 8 illustrated several commonly cited limitations put forth by the authors from the included studies, as well as a variety of recommended techniques for motivating an orthopaedic surgeon's decision to use VRT during the learning period.

Orthopaedic surgical training has always received continuous pressure to tackle two main limitations, financial and workload among the surgeons. As a result, both cost-effectiveness and working hour were cited as common limitations. Interestingly, two authors that study VR applications in fracture fixation and osteotomy, highlighted the state of literature of VR simulation that is exclusively arthroscopy. Consequently, diversification of the VR application should be the focus in future studies. Another peculiar but interesting finding was the mention of bias in evaluation of trainee's progress by the training surgeons. This is overcome by the objective evaluation provided by many of the programmed

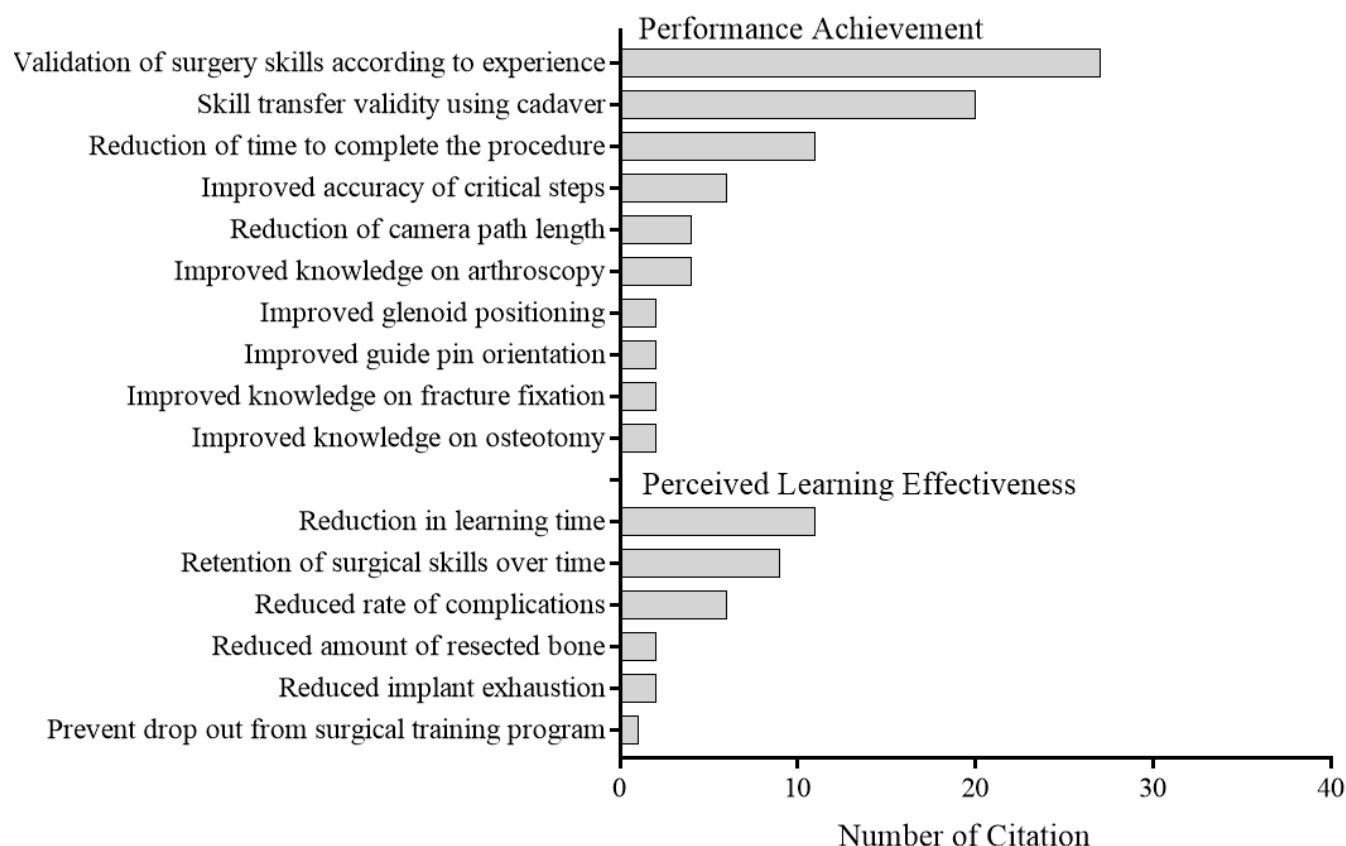


FIGURE 10. Citation distribution for CSFs related to learning outcome.

virtual trainers. The other three CSFs, control and active learning, and student characteristics factors describe the internal factors that influence success in VR training. Citation distributions for these two CSF categories are displayed in Fig. 9. CSFs in control and active learning factors include teaching methods, evaluation capabilities, ability transition, rapid surgical training and learning, and shorter learning curves.

