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VITA—an everyday virtual reality setup for prosthetics and upper-limb rehabilitation

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Abstract

Objective. Currently, there are some 95 000 people in Europe suffering from upper-limb impairment. Rehabilitation should be undertaken right after the impairment occurs and should be regularly performed thereafter. Moreover, the rehabilitation process should be tailored specifically to both patient and impairment. *Approach.* To address this, we have developed a low-cost solution that integrates an off-the-shelf virtual reality (VR) setup with our in-house developed arm/hand intent detection system. The resulting system, called VITA, enables an upper-limb disabled person to interact in a virtual world as if her impaired limb were still functional. VITA provides two specific features that we deem essential: proportionality of force control and interactivity between the user and the intent detection core. The usage of relatively cheap commercial components enables VITA to be used in rehabilitation centers, hospitals, or even at home. The applications of VITA range from rehabilitation of patients with musculodegenerative conditions (e.g. ALS), to treating phantom-limb pain of people with limb-loss and prosthetic training. *Main results.* We present a multifunctional system for upper-limb rehabilitation in VR. We tested the system using a VR implementation of a standard hand assessment tool, the Box and Block test and performed a user study on this standard test with both intact subjects and a prosthetic user. Furthermore, we present additional applications, showing the versatility of the system. *Significance.* The VITA system shows the applicability of a combination of our experience in intent detection with state-of-the art VR system for rehabilitation purposes. With VITA, we have an easily adaptable experimental tool available, which allows us to quickly and realistically simulate all kind of real-world problems and rehabilitation exercises for upper-limb impaired patients. Additionally, other scenarios such as prostheses simulations and control modes can be quickly implemented and tested.

Keywords: myocontrol, virtual reality (VR), rehabilitation, phantom-limb pain (PLP), intent detection, human machine interface (HMI), Box and Block test

(Some figures may appear in colour only in the online journal)

1. Introduction

The reported rate of people who underwent upper-limb amputation ranges from 0.1 to 0.19 per 10 000 [1–3]. In order to achieve a successful therapy and recovery for these patients, it is important to start with rehabilitation early on and pursue it continuously [4]; moreover, the therapy is highly dependent on the condition as well as on the patient, and given the size of the patient population, it must be issued on a mid- to large scale. In the ideal case we need a device/medical setup which can be easily adapted to the disease and patient's needs, it is easy to use and cheap, and it provides an effective, yet exciting and motivating experience, quickly leading to recovery. The need for both a patient-tailored therapy and its deployment in the mid- to large scale implies that the device enforcing it must be fast and easy to calibrate upon each patient; moreover, such a calibration must be easily updated in real time whenever required, for example because the patient requests a new feature to be added. We propose to address all the aforementioned problems with a highly immersive virtual reality (VR) environment in which upper-limb disabled persons can perform rehabilitation exercises and therapies designed by physiatrists and therapists. The usage of a modern intent-detection system, to be interactively trained along with the patient, could help regain the lost functionality. Such a system should employ commercial-strength hardware in order to provide reliability and be easily mounted/dismounted/shared in clinics, hospitals, rehabilitation facilities, and even at home.

In this work we propose a prototype of such a system, that we call *VITA* for *virtual therapy arm*. VITA consists of a *vive* VR system by HTC (www.vive.com), coupled with an *Myo* armband by Thalmic Labs (www.myo.com), (see figure 2). Both systems cost in total less than 1000 EUR in Europe, and are sold commercially; if we add the cost of a VR-capable PC or laptop, i.e. with good graphic capabilities, we get to a total price of about 3000 EUR. The trackers of the vive system provide the position and orientation of the user's arm and wrist, whereas the eight sEMG sensors embedded in the Myo Armband are used to detect the user's intent to grasp in several different ways, interactively and proportionally.

Let us consider a paradigmatic example of this idea. After amputation of a limb, the majority of people suffer from *phantom limb pain* (PLP—between 60% and 85%, [5–7]). Although the underlying causes of PLP are not entirely clear [8, 9], the most widely accepted explanation is that PLP is caused by a cortical reorganization happening in the brain area that was responsible for controlling the amputated limb. This area is taken over (cortical reorganization) by the neighboring regions, leading to a sensorimotor discrepancy that the brain interprets as pain. Most treatments for PLP include the elicitation of muscular activity linked to visual feedback, *mirror therapy* [10] probably being the most known example. Cheap and simple as it is, mirror therapy alleviates PLP in a relevant fraction of the cases [11].

