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Designing a Virtual Reality Myoelectric Prosthesis Training System for Amputees

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Electrical signals produced by muscle contractions are found to be effective in controlling accurately artificial limbs. Myoelectric-powered can be more functional and advantageous compared to passive or body-powered prostheses, however extensive training is required to take full advantage of the myoelectric prosthesis' usability. In recent years, computer technology has brought new opportunities for improving patients' training, resulting in more usable and functional solutions. Virtual Reality (VR) is a representative example of this type of technology. These preliminary findings suggested that myoelectric-powered training enhanced with VR can simulate a pain-free, natural, enjoyable, and realistic experience for the patient. It was also suggested that VR can complement prosthesis training, by improving the functionality of the missing body part. Finally, it was shown that VR can resolve one of the most common challenges for a new prosthesis user, which is to accept the fitting of the prosthetic device to their own body.

CCS CONCEPTS • Human-centered computing • Human-computer interaction (HCI) • Haptic devices • User studies

Additional Keywords and Phrases: Myoelectric-Powered Prosthesis, Virtual Reality, Amputees, User-Centered Designed, Artificial Limb

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1 INTRODUCTION

There is an estimated of ten million people living with amputation worldwide, of which more than the one-third are suffering from upper limb amputation, which is linked to body image dissatisfaction and low levels of body ownership (i.e., how well one is aware of bodily sensations) which presents difficulties in accepting the artificial limb as part of the body [29] and in most cases results in neglecting the prosthetic device [13, 34]. More specifically, 71.43% of prosthetic wearers reported difficulties in using the artificial limb [12], and the abandonment rate of transhumeral prosthetic devices is up to 60%, the most frequent reasons were "residual limbs were too short" (30%), pain (20%), the weight of the device (20%), or inability to control the device (10%) [28, 51]. Prosthetic wearers who reported to be satisfied with the artificial limb reported limited improved mobility and quality of life since they were also encountered difficulties with the prosthetic arm control [30, 32]. As a result, adjustment to prosthesis use and prosthetics satisfaction of an artificial limb in people with limb amputation has been a complex and sensitive process because of the physiological (e.g., presence of physical pain and sensations related to the missing body part) and psychological (e.g., depressive and anxiety episodes emerging from body image dissatisfaction) boundaries it encompasses [10, 23, 26].

The necessity of comprehensive patient training is required to increase artificial limb acceptance by influencing positively the prosthetic fitting and the patient's satisfaction, which will improve the movement capacity and promote early return to functional activities and abilities of daily living [6, 26, 48]. However, this type of training is considered to be expensive since it needs high-end technologies (e.g., myoelectric prostheses) and substantial monitoring by medical and paramedical staff [31]. To date, myoelectric technologies, have been considered to be a low-cost solution, widely and successfully available to act as an input to control the prosthetic limb based on myoelectric signals [2, 16, 20, 25, 38, 41], which are electrical impulses that occur naturally during muscle contraction and have been the most common and efficient technique for controlling accurately artificial prosthetic limbs through the use of electromyographic sensor [35, 49, 50].

Research has examined various uses of technology to aid and assist people with amputations or congenital limb deficiency. Such research is mostly aimed at providing interventions for relieving pain (e.g., transcutaneous electrical nerve stimulation units) [8, 17], reducing thermal discomfort (e.g., a helical cooling channel within the prosthetic socket) [14], clarifying the heat produced by metabolic reactions in the enclosed socket during the swing phase of human gait (e.g., air-conditioned socket to determine adequate air velocity by a general heat balance equation) [59], improved training, rehabilitation and increased functionality of the missing body part (e.g., game-based training tools/augmented reality) [2, 3, 29, 38, 41, 49, 50] and finally, decreased time and increased accuracy of task performance (e.g., vibrotactile feedback to myoelectric prosthesis) [19, 39, 40, 46, 47] to promote a more natural and intuitive control and, consequently, improve the acceptance of the prosthesis in the activity of daily life [7].

Virtual Reality (VR) has also been examined in the research field of amputees' care. Specifically, in the past VR has been used with positive results for the treatment of pain arising from an amputation, suggesting that VR can offer a neurorehabilitation platform regimen [1, 22, 27, 33, 36, 43, 44, 45, 58]. It was found that VR can increase hand control operation in amputees [31, 37, 61]. A preliminary study with healthy right-handed participants wearing a body-powered prosthesis simulator on their non-dominant hands revealed that VR training improved bilateral manual dexterity in the prosthetic control skills bowknot task (BKT) and significantly improved short-term prosthetic control acquisition. Additionally, it appeared that the higher the immersion score was, the shorter the execution time of the BKT task [61]. While it can also improve the procedure and acceptance of the prosthetic device prior [42] and during the fitting process [21].

