Extended Reality "X-Reality" for Prosthesis Training of Upper-Limb Amputees: A Review on Current and Future Clinical Potential

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***Abstract*—The rejection rates of upper-limb prosthetic devices in adults are high, currently averaging 26% and 23% for body-powered and electric devices, respectively. While many factors influence acceptance, prosthesis training methods relying on novel virtual reality systems have been cited as a critical factor capable of increasing the likelihood of long-term, full-time use. Despite that, these implementations have not yet garnered widespread traction in the clinical setting, and their use remains immaterial. This review aims to explore the reasons behind this situation by identifying trends in existing research that seek to advance Extended Reality "X-Reality" systems for the sake of upper-limb prosthesis rehabilitation and, secondly, analyzing barriers and presenting potential pathways to deployment for successful adoption in the future. The search yielded 42 research papers that were divided into two categories. The first category included articles that focused on the technical aspect of virtual prosthesis training. Articles in the second category utilize user evaluation procedures to ensure applicability in a clinical environment. The review showed that 75% of articles that conducted whole system testing experimented with non-immersive virtual systems. Furthermore, there is a shortage of experiments performed with amputee subjects. From the large-scale studies analyzed, 71% of those recruited solely non-disabled participants. This paper shows that X-Reality technologies for prosthesis rehabilitation of upper-limb amputees carry significant benefits. Nevertheless, much still must be done so that the technology reaches widespread clinical use.**

***Index Terms*—Prosthesis, virtual reality, augmented reality, serious games, rehabilitation, upper-limb.**

I. Introduction

THE development of prosthetic devices for individuals with missing limbs continuously advances as a consequence of technological progress. Modern devices utilize robotic integration to address the demand for improved functional restoration [1]. Furthermore, incorporating signal processing modalities has opened the door for better control systems and made anthropomorphic biomechanics more accessible. Overall, establishing the state-of-the-art in limb-loss rehabilitation holds great promise for improving patient quality of life. However, limitations are still a cause for concern. Rejection rates of upper-limb prostheses in adults most currently fall at an average of 26% and 23% for body-powered and electric devices, respectively [2]. Such rates are partially due to the difficulty of use associated with such devices. Coupled with the complexities of hand-object interactions in daily living, the utility of upper-limb prosthetics remains a challenging problem [3]. To further examine this issue, it is necessary to understand the functional taxonomy of these devices. Upper extremity prostheses can be grouped into one of two categories: passive or active prostheses [4]. Passive devices can either serve as a cosmetic purpose or provide limited functional assistance such as pushing, pulling, and light grasping [5], [6]. On the other hand, an active prosthesis is a biocompatible mechatronic device that aims to restore anthropomorphic physiological functions following limb difference [7]. Active prostheses include body-powered, myoelectric, and neural prostheses [4], [8]. Controlling an active prosthesis is not an intuitive process, and users often face challenges, which, in turn, negatively impact device acceptance [9]. To counteract those issues, prosthetic training is offered to patients as a rehabilitative means of easing their transition and allowing them to adjust to using the device in daily life [10]. Prosthesis training has been cited as a critical factor in increasing device acceptance and increasing the likelihood of long-term, full-time use [11].

Conventionally, prosthesis training is conducted using traditional motor rehabilitation methods under the supervision of a physical or occupational therapist [12]. Such training modality can be very strenuous for the patient, and technology is often utilized to provide support and ease the physical and mental burden required throughout the process [11]. For example, physical prosthesis simulators, or exoskeletons, have been implemented to help the subject perform various movements without the actual prosthesis [13]. Researchers have also combined signal processing, remote control systems, and "serious gaming" to improve muscle isolation and facilitate learning of

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myoelectric control schemes used in prostheses [14]. Despite the improvements that such adaptations provide, the nature of the process remains physically and mentally challenging, and many participants become fatigued, with some abandoning training altogether [2].

Upon further investigation of this issue, research has determined various factors that can lead to successful upper-limb prosthesis rehabilitation and use. Social factors such as completion of high school education, employment status at the time of amputation, rapid return to work, acceptance of the amputation, and perceived cost of the prosthesis have been reported as playing a role in eventual user acceptance [15] However, training quality seems to be one of the most influential aspects shaping user's experience with the prosthesis [11]. In some cases, amputees who have not been prosthetic users for a long time decide to adopt a device after receiving extensive quality training [11]. However, current training methods are still viewed as repetitive, long, tedious, and discouraging [16]. Clinicians seek to prevent this by modifying specific aspects in their approach to address the needs of advanced prosthesis users [11] by offering specialized engaging methods [16]. Incorporating virtual reality in prosthesis training has been suggested as a solution to provide a more immersive and engaging training experience for the patient [16]. A virtual reality (VR) system is, in essence, defined as the sum of the hardware and software components designed to create the all-inclusive, sensory illusion of being present in a different environment [17]. Virtual reality systems have been previously used in a wide range of interventions in medicine, higher education, and other fields due to their ability to reinforce the learning framework [18]. The technology offers tools to strengthen analytical and problem-solving skills, improve communication and collaboration, and influence behavioral change. Virtual reality systems are not the only method to recreate sensory-motor and cognitive activities in an artificial environment. Augmented reality (AR) [19] creates a new space combining the real and virtual environments [20]. Inconsistencies appear in the literature regarding the term mixed reality (MR) [21]. The general consensus is that the Reality-Virtuality continuum refers to the different points on the continuum where real and virtual objects are merged [22]. While the continuum has been used for over two decades as a reference to classify the different realities, novel taxonomies have been proposed that extend beyond it and describe new realities that have appeared with the emergence of more sophisticated technologies [21]. For simplification purposes, we will refer to the collective spectrum of existing amalgamations on the Reality-Virtuality continuum, as well as any possible extensions of it by the term "Extended Reality" or X-Reality (XR) for short (Fig. 1).

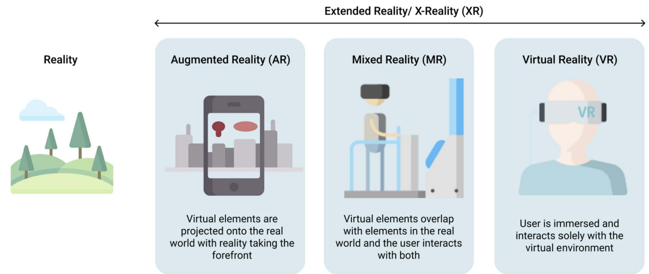

Fig. 1. Illustration showing the relationships between the most commonly established realities (augmented, mixed, and virtual reality), their etymologies, and the definitions of X-Reality (XR).

