Abstract

Background: Prosthetic motor rehabilitation usually relies on the highly repetitive training of movements. Patients might drop out of training because the rehabilitation process is long and often discouraging. Game-based interventions provide a potentially useful alternative to standard myoelectric (electromyographic [EMG]) training and can increase engagement with training.

Objective: To assess the short-term impact of a game-based rehabilitation protocol on parameters for EMG control, evaluate how game-based interventions affect patient motivation, performance, and effort, and compare the game-based intervention with a standard tool in rehabilitation (MyoBoy).

Design: This randomized controlled trial included 2 patient groups and 1 control group. After establishing a baseline, the 2 patient groups received different interventions that were compared with each other and with the able-bodied control group.

Setting: University hospital-based study.

Participants: Fourteen patients with traumatic transradial or transhumeral upper extremity amputation and 10 able-bodied participants.

Methods: For the game-based intervention, EMG proficiency was assessed before and after playing the games and 2 days later as follow-up to measure retention rate. EMG proficiency was measured using maximum voluntary contraction, proportional precision control, signal separation, and muscle endurance. Questionnaires for rating the game-based intervention and intrinsic motivation were provided after the intervention.

Outcomes: Outcome measures for EMG proficiency were provisional maximum voluntary muscle contraction, precise proportional control, electrode separation, and muscle endurance. Quantitative outcome measures for participant experience were intrinsic motivation, enjoyment, pressure, exerted effort, and usefulness of the intervention. The qualitative outcome measure was the surveyed attitude toward the game-based intervention.

Results: Results showed an overall improvement in EMG control, fine muscle activation, and electrode separation. Patients stated that racing games provided slightly more fun, but rhythm-based games were considered to provide better challenges for EMG control.

Conclusion: Game-based interventions provide a useful addition to standard EMG training and can achieve better results in clinical outcome measures. The racing and music game genres provide solid starting points for interventions. Further studies can look at a wider range of genres and identify more specific game mechanics suitable for training.

Level of Evidence: I
prosthesis are muscle contraction strength, proportional electrode activation, single-electrode activation, and voluntary activation of the 2 electrodes at the same time [6, 7]. Because most myoelectric prostheses allow so-called proportional control (ie, a low signal corresponds to slow movements and a high signal corresponds to fast movements), the ability to generate different muscle activation strengths including high activation is required [8]. In prosthetic devices using direct control (ie, 1 electrode corresponds to 1 prosthetic movement), the patient needs to activate one muscle without the other to avoid unintentional prosthetic movements. Adding more electrodes makes this task more complex and leads to an increased need of supervised training with electromyographic (EMG) biofeedback [5]. In addition, voluntary activation of the 2 electrodes at the same time is often used to switch control between different grip patterns or prosthetic joints. This feature is needed when there are fewer signals available than prosthetic movements [9].

Conventional rehabilitation methods after nerve transfer or amputation of the upper extremity are based on performing repetitive exercises during which the patient’s long-term motivation and effort are difficult to sustain. Because EMG biofeedback can increase training motivation and allows the patient to observe otherwise unrecognized muscular activity, simple biofeedback devices have been used in the clinical setting for years [10]. In this way, patients can train the relevant muscle(s) in a targeted way. Although these simple devices are helpful in clinical practice to visualize EMG activity, they usually do not provide much diversity in training. Because more enhanced virtual training environments can offer a range of incentives for therapists and patients, they lead to more repetitions of exercises and a higher degree of patient motivation [11-14].

Game-based interventions have successfully been used for motor rehabilitation in stroke rehabilitation [15, 16] and Parkinson disease [17]. In recent years, game-based approaches have increasingly gained popularity for upper limb amputee rehabilitation for myoelectric prosthesis control. The mechanics of these games is based on feedback from the patient who can control the game through precise muscle activation. However, not every game-based intervention has incorporated all parameters needed for proper motor control [18-25].

In previous work, Guitar Hero (Activision, Santa Monica, CA) [23] and Pong (Atari, Paris, France) [26] were modified to accept myoelectric signals as controller input. Using such off-the-shelf video games to display biofeedback is cheap and easy to access compared with virtual reality or augmented reality applications. Without expensive technology and difficult setups, training can be performed easily alone and at home. Others have modified the hardware of the Nintendo WiiMote (Nintendo, Kyoto, Japan) controller to assign EMG signals to various buttons of the controller [20]. These approaches mark an auspicious beginning in using games in prosthetic motor rehabilitation, because they increase patient motivation and engagement. However, there is a necessity to offer more movements that are similar to everyday activities when using a prosthesis.