VR seems to be a conceivable solution for complementing myoelectric-powered prosthesis training since it can recreate the fundamental aspects of self and body ownership which are responsible for the acceptance of the artificial limb as part of the body [29, 55, 11]. Via VR, the user can increase the predictable control over the missing body part through the virtual embodiment. Previous research suggested that situations where direct control over a virtual hand was possible, an increased perception of ownership over the virtual limbs occurred for the participant. When the same experiments altered the hands to become immobile or unpredictable, the participants did not associate the limbs with the self [56]. The above findings were further enhanced by a study that proved that a virtual hand can be embodied by the user and perceived as a real part of the body [52].

The therapeutic power of immersive VR is based on the principles of brain plasticity and the sensory-motor learning approach, suggesting that the neural networks can change through growth and reorganisation [9, 15, 24]. Visual feedback (e.g., naturally reaching out and grabbing a virtual object with an amputated limb) activates the neuron networks in the brain that are involved in sensorimotor learning, called mirror neurons [54, 55]. Mirror neurons can be activated through the reproduction or observation of movements [5, 18, 53].

With this study, we aim to understand how VR could be used to complement traditional training of prosthetics based on the restrictions it possesses through a user-centred designed approach. Through this study, we aimed to contribute to the research in the design community by examining the opportunities VR could offer to this patient group and further explore the design to capitalise on the effective use of VR to increase patients' acceptance of the prosthetic fitting and satisfaction of the artificial limb.

2 METHODS

2.1 Ethics

Ethical approvals were sought from NRES Committee London - Riverside (14/LO/11). All participants signed a consent form before the study. The study was performed under the Declaration of Helsinki [54].

2.2 Participants

Seven patients with trans-radial (amputation occurring between the wrist and the elbow) (*n* = 6 unilateral and *n* = 1 bilateral) upper limb amputees (*n* = 5 males and *n* = 2 females), aged between 30 to 68 years (*M* = 52.29, *SD* = 13.23) were recruited from the National Health Service (NHS) Foundation Trust hospital. All participants had normal or corrected to normal vision and no history of mental health disorders.

2.3 Instruments

Semi-structured interviews were conducted to reflect on patients' experience using VR to complement traditional training of prosthesis. Acceptance of the prosthetic fitting and satisfaction of the artificial myoelectric-powered prosthetic limb was the main focus. The interviews were audio-recorded and transcribed.

Observation notes were taken in detail to classify the interactions and behavioural responses towards the VR myoelectric-powered prosthetic training. We focused on identifying the aspects, challenges, design, and deployment issues prosthesis users encountered.

2.4 Apparatus

VR System: An *HTC VIVE VR*[1] Head Mounted Display (HMD) system was used to stream the audial and visual content. The VR system was developed using the Unity Engine[2]. The 3D models of the virtual environment were created in Autodesk 3DS Max[3] (Figure 1). The 3D model of the Bebionic prosthetic arm was supplied by the prosthetic maker Steeper[4] to match the actual appearance of the prosthetic device (Figure 2). The VR content was displayed on a laptop screen, mirroring the user's real-time virtual interactions.

Myoelectric Control System: A *Myo Armband by Thalmic Labs*[5], which is a consumer-grade EMG sensing armband and an affordable, reliable, accurate and effective input device for medical training [41, 50, 60], was adjusted to the amputee limb to allow the user to interact with the virtual features.

Figure 1: Representation of the Virtual Environment.

Figure 2: To the right, the real Bebionic prosthetic arm. To the left, the VR Bebionic 3D model of the prosthetic arm.

Additional tracking devices: Initially *Microsoft's Kinect* was used to track the amputee's body using a depth sensor to enable the amputee to walk around the virtual environment. However, an initial trial with the patients

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[1] https://www.vive.com/
[2] https://store.unity.com/
[3] https://www.autodesk.com/education/free-software/3ds-max
[4] http://rslsteeper.com/
[5] https://developerblog.myo.com/author/thalmic-labs/

proved *Microsoft's Kinect* to be unsuitable for effective body tracking because of the missing body part. Later, *Microsoft's Kinect* was replaced by *HTC VIVE Controllers*[6]. A custom band was created using a 3D printer to secure the controller around the missing limb. The controller was placed upside down to make it more comfortable to wear. Alterations to code and the model were made to compensate for its incorrect position and orientation (Figure 3).

Figure 3: Representation of the system's use.

2.5 Study Design and Procedure

The study design emerged from rigorous discussions with experts (*n* = 5) in the field of medical consultation *(n* = 1), occupational *(n* = 1) and physical (*n* =1) therapy (e.g., responsible to employ training activities to improve patients' muscle activation skills, helping them to learn how to operate and adapt to a myoelectric-powered prosthetic [4]), and HCI in healthcare professions in computer science/game development (*n* = 1) and health psychology (*n* = 1). The interventions were carefully designed based on the successful completion of traditional medical training.