In the context of motor rehabilitation XR systems can either be immersive, using a headset, or non-immersive, using a screen projected avatar [23]. Existing reviews have explored the use of XR for mobility training, gait rehabilitation of stroke, and treatment of phantom limb pain [24], [25]. The strengths of these technologies lie in their consistency to provide stimulus control, promote self-guided exploration by offering a safe environment for "error-free learning," and promote independent practice [26]. So far, the evidence is not conclusive whether these methods offer a significant functional improvement in the clinic when compared to traditional methods, and further studies are necessary [27], [28]. Research has also adapted XR for prosthesis rehabilitation. Yet, despite their potential, these implementations have not garnered widespread traction in the clinical setting, and their use remains insubstantial [29].

In light of the above, the current review explores answers to the following questions:

1) How prevalent is the use of X-Reality technology in clinical prosthesis rehabilitation?
2) Is it significant compared to other rehabilitation protocols?
3) If not, what are the limitations and barriers to deployment in a clinical environment?
4) Is research in this field advancing in a direction that enables widespread clinical use in the near future?

A more in-depth analysis of XR applications in prosthesis rehabilitation is required to answer these questions and determine the effectiveness of such systems as potential clinical treatment modalities. While assessing the state of the art, it is also important to perform a comprehensive examination of the available technology. In so doing, we will be able to break down the technological outcomes in accordance with the required clinical goals. Comparing these outcomes with evaluations of existing rehabilitation methods enables us to explore whether widespread clinical use of these technologies is a realistic possibility. For this reason, this review aims to (1) explore research seeking to advance XR systems for the sake of upper-limb prosthesis rehabilitation and (2) analyze existing barriers and present pathways to deployment for successful clinical adoption in the future.

II. Literature Search

Studies have proposed utilizing augmented, virtual and mixed reality environments to supplement or replace conventional training methods. A broad overview seems to point to the possibility of combining XR technologies with other methods to facilitate and improve traditional prosthetic training protocols. A systematic literature search was conducted to identify relevant research articles using PubMed, Science Direct, IEEE

Xplore, Web of Science, Google Scholar, and SCOPUS databases. The initial round of selection was performed by two of the authors and the other authors were responsible for handling possible disagreement and adjustments in the selection. The search was performed using the following keywords:
[training AND reality]
[training AND augmented OR virtual reality]
[training AND reality AND game]
[prosthesis AND training]
[prosthesis AND training AND virtual reality OR augmented reality]
[prosthesis AND training AND virtual OR augmented AND game]
[prosthesis AND training AND reality AND upper limb]
[prosthesis AND training AND reality AND upper limb AND game]
[prosthesis AND training AND reality AND clinical].

First, all articles containing the key terms described before were extracted from the databases. Related review papers were further used to identify additional articles that may have been overlooked in the initial search. The relevant articles were then scanned for duplicates. Any studies not related to prosthesis training of the upper limb were eliminated. An in-depth analysis was conducted on the remaining 42 research papers. The papers were separated into two categories: i) articles that explored backend control systems in training applications for upper limb prosthetics, and ii) articles that focused on the frontend and whole system user testing. 22 articles and 20 articles were placed in each category respectively. While articles in the first category provide insights into the technical aspects of virtual prosthesis training, articles in the second category often used user evaluation procedures to ensure applicability in a clinical environment.

III. Technical Elements

We started our analyses by examining the functional aspects of existing XR systems to determine their potential to improve upper-limb prosthesis rehabilitation (Table I). We analyzed the structural workflow and the commonly used hardware and software components in order to gain insights into the frontend aspect of the technology and the interfaces that users and therapists interact with, which, in turn, were directly related to user perception and acceptance [30]. We also analyzed the backend control structures that formed the baseline system architecture of state-of-the-art virtual training platforms. These input, output, and feedback mechanics encompassed the practical training protocols and significantly impact the user experience.

XR systems are almost all about interaction. As such, the technical attributes that allow proper immersive or non-immersive experience are paramount to the success of the training and rehabilitation procedures. As shown in Table I, a variety of input mechanics have been employed for user interaction with virtual systems. Technologies involving bioelectric signal control, specifically utilizing EMG (electromyography) [31]–[34] or neural signals [35], have been used in an attempt to improve interaction with virtual prostheses.

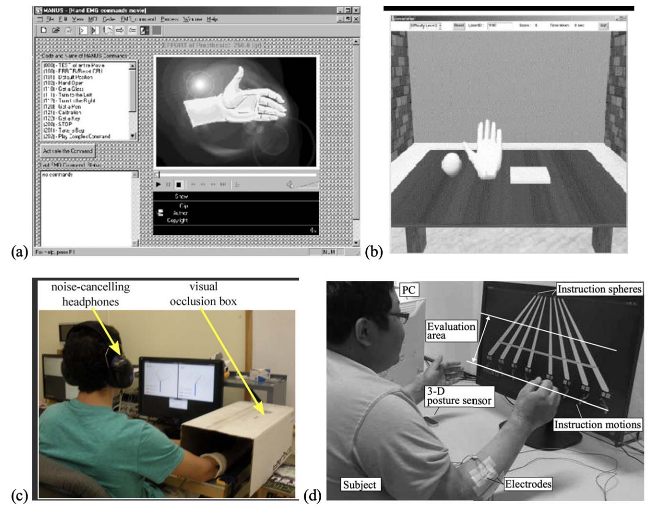

Fig. 2. Images showing the development of various non-immersive virtual environment prosthesis training systems over the past 15 years: (a) MANUS - an EMG controlled prosthesis [51]; (b) a virtual pick and place game in the virtual environment [48]; (c) a haptic system to improve accurate wrist positioning during virtual prosthesis training [44], and; (d) a system that combines EMG and 3D postural patterns to improve dual-arm cooperation during training [38].

Motion tracking methods and kinematic control have also been deployed for the same purpose [36], [37].