In mirror therapy for the upper limbs, in our case hands for instance, the contralateral limb is mirrored onto the ipsilateral one to create the illusion that the latter has reappeared. While also activating the muscles in his or her phantom limb the patient sees bimanual, strictly symmetrical movements, and this combination of activity in the muscles and the visual feedback due to the mirror helps treating PLP over time. VITA can implement a similar treatment in VR, but without the limitation of symmetrical bilateral movements: using intent detection and motion tracking we can visualize the ipsilateral limb of an upper-limb amputated person at the anatomically correct position, and use the remaining muscle signals to control the motion and grasping. This is a major advantage over conventional mirror therapy in terms of Immersion. Studies with PLP patients have shown that similar systems have reduced PLP after treatment [12–15]. In [15] participants even state that the reduction is greater than expected from traditional distraction therapy alone.

Furthermore, from our experience working with prosthetics, two characteristics are crucial for successful intent detection: *proportionality*, meaning the ability to detect and predict non-discrete states of the hand; and *incrementality*, meaning the ability to update or even retrain the model of the underlying machine learning system at any time, on demand, leading to *interactivity* between man and machine and reciprocal adaptation over time. Note that *updating* in this context does not replace data, but rather adds new data to the previously trained model. These characteristics have already been called for by the scientific community [16, 17] and implemented by several groups around the world [18–21].

The application of those key elements can be seen in figure 1: the incrementality is shown by the ability to update the training in the VR environment at any time (upper right); and the proportional control is depicted by a pressure sensitive toy (lower right). This leads to an easy and intuitive control in VR, even for patients with severe hand impairments like amputations.

In this paper we first describe the system and then evaluate it by engaging 15 healthy subjects and a prosthesis wearer in a standard hand assessment test, the *Box and Block test*. By combining recent developments in the VR and gaming industry with our knowledge in intuitive, muscle based prosthetics control, we built a virtual simulation of this test. Furthermore, we developed a modular and affordable rehabilitation environment in VR. In the next section we discuss the relation of our approach to related works, followed by a description of our system (section 2). Thereafter we evaluate our system in a user study in section 3. This section contains the results as well as the discussion of the said study. To demonstrate the versatility of our VR environment we describe further applications in section 4 and finally we conclude our findings in section 5 and also provide a short outlook.

1.1. Related work

The idea of using VR in prosthetics and rehabilitation goes a long way back.

Several groups have investigated the usage and simulation of prosthetic control in VR. For example Hauschild [22] *et al* built a VR model of a simulated prosthetic arm in order to virtually train patients with that prosthesis. The VR environment is custom-built in that case, a magnetic tracking system is used and the sEMG control is very basic, consisting only of open/close commands. Similarly Lambrecht *et al* [23] show the usage of a VR environment for testing different control strategies. As we present in our work, Lambrecht *et al* also show a virtual Box and Block test (see section 3), however, based on very basic sEMG control methods. The work presented by Phelan *et al* [24] follows a similar concept to ours: comparable hardware is used to build a prototype VR training tool to familiarize amputees to their new prosthesis. However, in this proof of concept no quantitative results are shown. Another similar work by Garcia *et al* [25] uses sEMG data to control a simulated prosthetic hand. An interesting property of this approach is that the user can also vary the stiffness of the simulated prosthetic device. However, only one degree of freedom is controlled and the simulator is a very simplified depiction on a computer screen.