People with trans-radial upper limb amputees were invited to use the VR and the Myo Armband for a prosthesis training in a familiar room of the hospital. The VR intervention was described to them and five-minute navigation of the virtual environment was offered, to reduce the potential risk of nausea from the HMD. The patient then was instructed to perform daily living activities into a virtual kitchen. The activities replicated the tasks which were routinely used during the traditional occupational therapy training and the activities assessed whether an amputee was able to control the prosthetic device adequately. Observational notes were made by an HCI researcher. The VR myoelectric-powered prosthetic training lasted approximately 15 minutes. The training was followed by semi-structured interviews. Overall, each session lasted approximately one hour.

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[6] https://www.vive.com/eu/accessory/controller/

3 FINDINGS, CHALLENGES AND DISCUSSION

3.1 Acceptance of the Myoelectric-Powered Prosthetic Device

One of the most common challenges for new prosthesis users is for the patients to accept the fitting of any kind of prosthetic device to their own body. Many of the patients reject the prosthesis because of the unfamiliarity of the artificial limb on their arm [26, 23, 32]. The rejection rate is even higher for congenital deficiency patients [2]. Most of our patients expressed no concern about the Myo armband fitting, since the tight strap of the Myo Armband, offered to the patient a sense of security. This was further supported by a patient with a congenital deficiency.

3.2 Myoelectric Signals, Prosthetics Limb Activation and Virtual Interactions

A crucial factor that can help to overcome patients' concerns is the patient's ability to activate the muscles of the affected limb [21, 60]. It is equally important for the myoelectric device to detect those electrical impulses that occur naturally during muscle contraction to respond accurately to the muscle commands and control the artificial limb [2].

This study is not the only one to report connectivity issues [2, 20]. Myoelectric signal recognition is especially challenging for amputees since the residual limb is usually linked either to a congenital deficiency or muscle atrophy which arises from lack of use. To overcome these issues, we secured tightly the Myo armband around the patient's stump and left it in place for five minutes, for the sensors to make a good connection with the skin (Figure 4). Also, we pre-installed the Myo testing software to determine that the Myo armband was set up correctly before exposing the amputee patient into the VR. Finally, to improve pairing time and accuracy, the Myo armband construction code was altered to specify what arm was to be used instead of using the calibration system. This is because the calibration process of the system requires hand gestures which are limited to amputees.

Difficulties were also presented in terms of body asymmetry and Microsoft's Kinect reliability. Similarly, to previous studies, boundaries were faced in response to effective body tracking because of the missing body part. However, previous research indicated that by registering the position and orientation in the frame of reference of Microsoft's Kinect, the hand can accurately interact with virtual objects [40].

Our solution, to reduce the erratic tracking due to the missing limb, was for the patient to perform a workaround with reduced movements of the upper limb and to increase the time to extrapolate the patient's movements from the Microsoft's Kinect device. In addition to that, we increased the smoothing of the tracking of Microsoft's Kinect which gave a very slight delay to the movement and reduced the tracking noise. Even though the above developments resolved the asymmetry issues, this resulted in spending important training time in positioning the arm instead of focusing on generating the correct muscle activity. We, therefore, used HTC VIVE Controllers with a custom band to track accurately the rotational movement of both hands (see Apparatus). It worth mentioning that HTC VIVE has now launched VIVE trackers which are easy to attach to any limb. Therefore, VIVE trackers are of consideration for future deployments.

Figure 4: VR myoelectric-powered prosthetic training: To the left: An actual picture of an amputee patient using the system. To the right: Representation of the task performed by the amputee patient -Picking a virtual apple with the missing limb.

3.3 Attitudes and Effective Responses of the VR Myoelectric-Powered Prosthetic Training

Our findings suggested that a myoelectric-powered training which is enhanced with VR can simulate a natural, enjoyable, and realistic experience for the patient with amputation through a high degree of presence. Specifically, it was stated that during the VR exposure the environment felt “real” as if they were at that particular space.

> “It felt like it was my arm in my kitchen. The kitchen setup was the same as my kitchen. So, once I saw the [virtual] apples I wanted to grab them, so I reached out to the apples in the fruit bowl and picked up one with my [virtual - amputated] arm. It was like I was picking up things with my real arm.” [Patient 1]

> “It was reasonably easy and straight forward [referring to the VR interactions]. It wasn’t complicated or intrusive for me. I enjoyed using a hand for the first time in my life.” [Patient 7]

The immersive experience the VR offered to the patient demonstrates improvements to the performance of tasks and functional abilities of the patient due to brain plasticity [15, 24, 52]. The above finding can be explained based on brain imaging approaches and how the perceived visual feedback activates the mirror neurons reaching an improvement on prosthetics control ability [5, 18, 62]. Therefore, the ability to correctly perform a grabbing task with the missing limb through the embodied virtual arm ensured it is perceived by the patient as a real part of the body. Note that none of the patients reported pain during the trial. Our findings suggested that VR can empower myoelectric training with natural and immediate responses.