Among all the control strategies used in prosthesis training, EMG control appears to be the most prolific. The ability to extract the control signals from the skin's surface allows the process to remain non-invasive, reducing any unnecessary discomfort for the patient. In terms of generating upper-limb movement, EMG signals appear most similar to natural arm control [52]. Challenges arise, however, when using EMG signal control as the primary method of myoelectric prosthesis control. Surface electromyographic (sEMG) signals are invariably contaminated by external sources and noise signals originating at the skin-electrode interface [53]. Conditional changes have also been tied to shifts in the cumulative power of EMG signals [54]. EMG pattern recognition models are often used to expand the possibilities for controlling more complex dexterous prostheses, facilitating user adaptation, and improving performance [55]. EMG has also been associated with kinematic data in an effort to improve arm motion tracking and prosthesis embodiment within the virtual environment. Blana *et al.* [41] gathered EMG signals from six locations on the user's proximal humerus and combined them with kinematic data for the humeral angular velocity and linear acceleration. The data was then used to train an artificial neural network with the goal of improving intuitive and natural upper-limb control in multiple degrees of freedom.

However, the control modality is only one of the components when considering the interactions with the X-Reality systems. A good interface must also support the chosen XR modality and provide a natural and intuitive prosthetic training environment. Immersive virtual interfaces often utilize stereoscopic technology to simulate depth perception, and

TABLE I

CHARACTERISTICS OF CONTROL MODALITIES USED IN X-REALITY INTERVENTIONS FOR PROSTHESIS TRAINING. IVR: IMMERSIVE VIRTUAL REALITY– OFTEN ACHIEVED WITH THE USE OF HMDS, NI-VE: NON-IMMERSIVE VIRTUAL ENVIRONMENT; AR; AUGMENTED REALITY, MR: MIXED REALITY; SEMG: SURFACE ELECTROMYOGRAPHY; EEG: ELECTROENCEPHALOGRAPHY; PHAM: PROSTHESIS HAND ASSESSMENT MEASURE; DOF: DEGREE OF FREEDOM; MEMS: MICROELECTROMECHANICAL SYSTEMS; ITCS: INDUCTIVE TONGUE CONTROL SYSTEM

Reference	XR Environment	Control Intervention	Subject pool	Input Signal(s)	Feedback mechanism	Technological outcome
Shibanoki et al., 2020 [38]	NI-VE	A system to train muscular cooperation timing of both arms.	1 experienced participant.	sEMG, 3D posture data.	Visual	Users were able to generate accurate EMG patterns at specified timings, even in dual-arm tasks.
Odette & Fu, 2019 [39]	I-VR	Physics-based engine assesses user performance quantitatively using movement kinematics and interaction forces.	4 able-bodied subjects.	sEMG	Visual	Subjects prioritized completion speed over ergonomic factors, using compensatory motions to overcome limitations of the terminal devices.
Melero et al., 2019 [34]	AR	A dance game, Upbeat, designed to improve rehabilitation therapies in upper limb amputees using PHAM protocols.	3 able bodied subjects.	sEMG	Visual	Offers a prototype for gamified AR rehabilitation therapy and may be used to conduct a clinical trial to evaluate its efficacy in achieving the envisioned goals.
Li et al., 2019 [32]	NI-VE	Enhanced EF control rehabilitation system .	10 able-bodied subjects.	sEMG	Electrotactile, Visual	EF is helpful to both reduce the rehabilitation duration and improve the virtual grasping success rate.
Sharma et al., 2018 [37]	MR	Game environment delivering touch feedback and proprioception information through vibrational feedback.	2 able bodied volunteers	Kinematic	Perioceptive (using vibrations), Tactile, Visual	Improved performance in training time, overshoot and completion rate with proprioceptive and tactile feedback.
Earley et al., 2017 [40]	NI-VE	Audio feedback of joint velocities to improve performance and adaptation to dynamic perturbations.	10 right hand-dominant, non-amputee participants	sEMG	Audio, Visual	Initial errors were reduced in the presence of audio feedback likely due to improved muscle activation detection and subjects identifying limb dynamics sooner.
Blana et al., 2016 [41]	I-VR	Time-delayed artificial neural network to predict elbow flexion/extension and forearm pronation/supination.	10 able-bodied subjects.	Kinematic, sEMG	Visual	Signals from the proximal humerus provided good prosthesis control.
Johansen et al., 2016 [42]	NI-VE	A control scheme combining EMG and control signals from an ITCS.	10 able-bodied subjects	ITCS, sEMG	Haptic	A statistical significance in favor of the ITCS control scheme indicates that it can be used as a means of enhancing prosthesis control.
Putrino et al., 2015 [35]	NI-VE	Virtual upper limb prosthesis in VRE with 27 independent dimensions.	2 non-human primates (Macaca mulatta)	Kinematic, processed neural signals	Visual	System can receive and interpret multiple inputs from a range of sources to drive the prosthesis in real-time at variable dimensions.
Phelan et al., 2015 [43]	I-VR	Uses commercial motion and signal capture devices to create a unique, cost effective training tool.	-	Kinematic, sEMG	Visual	Decreases the cost and time it takes for a transradial amputee to train how to use a Myoelectric prosthetic arm.
Erwin & Sup, 2015 [44]	NI-VE	Haptic feedback scheme used for accurately positioning a 1DOF virtual wrist prosthesis by relaying 11 discrete haptic stimuli to the user.	8 able-bodied participants with no sensory impairments.	sEMG	Haptic	Using haptic feedback was substantially better than no feedback at accurately positioning the virtual wrist.
Bunderson, 2014 [45]	NI-VE	Physics-based interactions with virtual objects simulating dynamics of frictional contact, and inertial limb dynamics.	4 nonamputee subjects and 1 shoulder disarticulation subject.	sEMG	Visual	Virtual object transfer rate was just under two objects per minute and the environment is configurable in terms of the virtual arm design, control strategy, and task.
Rezazadeh et al., 2012 [46]	NI-VE	Co-adaptive human-machine interface (HMI) developed to control virtual forearm prosthesis over a long period of operation.	16 users (including an amputee)	EEG	Visual	The proposed system can adapt itself to the mental states of a user, thus improving its usability with adaptive HMI outperforming non-adaptive HMI.
Mattioli et al., 2011 [33]	NI-VE	Neural Networks for real-time classification of EMG signals.	3 healthy subjects	sEMG	Visual	Classification technique resulted in a 95% success rate when discriminating 4 different hand movements.
Lambrecht et al., 2011a [29]	S-VR	Simulates the prosthesis dynamics and displays the combined residual limb and prosthesis movements.	3 normally-limbed subjects.	Kinematic, sEMG	Visual	Results were similar to those obtained when experiments were performed using a physical prosthesis.
Lambrecht et al., 2011b [47]	S-VR	Physics engine for force-based interactions with virtual objects allowing for controlling multiple DOF intuitively and efficiently.	-	Kinematic, sEMG	Visual, haptic	Haptic feedback is useful for more realistically simulating the task. However, without haptic feedback, the simulator is portable, easy to setup, and relatively inexpensive, allowing for widespread clinical use.
Lamounier et al., 2010 [48]	NI-VE, AR	A neural network for signal classification to simulate prosthesis movement in real-time.	One case study	sEMG	Visual	System reproduced the manipulation of a prosthesis using Virtual and Augmented Reality techniques.
Barraza-Madrigal et al., 2010 [49]	NI-VE	"Virtual Reality Toolbox" as a solution for visualizing and interacting with dynamic systems in a tridimensional VR environment.	One amputee	sEMG	Visual	This system can realize simple movements or defined tasks, allowing the user to have different levels of difficulty, and may even change the tasks to be performed.
Churko et al., 2009 [36]	NI-VE	An inertial measurement unit (IMU) and a linear displacement sensor are applied to a prosthetic arm to track its movement in 6DOF.	-	Kinematic	Visual	Even with advances in MEMS sensor technology integration error is likely too significant to make an IMU an acceptable choice for position measurement.
Davoodi et al., 2008 [?]	I-VR	Software for modeling and simulating human and prosthetic limbs to analyze prosthetic movement control systems.	-	sEMG, EEG, kinematic	Visual	Offers framework for virtual prototyping of neural prosthetic systems in paralyzed and amputee patients.
Hauschild et al., 2007 [50]	I-VR	System offering support for multiple configurations, a wide variety of input devices, and different output devices.	Two subjects	sEMG, EEG, kinematic	Visual, Haptic	Initial evaluation provided satisfactory performance allowing the system to be used in different ways by researchers and clinicians to design and fit novel prosthetic devices.
Pons et al., 2005 [51]	NI-VE	Novel three-bit EMG command language concept as a user interface for the multifunctional MANUS prosthesis.	15 limb absent individuals	sEMG	Visual	The command language can be effectively implemented for commanding the multifunctional prototype, but thorough clinical evaluation is needed.

