Virtual Reality can mediate the learning phase of upper limb prostheses supporting a better-informed selection process

Abstract

With the emergence of sophisticated bionic prostheses for upper limb amputees, the selection of the most appropriate device for each individual might become a challenge. Owing to the cost and complexity of such devices and the required time to learn their usage, it would be relevant to facilitate access to a wide range of them for intensive testing in ecological environments. In this paper, we report the development of a virtual reality setup that emulates three representative bionic prostheses and their key grasp selection methods. Twelve able-bodied participants and one transradial amputee participated in a study whose objective was to assess the influence of this setup in quantifying the perceived usability of the virtualised devices, and thus to guide a better-informed selection process of a preferred device based on the most suitable grip selection method for each individual. Results show that the user learning curve with the three simulated devices and their perceived usability was different, and that this had an influence on the final device selection. In particular, more than half of the users changed their favorite device after the experiment in virtual reality. In sum, this paper provides a proof of concept that virtual reality is a valuable tool to support a better-informed selection process of an upper limb myoelectric prosthesis that is personalized to individual preferences and capabilities by mediating its learning phase.

Keywords: prosthesis, selection, usability, learnability, HMD

1 Introduction

Upper limb amputation is a traumatic event which leaves a person with serious impairment, significantly affecting their quality of life. Human hands are ubiquitous instruments for everyday tasks, allowing steady gripping, dexterous manipulation, and tactile exploration of the surroundings, as well as communication with others [1]. Upper limb amputees (ULA) may be fitted with a prosthesis to replace their amputated hand. A prosthesis is used to restore impaired arm and hand function so that individuals with upper limb amputation can independently fulfill activities of daily living (ADLs) [2]. The ideal prosthetic hand should re-establish the lost motor and sensory functions [3] and mimic shape, size, and weight of its biological counterpart [4]. However, upper limb prosthesis rejection rate reaches 25% in adults and almost 50% in children [5]. These figures vary as a function of the characteristics of the user and prosthesis, the amount of training or skill development with prosthesis, and the development of one-handedness and resulting independence [6, 7]. ULA have the choice between two main categories of prosthesis with respective pros and cons: passive and active devices [8]. Most prostheses used nowadays are passive and serve as an additional support or instrument of social function and patient assistance, with limited motor and/or sensory restoration. [9–11].

Myoelectric prostheses form a particular class of active prostheses. They are controlled using electromyography (EMG), i.e. sensing of the electrical activity of the user's residual forearm muscles to determine their motor intention, and command the prosthesis appropriately [12]. Most commercial systems are controlled using a two-channel direct and proportional control [12] and are not intuitive to use for every user [13]. Consequently, controlling a myoelectric prosthesis is a demanding task for a potential user, regardless of its complexity [14]. In particular, this requires being able to selectively activate muscles and regulate their activity for proportional control. This usually necessitates substantial training [15]. A growing number of advanced myoelectric prostheses are being developed by different companies [4]. Matching the user with the most suitable one is a challenge, and the large number of factors that could determine prosthesis choice makes this choice even harder [16]. Another reason that complicates prosthesis choice is that the motivation of prosthesis use varies from one person to another [5]. While some users may require the prosthesis to carry out specific daily activities, others may place more value on aesthetics and social integration [5]. Therefore, it is crucial to clearly identify the user's individual preferences and facilitate user-involvement in the prosthesis selection process. The current emphasis on shared decision-making in healthcare, particularly for selection process taking individual preferences into account, supports the need for testing and acquiring knowledge about prostheses in ecological situations [17, 18].

To facilitate prosthesis selection, several devices can be implemented in a virtual reality (VR) environment. To create the most realistic simulator, an immersive VR environment with a head-mounted display is suited to provide the "sense of presence", i.e. the ability for the user to feel physically present in the simulation settings [19]. According to [20], there have been several attempts to develop such VR systems. Typically, VR was used as a displaying method in a limited number of previous studies, and they mainly aimed at facilitating training either for hand opening and closing movements [21–27] or more complex gripping patterns [28]. Moreover, among these studies, only one used the conventional dual EMG electrodes channel that corresponds to commercially available configurations [23]. The others used an eight EMG electrodes channel as well as an advanced pattern recognition controller [21, 22, 24, 26–28]. Pattern recognition and multiple EMG electrodes may be the future for myoelectric prostheses, although, it is not today's reality that ULA must face with their current myoelectric prosthesis [12, 29]. Last but not least, to our knowledge, no study has so far compared different devices and their grasp selection methods to support a better-informed selection process.

Virtual testing could offer ULA the opportunity to test the key grip pattern selection systems of different commercially available myoelectric prostheses; although the extent to which abilities learned in a simulated environment may be transferred to a real-world activity is still an open question [30–32]. The goal of the present study is to describe and assess the feasibility of a VR system to implement such a testing environment, and thus to potentially mediate the learning phase supporting a better-informed selection process. Three simulated prostheses, inspired by commercially available myoelectric ones, have been implemented. They are controlled by 2 surface EMG electrodes, placed on the forearm of the participants, who conducted tasks requiring to switch between different grip patterns. The users can thus learn to use these different grip patterns and to interact with virtual objects in the virtualised environment. We tested this system to assess whether this VR environment can influence the perceived usability of the three implemented prostheses, and consequently mediate the learning phase of these devices by human individuals. We further studied if this perception is correlated with actual learning or overall performance metrics of each device.

2 Methods

2.1 Participant details

Twelve able-bodied participants and one ULA voluntarily participated to this study (Table 1). Inclusion criteria for able-bodied participants were: aged between 18 and 40 and being fluent in French. Able-bodied participants were excluded

Table 1 Participant demographics. S13 is the ULA participant, all the others are able-bodied.

Participants	Gender	Age	Handedness
S01	M	24	R
S02	F	23	R
S03	F	25	R
S04	M	21	R
S05	F	23	R
S06	F	23	R
S07	M	22	R
S08	M	22	R
S09	F	24	R
S10	M	26	R
S11	F	24	R
S12	F	24	L
S13	M	27	L

if they had any impairment and/or any previous experience with EMG control. All participants provided their written informed consent for the collection and use of their data.

The ULA participant who was included in the experiment was recruited as a preliminary pilot to compare performance with the able-bodied group. He is a male born with unilateral missing forearm on the right side. He has been using myoelectric prostheses since the age of six. He currently uses a Michelangelo prosthesis (Otto Bock, Duderstadt, Germany). The first myoelectric prosthesis he had was a Greifer (Otto Bock, Duderstadt, Germany). He has always chosen his prostheses based on their commercial descriptions. He is comfortable with the use of his residual limb and is not affected by phantom pain.