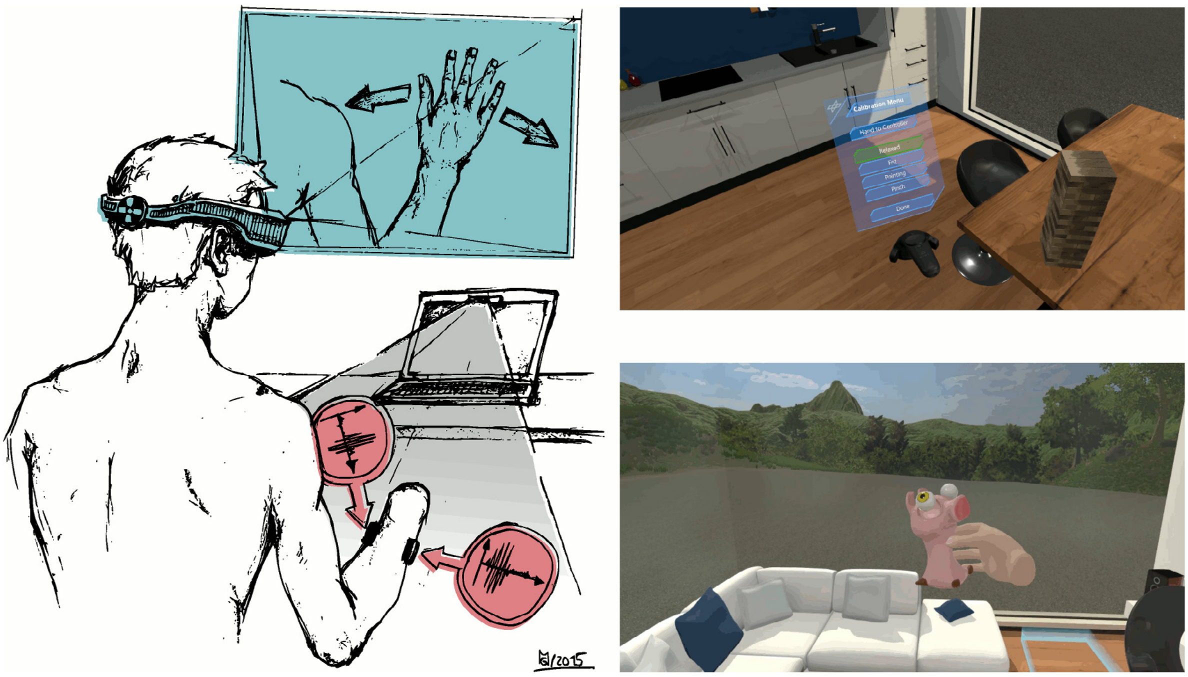


Figure 1. An artist's rendering of VITA (left), showing the components of the setup as well as its two main features: *interactivity* (upper right) and *proportionality* (lower right).

Furthermore, studies to assess VR in rehabilitation scenarios, e.g. to reduce PLP, have also already been performed. A system and an associated study, which shows promising results in reduction of PLP, is shown by Snow *et al* [14], where a VR input device is coupled with haptic feedback provided by a robotic arm. In [12] Ortiz-Catalan *et al* use augmented reality (AR) to achieve the same results on reduction of phantom limb pain. Based on this system, a study has been performed to investigate the reduction in PLP in amputees [13]. In both studies, only very basic control commands based on extracted sEMG data (like open/close) are used.

A crucial element in the usage of VR and subsequently in the functionality as a tool for rehabilitation is the authenticity of the illusion that is being created. We believe that an interactive, intuitive and natural control will strengthen the immersion in VR. As far as dexterous intent detection and control is concerned: inspired by recent research developments in the field of prosthetic control based on muscle signals, we developed a control system which allows (a) continuous estimation of single-finger activations, and (b) incremental learning and updating, leading to intuitive training and retraining. Whereas (a) is already a key trend in the myocontrol literature under the name 'simultaneous and proportional control' [26, 27], (b) incrementality still needs to find its way in the community, although promising results have been reported of [19, 20] and it is recommended as a key feature to improve robustness and reliability of myocontrol systems [17]. In this work we try to bring together the optimum of the VR technology and of research on dexterous intent detection and perform a user study to demonstrate the potential of these technologies. Namely, we use available, consumer-level VR hardware and software, in order to obtain the best experience and immersion for the subjects: we deploy off-the-shelf tools from gaming industry to obtain a very realistic and modular VR environment, which can be easily adapted and expanded for other purposes.

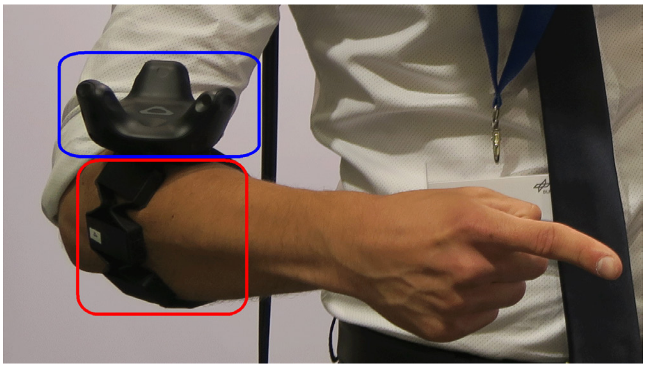


Figure 2. The employed input device, consisting of a Myo sEMG armband (marked red) combined with an attached tracker of the HTC Vive system (marked blue).

2. System description

In this work we investigate how a VR environment can be used to perform assessment tests and eventually be applied to rehabilitation of patients suffering from hand or lower arm impairments.