have been implemented using various head-mounted displays (HMD), such as Occulus Rift Headset, HTC VIVE Pro, and Microsoft Hololens [39], [41], [43]. Non-immersive platforms, on the other hand, rely on user-controlled avatars presented on a screen [38], [40], [42], [48]. Other applications substitute the virtual environment for a mixed [37] or augmented [34] environment. These scenarios aim to generate improved immersion by allowing the user to visualize an environment that combines both real and virtual objects. Consistently, immersive virtual environments have demonstrated an ability to convey the illusion of presence to the user, which positively affects attention and engagement, due to their ability to minimize distractions and provide sensory information directly to the user [56], [57]. The incorporation of serious gaming into the training module has also been reported as a powerful strategy to facilitate training and improve user engagement [58]–[62]. Task-oriented gaming can increase motivation and improve flow during training [63]. Furthermore, user concentration, perceived ease of use, and usefulness of the protocol are significantly enhanced when serious gaming is implemented in the learning environment [64].

Ideally, the training environment should provide different levels of difficulty so that the users can progress from simple to more complex tasks. While some systems do not allow the user to evolve alone or adapt the level of difficulty [49], [65]–[67], others have been designed to be adjustable or to adapt to the user's skills [16], [68]–[70]. Allowing the user to advance only after completing previous levels of difficulty prevents frustration, adds an element of challenge that improves engagement, and positively impacts learning [71]. In some cases, machine learning algorithms have been deployed to tailor the training regimen to each user's capabilities [29]. Enabling the system to consistently adapt to respond and automatically adapt to the user's potential ensures that the application continues to offer a balanced, challenging experience throughout the training process.

Over the past fifteen years, the literature exploring XR control systems for prosthesis rehabilitation has focused mainly on myoelectric prosthesis training (I). While a physical upper-limb prosthesis can use a variety of electrical and mechanical control mechanisms, depending on the prosthesis class (e.g., myoelectric and body-powered devices), 45% of articles explored used control modalities solely based on sEMG. Myoelectric control has also seen a steady shift from direct myoelectric control to a pattern recognition-based myoelectric control, which utilizes machine learning methods for signal classification of the extracted EMG signals [31].

Another important factor that holds significant relevance when discussing prosthesis control and training is the type of feedback provided to the user. Feedback is especially beneficial when performing complex tasks, such as those required in game-based prosthesis training, and can improve prosthesis control and perceived embodiment [72]. While various studies considered providing no additional feedback to the user, besides standard visual feedback [49], [67], [73], others proposed the use of sensory [59], tactile [50], and auditory [74] feedback to relay sensory information to the user allowing them to engage and better respond to the training protocol. Advancements in feedback and control technologies have enabled major developments in the field, specifically rehabilitation training that relies on using XR environments. Visual feedback has been significantly enhanced by the development of physics-based engines that incorporate complex user-object interaction within the virtual environment, facilitating a more well-rounded user experience [39], [45], [47]. The number of studies experimenting with additional feedback methods, such as haptic and electrotactile, or a combination of modalities, has also increased over the years, at the same rate as XR-based protocols associated with serious gaming gained popularity. Understanding these trends allows us to project future paths for the field. We can now foresee an increase in experimental testing involving more complex, integrated XR training systems over the coming years. It is also likely that the rise in the use of machine learning techniques within such systems will enable the testing and development of more intelligent and responsive systems in terms of adaptability, feedback generation, and serious gaming options.

IV. Functional Relevance to Clinical Outcomes

The clinical assessment of prosthetic user outcomes usually falls into two categories: subjective self-report measures and objective performance-based tests [85]. Self-report measures enable the user to reveal subjective information about improvement in daily activities, assess user satisfaction with the device, and evaluate impacts on life quality. The Orthotics and Prosthetics User's Survey (OPUS) and the Trinity Amputation and Prosthesis Experience Scale (TAPES) are two prominent measures in that class. On the other hand, performance-based measures provide objective, unbiased, and reproducible results to demonstrate functional performance related to everyday tasks and daily living activities [85]. A screening of the existing literature yielded a list of 17 commonly used clinical outcome measures for performance-based evaluation of upper-limb training [86]. The Box and Block test, the Nine Hole Peg Test, and the Target Achievement Control (TAC) test are all examples of commonly used indicators of upper-limb mobility and function.