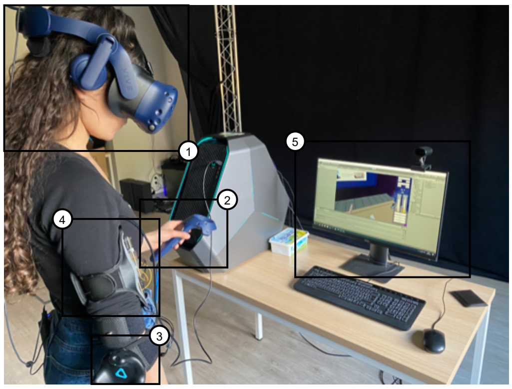

Fig. 1 Overview of the experimental setup: (1) HTC Vive HMD, (2) HTC Vive Controller, (3) MyoWare^{TM} electrode covered by HTC Vive Tracker, (4) in-house EMG processing interface, and (5) visualization screen for the experimenter. Base stations are not visible in this picture.

2.2 Experimental setup

The system follows a closed-loop control similar to a real bionic prosthesis. The actuation pathway consists in the acquisition of the myoelectric signals from the participant. These signals are translated into an intention that is encoded into the control command leading to actuation of the prosthesis. This loop allows the opening/closing of the prosthesis as well as the change of grip patterns. The sensory feedback loop consists in the detection of stimuli from virtual objects. These signals are processed in the software and encoded into a visual and auditory feedback signal that is displayed in the VR environment. For example, some grip pattern changing methods require two consecutive particular myoelectric signals, so an auditory feedback is implemented to indicate whether the first signal has been taken into account.

Experiments were conducted in a VR room with a table in its center, see Figure 1. Since the hardware barely limited movements, the participants were free to move in the environment around the table. The VR hardware consisted

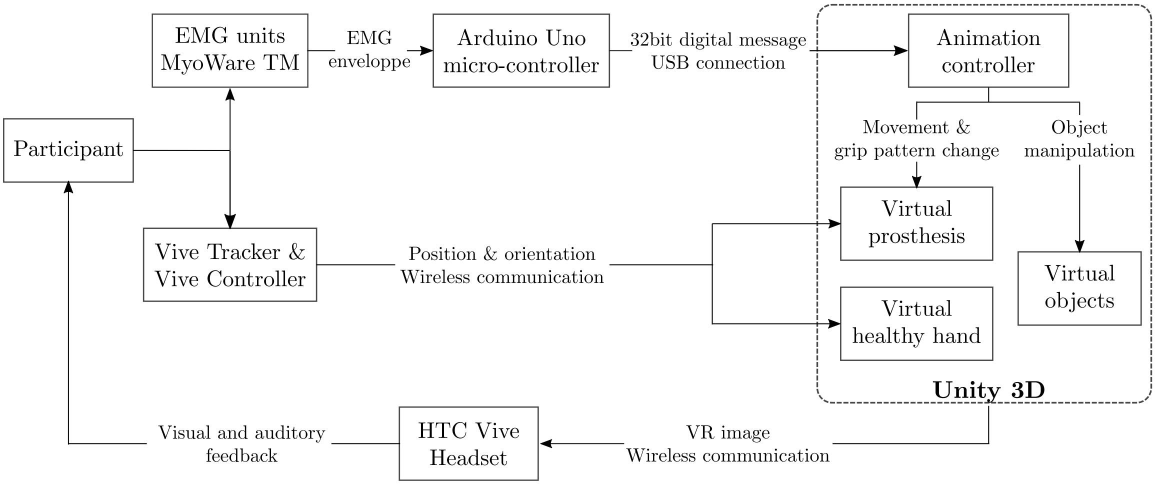

Fig. 2 Overview of the system architecture with main components and data flow: an Arduino Uno micro-controller is used to process the myolectric signals from the EMG units MyoWare^{TM} and the animation controller manages the opening and closing of the prosthesis as well as the changing of available grip patterns. Localisation of the virtual prosthesis and healthy hand is managed by the Vive Tracker and Controller. A visual and auditory feedback is provided by the HTC Vive Headset. Further details are provided in the text.

of a High Tech Computer (HTC) Vive head-mounted display (HMD), tracker, controller and four base stations. All these components are from the Vive model (HTC Corporation, Taoyuan, Taiwan). It also required a high-end computer and finally an in-house built EMG controller composed of EMG units MyoWare^{TM} (Advancer Technologies, Raleigh, US) coupled with an Arduino Uno micro-controller (Arduino, Somerville, US).

An overview of the system architecture is provided in Figure 2. EMG units transmited an EMG envelope to an Arduino Uno micro-controller. It provided the collected data to the main computer where they were processed by the Unity software (Unity Technologies, San Francisco, US) to control the virtual prosthesis. The system also required having the position and orientation of the virtual prosthesis and the healthy hand. For this purpose, four base stations fixed in the VR room tracked wirelessly two hand-held joysticks, i.e. the Vive tracker for the prosthesis and the Vive controller for the healthy hand. In order to emulate the use of transradial bionic prostheses, the Vive tracker was placed, both for able-bodied and ULA, on the right forearm near the elbow, at the end of the (simulated) residual limb. Based on the myoelectric signals and the tracking devices location, a visual and auditory feedback was displayed in the VR environment. Eventually, the HTC Vive headset provided this feedback to the participant.

The participants were immersed in a VR environment composed of several scenes (Figure 3). The structure of the scenes was made of a corridor, i.e. a main menu, leading to four rooms. In the Calibration room, the intensity of the signals collected by the two EMG units is displayed in real time, in order to manually adjust the minimal threshold for activation for each of the participants. Any signal above this threshold produced a visual feedback from the animation controller during the activities in the other rooms. In the EMG interface learning room, the participants underwent three velocity controlled mini-games allowing them to become more familiar with the interface and controlling actions via EMG signals. The Prosthesis Selection room aimed at selecting the prosthesis and providing the participants with a quick review of its main features. These three rooms did not generate quantitative or qualitative results analyzed in this paper, but were useful for the whole familiarization process with the device. The Learning room offered the possibility to virtually test the previously selected prosthesis by performing various tasks. Quantitative results reported in this paper were collected in that last room. This scene displayed a table with cubes of different sizes on top of it. The participants could interact with these objects through the virtual prosthesis to fulfill the tasks.