Finally, the Bebionic model of the virtual arm was found to be aesthetically pleasing for the patients, since it corresponded to the actual Bebionic prosthetic device the patients owned. Explicitly, a patient mentioned that the virtual arm appearance was the same as the Bebionic prosthetic device the patient was wearing.

> “It felt like a Bebionic, if I took that off [referring to the Bebionic prosthetic device] and I put that on [referring to the VR device], I ‘ll say yeah that’s a fairly good comparison.” [Patient 5]

4 CONCLUSIONS AND FUTURE WORK

The key motivation for this study was to investigate the potential for using VR to enhance traditional myoelectric-powered prosthetic training. Our results showed that VR myoelectric-powered prosthetic training can be effective in providing amputees with quality training. It has the potential to reduce rejection rates and increase the ability for them to control the prosthetic arm [30, 32]. The patients reacted positively to the VR training and identified how it could provide a greater opportunity for amputees to learn from experience before a fitting [10, 23, 26].

It should be mentioned that the study had some limitations that we aim to overcome in future research. There was limited data available to investigate the effectiveness of the immersive VR scenarios for training. The number of trans-radial amputees in the population was low compared to other amputations, which made it difficult to get a larger sample size. A future study would look at involving multiple clinical sites to get a more substantial number of amputees to better determine the effectiveness of the system. Also, in a future study, the outcomes should be measured with quantitative data as well, such as pain scales, OptiTrack data, etc.

Future work would aim to improve and add functionality to the system. Advancements in 3D printed prosthetics are making myoelectric prosthetics more obtainable because of reduced costs; alterations to the system would look to incorporate future 3D printed prosthetics [28, 51]. Adapting to the extra weight has been one of the primary reasons for the rejection of a prosthetic. This absence of weight of a prosthetic would be addressed in an updated system. Along with providing further scenarios such as driving and office use, the additional focus would be on delivering advanced functionality training to register degrees of muscle activity. Finally, further discussion on the relevance of embodiment and its importance for successful training of myoelectric prosthetics requires additional research.

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REFERENCES

[1] S Adaikkammai, Manan Singhal, Evangeline Smita, Suhas Sreenivas, and Abhishek Appaji. 2019. Virtual Reality in Rehabilitating Amputees Suffering from Phantom Limb Pain. In International Conference on Communication Systems & Networks. IEE, Bengaluru, India, 801-806. https://doi.org/10.1109/COMSNETS.2019.8711374

[2] Alcimar Barbosa Soares, Edgard Afonso Lamounier Júnior, Adriano de Oliveira Andrade and Alexandre Cardoso (Eds.). 2012. Computational Intelligence in Electromyography Analysis-A Perspective on Current Applications and Future Challenges (1st. ed.). Intech, Rijeka, Croatia. https://doi.org/10.5772/50600

[3] José A. Barraza-Madrigal, Alfredo Ramírez-García, and Roberto Muñoz-Guerrero. 2010. A virtual upper limb prosthesis as a training system. In 7th International Conference on Electrical Engineering Computing Science and Automatic Control. IEEE, Tuxtla Gutierrez, Mexico, 210-215. https://doi.org/10.1109/ICEEE.2010.5608586

[4] Hanneke Bouwsema, Corry K. van der Sluis, and Raoul M. Bongers. 2010. Learning to control opening and closing a myoelectric hand. Archives of physical medicine and rehabilitation 91, 9 (Aug. 2010), 1442-1446. https://doi.org/10.1016/j.apmr.2010.06.025

[5] Johannes Brand, Marco Piccirelli, Marie-Claude Hepp-Reymond, Kynan Eng, and Lars Michels. 2020. Brain activation during visually guided finger movements. Frontiers in Human Neuroscience 14, 309 (Aug. 2020), 1-12. http://dx.doi.org/10.3389/fnhum.2020.00309

[6] Jill M. Cancio, Andrea J. Ikeda, Shannon L. Barnicott, Walter L. Childers, Joseph F. Alderete, and Brandon J. Goff. 2019. Upper Extremity Amputation and Prosthetics Care Across the Active Duty Military and Veteran Populations. Physical Medicine and Rehabilitation Clinics 30, 1 (Feb. 2019), 37-87. https://doi.org/ 10.1016/j.pmr.2018.08.011

[7] Patricia Capsi-Morales, Cristina Piazza, Manuel G. Catalano, Antonio Bicchi, and Giorgio Grioli. 2020. Exploring stiffness modulation in prosthetic hands and its perceived function in manipulation and social interaction. Frontiers in Neurorobotics 14 (Jun. 2020), 33, 1-20. http://dx.doi.org/10.3389/fnbot.2020.00033

[8] Brian Chau, Ivan Phelan, Phillip Ta, Sarah Humbert, Justin Hata, and Duc Tran. 2017. Immersive virtual reality therapy with myoelectric control for treatment-resistant phantom limb pain: Case report. Innovations in clinical neuroscience, 14, 7-8 (2017), 3-7.