While a subjective self-reported test offers a more in-depth insight into the patient's experience while using the device, it offers a biased view and can be affected by the memory of previous events and perspectives. An objective, performance-based measure accounts for these issues but does not address the user's attitude towards the device. In other words, a testing methodology that solely contains performance-based measures lacks a user-centered understanding of the patient experience, risking overlooking complex issues that may be cause for concern in the long-term. As a result, the clinical rehabilitation tool must be thoroughly tested, using both self-reported and performance-based measures to determine effectiveness and suitability for the impact it is expected to achieve upon deployment. Table II shows the relevant works focused on testing XR systems by measuring patient performance and other elements associated with possible clinical deployment. The assessment tools used in the articles are divided into self-reported and performance-based categories. A summary of the results is presented in Fig. 3.

TABLE II

CHARACTERIZATION OF EVALUATION METHODS FOR WHOLE SYSTEM TESTING OF X-REALITY INTERVENTIONS FOR CLINICAL UPPER-LIMB PROSTHESIS REHABILITATION.I-VR: IMMERSIVE VIRTUAL REALITY; NI-VE: NON-IMMERSIVE VIRTUAL ENVIRONMENT; AR: AUGMENTED REALITY; VF: VISUAL FEEDBACK, AF: AUDITORY FEEDBACK; TF: TACTILE FEEDBACK; MF: MOVEMENT FEEDBACK; PCF: PROPRIOCEPTIVE FEEDBACK; BBT: BOX AND BLOCK TEST; IMI: INTRINSIC MOTIVATION INVENTORY; UES: USER EVALUATION SURVEY; SUS: SYSTEM USABILITY SCALE; TAC: TARGET ACHIEVEMENT CONTROL; SHAP: SOUTHAMPTON HAND ASSESSMENT PROTOCOL; JHFT: JEBSEN-TAYLOR TEST OF HAND FUNCTION; uMARS: THE USER MOBILE APPLICATION RATING SCALE

Reference	Technological Features	Subject pool	Evaluation procedure	Conclusion
Kristoffersen et al., 2020 [75]	Serious game-based NI-VE	25 able-bodied participants	Motion Test	Participants who followed game training showed 51% more separated EMG patterns. Serious game training that utilizes an external focus of attention and implicit learning can be considered as a viable alternative to conventional training.
Dhawan et al., 2019 [76]	Serious game-based I-VR	34 non-amputees and 2 transradial amputees	SUS	Preliminary results show up to 47.3% in overall improvement when using the prototype tool, demonstrating a successful proof of concept for a training system using commercial devices (HTC Vive & Thalmic Labs Myo Gesture Control Armband).
Woodward & Hargrove, 2019 [77]	I-VR	16 able-bodied subjects and 4 with major upper limb amputations	TAC test	Actively trained classifiers performed significantly better than passively trained classifiers for non-amputees. Results support previous work which suggested active movements during data collection can improve pattern recognition systems in a neural network, furthermore, adaptation within a guided serious game can improve real-time performance of myoelectric controllers.
Nissler et al., 2019 [78]	I-VR	5 able-bodied subjects & 1 with a congenital deficiency of the right hand	BBT	Results showed a significantly better performance of a prosthetic user in the virtual environment than in exercises performed with a physical prosthesis.
Prahm et al., 2019 [68]	Serious game-based mobile based NI-VE	15 able-bodied participants, 15 amputees for game evaluation & 3 amputees participated in a 4-week clinical intervention	SUS, uMARS, & clinical parameters (e. g. maximum contraction strength & muscle endurance)	Significant improvements, up to 62%, could be seen in all assessed parameters, thereby supporting the idea that a game-based mobile app can be used to train EMG motor signals for prosthetic control.
Manero et al., 2019 [79]	NI-VE	50 able-bodied participants	SUS and motion-based task tests	Results showed significant pre-test to post-test improvements with the training intervention, which may be partially attributed to a more engaging training experience, supporting the use of this neuroprosthesis training in pediatric patients following a clinical assessment.
Hargrove et al., 2018 [80]	NI-VE	9 subjects with transhumeral amputations who previously had targeted muscle reinnervation surgery	SHAP, JHFT, BBT, TAC, & Clothespin Relocation task	This clinical trial showed that in-home practice with a PGT prosthesis improves functional control, as measured by both virtual and physical outcome measures. However, virtual measures need to be validated and standardized to ensure reliability in a clinical or research setting.
Prahm et al., 2018 [16]	Serious game-based NI-VE	14 patients with transradial or transhumeral amputation & 10 able-bodied participants	IMI survey & assessing electrode separation in combination with muscle endurance	Game-based interventions provide a useful addition to standard myoelectric training and can achieve better results in clinical outcome measures. Future studies can aim to look at a wider range of game genres and identify specific mechanics suitable for training.
Perry et al., 2018 [66]	NI-VE	13 active-duty military personnel with upper extremity loss	Three motion sets of increasing complexity (Basic, Advanced, and Digit)	Participants can be trained to generate muscle contraction patterns in residual limbs that are interpreted with high accuracy, $>95\%$, by computer software as distinct active motion commands.
Winslow et al., 2018 [70]	Serious game-based mobile-based NI-VE	12 able-bodied participants	UES, IMI, and SUS	Significant improvement was reported in factors underlying successful prosthesis use, such as muscle control, sequencing, and isolation. Participants reported high levels of usability, and motivation.
Prahm et al., 2017 [69]	Serious game-based NI-VE	11 able-bodied participants	UES and IMI	Participants viewed myoelectric control as more fun and engaging when collecting items and facing challenging game play.
Tabor et al., 2017 [61]	Serious game-based NI-VE	6 current and past prosthesis users and 3 subject matter experts	Nine playtest interview sessions	User-Centered Design (UCD) highlighted input from patients who felt a perceived need for out-of-clinic training tools & a indicated a noticeable difference between striving for targeted training behavior and providing a positive, engaging experience.
Woodward et al., 2017 [62]	Serious game-based I-VR & NI-VE	4 subjects upper-extremity amputation and 6 clinicians specialized in their care	Clinical needs assessments conducted using focus groups	The system is capable of improving targeted neuromuscular rehabilitation by collecting data in the background of the gaming environment, which will be used in improving pattern classification control methods. Special attention should be given to game elements which show the most promise for increasing player motivation.
Van Dijk et al., 2016 [59]	Serious game-based NI-VE w/ PCF and VF to indicate virtual object properties (e.g. fragility)	41 able-bodied right-handed participants	Task tests (e.g. catching, interceptive, etc…)	The specificity of the learning effects suggests that research into serious gaming will benefit from placing specific constraints pertaining to activities of daily life on game development.
Boschmann et al., 2016 [81]	AR	4 able-bodied subjects	TAC test	Novel system provided a more realistic experience compared to a classic two-dimensional implementation resulting in improved subject performance.
Anderson & Bischof, 2014 [82]	AR	12 able bodied volunteers	Adapted version of the IMI questionnaire	The system is superior to traditional methods in a number of subjective dimensions such as enjoyment, perceived effort, competency, and pressure.
Bouwsema et al., 2014 [58]	Serious game-based NI-VE w/ VF and MF	32 able-bodied subjects	Ball throwing game, BBT, & test tasks (e.g., tracking, matching, object recognition)	Subject performance significantly improved by 48%, however, grip force control only improved while performance information was provided.
Nakamura et al., 2013 [83]	NI-VE	2 able-bodied subjects	BBT	Improvement in the number of tasks successfully completed confirmed that the proposed system could be used for MyoBock prosthesis training.
Simon et al., 2012 [84]	NI-VE	2 individuals with a transhumeral amputation	Observational analysis, verbal feedback, and task performance measures	By using a virtual training approach followed by functional training using a physical prosthesis, pattern recognition control (PGT) is anticipated to advance from the laboratory to the home environment.
Resnik et al., 2011 [74]	NI-VE w/ AF, VF, and TF	1 case study	Interviews with the subject throughout training	Analysis of interview feedback indicates that a virtual environment is valuable for upper limb amputees who must master a large number of controls as well as amputees who need a structured learning environment.