In this research, three representative prostheses have been implemented, each of them being inspired by a commercially available device (Table 2). They are named “Prosthesis 1”, “Prosthesis 2”, and “Prosthesis 3” and respectively capture the most salient features of the Greifer (Otto

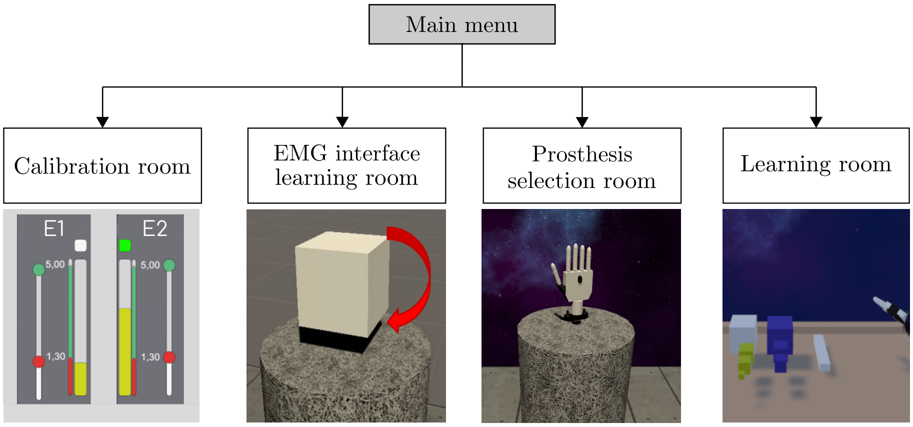

Fig. 3 The VR environment, built with Unity, is composed of a main menu leading to four rooms: (1) the calibration (setting the minimal and maximal EMG threshold), (2) EMG interface learning (EMG-driven mini-games), (3) prosthesis selection (review and selection of the prosthesis to test) and (4) learning room (prosthesis testing through virtual tasks). Details related to each room are provided in the text.

Table 2 Overview of the implemented prostheses.

	Prosthesis 1	Prosthesis 2	Prosthesis 3
Model prosthesis	Greifer (Otto Bock, Duderstadt, Germany)	Bebionic (Otto Bock, Duderstadt, Germany)	i-Limb (Össur, Reykjavik, Iceland)
Opening/Closing	2 electrodes	2 electrodes	2 electrodes
Amount of grip patterns	1	8	5
Pattern changing	-	Electrode, button, thumb	Electrode, gesture, grip chip
Wrist rotation	Manual	-	-

Bock, Duderstadt, Germany), Bebionic (Otto Bock, Duderstadt, Germany), and i-Limb Quantum (Össur, Reykjavik, Iceland) prostheses. These prostheses offer a good mix of different grip selection mechanism and difficulty. The Greifer is a simple clamp intended to provide fast and strong grip, while the Bebionic and i-Limb Quantum have a hand shape appearance. They differ in the way their thumb is motorized. It is passive in the Bebionic while it is active in the i-Limb Quantum. In former, this requires rotating the thumb manually. Both devices have different mechanisms for changing the grip pattern. The selection of implemented features and functionalities was made based on a trade-off between the realism they bring to the representative prosthesis and the overall complexity they add to the experience. To assess perceived usability of the virtualised prostheses, a key feature is the grasp selection methods for a given one.

Therefore, the basic mechanisms for changing the grip pattern of Prosthesis 2 and Prosthesis 3 have been implemented as detailed in Figure 4. Prosthesis 1 does not need a grip adjustment mechanism. Changing the grip pattern for Prosthesis 2 is done by three different channels, namely using specific EMG signals, manually changing the thumb position, or pushing the button on the back of the hand. The eight implemented grip patterns are placed in four groups of two. Two consecutive EMG opening signals trigger the switch from one grip pattern to another within the same group. The position of the thumb, i.e. either lateral or opposite, triggers the transition from groups 1-2 to groups 3-4. The button triggers the transition from groups 1-3 to groups 2-4. The mechanisms of grip pattern selection implemented for Prosthesis 3 rely on gestural and proximity control. Gestural control implies maintaining a long EMG opening signal, followed by a movement of the prosthesis in a specific direction (up, down, left, right) assigned to a given grip pattern. Proximity control implies the passage of the virtual prosthesis near a virtualised chip to access a fifth grip pattern. An auditory feedback is generated after the

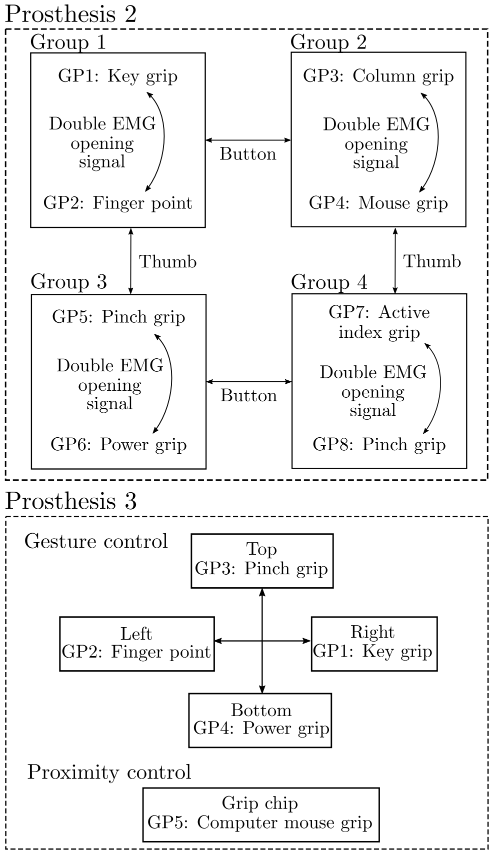

Fig. 4 Implemented mechanisms of grip pattern selection for Prosthesis 2 (top) and Prosthesis 3 (bottom). These diagrams were provided to the participants, in the Learning room, during the test of the prostheses. Details related to each mechanism are in the text. GP stands for Grip Pattern.

execution of a double or a long EMG opening signal to indicate to the user that the manipulation has been accomplished.

2.3 Experimental trials

The experiment was performed in three sessions over two weeks (Figure 5). The required time to perform each session was about one hour. Sessions were spaced approximately two to seven days apart while remaining within the two week period.

During the first session, a theoretical description of the three prostheses was delivered. Each implemented prosthesis was explained orally with the support of a video[1] made by the manufacturer of its real counterpart. After this, a survey was filled for the first time by the participants. Each session further required an installation step, to equip the participant with the different devices being used. The portable hardware was fixed on the participant's biceps and the EMG units were placed on their forearm. The participants were given an explanation of both movements required to control the prostheses, i.e. hand flexion and extension. Then, the EMG thresholds adjustment was performed. Based on the intensity of the received signal, the minimal thresholds were set at the signal intensity at rest, while the maximal thresholds were tuned to center the scale around the reachable range of values. This was used to adapt the opening/closing velocity of the prosthesis. Then, the main VR session could start. After the third session, the survey was asked to be completed for the second time.