[9] Irene Cortés-Pérez, Francisco A. Nieto-Escamez, and Esteban Obrero-Gaitán. 2020. Immersive virtual reality in stroke patients as a new approach for reducing postural disabilities and falls risk: A case series. Brain Sciences 10, 296 (May. 2020), 1-13. http://dx.doi.org/10.3390/brainsci10050296

[10] Yasin Demir, N. Merve Örücü Atar, Ümüt Güzelküçük, Koray Aydemir, and Evren Yaşar. 2019. The use of and satisfaction with prosthesis and quality of life in patients with combat related lower limb amputation, experience of a tertiary referral amputee clinic in turkey. Gulhane Medicine Journal 61,1 (Mar. 2019), 6-10. http://dx.doi.org/10.26657/gulhane.00044

[11] Brian Day, Elham Ebrahimi, Leah S. Hartman, Christopher C. Pagano, Andrew C. Robb, Sabarish V. Babu. 2019. Examining the effects of altered avatars on perception-action in virtual reality. Journal of Experimental Psychology: Applied 25, 1 (Mar. 2019), 1-24. http://dx.doi.org/10.1037/xap0000192

[12] Israel Dudkiewicz, R. Gabrielov, Itzhak Seiv-Ner, Gabriel Zelig, and Michael Heim. 2004. Evaluation of prosthetic usage in upper limb amputees. Disability and rehabilitation 26, 1 (2004), 60-63. https://doi.org/10.1080/09638280410001645094

[13] Anne E. Edmondson, Jill M. Cancio, and Kathleen E. Yancosek. 2018. Modified Constraint-Induced Movement Therapy for persons with unilateral upper extremity amputation: A case report. Journal of Hand Therapy 33, 4 (Oct. 2018), 1-5. https://doi.org/10.1016/j.jht.2018.09.007

[14] Cheng-Han Fang, Ming-Jer Huang, You-Li Chou, and Gwo-Feng Huang. 2004. The study of thermal comfort for below-knee prosthesis. Biomedical Engineering: Applications, Basis and Communications 16, 1 (Feb. 2004), 7-14. https://doi.org/10.4015/S1016237204000037

[15] Toshiyuki Fujiwara, Junichi Ushiba, and Surjo R. Soekadar. 2019. Neurorehabilitation: Neural plasticity and functional recovery 2018. Neural Plasticity 1 (Jan. 2019), 1-3. http://dx.doi.org/10.1155/2019/7812148

[16] Gonzalo A. García, Ryuhei Okuno, and Kenzo Akazawa (Eds.). 2013. Electrodiagnosis in New Frontiers of Clinical Research (1st. ed.). Intech, Rijeka, Croatia. https://doi.org/10.5772/55503

[17] Kamiar Ghoseiri, Mostafa Allami, Mohammad R. Soroush, and Mohammad Y. Rastkhadiv. 2018. Assistive technologies for pain management in people with amputation: a literature review. Military Medical Research 5, 1 (Jan. 2018), 1-6. https://doi.org/10.1186/s40779-018-0151-z

[18] Calum Gordon, Alba Barbullushi, Stefano Tombolini, Federica Margiotta, Alessia Ciacci, Lama Shekh Yosef, Leon Barker, and Matteo Martini. 2019. Visuo–tactile stimulation, but not type of movement, modulates pain during the vision of a moving virtual limb. Pain Management 9, 5 (Aug. 2019), 449-449–460. http://dx.doi.org/10.2217/pmt-2019-0019

[19] Emily L. Graczyk, Linda Resnik, Matthew A. Schiefer, Melissa S. Schmitt, and Dustin J. Tyler. 2018. Home use of a neural-connected sensory prosthesis provides the functional and psychosocial experience of having a hand again. Scientific Reports 8, 9866 (2018), 1-17. http://dx.doi.org/10.1038/s41598-018-26952-x

[20] Levi J. Hargrove, Kevin B. Englehart, and Bernad Hudgins. 2006. The effect of electrode displacements on pattern recognition based myoelectric control. In International Conference of Engineering in Medicine and Biology Society. IEEE, New York, NY, USA, 2203-2206. https://doi.org/10.1109/IEMBS.2006.260681

[21] Markis Hauschild, Rahman Davoodi, and Gerald E. Loeb. 2007. A virtual reality environment for designing and fitting neural prosthetic limbs. IEEE Transactions on Neural Systems and Rehabilitation Engineering 15, 1 (Mar. 2007), 9-15. https://doi.org/10.1109/TNSRE.2007.891369

[22] Hunter G. Hoffman, David A. Boe, Eric Rombokas, Christelle Khadra, Sylvie LeMay, Walter J. Meyer, Sam Patterson, Ann Ballesteros, and Stephen W. Pitt. 2020. Virtual reality hand therapy: A new tool for nonopioid analgesia for acute procedural pain, hand rehabilitation, and VR embodiment therapy for phantom limb pain. Journal of Hand Therapy 33, 2 (May 2020), 254-262. http://dx.doi.org/10.1016/j.jht.2020.04.001