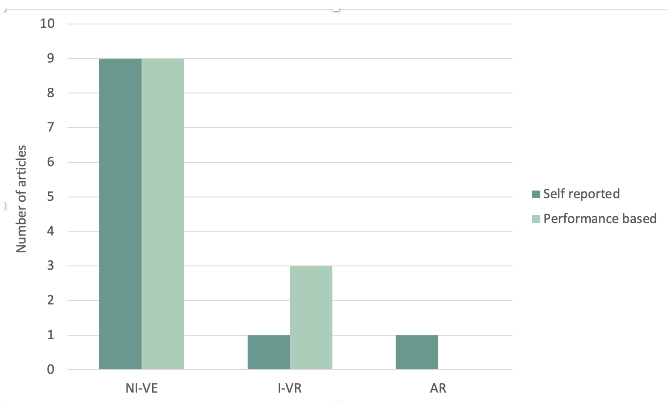

Fig. 3. Number of articles utilizing subjective self-reporting and objective performance-based assessments for the different XR modalities. While the graph is based on data from 20 articles, some experiments used both categories of assessment tools during their studies, yielding a total of 25 plotted values. I-VR: immersive virtual reality; NI-VE: non-immersive virtual environment; AR: augmented reality.

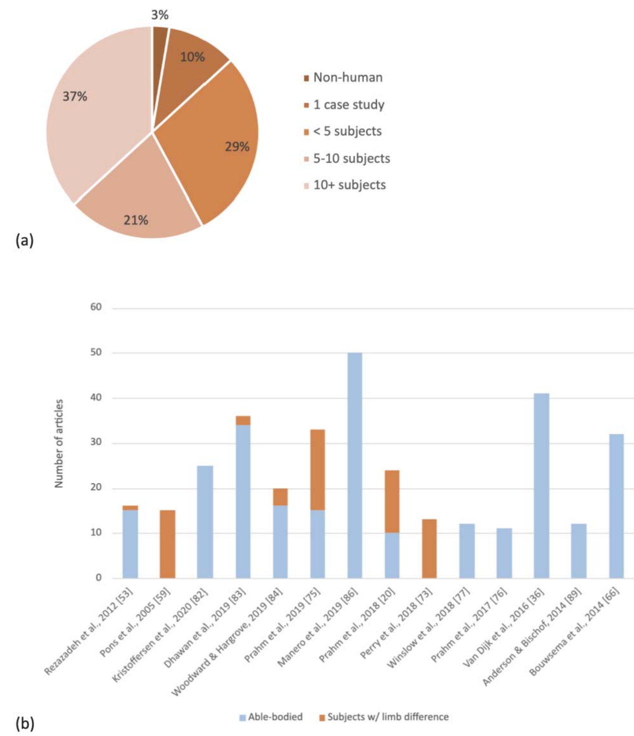

Fig. 4. (a) Proportional distribution of the subject pool sizes in the existing literature as summarized in Table I and Table II. (b) Subject profiles in more extensive experimental studies (10+ participants).

Our analysis shows that assessments featuring NI-VE systems were the most prolific. Eighteen out of the 20 analyzed articles in Table II focused on testing NI-VE systems for clinical use, consistent with the information gathered after examining the literature in Table I, which focused on research seeking to advance the technology. In that case, 13 out of 22 articles focused on NI-VE testing. However, there was no clear preference with regard to the type of functional assessment. Eleven studies used self-reporting tools, and twelve relied on performance-based assessments. The chosen outcome measure seems to be mainly associated with each research group's preferences and some specific aims of the experiments. We argue that a thorough analysis requires a combined approach, using both self-reporting and performance-based assessment tools.

Furthermore, there is an evident shortage of studies assessing other forms of XR systems, such as I-VR and AR, M-VR. In particular, our research found that only one study has been conducted to demonstrate user responses for Augmented Reality systems. Moreover, before clinical deployment, the technology must be tested in large-scale clinical trials to ensure its validity and safety. For clinical trials concerning medical devices, the US Food and Drug Administration (FDA) recommends a subject pool of around 10-40 participants for most devices [87]. Consequently, to understand where XR technology lies on the timeline of widespread clinical adoption and what stages must first be completed to reach that goal, we further analyzed the collected literature (Table I, Table II). The goal was to inspect the size of the studies and profiles of the participants recruited (Fig. 4).

We divide all the articles in Tables I and II by the number of participants in the studies. The pie chart in Fig. 4 portrays the percentage of articles that fell into each category. Following the subject pool recommended by the FDA, the division that is most relevant to clinical application is the one containing all studies featuring at least 10 participants. Incidentally, this category contains the largest portion of articles (Fig. 4a), representing 37% of the inspected literature. Two of the articles in that category focused on advancing the technology (Table I). The remaining articles focused on understanding subject responses using self-reported or performance-based assessment tools, assessing user interaction with the technology, and validating XR systems for potential clinical use.