The objectives of this study were:

1. To assess the short-term impact of a game-based rehabilitation protocol on parameters for classic 2-electrode EMG control (does the game-based intervention improve EMG control more than just performing the EMG assessments?)
2. To further evaluate how game-based interventions affect patient motivation, performance, and effort (which game-based intervention motivated patients most, which did they enjoy most, and which did they think was most useful?)
3. To compare the game-based intervention with the MyoBoy (Ottobock Healthcare GmbH, Duderstadt, Germany), a standard tool in rehabilitation—(do patients exert themselves more during game-based interventions compared with the MyoBoy?)

Methods

Participants

Fourteen patients with a traumatically amputated upper limb at the transradial (below the elbow) or transhumeral (below the shoulder) level and 10 able-bodied participants took part in this study. Of those, 13 patients and all able-bodied participants did not have experience in controlling a myoelectric prosthesis. All patients had experience using the MyoBoy, a tool to visualize the activation of 2 electrodes in the form of 2 colored, moving LED bars, before starting the study or afterward.

Participants were allocated to 1 of 3 groups: 7 patients were randomly assigned to the intervention (group A) or the control group (group B), respectively, and the 10 able-bodied participants constituted the control group (group C). Patients who were not assigned to the game-based intervention group received no training during the pre- and post-measurements. Able-bodied participants underwent the game-based protocol (Table 1).

This study was approved by the ethics committee at the Medical University of Vienna (Vienna, Austria; 1301/2015) and all participants provided their consent before the study.

Table 1

Overview of participants and interventions

<table>
<thead>
<tr>
<th>Group</th>
<th>Participants</th>
<th>Participants, n</th>
<th>Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Patients</td>
<td>7</td>
<td>Game-based</td>
</tr>
<tr>
<td>B</td>
<td>Patients</td>
<td>7</td>
<td>None</td>
</tr>
<tr>
<td>C</td>
<td>Able-bodied</td>
<td>10</td>
<td>Game-based</td>
</tr>
</tbody>
</table>
**Experimental Setup**

Each participant was seated in front of 2 computer screens, one showing the EMG signals and the other showing the currently played game (Figure 1). Two active surface electrodes (13E200; Ottobock Healthcare GmbH) were placed on top of the flexor and extensor muscle group of the wrist in transradial amputees and on top of the biceps and triceps in transhumeral amputees. In able-bodied participants, the electrodes were placed on the same muscle group as for the transradial amputees (wrist flexor and extensor). Electrodes were held in place on the residual limb by a wristband or the prosthetic socket. The electrodes transmitted filtered, rectified, and root mean squared EMG data sampled at 1000 Hz.

**Experimental Protocol**

Each participant underwent EMG proficiency assessments before the intervention, after the intervention, and at follow-up 2 days later.

Participants had to perform the first EMG assessment at the beginning of the study. Afterward, groups A and C received the game-based intervention, whereas group B was asked to exercise random EMG activation, which consisted of short and sustained contractions of any muscle left in the stump without any apparent pattern. After playing the games, participants were asked to complete a short user evaluation survey and, after they finished playing all 3 games, a modified Intrinsic Motivation Inventory (IMI) questionnaire.

After a short break, the EMG assessments were repeated for the postintervention measurement. All participants were invited 2 days later to perform the EMG assessments one last time to evaluate short-term retention rate, and group B was given the opportunity to play and evaluate the games.

**Game-Based Intervention**

All games were controlled through the patients’ biofeedback, which involved quick and sustained muscle contractions for activating the corresponding electrode and a simultaneous contraction of the 2 muscles to switch between degrees of freedom (DoFs). One DoF in the game controlled a left-and-right movement and another controlled an up-and-down movement. Translating this into prosthesis control, these DoFs would correspond to switching between prosthetic joints.