[23] Nathan T. Kearns, Warren T. Jackson, Timothy R. Elliott, Tiffany Ryan, and Trey W. Armstrong. 2018. Differences in level of upper limb loss on functional impairment, psychological well-being, and substance use. Rehabilitation Psychology 63, 1 (Feb. 2018), 141-147. http://dx.doi.org/10.1037/rep0000192

[24] Jiří Keller, Ivana Štětkářová, Vince Macri, Simone Kühn, Jakub Pětioký, Stefano Gualeni, C. Douglas Simmons, Sajay Arthanat, and Paul Zilber. 2020. Virtual reality-based treatment for regaining upper extremity function induces cortex grey matter changes in persons with acquired brain injury. Journal of Neuroengineering and Rehabilitation 17 (Dec. 2020), 1-11. https://doi.org/10.1186/s12984-020-00754-7

[25] Joris M. Lambrecht, Christopher L. Pulliam, and Robert F. Kirsch. 2011. Virtual reality environment for simulating tasks with a myoelectric prosthesis: an assessment and training tool. Journal of prosthetics and orthotics 23, 2 (Apr. 2011), 89-94. https://doi.org/10.1097/JPO.0b013e318217a30c

[26] Lisiane P. Luza, Elizandra G. Ferreira, Rafaela C. Minsky, Greicy K. Pires, and Rudney da Silva. 2019. Psychosocial and physical adjustments and prosthesis satisfaction in amputees: a systematic review of observational studies. Disability and Rehabilitation: Assistive Technology 17, (Apr. 2019), 1-8. https://doi.org/10.1080/17483107.2019.1602853

[27] Marta Matamala-Gomez, Tony Donegan, Sara Bottiroli, Giorgio Sandrini, Maria V. Sanchez-Vives, and Cristina Tassorelli. 2019. Immersive virtual reality and virtual embodiment for pain relief. Frontiers in Human Neuroscience 13, 279 (Aug. 2019), 1-12.

http://dx.doi.org/10.3389/fnhum.2019.00279

[28] Lynne V. McFarland, Sandra L. Hubbard Winkler, Allen W. Heinemann, Melissa Jones, and Alberto Esquenazi. 2010. Unilateral upper-limb loss: Satisfaction and prosthetic-device use in veterans and servicemembers from Vietnam and OIF/OEF conflicts. Journal of Rehabilitation Research & Development 47, 4 (Jul. 2010), 299–316. https://doi.org/10.1682/jrrd.2009.03.0027

[29] Marina Melero, Annie Hou, Emily Cheng, Amogh Tayade, Sing Lee, Mathias Unberath, and Nassir Navab. 2019. Upbeat: Augmented Reality for Prosthetic Rehabilitation of Upper Limb Amputees. Journal of healthcare engineering, (Mar. 2019), 1-9. https://doi.org/10.1155/2019/2163705

[30] Manelle Merad, Étienne de Montalivet, Amélie Touillet, Noël Martinet, AgnèsRoby-Brami, andNathanaël Jarrassé. 2018. Can we achieve intuitive prosthetic elbow control based on healthy upper limb motor strategies?. *Frontiers in Neurorobotics* 12, 1 (Feb. 2018), 1-11. http://dx.doi.org/10.3389/fnbot.2018.00001

[31] Go Nakamura, Taro Shibanoki, Yuichi Kurita, Yuichiro Honda, Akito Masuda, Futoshi Mizobe, Takaaki Chin, and Toshio Tsuji. 2017. A virtual myoelectric prosthesis training system capable of providing instructions on hand operations. International Journal of Advanced Robotic Systems 14, 5 (Sep. 2017), 1-10. https://doi.org/10.1177/1729881417728452

[32] Kristin Østlie, Rosemary J. Franklin, Ola H. Skjeldal, Anders Skrondal, and Per Magnus. 2011. Musculoskeletal pain and overuse syndromes in adult acquired major upper-limb amputees. Archives of Physical Medicine and Rehabilitation 92, 12 (Dec. 2011), 1967-1973. https://doi.org/10.1016/j.apmr.2011.06.026

[33] Michihiro Osumi, Kazunori Inomata, Yuji Inoue, Yuko Otake, Shu Morioka, and Masahiko Sumitani. 2019. Characteristics of phantom limb pain alleviated with virtual reality rehabilitation. Pain Medicine 20, 5 (May 2019), 1038-1046. http://dx.doi.org/10.1093/pm/pny269

[34] J. V. V Parr, S. J. Vine, M. R Wilson, N. R. Harrison, and G Wood. 2019. Visual attention, EEG alpha power and T7-fz connectivity are implicated in prosthetic hand control and can be optimized through gaze training. Journal of Neuroengineering and Rehabilitation 16, 5216 (Nov. 2018), 1-9. http://dx.doi.org/10.1186/s12984-019-0524-x