The main VR session was divided into two steps (Figure 6). First, before trying the different prostheses, the participant was asked to perform three mini-games using only the EMG signals. This preliminary step aimed at learning the use of the interface. These mini-games were presented in the form of an object, i.e. a cube, a sphere, or a clamp, floating in the center of the room. Each object could move in a certain way. The cube could rotate on itself, the sphere could translate from left to right and the clamp could open and close. The velocity of movement depended on the intensity of the EMG signal generated by the user and its direction depended on whether the signal was measured on the extensor or flexor muscle. Since a continuous visual feedback of generated EMG signals was displayed, this activity allowed the participants to become more familiar with the control of this type of signal. The mini-games were an easy way to get familiar with this aspect. For two mini-games, i.e. the sphere and the clamp, a scoring system was implemented in order to stimulate learning. Concretely, small virtual items were instantiated at the top of the room within the range of movement of the object controlled through the EMG signals. These items fell slowly to the ground and the participant was

[1] Prosthesis 1 demo video: https://www.youtube.com/watch?v=PnFtdBlH7eE&list=PL7mB-asdJqTXylUZY34VgwJXoZop5phLC; Prosthesis 2 demo video: https://www.youtube.com/watch?v=tCAgGVcxrb8&list=PL7mB-asdJqTXylUZY34VgwJXoZop5phLC&index=2; Prosthesis 3 demo video: https://www.youtube.com/watch?v=Hlm0xpLPqp0

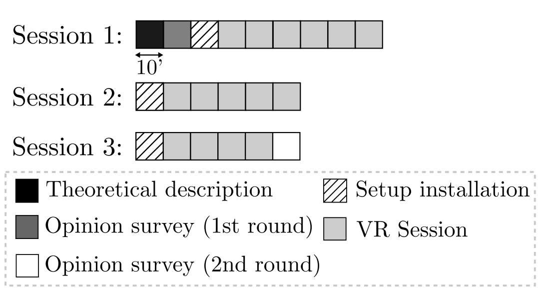

Fig. 5 Experimental timeline. Experiment was performed in three sessions over two weeks. Opinion surveys were completed at the beginning of session 1 and at the end of session 3. Each box in the timeline corresponds to approximately ten minutes.

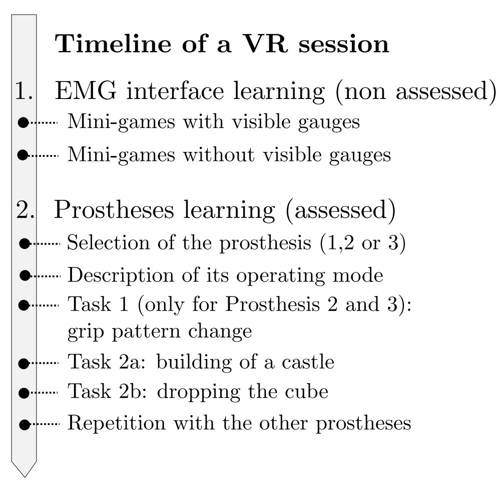

Fig. 6 Timeline of the virtual reality tasks. Participants started with EMG interface learning and then tested the three implemented prostheses. The order of testing the different devices was randomized across participants.

asked to translate the sphere or open/close the clamp in order to collide with a maximum of them. Each collided item increased the final score by one point. Each mini-game lasted one minute and the participants played each mini-game twice, i.e. once with a visual feedback of generated EMG signals and once without. Once this familiarization stage was completed, the testing of the different prostheses could begin. All participants started the first session with Prosthesis 1, i.e. the simplest one in order to become familiar with controlling movements in the VR environment and opening/-closing the prosthesis. For the rest of the first session and all the other sessions, the order of tested prostheses was randomized.

Two evaluation methods were used, leading to objective and subjective outcomes. On one hand, several virtual tasks had to be performed with each prosthesis, in the Learning room. This series of tasks was set up to guide the participants during the testing of each prosthesis to make sure that they were using all the implemented features. In addition, these tasks also allowed to collect quantitative data for analysis.

The first task was to explore prosthetic control by activating the implemented grip patterns. This task allowed the learning of a crucial aspect of the prostheses usability, namely the way to change grip patterns. It aimed at familiarizing the participants with these mechanisms and measuring their performance in changing grip modes with a given prosthesis. The second task required the participants to interact with virtual blocks placed on top of the virtualised table (Figure 7). The main purpose of this task was to test the participants' ability to move the prosthesis in the virtual environment and to interact with objects. The goal of this task was to construct a castle out of six different sized and shaped blocks (task 2a). This task required the participants to use the appropriate grasping mode, i.e the pinch grip, to grasp the different blocks and to keep this grip pattern during the whole task. If the participant involuntarily activated another grip pattern, they had to return to the mode allowing interaction with the virtual objects to continue the task. After the castle was raised, the participant was instructed to flick the smallest cube using another grip pattern, i.e. the finger point, without crushing the whole structure (task 2b). This second part of the task was added in order to force the participants to change their grip mode during a concrete exercise.

On the other hand, surveys were proposed to assess the participant's opinion about the prostheses and to evaluate the perceived usability of the virtualised devices. A before/after VR session questionnaire, i.e. a survey filled twice by the participants, was administered to assess if testing prostheses in VR changed or consolidated the individual preferred one. The terms "before" and "after" correspond to the moment when the participant completed it, i.e. before or after the VR sessions. Therefore, participants relied on the preliminary description of the prostheses to answer the first survey and on the additional knowledge obtained from VR testing for the second survey. First, based on specific criteria, i.e. functionality,