The key element of our system is that it is *controller-less*, i.e. no device has to be held in the hand: by applying machine learning methods the system is able to learn the specific muscle patterns for certain actions, making it possible to predict the intention of the user.

These predictions are based on signals produced by muscles when they contract. Different methods exist for measuring muscle

(a) (b)

Figure 3. The calibration routine, showing (a) the calibration menu, with which the user can interactively train the system, and (b) the EMG signal, which is displayed to the user.

contractions [28]. The most common one is electromyography (EMG). EMG detects the electric field generated by the depolarization of the muscle fibers. These signals can be measured on the surface of the skin, which leads to the name surface EMG or sEMG. sEMG can be used to control self-powered prosthetic hands. Most self-powered hands only allow for an open and close command. However, in research and slowly as well in clinics so-called pattern recognition approaches are being applied. Different hand gestures are realized using different muscles. These nuances can be detected, interpreted by machine learning algorithms and fed back as commands to the prosthetic hand.

The following subsections detail the different hardware and software components and the employed machine learning method to process the measured signals.

2.1. Hardware description

The systems consists firstly of a HTC Vive VR System. An additional tracker of HTC is attached to a Myo armband of Thalmic Labs. Both armband and tracker can be seen in figure 2. The Myo armband consists of eight sEMG sensors, which are used to measure the electric muscle activity of the user on the skin surface. Most muscles controlling finger and hand motions are located in the forearm; therefore the users are wearing the armband on their forearms. The tracker of the HTC Vive system provides the position and orientation of the users arm. Note that because we are targeting impaired or amputated users, there is no hand tracking conducted at all, but all movements of fingers are directly predicted based on the muscle signals obtained. The acquired sEMG signals are transmitted wirelessly via Bluetooth.

All processing, which is signal acquisition, filtering, training and prediction is done on an off-the-shelf, powerful laptop (Dell Alienware15) with a dedicated GPU, namely an NVIDIA Geforce GTX 1070.

2.2. Interface description

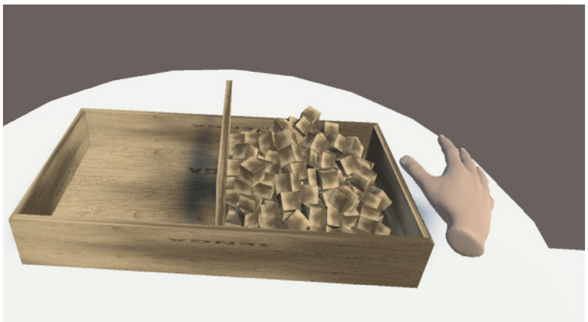
Crucial for a successful interaction is the ability to (re)train the system at any time. Therefore, an intuitive, inbuilt training procedure can be invoked by the user at any time. An example can be seen in figure 3 which shows the invoked menu (figure 3(a)), and the acquired sEMG signal (figure 3(b)), which is directly shown during the training procedure, giving feedback about signal quality to both user and experimenter/rehabilitation specialist.

Like mentioned before, key to a successful interaction for impaired subjects—both in VR and in the real world—is the ability to do fine manipulation and intent detection. This means, that the users can precisely control their intended motions and the force they want to apply.

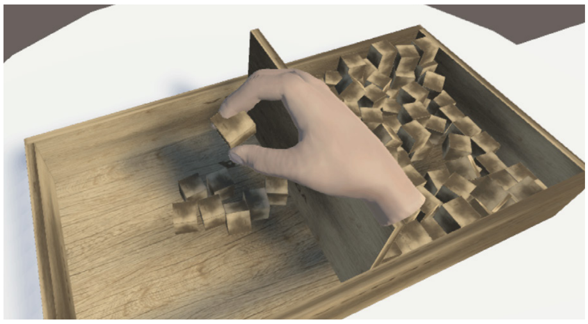
The environment was built with the Unity game development platform. Using an object-oriented programming approach, a modular structure allows an easy adaptation to new applications and rehabilitation scenarios. This is shown in section 3, where a classical hand functionality assessment protocol is fully implemented in our environment.