For the student characteristics, cited CSFs include adaptive learning, motivation for self-learning, innate interest in the surgical procedure, talent, confidence, independence, prior surgical experience, prior knowledge on assessment, feedback to identify weakness, opportunities for repetition to improve recall, and gender difference. Both of these categories represented internal factors within the surgical trainees that led to successful outcome in VR training. None of these factors are modifiable, hence, cannot contribute to the recommendations in improving the VR design. However, they should give an idea on the target demographics that any design in VR should address.

The last CSF category is the learning outcome. Citation distribution of these factors are illustrated in Fig. 10. Among the learning outcome factors are improved orthopaedic surgical efficiency, improved OR performance, improved wet laboratory performance, improved performance, reduced rate

of complications, improved patient safety, better patient outcomes, time savings, and lower error rates. However, these factors are basically an indicator of the success in VR implementation in orthopaedic surgeons and cannot be used to improve design of future VR adaptations.

Most healthcare professionals have embraced VR-based preparation and will continue to do so. As a result, before applying such technologies, a variety of CSFs must be carefully calculated. The method of establishing and developing an integrated information management infrastructure for the purpose of creating a VR ecosystem for training purposes is extremely complicated. The authors' impressions and the number of citations of chosen articles were used to determine the six VRT CSF categories.

A substantial number of CSFs have been identified and classified into six groups in this study. Although the proposed CSFs are not limited to the information reported in this article, they are relevant in providing certain guidelines for using VR for learning or teaching in the domains of orthopaedic (in particular) and healthcare (in general).

Taking one of the categories, such as Contents and Structure, it can be seen that this aspect is clearly critical to the progress of VR. The capturing of domain information from subject matter experts (SMEs), such as orthopaedic surgeons, nurses, and medical students, is needed for the development

of VR content. It is difficult to make these SME's implicit experiences clear. Furthermore, the lack of monitoring and instruction is extremely important. VR's latest high-quality technology, such as its excessive realism level and modern immersion technology, has made the VR world very large and complex. As a result, it is critical to ensure that users, such as medical students, can access immersive environments without getting lost. Indeed, in the orthopaedic domain, resolving problems relevant to CSFs, such as content and form, may be critical in minimising any hazards to patients or obtaining deficiency adoption by the health committee.

V. LIMITATION

Over the course of this research, a number of limitations were encountered. For starters, owing to restricted open access to articles in certain journals, the researchers had difficulty downloading more documents. The researchers struggled to overcome the lack of a comprehensive analysis of CSFs for recorded VR performance, especially during the systematic literature review phase, in terms of obtaining more important factors to support this study. Finally, the suggested considerations are mainly captured in the form of virtual reality (VR) applications recorded in the arthroscopy surgery. As a result, the researchers are unable to say that the proposed CSFs are rigorous.

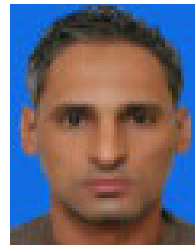
VI. CONCLUSION

In conclusion, this study makes important suggestions for upcoming research by developing a new CSF paradigm for VR-based training. The taxonomy proposed by this study is a strong starting point for both programme designers and researchers involved in the CSFs discussed. The suggested taxonomy can be used to provide a theoretical structure or model, as well as forecast behavioural intent to use VR-based training before it is implemented. Furthermore, this research adds to the systematic literature analysis of CSFs, VR-based learning in the field of orthopaedic. This is the first research in this area. Most importantly, this research could aid healthcare executives in their future efforts to implement VRT technology, as well as designers in the development or renovation of current simulators. Nonetheless, this research is a first effort to emphasise the importance of defining CSFs for VR uses, mostly in healthcare, such as orthopaedic, for training purposes. As a result, further research into CSFs for VR based learning success in particular and VR application success in general can be undertaken, potentially opening up more doors for research into CSFs for VR based learning success in particular and VR application success in general.

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