The patients were presented with 3 video games that used different control options:

1. A game for dexterity, in which the patient had to maneuver through a 2-dimensional labyrinth with up, down, left, and right movements (2 DoFs) [27]
2. A racing game, in which the player raced against AI-controlled co-players and could turn left or right (1 DoF) [28]
3. A rhythm game, in which the player needed to match the muscle activation to the beat of a song (1 DoF) [29]

**EMG Proficiency Assessments**

Participants had to perform 3 basic EMG assessments to evaluate changes in their myoelectric aptitude. Assessments consisted of a test of provisional maximum voluntary muscle contraction (MVC) used as calibration, a test for precise proportional control, and a test for assessing electrode separation in combination with muscle endurance.

**Assessment of Proportional Precision Control**

This test evaluated the ability of participants to contract their muscles as accurately as possible according to a given target of EMG activation. The required muscle activation was 10%-90% of their MVC. Thirty randomly preselected targets were presented for each electrode, which the participants needed to hold for 300 ms. The target EMG activation was indicated by a red triangular mark on the EMG bar. The percentage of deviation around the activation target was taken as the outcome measure.

**Assessment of Muscle Separation**

This assessment determined whether, during the proportional precision control assessment, the opposing electrode, which should remain silent, also was involuntarily activated (co-contraction) and therefore separate muscle activation was not realized. The output of this assessment was “true” or “false.” The opposing electrode was considered active if it crossed a threshold of 15% of the MVC.

**Assessment of Endurance Control**

The task in this assessment was to retrace a sine curve of 0.25 Hz as closely as possible with the EMG signal for 300 seconds. The maximum amplitude of the sine curve corresponded to 60% of the MVC [30]. If the 2 electrodes were active, then the difference in electrode activation was used to calculate the EMG trajectory. Therefore, to easily reach the peaks of the sine curve, only 1 electrode should be active at a time while the other should remain silent.

**Questionnaires**

Two questionnaires and 1 survey were given to the participants after finishing the game-based training and EMG assessments to evaluate various aspects of the patients’ perception of the played games, the MyoBoy, and the EMG assessments.
IMI Questionnaire—Games
A 26-item version of the IMI with 5 subscales was used to assess the experience of playing the games [31,32]. Subscales included in this study were enjoyment, pressure, competence, effort, and usefulness. The questions were adapted to fit the study by exchanging “working” and “doing” in the original IMI with “playing.” Participants could mark their answer on a 7-point Likert scale ranging from 1 (“strongly disagree”) to 7 (“strongly agree”). Questions were randomized for each game to prevent memory effect and respondent bias owing to the imposed order of options.

IMI Questionnaire—MyoBoy
This version of the IMI was analogous to the version assessing participants’ attitude toward the played games; only the word “doing” was changed to “using the MyoBoy.” Only patients had to complete this questionnaire.

User Evaluation Survey
The participants were asked 5 questions to rate the played game on a scale from 1 to 5, with 5 being the best rating, for fun, motivation, input, and game controls. They had to complete this survey after each game and thus completed the survey 3 times.

Results
All analyses were conducted using IBM SPSS 24 (IBM Corp, Armonk, NY) and Matlab 2015b (MathWorks, Natick, MA). Normal distribution was assessed by Q-Q plots and Shapiro-Wilk test. Nonparametric tests were chosen for non-normally distributed data. A Bonferroni correction was applied to 2 repeated comparisons on the same data for the analysis of proportional precision control and muscle separation. Significance was set at an $\alpha$ value equal to 0.05.

EMG Proficiency Assessments
Maximum Voluntary Muscle Contraction
The MVC values used as baseline calibration for the EMG assessments increased significantly for groups A and C after playing the games ($P = .02$), denoting a stronger muscle contraction. This effect was not observed in group B, whose MVC values changed without a particular trend.

Assessment of Proportional Precision Control
The EMG target levels were divided into 3 equidistant intensity sections: low, middle, and high. A Bonferroni-corrected paired-samples $t$-test evaluated differences among the 3 measurements (before and after intervention and follow-up). Figure 2 presents the deviation around the target value in the percentage of the respective MVC of the participant. Results for groups A and C showed significant improvement in proportional precision control from pre-intervention to follow-up measurement for all target intensities ($P < .01$), whereas group B showed significant improvement from pre-intervention to follow-up measurement only for the middle intensity targets, but not for low or high intensity targets. Although the means and standard deviations measured during the first session (before intervention) for groups A and B were comparable, the fluctuation of deviation around the target intensity level decreased in all groups. The standard deviation around the target was smallest in the follow-up measurement. Moreover, for groups A and C across all measurements, the low goal activation level was significantly easier to reach than the high goal activation level ($P < .01$).