2.3. Signal processing

The intuitive interaction ability is achieved by the employed state-of-the-art machine learning algorithm: the proportional and simultaneous control of six degrees of freedom (DOFs) of the virtual hand was implemented by feeding the eight sEMG signals to a machine learning algorithm, sc. Ridge regression with random Fourier features, already utilized several times in online myocontrol [19, 20]. This algorithm, a finite-dimensional approximation of RBF-kernel-based linear regression, has at least four desirable characteristics that make it suitable for this task: it is inherently incremental, i.e. its model can be updated online at a reduced computational cost; it is bounded in space and time, that is, its performance does not depend on the number of acquired samples, which is potentially unlimited; it runs quickly enough on standard



(a)



(b)

Figure 4. The VR Box and Block test, in the initial state (a) and during the experiment (b).

consumer-level hardware, so it provides a smooth experience to the user; and, lastly, it is a non-linear regression method—it provides simultaneous and proportional control, given a few input signals.

As shown in the calibration menu (figure 3(a)), four actions can be trained, namely relaxed, fist, pointing and pinch[1]. The users train successively the different actions by mimicking the displayed action with their hands, or attempt to do so in the case of amputees. An action in this context means a certain configuration of the six DOFs of the virtual hand.

By implementing this method in real-time directly in the VR environment, we are able to run a very intuitive training routine, shown in figure 3. This not only makes it possible to use the system for a multitude of users, even for amputees with very different muscle configurations due to traumatic injuries. It also allows a retraining at any time, which is important for long-time use, for example because of signal degradation in sEMG sensors due to changes in skin conductance.

Note that this method is not limited to controlling a virtual hand, like shown here, but can (and also has been) successfully applied to control a prosthetic hand in the same way [19, 20].

3. User study

A standard test to assess hand functionality is the so-called Box and Block test [29, 30]. This test consists of a box with two compartments and a divider in between. Goal of the test is to transport as many blocks as possible from one side to the other in the time span of 60s. We created a virtual version of this test using the software package *Unity* (see figure 4). The figure depicts the starting position of the Box and Block test (figure 4(a)) and the test in progress (figure 4(b)). A realistic impression for the user is realized by the two central features of our framework, which are an intuitive and individual training procedure and precise control.

We followed the procedure of the conventional Box and Block test as closely as possible. The participants of this study were 15 able-bodied subjects (three female, 12 male) with an average age of 31.0 $\pm$ 7.6 years old (mean $\pm$ std) and one prosthesis user (male, age 33) having a congenital amputation of his right hand with a 15 cm stump. The 15 able-bodied subjects were further divided into five expert and ten naive users. We deem a subject expert after using our myocontrolled VR environment for more than 10 h. The subject with congenital amputation wears a Michelangelo prosthetic hand by Ottobock with standard two-electrode control between 7 to 9 h a day and never did the Box and Block test in the past. He also accumulated several hours of usage of this myocontrol system as well as of a similar VR environment (described in section 4).

Each subject was performing a training phase as described before, showing the system both a relaxed and a grasping action. After that, the subjects were allowed to test their performance as long as they wanted, allowing for retraining if they were not satisfied with the performance. If they felt confident, the real test phase started.

Please note that, as shown in figure 3, the users are not limited to these two actions, but can currently train up to four actions. The application of this can be seen in section 4, refer especially to figure 6. This decreases the robustness slightly, thus here only two actions were chosen.

The usual Box and Block test consists of two phases, an initial 15s phase, where the user gets a trial run followed by a scored 60s phase [30]. Here, the blocks that are passed across the partition are counted, discounting multiple blocks moved at once and blocks that were dropped without the fingers passing the partition. The instructions are scripted and were read to each user according to the manual of the test.

Additionally to the virtual Box and Block test, all subjects performed the conventional Box and Block as well. The 15 able-bodied users performed this test with their dominant hand, while the prosthesis user did so with his prosthesis. To avoid influence of fatigue and/or learning we alternated the order of virtual and conventional Box and Block from participant to participant. A further note, while each able-bodied subject performed virtual and conventional Box and Block only once, the prosthesis user performed the virtual exercise eight times and the conventional one three times.

The experiments were performed according to the WMA Declaration of Helsinki, were beforehand approved by the work council of the DLR, and all subjects gave written informed consent before each experiment began.

3.1. Experimental results

The results of this study are summarized in figure 5 and can be found more in details in table A1 in the appendix.

[1] However, for the hand assessment based user study that we performed we only used two actions, namely relaxed and pinch.