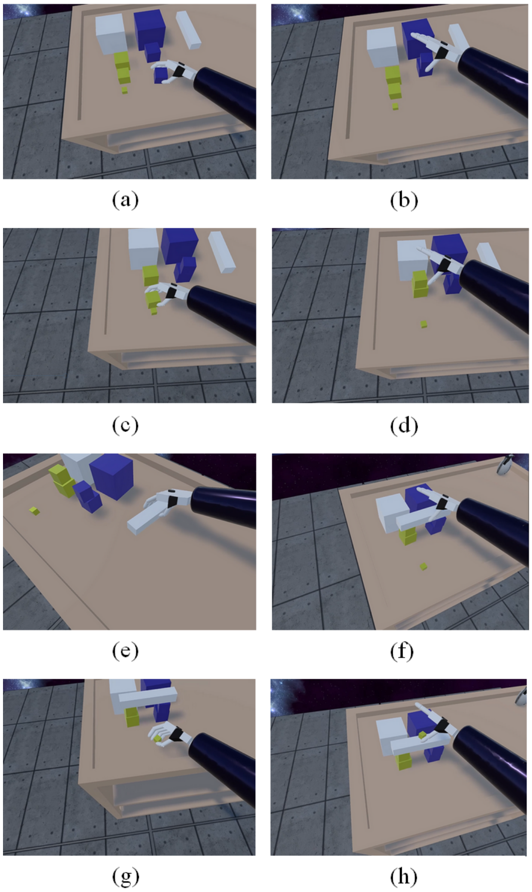

Fig. 7 Screenshots from a successful trial in task 2. The participant built the block castle with one of the implemented prostheses. The screenshot corresponds to the visual feedback given by the HTC Vive Headset to the participant completing the task in VR.

robustness, intuitiveness, innovation, motivation and simplicity, the participant was asked to rank the prostheses in order of preference. These different criteria gave a general overview of how participants felt about a given prosthesis. Then, on the basis of eight ADLs, i.e. eating, dressing, using phone, shopping, cooking, cleaning house, laundering, and travelling, proposed to the participants, they were asked to check off activities that they would feel comfortable doing with the evaluated prosthesis. Eventually, participants had to choose the prosthesis they preferred and specify whether or not the VR testing had an impact on their choice.

On top of this, the virtualised device usability was formally evaluated after the VR sessions by asking the participants to fill the System Usability Scale (SUS) questionnaire [33]. This 10-questions survey is a reliable “quick and dirty” tool aiming to represent a composite measure of the global usability of the studied system. It is based on a scale that allows the user to answer from “strongly disagree” to “strongly agree”, and is known to give reliable results even for small sample sizes. The outcome of this survey is the SUS score, i.e. a score between 0 and 100 that describes usability performance in the aspects of effectiveness, efficiency, and overall ease of use. Although each responses yield a score on a scale of 0 to 100, this score does not represent a percentage of usability. SUS scores can be analysed with a 7-point adjective scale quantifying acceptability [34]. The scale contains adjectives including “good”, “ok”, and “poor” and indicates whether this usability is “acceptable”, “not acceptable” or “marginal”. The average SUS score is 68, meaning that a device with this score will have a usability perceived as “ok” and “marginal”.

2.4 Data collection and analysis

During the exploration of the prosthesis control, i.e. task 1, and the manipulation of the blocks, i.e. task 2, the quantitative variables measured were the task duration and amount of co-contractions occurrence per second. If the prosthesis opening and closing EMG signals both exceeded their respective thresholds at the same time, this was considered to represent one co-contraction event. Since the prosthesis received two antagonistic instructions, i.e. simultaneous opening and closing, it did not move. The measurement was performed during the three VR sessions for each prosthesis.

Statistical analysis was performed using Statistical Package for the Social Sciences (SPSS) software (IBM, New York, US). The free variables were the task duration and the co-contractions occurrence per second generated during this task. The two fixed factors were the session and the prosthesis used. The results of the able-bodied group were compared using a two-way Analysis Of Variance (ANOVA). The SUS score for each prosthesis was also reported and compared using a one way ANOVA. A posthoc analysis was performed using Tukey’s honestly significant difference criterion for pairwise comparison. The results were reported as median/interquartile range. Outliers were not incorporated in these statistical tests. An individual data point was considered to be an outlier if it was outside 1.5 times the interquartile range. This concerned about 2% of the data in total. A correlation analysis was conducted between the SUS score and the quantitative outcome measures from the tasks and reported using the Pearson coefficient. No statistics was performed on the data collected with the ULA participant. These data are simply reported next to the able-bodied group in the following figures.

Concerning the before/after VR sessions survey, a global score was computed based on the individual answers provided to the criteria-based and ADLs-based questions. The score for each criterion was calculated from the ranking of the prosthesis for each participant. If a prosthesis was ranked first; it received one point, second - half a point or no point if it was ranked third. The maximum score for each criterion for a given prosthesis was therefore 13 points, since there was 13 participants. The score for each ADLs was calculated from the number of participants who reported feeling comfortable to perform the activity with a given prosthesis. If the participant reported to feel comfortable to perform the activity, one point was given to the corresponding device, otherwise no point was given. The maximum score for each ADLs for a given prosthesis was therefore 13 points, since there was 13 participants.

3 Results

3.1 Learnability

The task duration and the co-contractions occurrence per second across the sessions and the prostheses for the able-bodied group during task 1 and task 2a are shown in Figure 8. During the sessions, the participants reproduced the different grip patterns (task 1) and built a block castle (task 2a) using the developed VR system.

The difference in task duration between sessions 1 and 2 ($p < 0.05$), and between sessions 1 and 3 ($p < 0.001$) was statically significant for task 1 and 2a. At the end of the last session, the average duration needed to perform each task decreased of about one minute as compared to the first session for all prostheses. Over all sessions, Prosthesis 3 required less time than Prosthesis 2 to perform task 1 ($p < 0.05$) and Prosthesis 1 required less time than Prosthesis 3 to perform task 2a ($p < 0.05$). The amputee participant demonstrated similar decrease as the able-bodied group.

The amount of co-contractions occurrence per second was similar between the first and subsequent sessions for all prostheses in each task. Consequently, significance was not reached in the ANOVA statistics for that metric.

3.2 Usability

The SUS survey results, for the able-bodied group and ULA, are plotted in Figure 9. Significance was reached between Prosthesis 1 and Prosthesis 2 ($p < 0.001$) and between Prosthesis 1 and Prosthesis 3 ($p < 0.05$).