Assessment of Muscle Separation
Figure 3 shows the activation of the opposing electrode during the previous assessment of precision control across all 3 groups. Because the assessment of muscle separation was interconnected with the precision control assessment, the division of intensity
sections remained the same (i.e., low, middle, and high). The data derived from this test were binary (i.e., "true" or "false"); therefore, the opposing electrode was activated or it was not. Arrows in Figure 3 indicate significant improvement in performance, which was assessed with Bonferroni-corrected related-samples Wilcoxon signed rank test. For all groups, except 1 instance in group C, the opposing electrode was significantly less activated during low goal intensity levels compared with high goal intensity levels ($P = .01-.046$; Figure 3, arrows marked with a). Therefore, lower intensity goals were easier to reach for all participants. Groups A and C showed a significant decrease of involuntary activation of the opposing electrode from the first to third measurements for low goal intensity levels ($P = .02-.04$; Figure 3, arrows marked with b), in contrast to group B, which received no intervention. Overall, muscle separation improved in almost every instance, although not always significantly.

**Assessment of Endurance Control**

A comparison of the sine curve retracing correlation ($r^2$) for each group is presented in Figure 4. The related-samples Wilcoxon signed rank test determined a significant difference ($P < .01$) between the correlation from the first measurement and the correlation from the follow-up measurement for groups A and C, but not for group B ($P = .7$). Groups A and C showed improved endurance control and muscle isolation, except for 1 patient from group A, who was excluded from this

![Figure 2. Results of proportional precision assessment. Deviation around the target intensity level improved for all groups, but significantly across all intensity levels only for groups A and C. Group B improved significantly only for the middle intensity target. Significant changes are marked with an asterisk.](image)

![Figure 3. Results of muscle separation assessment. All 3 groups showed improvement in electrode separation, with some significant changes (arrows).](image)
analysis because he could activate only 1 of the 2 electrodes during the follow-up measurement.

**Questionnaires**

**IMI Questionnaire—Games and MyoBoy**

The mean scores with standard deviations of the 5 subscales compared with scores of the IMI regarding usage of the MyoBoy are presented in Figure 5. Patients enjoyed playing the games significantly ($P < .01$) more than using the MyoBoy and exerted more effort while doing so ($P = .01$). Significance was tested using the Wilcoxon signed rank test. Patients felt slightly more pressured while playing the games compared with using the MyoBoy but felt equally confident in playing the games and handling the MyoBoy. Although the patients did not enjoy the MyoBoy very much, they deemed it a very useful tool to train EMG signals but rated the games as even more useful.

**User Evaluation Survey**

Participants were asked 5 questions for each of the 3 games and 1 question regarding the EMG assessments. Results showed a great difference of opinion regarding the game for dexterity, whereas the games for rhythm and racing were rated equally high. However, the input and game controls were perceived to be better in the rhythm game, whereas the fun and motivational factor were slightly, but not significantly, higher in the racing game. The enjoyment of EMG assessments were rated rather highly in the beginning (mean precision control = 4 of 5 maximum; mean sine curve = 4) but decreased over the course of the 3 ratings (after intervention: mean precision = 3.5; follow-up: mean precision = 3.5; mean sine curve = 3).

**Discussion**

The results of this study showed increases across all 3 basic EMG parameters: proportional and precise electrode control, electrode separation, and muscle endurance.

Contrary to our expectation, the MVC value increased for patients and able-bodied participants after playing the game, instead of decreasing. However, it did not increase for patient group that did not receive an intervention. The change could be attributed to heat or sweat changing the resistance of the electrodes. At the same time, this could indicate that playing was not exhausting for the users. Able-bodied participants performed expectedly well in all EMG assessments, but still decreased their deviation around the target value, the deviation around the goal value, and the involuntary activation of the opposing electrode.

In the proportional precision control assessment, although the 2 patient groups started with similar values and standard deviations, there was less significant progress in reaching the target value in group B (no intervention) compared with group A (with game-based intervention). Group A showed a strong decrease in deviation around the goal value and showed the most improvement of all groups. However, for middle and high intensity targets, group A did not keep the opposing electrode under the 15% threshold, which would mark that electrode as active, although it was activated significantly less for low intensity targets, which improved from the pre-intervention to the follow-up measurement.