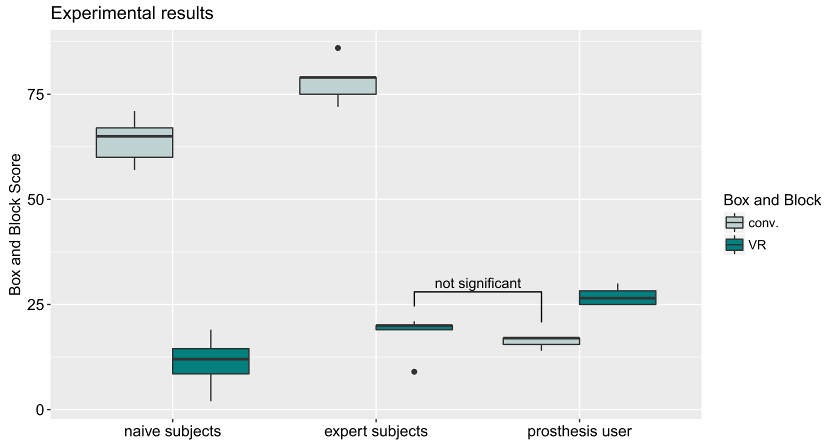


Figure 5. Boxplot of the experimental results, comparing a conventional Box and Block test with a simulated one in VR. The Box and Block score on the y-axis depicts the moved blocks in 60 s according to the standard test. Three subject groups took part, naive subjects with no experience using the system, subjects with more than 10 h experience, and one prosthesis user. If not otherwise stated all interactions are significant.

The figure shows a boxplot for each combination of factors. Furthermore, we evaluated the results statistically using a two-way ANOVA with the factors *subject type* (prosthesis user, naive and expert) and *Box and Block type* (conventional and virtual). A correction has been performed to account for the multiple repetitions performed by the prosthetic user. The scores from different able-bodied subjects were considered from different sources, while the repeated scores were considered to be from the same source. The results for the main factors are $F(1, 40) = 4823.177, p < 0.001$ for *Box and Block type* and $F(2, 40) = 165.488, p < 0.001$ for *subject type*. Furthermore, the interaction effect between the factors was significant as well with $F(2, 40) = 1023.932, p < 0.001$. Following the two-way ANOVA we performed the *Tukey*-test to determine the pairwise interaction between the factors and the factor combinations.

Considering the factor *Box and Block type* participants performed significantly better at the the conventional type than at the virtual one (with $p < 0.001$). For the factor *subject type* all groups differ from one another significantly (with $p < 0.001$).

The post-hoc *Tukey*-test revealed that all but one pairwise interaction are significant. The exception is the difference between the expert users in VR and the prosthesis user using his prosthesis (with $p = 0.784$).

3.2. Discussion

We were able to engage 15 able-bodied participants and one prosthesis wearer in the user study, showing the performance in both a virtual and a conventional Box and Block test. The results show significant differences between the three groups, which were naive and expert participants and a regular prosthesis user. Although the expert users are very familiar with the VR system, the performance of the regular prosthesis user was significantly better, which suggests a certain level of knowledge transfer from prosthetic control to VR.

Furthermore, we were able to find significantly better performance of the expert users in the conventional as well as in the virtual Box and Block test over the naive users. At least to some degree we associate this effect to the fact that the expert users were aware of the norm scores for adult participants in the Box and Block test.

In general the factor *Box and Block type* (conv. or VR) is significantly different within each of the three groups of subjects. Interestingly, we found no significant difference in the specific interaction between the expert users in VR and the prosthesis user using his prosthesis with $p = 0.784$ (bracket saying *not significant* in figure 5). Although this does not mean that the performance can be seen as equivalent, there is potential to simulate prosthesis behavior in VR by experts. This could simplify user studies to the extent that one does not have to build custom sockets for each subject, but can simply implement new features, perform studies and draw conclusions for prosthesis behavior in daily life.

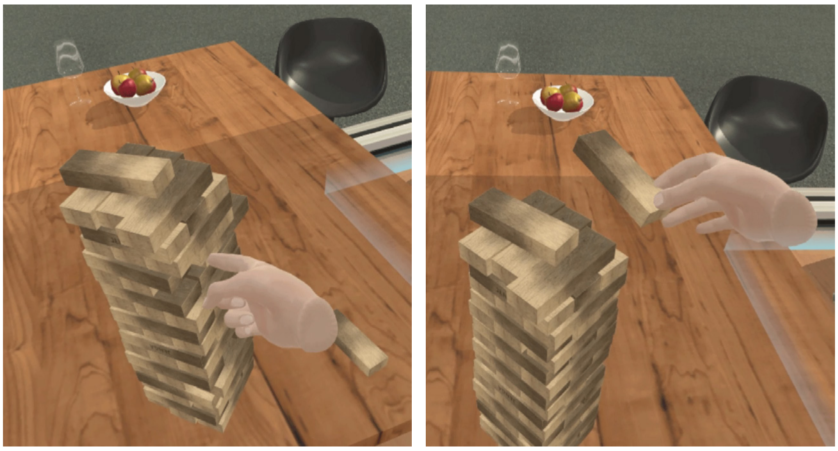
Lastly, we would like to raise attention to the performance of the prosthesis user compared to the expert subjects. We can see that the prosthesis user outperforms the experts in VR, but fails to transfer these skills to the real world Box and Block test. We attribute this behavior to the shortcomings of the prosthesis. We argue that the increase in performance compared to the experts can be transferred to the real world with an adequate prosthetic control scheme and potentially improved hardware.