[35] Benoit Penelle, and Olivier Debeir. 2014. Multi-sensor data fusion for hand tracking using Kinect and Leap Motion. In Proceedings of the 2014 Virtual Reality International Conference. ACM, Laval, France, UE, 22-29. https://doi.org/10.1145/2617841.2620710

[36] Briana N. Perry, Catherine Mercier, Steve R. Pettifer, Jonathan Cole, and Jack W. Tsao. 2014. Virtual reality therapies for phantom limb pain. European Journal of Pain 18, 7 (Jul. 2014), 897-906. https://doi.org/10.1002/ejp.559

[37] Ivan Phelan, Madelynne Arden, Carol Garcia, and Chris Roast. 2015. Exploring virtual reality and prosthetic training. In IEEE Virtual Reality. IEEE, Arles, France, EU, 353-354. https://doi.org/10.1109/VR.2015.7223441

[38] Michael A. Powell, Rahul R. Kaliki, and Nitish V. Thakor. 2013. User training for pattern recognition-based myoelectric prostheses: Improving phantom limb movement consistency and distinguishability. IEEE Transactions on Neural Systems and Rehabilitation Engineering 22, 3 (Oct. 2013), 522-532. https://doi.org/10.1109/TNSRE.2013.2279737

[39] Eitan Raveh, Jason Friedman, and Sigal Portnoy. 2018. Evaluation of the effects of adding vibrotactile feedback to myoelectric prosthesis users on performance and visual attention in a dual-task paradigm. Clinical rehabilitation 32, 10 (Mar. 2018),1308-1316. https://doi.org/10.1177/0269215518774104

[40] Eitan Raveh, Sigal Portnoy, and Jason Friedman. 2018. Myoelectric prosthesis users improve performance time and accuracy using vibrotactile feedback when visual feedback is disturbed. Archives of physical medicine and rehabilitation 99, 11 (Nov. 2018), 2263-2270. https://doi.org/10.1016/j.apmr.2018.05.019

[41] Linda Resnik, Katherine Etter, Shana Lieberman Klinger, and Charles Kambe. 2011. Using virtual reality environment to facilitate training with advanced upper-limb prosthesis. Journal of Rehabilitation Research & Development 48, 6 (Aug. 2011), 707-18.

[42] Aidan D. Roche, Hubertus Rehbaum, Dario Farina, and Oskar C. Aszmann. 2014. Prosthetic myoelectric control strategies: a clinical perspective. Current Surgery Reports 2, 3 (Jan. 2014), 44-55. https://doi.org/10.1007/s40137-013-0044-8

[43] Andreas Rothgangel and Robin Bekrater-Bodmann. 2019. Mirror therapy versus augmented/virtual reality applications: Towards a tailored mechanism-based treatment for phantom limb pain. Pain Management 9, 2 (Jan. 2019), 151-159. http://dx.doi.org/10.2217/pmt-2018-0066

[44] Thomas Rutledge, Deborah Velez, Colin Depp, John R. McQuaid, Garland Wong, R. Carter W. Jones, Hampton Atkinson, Bosco Giap, Alex Quan, and Huan Giap, 2019. A virtual reality intervention for the treatment of phantom limb pain: Development and feasibility results. Pain Medicine 20, 10 (Oct. 2019), 2051-2059. http://dx.doi.org/10.1093/pm/pnz121

[45] Yuko Sano, Akimichi Ichinose, Naoki Wake, Michihiro Osumi, Masahiko Sumitani, Shin-ichiro Kumagaya, and Yasuo Kuniyoshi. 2015. Reliability of phantom pain relief in neurorehabilitation using a multimodal virtual reality system. In Proceedings Annual International Conference of Engineering in Medicine and Biology Society. IEE, Milan, Italy, EU, 2482–2485. https://doi.org/10.1109/EMBC.2015.7318897

[46] Jonathon S. Schofield, Courtney E. Shell, Dylan T. Beckler, Zachary C. Thumser, and Paul D. Marasco. 2020. Long-term home-use of sensory-motor-integrated bidirectional bionic prosthetic arms promotes functional, perceptual, and cognitive changes. Frontiers in Neuroscience 14, 120 (Mar. 2018), http://dx.doi.org/10.3389/fnins.2020.00120

[47] Jacob L. Segil, Ivana Cuberovic, Emily L. Graczyk, Richard F. ff. Weir, and Dusti Tyler. 2020. Combination of simultaneous artificial sensory percepts to identify prosthetic hand postures: A case study. Scientific Reports 10, 6576 (2020), 1-15. http://dx.doi.org/10.1038/s41598-020-62970-4