When conducting large-scale clinical testing, the experiments must be performed with subjects representing the device's final user demographics. We inspected the participants' profiles in large-scale studies recruited at least ten subjects (Fig. 4b). All works in this category were performed with non-disabled participants as well as individuals with missing upper limbs. An analysis of the results showed that 7 of 14 (50%) of the studies recruited at least one subject with a missing limb. However, only 4 out of 14 (29%) of the studies recruited enough amputees to constitute at least half of the total sample. Besides, a more in-depth analysis indicates that only one of the twenty collected studies constituted a clinical trial [80]. The maximum number of subjects in any of the studies was 50. These results highlight the importance of further clinical evaluations of XR technologies for prosthesis training, specifically by performing more extensive clinical studies with amputees.

V. Adoption Barriers and Facilitators

Most in-lab research associated with developing new technologies for disabled people is usually focused on technical aspects of the problem. It generally overlooks user satisfaction issues and other social and economic aspects [88]. Without thoroughly studying every facet of the problem, we risk an inaccurate understanding of how the technology will fare once it is deployed. Social, organizational, or economic barriers may significantly hinder or entirely prevent a solution from being realized to its full potential in the clinical environment. Here, we seek to determine the qualitative and quantitative advantages that X-Reality rehabilitation platforms offer to assist prosthesis training and the challenges they may face upon deployment that can prevent them from gaining traction despite the advancements in technology.

A. Technological Limitations

The flexibility and the various functional elements offered by the XR-based prosthesis training arguably constitute the main factors supporting its use in a clinical environment. Thus, before addressing social, organizational, and economic adoption barriers, it is necessary to acknowledge limitations in the existing technology and the testing and validation processes. Reported issues include, but are not limited to: problems related to the set-up deployment, ease of use, realistic sensations, intensity and number of training levels and sessions that are necessary on an individual basis, and anthropomorphic product design [89]. A notable limitation of training in a virtual simulator is that users usually do not receive any feedback other than visual and auditory. The lack of feedback that is related to physical motion and weight can considerably limit the overall results. While XR-based systems are claimed to reduce the patient's cognitive load, the weight difference and inertial effects may influence the muscle signals recorded from the limb during training using, for instance, myoelectric virtual prosthesis [29].

Literature investigations revealed that XR-based training methods have not matured at the same pace as the development of novel dexterous multifunction prostheses and new and more advanced functional assessment models [90]. Prosthesis designs have rapidly advanced to include various control mechanics such as on-off, proportional, continuous, control, machine learning-based. These new developments aim to make prosthesis control more intuitive and less strenuous on the patient [91]. Furthermore, advancements in the field of human-prosthesis interfaces have examined novel control modalities, such as invasive neural interfaces, brain-machine interfaces, and combined signal processing [4]. Among all the articles analyzed in this review, only four articles examined the possibility of using neural control or EEG signals for prosthesis training in X-Reality [35], [46], [50]. Devices using biological signals for control often require the most training when compared to body-powered or passive prosthetics. Thus, a more significant effort is required to match X-Reality rehabilitation models with state-of-the-art prosthesis technology.

B. Human Factors and Social Barriers

Surveys seeking to understand the perceived benefits and barriers of adopting e-Health applications found that participating physicians cited the time and effort involved in learning to use the technology as a significant barrier to adopting the technology [92]. Privacy concerns play a role as well. Many virtual systems are web-based, leading to physicians' and patients' concerns that their data may not be secure. The individual's need is a significant indicator of technological acceptance. Perceptions of therapists and patients towards the technology and perceptions of themselves as being "tech-savvy" are of fundamental importance for adopting virtual systems in clinical rehabilitation [93]. Therefore, addressing these concerns and accounting for perceived patient attitudes is vital to creating solutions that reflect the target user's needs.

Our study has shown that most research works focused on the acquisition of technical knowledge and often take a technology-centered approach. Of the articles examined in this review, 52% of them focused on exploring specific technological elements as opposed to whole system testing [29], [32]–[51]. However, a more natural and human-friendly interface between the technology and the patient is essential to developing a viable treatment and clinical rehabilitation device [94], [95]. Teams working with XR systems should seek to explore new solutions, preferably involving potential users in all phases of the process, from brainstorming to design, experiment, and deployments processes. Establishing a patient-centered approach and ensuring that human factors are considered from the beginning of the design process is crucial to avoiding complex, long-term issues that may arise when developing suitable devices that can successfully perform their intended purpose [96].

C. Organizational Barriers

Technology translation, from the labs to industry and users, is one of the most critical issues facing widespread innovative healthcare solutions. The lack of evidence-based decision-making on both the clinical and managerial levels has been identified as a critical contributor [97]. Adopting new medical solutions requires a redistribution of responsibilities and rearrangement of activities also within the clinical organization [89]. This new condition can lead to push-back from individuals involved in the decision-making process and personnel affected by it. As a result, the status quo is often maintained because it presents a path of least resistance. Legal barriers also present a significant barrier since liability and malpractice laws create a climate of uncertainty among physicians, especially in countries like the United States [92].

Much has been written in the literature about the different ways in which people seeking to introduce novel solutions can overcome barriers to organizational change. One example of such a solution is to foster a climate of trust and flexibility within the organization while promoting open communication and feedback [98]. Allowing decision-makers to gain a complete understanding of the technology may also eliminate the uncertainty surrounding the shift from physical to X-Reality therapies. It seems clear that these organizational issues should also be taken into account during research and development. Organizations are more likely to accept novel technology if their established systems already support it. Integration with hospital systems, including privacy and security protocols to protect patient data, is necessary to facilitate adoption within clinical organizations.

(a) (b)

Fig. 5. (a) Volunteer using immersive VR platform using HTC VIVE Pro with EMG signal processing controller and tactile feedback. (b) the training protocol with serious games tasks and virtual prosthesis controlled by the user.