4. Further applications

To illustrate the modular character of our VR environment we developed a home-like scenario, consisting of a living room and a kitchen. In order to showcase and test the features of the system, several example applications have been built.

A key element for a successful continuous rehabilitation process is that the rehabilitation has to feel entertaining for the user, which is also often called 'serious games' [31]. To show the ability of a fine manipulation, a Jenga game was developed, in which the user has to take blocks out of a tower, without toppling it over, see also figure 6.

Another application showing specifically the ability of the system to detect intended forces is showcased with a



(a) (b)

Figure 6. The implemented Jenga application, showing the versatile manipulation possibilities, e.g. a pointing action (a) and a grasping action (b).

(a) (b)

Figure 7. A squeezable toy, showing the ability to continuously estimate force levels applied by the user, where in (a) no force is applied, whereas in (b) the user is applying more force.

(a) (b)

Figure 8. An example of the interactivity of the environment, showing a kitchen scenario, in which, e.g. cupboards can be opened (a) and objects can be grasped (b).

squeezable toy, which deforms under pressure, the eyes popping out proportionally to the force applied, see also figure 7.

The video clip provided at https://youtu.be/0nZ5x978kuA shows a demonstration of the system and the application possibilities.

Apart from these two example applications, the environment is fully interactive: drawers can be opened; objects can be grasped and carried to other locations. With this, household tasks can be simulated and trained for impaired users in a realistic way, which can be seen in figure 8.

Such a practical scenario, based upon virtual daily-living activities raises a further interesting point. Namely, in such a case, the subject is naturally induced to move around the kitchen and manipulate objects which lie at different heights; she is also induced to squat, stretch and bend over. We speculate that this amount of movement and physical exercise (exerted by muscles other than the missing ones) could be beneficial, too, acting as a ‘side-effect’ physical therapy.

5. Conclusions and outlook

In this paper we have introduced VITA, an integrated intent-detection and VR setup, initially aimed at upper-limb rehabilitation. Several applications have been described and a single user study has been reported of, performed on 15 intact subjects and one person with congenital limb deficiency, using a virtual rendering of the Box and Block functional assessment test. The results of the user study reveal that there is a significant better performance of a prosthetic user in VR than with the real exercise with his actual prosthesis. Also, a strong training effect between naive and expert users is visible.

The main novelty of VITA with respect to the state of the art is at least twofold: firstly, it enforces simultaneous and proportional myocontrol, allowing for the modulation of muscle activation (and consequently of the forces applied in the VR environment); secondly, it achieves *robust* and *extensible* intent detection thanks to incremental learning driven by direct user interaction in the VR environment. Robust, in that the machine-learning model can be updated to take into account changes in the biosignals; extensible, meaning that the same update procedure can be used to learn as many new patterns as the input device allows for. The shown system comes at an overall material cost of around 3000 EUR, meaning that it can be reproduced in most rehabilitation/assistive facilities as well as in hospitals and orthopedic clinics; it can even be thought as a home application, to be lent to or to be bought directly by the upper-limb disabled. The unlimited flexibility of VR allows for a *potentially endless number of applications* to be employed at home or in the hospital.

To the best of our knowledge, there is no standard assessment test for proportional force control. As a result, we replicated a standard functional assessment test by implementing a VR Box and Block test to compare with real-world results. However, also in VR, proportional control is important to maintain a grasp during manipulation of blocks.