The before/after VR sessions survey led to prostheses classification according to general criteria and ADLs as shown in Figure 10. The criteria-based scores for Prosthesis 1 varied little between both admissions of the survey. For the criteria Functionality, Innovation, and Motivation, the scores were close to 0; while for the criteria Simplicity, Intuitiveness and Robustness, the scores were close to the maximum and well above the other prostheses. Prosthesis 2 received balanced criteria-based scores for each criterion. The

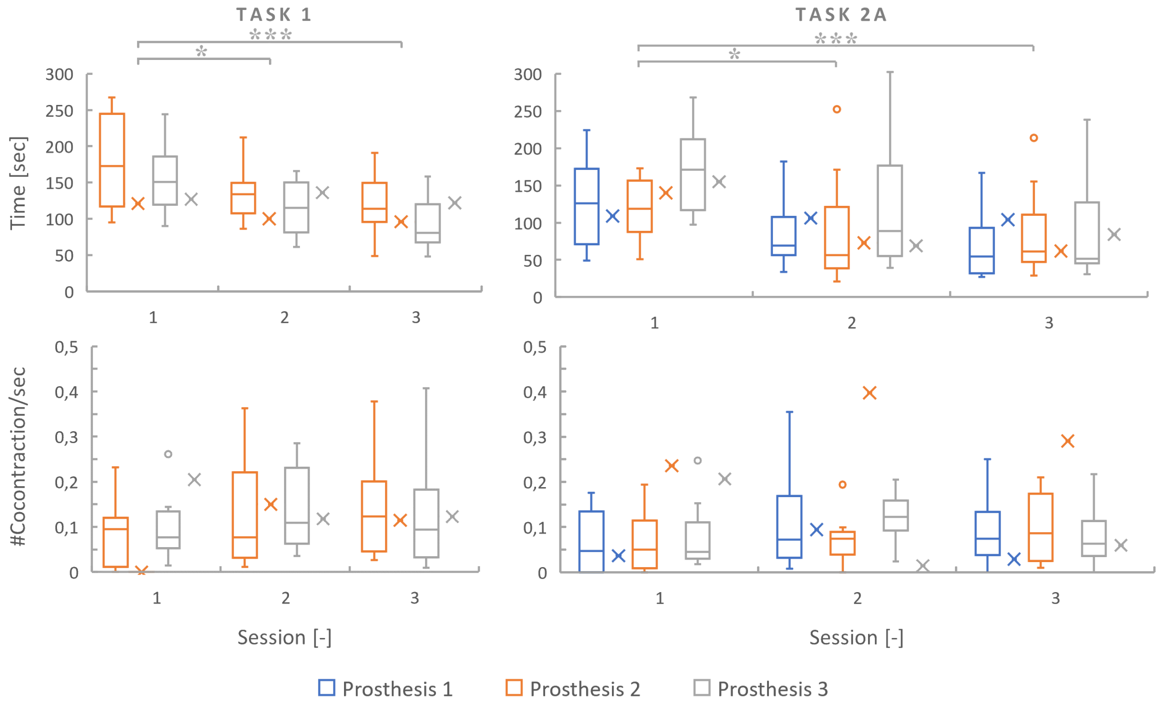

Fig. 8 Duration and co-contraction occurrence per second during task 1 and task 2a across sessions and prostheses for the able-bodied group (boxplots) and the ULA participant (cross). The boxplots depict median (horizontal line), interquartile range (box), min and max values (whiskers), and outliers (circle). The horizontal bars indicate statistically significant difference (*, p<0.05; ***, p<0.001).

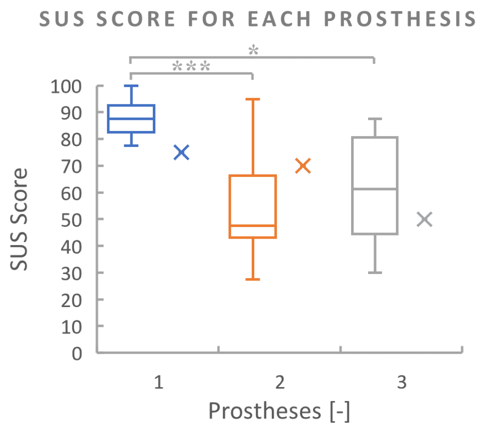

Fig. 9 Score of the SUS survey across the prostheses for the able-bodied group (boxplots) and the ULA participant (cross). The boxplots depict median (horizontal line), interquartile range (box), min and max values (whiskers). The horizontal bars indicate statistically significant difference (*, p<0.05; ***, p<0.001).

scores for the Simplicity and Functionality criteria decreased after testing in VR. Prosthesis 3 had the highest scores for Functionality, Innovation and Motivation but also the lowest score for Robustness. The scores for Simplicity and Robustness increased slightly after the VR tests. Prosthesis 1 had the lowest ADLs-based scores for each activity compared to Prosthesis 2 and 3 which had more balanced scores and close to maximum for almost all activities. The ADLs-based scores varied only slightly between before and after testing the prostheses in VR. In general, the scores tended to decrease after testing the prosthesis.

The distribution of favorite prosthesis selection before and after the VR sessions is indicated in Table 3. Interestingly, seven participants out of the thirteen changed their mind about which prosthesis they thought was the most suitable for them after testing in VR. All participants reported in the "after" survey that the training in VR had an

Table 3 Amount of participants having chosen the prosthesis, before and after virtual testing. Seven participants out of the thirteen changed their preferred device between before and after.

Preferred device	Before	After
Prosthesis 1	0 / 13	0 / 13
Prosthesis 2	7 / 13	4 / 13
Prosthesis 3	6 / 13	9 / 13