D. Economic Issues: Value Assessment

In many instances, budgeting concerns result in a low prioritization of novel technologies if current solutions are adequately beneficial. In a survey that assessed physician attitudes towards new healthcare technology, 80% reported the lack of financial support as the main barrier [92]. In addition, patient experience plays a factor. A greater positive experience for users improves user engagement and treatment adherence, adding value to the technology to offset implementation costs. Therefore, the value that a solution adds relative to its implementation cost is a significant factor that influences technology adoption [99]. Measuring value may be difficult because it is dependent on various organization-specific factors. However, one primary consideration when assessing the value of a new medical solution is the cost per quality-adjusted-life-years (QALY), or "what is the adjusted cost necessary to provide patients with more quality years of life?" While there is a shortage of literature examining the cost-effectiveness of X-Reality solutions in prosthesis rehabilitation, existing studies have assessed QALY results of technologies similar to X-Reality interventions. A study reviewing the cost impact of medical technologies estimated that telehealth operations showed a 62% probability of being more cost-effective for every added QALY, at a threshold of US$50,000 [100]. Since X-Reality interventions offer great potential for remote and telehealth applications, this analysis appears lucrative from an economic standpoint.

We also investigated the direct impact of possible improvements provided by the technology when compared to that of currently implemented motor rehabilitation techniques. In this context, we ask: are X-Reality approaches clinically more lucrative in prosthesis rehabilitation from the perspective of all parties involved? Once again, due to the lack of available comparison data on prosthesis rehabilitation, we compared traditional physical therapy and X-Reality rehabilitation methods for stroke patients. From an organizational perspective, the economic burden of physical therapy for post-stroke rehabilitation in Canada was US$35,000 per patient per year [101]. Replacing traditional equipment for an advanced, complete, permanent X-Reality system, on the other hand, costs US$20,950 annually per patient [102]. From a patient perspective, the annual cost for traditional physical therapy services is US$11,689 per patient [103]. Alternatively, a patient utilizing an in-clinic X-Reality rehabilitation service incurs a one-time payment of US$1,490, a significantly lower amount. This number is reduced even further for telehealth X-Reality services that can cost as little as US$835 [104]. Cost of treatment is a paramount factor for the patient and insurance companies which would be more likely to pay for and endorse a treatment that incurs a lower cost.

VI. Pathways to Deployment

A variety of factors associated with upper-limb prosthesis training advances using X-Reality were discussed in this review. This section summarizes the key takeaways that can be gathered from the analysis of the literature.

Overall, 45% of the articles focusing on improving XR-based prosthetic training utilized only EMG signals as a control mechanism. However, new advanced models based on sophisticated pattern recognition methods to improve control are already under investigation [4]. Nevertheless, EMG seems to be approaching its limit as a source of control, especially for more advanced dexterous prostheses. As such, future systems and research should seek to move further and aim for combined control mechanics based on neural control, either by means of electroencephalography or nerve implants, along with the necessary signal processing protocols. Novel tactile and sensory feedback systems should also be considered to provide intuitive and natural control during training and use, which would lead to a better embodiment of the prosthetic device. Adaptive systems and serious gaming can further provide novel and more engaging systems while offering patients the necessary 'challenges' to advance in the actual training. Regarding X-Reality interfaces, 54% of the reviewed research conducting whole system testing (Table II) was based on NI-VE. Therefore, additional research should be conducted using other X-Reality interfaces such as AR and I-VR. In any case, both self-reported and performance-based outcomes must be carefully observed to assess the results correctly. Furthermore, there is a lack of longitudinal studies examining abandonment rates following XR-based prosthesis training and rehabilitation [11]. Such a study could provide further evidence to support the use X-Reality technologies in the clinic.

Currently, there is a shortage of experiments performed with subjects suffering from limb difference in the field. Most often, studies were based on non-disabled subjects instead. A culmination of the aforementioned factors may be playing a significant role in the low interest of clinical personnel and institutions in adopting XR-based prosthetic training platforms, despite the advancements in signal processing and feedback control modalities.

Based on the data gathered in this review, our team has already began developing various experiments to investigate novel strategies, such as using iVR platforms for myoelectric upper-limb prosthesis training based on serious games and somatosensory feedback (vibrational and transcutaneous electric stimulation) to better engage the subject (Fig. 5). The subject can control a virtual prosthesis using EMG signals to perform the Box and Blocks Test while receiving tactile feedback when the virtual prosthesis touches and grabs a virtual object.

Once the technology is perfected and the clinical tests are performed, our next challenge will be to deploy the device to market. With regards to deploying rehabilitative X-Reality technology, there are some advantages. Since similar technology has been implemented clinically to treat issues such as stroke [104], the approval process may be less taxing. Furthermore, since most X-Reality systems contain no implantable elements, FDA classifies them as either Class I, indicating minimal risk, or Class II, for moderate risk If the device is classified as Class I, it is also possible to proceed directly to market without requiring any additional regulatory approval.

A significant advantage of prosthesis training using X-Reality is that it offers the possibility of distant learning. The benefits include increasing access to care in remote areas and facilitating training for patients who cannot come to the clinic or when physical attendance may be challenging, as is the case during the current COVID-19 pandemic. However, for such an approach to be successfully deployed, current technology must still be optimized for this purpose. For instance, the patient should be able to autonomously operate and use the device without a clinician's presence during training. On the other hand, the therapist should be able to gather data and conduct all necessary evaluation protocols despite not being physically present. Future efforts seeking to undertake this approach should consider human and social factors relating to individual needs, including older patients with limited mobility. Designing patient-centered functional rehabilitation methods is essential for making distance prosthesis training using XR systems a reality in the future.

VII. Conclusion

We answer the questions posed at the beginning of this paper by concluding the following:

1) Progress on XR-based prosthesis rehabilitation is largely constrained to academic research, with minimal clinical use.
2) At present, there are no studies that have integrated non-visual user feedback into the immersive virtual environment.
3) The most prominent focal point to promote acceptance is related to the low number of amputee subjects in current experimental trials.
4) Moving forward will require tests and clinical evaluations on large sample sizes. Furthermore, focusing on user needs and remote training options should pave a promising route towards future clinical deployment.

The technological aspects described in this paper, including signal control, feedback, adaptability, and serious gaming, can incidentally be combined to increase user engagement and ease of use to provide a structured and autonomous learning environment, both inside and outside the clinic. A promising alternative may arise from the combination of visual and somatosensory feedback in an immersive Serious Game using HMD. Such integration has the potential to provide the user with a high level of immersion combined with improved prosthesis embodiment in the virtual space.

X-Reality technologies applied to upper-limb prosthetic training and rehabilitation of amputees undoubtedly show promise, as demonstrated in this review. However, establishing a patient-focused, value-driven approach is critical towards overcoming the aforementioned adoption barriers in the near future.

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The statements made herein are solely the responsibility of the authors.

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