In fact, a further research plan is that of launching a multi-center nation- and Europe-wide experimental evaluation campaign to evaluate the capability of VITA to effectively reduce PLP. Since the underlying VR programming engine, Unity, has a sufficiently accurate physics calculation engine, the system can also be used as a pre-training tool for amputees, while they wait for their new prosthesis; the mechatronic model of the desired prosthesis, with all its delays and limitations, can be embedded in the system, allowing the users to choose the devices they prefer. This training in a controlled virtual environment also allows for possibilities currently not possible: for example it is possible to adapt the level of control the user is applying and how much control is taken over by a computer. This allows a gradually increasing level of control the patient has to apply in his or her rehabilitation process and at the same time a continuous report of the patient’s progress. It must be remarked here once again that each and every patient is different from all others, therefore the benefit of the therapy for the single patient can hardly be generalized as-is to the rest of the patient population. This is one more reason why we propose to have a system flexible enough to accommodate many different amputations and conditions. The potential future multi-center study will need to incorporate enough patients with diverse conditions, to shed light on the generalizability of the approach.

In this study we focus primarily on upper-limb amputees, employing an sEMG armband at the patients’ forearm. We also plan to extend this work to the rehabilitation of other disabilities. Like mentioned before, we are aiming for extending the application, e.g. to stroke patients. However, stroke symptoms are manifold: for patients suffering from high amount of spasticity or a complete paralysis of a limb this method is currently not applicable. On the other side many stroke patients suffer from *hemispatial neglect*, i.e. a deficit in awareness of one side of the patient’s body. For this condition our system seems a very promising tool, gradually raising awareness to the affected side or limb in VR. The exact therapeutical applicability will be evaluated in a clinical study in the near future.

Another interesting feature of our system is the inbuilt logging capabilities: by being able to record the movement of each component in the VR environment during execution, we are able to use this for assessing the general performance of rehabilitation sessions. For example it would be possible to not only evaluate the transported blocks in the Box and Block experiment, but also the trajectories used or the velocity of movements. In the future, we plan to extend our studies in a similar way as in [32], where a modified Box and Blocks test with complex motion tracking is evaluated. Our system is able to deliver those evaluations without any form of hardware extension, just based on the logged data.

Lastly, let us not forget that the intent-detection system we use is modular and can be used with several different input devices other than sEMG-based (e.g. optical- [33] or tactile-based [34]) to improve the quality and dexterity of the detection. All of these devices are not limited to controlling a hand in a VR environment. It is very straight-forward to apply the exact same techniques to control a modern prosthetic hand, or a robotic arm. It is crucial to remark that all such devices are controller-less. This makes the system interesting for manifold application areas beyond rehabilitation, e.g. as a general controller-less input device for video games, surgery, construction etc.

Acknowledgments

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Appendix

Table A1. Results of all the participants sorted by subject type. Norms of the Box and Block test are reported according to [30].

Subject type	ID	Test type	Score	Age	Hand dominance/hand used	Gender	First test	Norm. Score
Naive subjects	4	conv.	59	28	R/R	M	VR	85.0 (SD = 7.5)
		VR	13					
	6	conv.	63	24	R/R	M	VR	88.2 (SD = 8.8)
		VR	13					
	8	conv.	58	28	R/R	M	VR	85.0 (SD = 7.5)
		VR	15					
	10	conv.	57	32	R/R	M	VR	81.9 (SD = 9.0)
		VR	8					
	12	conv.	67	24	R/R	M	VR	88.2 (SD = 8.8)
		VR	16					
	3	conv.	64	40	R/R	M	conv.	83.0 (SD = 8.1)
		VR	19					
	5	conv.	66	26	R/R	F	conv.	86.0 (SD = 7.4)
		VR	2					
	7	conv.	71	29	L/L	M	conv.	84.1 (SD = 7.1)
		VR	10					
	9	conv.	68	35	R/R	M	conv.	81.9 (SD = 9.5)
		VR	11					
	11	conv.	67	29	R/R	F	conv.	86.0 (SD = 7.4)
		VR	7					
Expert subjects	0	conv.	79	32	R/R	M	VR	81.9 (SD = 9.0)
		VR	20					
	2	conv.	79	54	R/R	M	VR	79.0 (SD = 9.7)
		VR	9					
	14	conv.	72	26	R/R	F	VR	86.0 (SD = 7.4)
		VR	21					
	13	conv.	75	28	R/R	M	conv.	85.0 (SD = 7.5)
		VR	20					
	1	conv.	86	30	R/R	M	conv.	81.9 (SD = 9.0)
		VR	19					
Prosthesis user	15	—	—	33	R/L	M	VR	81.3 (SD = 8.1)
	Rep. 1	conv.	17					
	Rep. 2	conv.	14					
	Rep. 3	conv.	17					
	Rep. 1	VR	25					
	Rep. 2	VR	27					
	Rep. 3	VR	28					
	Rep. 4	VR	25					
	Rep. 5	VR	25					

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