[48] Kardem Soyer, Banu Unver, Seval Tamer, and Oziem Ulger. 2016. The importance of rehabilitation concerning upper extremity amputees: A Systematic Review. Pakistan journal of medical sciences 32, 5 (Oct. 2016), 1312-1319. https://doi.org/10.12669/pjms.325.9922

[49] Aaron Tabor, Scott Bateman, and Erik Scheme. 2016. Game-based myoelectric training. In Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts. ACM, Austin, Texas, USA, 299-306.

https://doi.org/10.1145/2968120.2987731

[50] Aaron Tabor, Scott Bateman, Erik Scheme, David Flatla, and Kathrin Gerling. 2017. Designing game based myoelectric prosthesis training. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems. ACM, Denver, Colorado, USA, 1352-1363. https://doi.org/10.1145/3025453.3025676

[51] Carolyn E. Taylor, Alex J. Drew, Yue Zhang, Yuqing Qiu, Kent N. Bachus, K. Bo Foreman, and Heath B. Henninger. 2020. Upper extremity prosthetic selection influences loading of transhumeral osseointegrated systems. PLoS One 15, 8 (Aug. 2020), e0237179. https://doi.org/10.1371/journal.pone.0237179

[52] Maria Matsangidou, Chee S. Ang, Alexis R. Mauger, Jittrapol Intarasirisawat, Boris Otkhmezuri, and Marios N. Avraamides. 2019. Is your virtual self as sensational as your real? Virtual Reality: The effect of body consciousness on the experience of exercise sensations. Psychology of Sport and Exercise 41, (Mar. 2019), 218-224. https://doi.org/10.1016/j.psychsport.2018.07.004

[53] Heather R. McGregor, Michael Vesia, Cricia Rinchon, Robert Chen, and Paul L. Gribble. 2018. Changes in corticospinal excitability associated with motor learning by observing. Experimental Brain Research 236, 10 (Jul. 2018), 2829-2838. http://dx.doi.org/10.1007/s00221-018-5339-7

[54] World Medical Association. 2013. World medical association declaration of Helsinki: ethical principles for medical research involving human subjects. JAMA. 310, 2191–4.

[55] Craig D. Murray. 2004. An interpretative phenomenological analysis of the embodiment of artificial limbs. Disability and Rehabilitation 26, 16 (Mar. 2004), 963-973. https://doi.org/10.1080/09638280410001696764

[56] Bernhard Terlaak, Hanneke Bouwsema, Corry K. van der Sluis, and Raoul M. Bongers. 2015. Virtual training of the myosignal. PloSone 10,9 (Sep. 2015), e0137161. https://doi.org/10.1371/journal.pone.0137161

[57] Athanasios Vourvopoulos, Octavio Marin Pardo, Stéphanie Lefebvre, Meghan Neureither, David Saldana, Esther Jahng, and Sook-Lei Liew. 2019. Effects of a brain-computer interface with virtual reality (VR) neurofeedback: A pilot study in chronic stroke patients. Frontiers in Human Neuroscience 13, 210 (Jun. 2019), 1-17. http://dx.doi.org/10.3389/fnhum.2019.00210

[58] Naoki Wake, Yuko Sano, Reishi Oya, Massahiko Sumitani, Shin-ichiro Kumagaya, and Yasuo Kuniyoshi. 2015. Multimodal virtual reality platform for the rehabilitation of phantom limb pain. In 7th International IEEE/EMBS Conference on Neural Engineering. IEEE, Montpellier, France, EU, 787–790. https://doi.org/10.1109/NER.2015.7146741

[59] Christina M. Webber, and Brian L. Davis. 2015. Design of a novel prosthetic socket: Assessment of the thermal performance. Journal of biomechanics 48, 7 (May. 2015), 1294-1299.

[60] Adam W. Wilson, Yves G. Losier, Philip Parker, and Dennis F. Lovely. 2010. A bus-based smart myoelectric electrode/amplifier. In 2010 IEEE International Workshop on Medical Measurements and Applications. IEE, Ottawa, ON, Canada, 86-91. https://doi.org/10.1109/MEMEA.2010.5480204

[61] Manabu Yoshimura, Hiroshi Kurumadani, Junya Hirata, Hiroshi Osaka, Katsutoshi Senoo, Shota Date. Akio Ueda, Yosuke Ishii, Seiji Kinoshita, Kozo Hanayama, and Toru Sunagawa. 2020. Virtual reality-based action observation facilitates the acquisition of body-powered prosthetic control skills. Journal of Neuroengineering and Rehabilitation 17, 113 (Jan. 2019), 1-12. http://dx.doi.org/10.1186/s12984-020-00743-w

[62] Jack J. Q. Zhang, Kenneth N. K. Fong, Nandana Welage, and Karen P. Y. Liu. 2018. The activation of the mirror neuron system during action observation and action execution with mirror visual feedback in stroke: A systematic review. Neural Plasticity ID 2321045 (Oct. 2018), 1-14. http://dx.doi.org/10.1155/2018/2321045