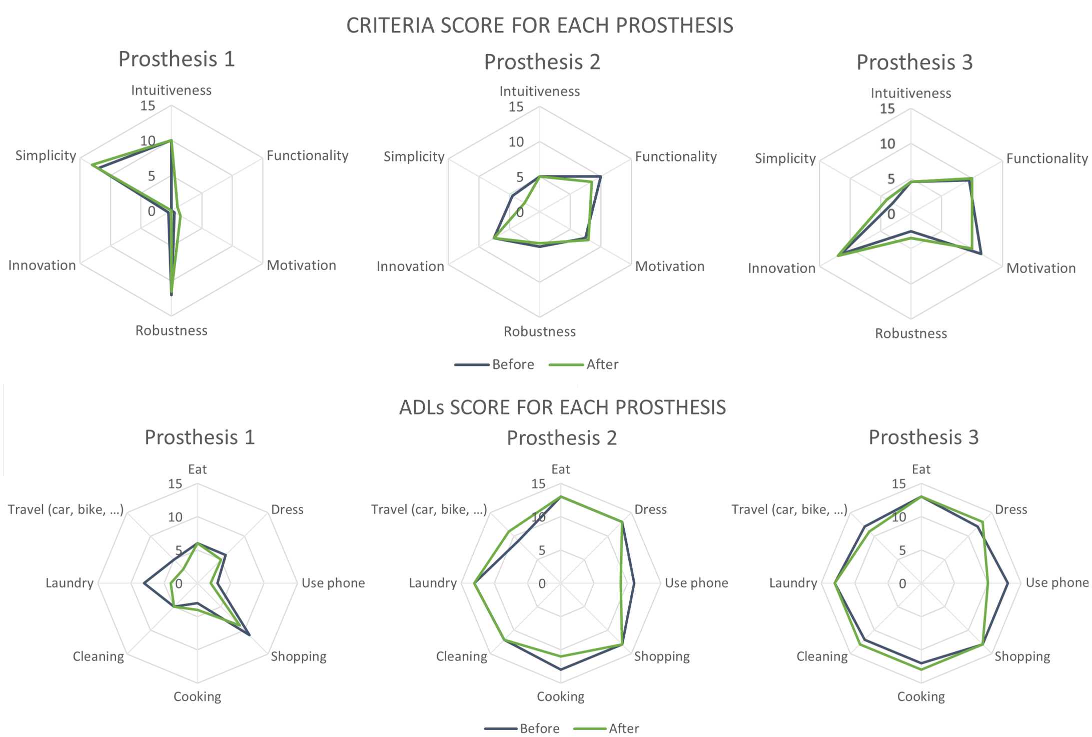

Fig. 10 Criteria score (top) and ADLs score (bottom) from the before/after VR sessions survey for each prosthesis. Scores given before the VR sessions are displayed as black lines, and those given after the sessions as green lines.

impact on the selection they would make for the best suited prosthesis.

According to the feedback from the participants, the changes in scores and choices they made are related to the awareness of additional challenges specific to the use of prostheses in general and/or the specific features of a given prosthesis. For example, the participants reported feeling that the double opening signal, required to change grip pattern in Prosthesis 2, requested more precision than maintaining a long opening signal, required by Prosthesis 3. In addition, it was observed that the auditory feedback delivered when doing these grip pattern change, mainly for the double opening signal, was crucial to support the user.

3.3 Correlation between objective and subjective measures

Based on the able-bodied data, we performed a Pearson correlation analysis between the subjective SUS score and the objective average task duration over all sessions and difference in task duration before and after the VR sessions, in order to focus on the absolute performance and learning aspects respectively. In other words, this analyzed

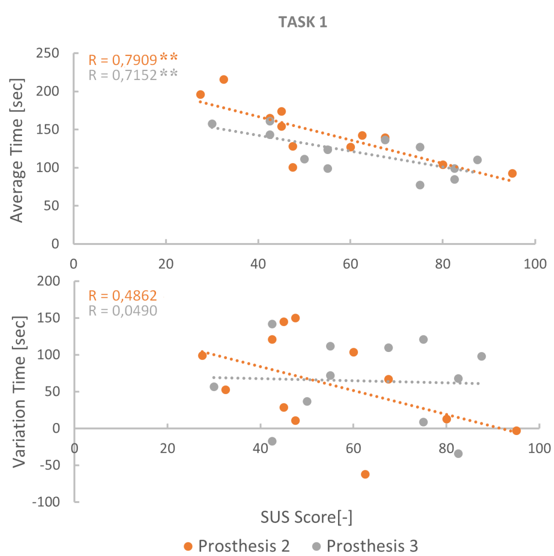

Fig. 11 Relationship between the SUS score given by each participant and the mean duration for task 1 over all sessions (top), as well as the difference in duration between the first and last session for each prostheses (bottom). The dotted line represents the linear trend line for Prosthesis 2 and 3 and R is the Pearson coefficient (* , p<0.05; **, p<0.01).

if people would tend to correlate the usability ranking of a given device either with their global performance with this device (average absolute time) or the amount of progress they made with it (difference between sessions 3 and 1). This analysis was performed for task 1 and is shown in Figure 11. The correlation between the average absolute duration and SUS score was statistically significant for each of the prostheses ($p < 0.01$). In contrast, the correlations with the change in duration did not reach significance for any of the prostheses. Similar analyses were conducted with task 2, and led to no significant result.

4 Discussion

We presented a VR environment that mediates the learning phase of myoelectric prostheses supporting a better-informed selection process. This was particularly embodied with three simulated devices inspired by commercially available ones. The system was assessed by implementing a protocol designed to better comprehend the mechanism for switching between different grip patterns and thus mastering a key aspect for controlling a myoelectric prosthesis that can be modeled in a VR environment. Furthermore, we evaluated the perceived usability of each virtualised prosthesis by the participants. The results have demonstrated that the developed framework was indeed effective: the user learning curve with the three simulated devices was different, showing that different devices might require different degrees of involvement or different skills to be fully mastered. Similarly, the perceived usability of the simulated prostheses was different. Altogether, this had an influence on the final device selection at the population level. In particular, more than half of the users changed their favorite device after the experiment in virtual reality. There is also a potential relationship between this perceived usability and the objective performance of the user with a given device. Indeed, the reported perceived usability was correlated with the duration of a specific task focusing on a critical aspect of the most advanced bionic prostheses, namely the grasp selection method. Having the possibility to switch between different grip patterns provides greater flexibility in everyday life, consequently the amount of available patterns and the mechanisms for accessing them are key elements in the usability of a given prosthesis.

Control mechanisms developed by manufacturers rely on conceptually different manipulations. Subsequently, users might feel more comfortable with one EMG signal manipulation and have more difficulty controlling another, leading to different individual performance for a given virtualised prosthesis. However, the eventual selection of a particular device does not only rely on its perceived usability. The final choice of the participants indicates that they might be more guided by criteria such as Functionality, Innovation or Motivation at the expense of criteria such as Simplicity, Intuitiveness or Robustness. Indeed, Prosthesis 1 obtained the best scores in these three criteria but was never chosen as the preferred device, whereas Prosthesis 3 obtained the best results in the other three criteria and was selected as the preferred device by the majority of participants. This might be explained by the range of tasks to be performed with the prosthesis. For instance, Prosthesis 1 is the only simulated prosthesis with perceived usability score above the average, i.e. 68. However, it did not allow users to feel comfortable in the achievement of certain activities. Therefore, its scores for all ADLs are lower than the scores of the other two prostheses. Moreover, it should also be noted that the SUS score of the virtualised prostheses may not account for some subjective considerations related to the real prostheses that influence participants' final choice.

A crucial factor in the selection of prosthesis was the control scheme for switching between grip patterns. Prosthesis 3 allowed to access to any desired grip pattern regardless of the current one, while Prosthesis 2 required to know the currently activated grip pattern at all times. This more advanced cognitive requirement regarding the mastering of control schemes might have impacted the participants' opinion. The results of the criteria-based score, computed for the before/after VR sessions survey, also support this observation since perceived Simplicity of Prosthesis 2 decreased after the VR sessions and conversely for Prosthesis 3. Furthermore, a similar trend is present in the ADL scores, indicating that participants felt more comfortable performing these activities with Prosthesis 3 than with Prosthesis 2. These different observations translated into a transfer of preference from Prosthesis 2 to Prosthesis 3 after the VR sessions. However, this is not so much the quantity of participants who changed their mind that allowed a better-informed selection of prosthesis, but rather the awareness of the different challenges related to the use of certain devices. If participants did not change their preferred device, the experience was still useful for consolidating their initial choice. These results highlight that decision making is a conscious process leveraging several considerations.