Compared with previous studies [20,26,33,34], participants also trained repeated activation of the flexor and extensor muscle group. The chief difference from those studies is that patients also successfully trained more complex muscle activations, which are more akin to using a prosthesis in real life: sustained contractions with different lengths, contractions with exact timing, and simultaneous contractions of the 2 muscle groups.

Although expected to be an engaging game, patients did not consider the dexterity game to be motivating or fun, although it used real life-like use of co-contractions to switch between DoFs. A potential explanation could be that it was primarily directed at children. The racing game was highly rated in the categories fun, affinity, and motivation. Its controls were much simpler; players could turn only left or right while the car accelerated...
automatically. Overall, the 3 tested games received high ratings for EMG input and game control, with the rhythm game being the highest rated game in these categories.

The participants’ experiences with each game were assessed using the IMI, which also has been used by other research groups for evaluating virtual environments in motor rehabilitation [19,35-37]. Novak et al [36] found that the right game type needs to be found for each patient, depending on skill and personality, but that all participants enjoyed playing the games. Mihelj et al [35] used the IMI to evaluate a game-based virtual reality system with stroke patients who scored highly during the clinical evaluation. In 2014 Anderson and Bischof [19] conducted a study with able-bodied participants for improving myoelectric control by comparing the MyoBoy with a virtual training system. Their IMI scores showed that using their augmented reality training system was preferable to the MyoBoy. In our study, we evaluated the intrinsic motivation after each of the 3 games in the actual patient group and able-bodied control group. We were interested in comparing the MyoBoy with the game-based intervention and can conclude that the main advantage of game-based EMG training compared with conventional motor therapy is clearly the motivational aspect. Initially we assumed that participants also would improve their EMG control by performing only the EMG assessments [38], but that over time the users would gradually lose interest and motivation, which could be prevented by the engaging context of a video game [39].

However, the patient group not receiving the game-based intervention showed no significant improvement during all EMG assessments, showing that there must be an aspect that trained the patients beyond what the EMG assessments provided. Also, ratings for the EMG assessments were quite high in the beginning but never decreased to a bad rating. Compared with the MyoBoy rating, it is reasonable to assume that patients also would just use the EMG assessments as a training method, if there were no other choice. However, in this study, we found that rehabilitation training does not need to be just average, but can be engaging, motivating, and nevertheless increase clinical EMG parameters.

**Limitations**

Although this study compared the MyoBoy with gaming approaches concerning clinical outcomes and engagement, it did not investigate the influence of the patient-therapist relationship on these parameters. As known from clinical practice, individual contact is a
great motivational factor and necessary for planning and conducting the different steps of rehabilitation [40]. Therefore, these games are not meant to replace contact with a therapist, but rather to expand possibilities in rehabilitation and incite necessary home training.

The present study constitutes a short-term intervention. Future research also should consider long-term perspectives on using game-based interventions in prosthetic motor rehabilitation. A greater emphasis on long-term approaches in games for health has been recommended in several overviews and systematic reviews [41-43]. In addition, more advanced control methods based on machine learning should be considered. This would allow for more DoFs when controlling the games and better prepare patients for future possibilities of prosthesis control as outlined in previous studies [44-47]. Games based on mobile devices or simple stationary setups also provide the possibility for patients to train at home, further increasing proficiency in prosthetic control [48].

Conclusion

Most upper limb amputees control their prosthesis with 2 surface electrodes. They need to be able to switch between DoFs and to proportionally activate their muscle signals over different periods. In this study we found that this control method can be trained by integrating a game-based intervention into the rehabilitation protocol, which not only helps sustain motivation and engagement but also leads to increased improvements over just performing the EMG control requirements. Playing the games was more engaging and enjoyable than using a standard tool for myoelectric rehabilitation and patients invested more effort while doing so. Although patients considered all evaluated possibilities useful, based on these results, further research will incorporate a mobile rehabilitation training app for long-term intervention.

Supplementary Data

Supplementary data associated with this article can be found in the online version at https://doi.org/10.1016/j.pmrj.2018.09.027.

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Disclosure

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