McFarland [35] reported that ULA are using up to three different prostheses daily. Yet, a systematic review [36] revealed that there is not enough evidence to determine which type of upper limb prosthesis is the most adapted for a given user, as each device has its pros and cons. However, without thorough knowledge of all available prostheses on the market, amputees can rely only on description provided by their prosthetist and their physiotherapist to choose which one fits them best. Therefore, the VR system prototyped in this research provides a complementary media for the user to learn about different prostheses. If this tool were to be developed in the future, this type of evaluation could be provided by the prosthetist, who plays a unique and neutral role in the accompaniment of amputees and the selection of their equipment.

Several attempts have been made to develop VR systems similar to the current solution [23–28]. Actually, only a few systems used VR as a displaying method for studies involving amputees. Even if VR rehabilitation programs are growing in popularity [37], to date none aimed at comparing different virtualised prostheses and their grasp selection methods with the objective to mediate their learning phase to support a better-informed selection process. Our system was evaluated in a pool of participants including one pilot ULA as a preliminary case study, and he globally displayed similar behavior as able-bodied ones. This is in agreement with the observation that individuals wearing simulated prostheses have functional task performance durations that are similar to the average durations of myoelectric prosthesis users [38].

A distinct advantage of the present VR system is that it offers a flexibility in designing the virtual prosthesis while providing immersion and realism due to the "sense of presence" allowed by the HMD. The framework can be adapted to include more simulated devices from different manufacturers and implement more complex grip pattern switching mechanisms. This system could also be adapted to be used in other applications such as R&D, which is costly in the prosthesis field, to test and refine different EMG-driven control scheme strategies. Moreover, the system currently allows the participants to discover grip patterns selection methods and myoelectric control by constructing a block castle but could be extended to other functional object manipulation tasks already used in virtual environments, such as the Clothespin [39], Box&Block or Pegboard tests [28, 40, 41]. Furthermore, continuous feedback of generated EMG signals can be displayed to the participant, as done during the threshold adjustment. As a result, the participants would be able to see how their muscle activation was converted into a particular movement while modulating muscular contraction. EMG feedback is a effective approach to faster learning and thus, acquiring skills in EMG-driven prosthesis control [42–45].

The present study, however, has limitations related to the realism of the implemented prostheses. By design, our environment only includes myoelectric prostheses and does not replicate all the functionalities of the real devices. Indeed, the simulated prostheses do not model all aspects of the commercially available prostheses and control scheme. The described VR environment only captures a limited part of the user experience and may influence the perceived usability of the virtualised devices and so the opinion of the participants. In addition, some features of the grasp selection methods may be more complicated to virtualise than others. The system in Prosthesis 2 relies mainly on a physical thumb, which is less realistic to virtualise, while other systems, such as the proximity chip in Prosthesis 3, are straightforward to implement virtually. The degree of scalability of these solutions is different, which is difficult to reproduce in a virtual environment. Therefore, the main limitation of this paper is the level of realism of the simulated prostheses and their control scheme.

Another limitation of this study is the quality of signal provided by the MyoWare^{TM} sensors, which is not comparable to standard myoelectric sensors. Indeed, the difficulty encountered by the participants to perform the double opening signal required by Prosthesis 2 was potentially related to the quality of this EMG signal. The performance and perceived usability of Prothesis 2 could have been improved with a system similar to that intended for use with a commercially available prosthesis. Moreover, our environment is not able to reproduce haptic feedback, i.e. force feedback (simulating object hardness, weight, and inertia) and tactile feedback (simulating surface contact geometry, smoothness, slippage, and temperature) [46]. Haptic feedback is a crucial sensory modality in interactions with objects that greatly affects the performance of the user [47]. Based on previous literature, it might be an interesting future development of the proposed learning tool [48, 49]. Futhermore, the reduced amount of training sessions that was offered to the participants is also a limitation, since presumably more practice would result in more efficient movement strategies [50]. Since the goal of the present study was to develop and pre-validate a framework mediating the learning phase of a simulated prosthesis in ecological environments, we believe that these limitations do not compromise the validity of our preliminary conclusions, and call for further developments of this setup, potentially in collaboration with manufacturers.

Upper limb prosthesis learning phase can potentially be mediated by virtual environments. Since Unity 3D is often used in video game development, it is especially well suited for serious gaming [30]. Serious games showed clinical evidence of improvement in EMG signal control [31, 51, 52]. Although the extent to which abilities learned in a simulated environment may be transferred to a real-world activity is still an open question. Indeed, research in motor control shows that skill learning is highly task specific [53, 54]. That is, similarity in goal-relevant features across training and ADLs tasks is necessary for transfer to occur [32]. Based on the literature, it is emphasized to prioritize transfer and take task-oriented considerations into account when developing a serious game with a myoelectric interface, i.e. myogame [32]. Transfer effects from a serious game to a myoelectric prosthesis task have been demonstrated while using a task-oriented myogame that augmented ADL-relevant features [32]. In this present study, we illustrated that VR myogaming is also a valuable tool to evaluate the usability of different virtualised bionic prostheses which is influenced by their learning phase, thus supporting a better-informed selection process for a particular user.

The designed framework combines diverse technologies. To allow further development, the design of the prototype and the source code are published and freely accessible via the following link: https://github.com/openhublln/VRforULA. The modular architecture, i.e. easily adaptable hardware and 3D virtual reality environment built with Unity, enables replacement of simple components or incorporation into other projects. Indeed, more scenarios may be developed by utilizing the extensive assets library of the Unity 3D platform's. Collision detection, grasping between the virtual prosthesis and objects, and several grip pattern changing methods are already included in our system.

5 Conclusion

The present paper described a novel system to mediate the learning phase of a myoelectric prosthesis and its grasp selection methods supporting a better-informed selection process. To allow the most realistic prosthesis simulation and facilitate the comparison between different virtualised devices, the system used an immersive virtual reality environment with a head-mounted display. The framework was tested by implementing a virtual prosthesis testing protocol including able-bodied participants and one amputee participant. Results illustrated that the tool was indeed effective leading to different learning curves and perceived usability for each simulated devices and that this had an influence regarding the final device selection. Therefore, the presented prototype highlighted a promising prosthesis learning tool and has consequently been released as an open source project to facilitate further work and development.

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