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Design and Assessment of Myoelectric Games for Prosthesis Training of Upper Limb Amputees

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***Abstract*—In this paper, we present the design and evaluation of our system, which provides an engaging game-based pre-prosthesis training environment for upper limb transradial amputees. We believe that patients who train using such a training tool will demonstrate significantly higher improvement in functional performance tests using a myoelectric prosthesis than when conventional pre-prosthesis training protocols are used. We re-designed two simple games to be playable using three muscle contractions which are appropriate to pre-prosthesis exercises and are detected by an EMG-based arm sleeve. Through user studies conducted with 16 non-amputee subjects, we show that the proposed games are enjoyable, fun to play, sustains motivation to continue playing and also helps in improving muscular control. Using an HMM trained on EMG data collected from the game play sessions of each user, we are able to detect if the subject felt fatigued, while continuously contracting the muscles to play the game, in 93% of the cases and with a latency of only ± 15 seconds. We are also able to understand the subject's quality of muscle isolation during the game play.**

I. Introduction

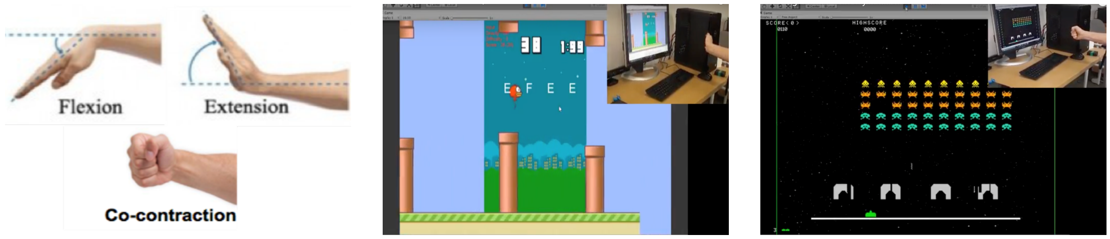
Usage of a robotic prosthetic arm can assist upper limb amputees to perform daily life activities independently. However, it requires remarkable skills to operate it efficiently by controlling the contraction of appropriate muscles [5]. Due to lack of proper pre-prosthesis training and incorporation of prostheses into daily life, the rejection rates of prostheses among upper limb amputees remain high (with documented rates as high as 81%) [3]. The key reasons for prostheses rejection are identified as the frustration due to pain and discomfort of prosthesis, lack of functional gain, inability to control the prosthesis due to lack of experience and proper training [3], [8].

Existing training methods for myo-electric prostheses are fairly primitive and mostly ineffective [17]. In the standard pre-prosthesis procedure (the period between amputation and receipt of the prosthetic arm), therapists encourage amputees to perform in-home exercises to voluntarily activate target muscle sites and isolate independent muscles. During the patients' clinical visits every few weeks, they perform certain exercises and the therapists assess their muscle strength. However, this kind of training is inefficient as the patients receive no feedback on their training and progress and lacks motivation to continue the training. Hence, by the time the amputees receive the actual prostheses, they get accustomed in performing most tasks with one hand and find it more troublesome to effectively use the prosthetic limb.

In this paper, we present the design and evaluation of two simple games that aims to provide an engaging training environment for pre-prosthesis patients. We hypothesize that patients who train using a system based on advanced rehabilitation protocols such as *Virtual Coach* [16], which provides active per-session feedback to the user, will demonstrate significant improvement in functional performance tests using a myoelectric prosthesis than when conventional pre-prosthesis training protocols are used. Our training tool targets to (i) improve the user's neuromuscular control of a prosthesis through targeted pre-prosthetic rehabilitation protocols, (ii) provide real time and offline tracking of outcome measures and therapy progression. The system will meet these criteria by providing a training environment involving games that are mapped to pre-prostheses exercises that can reflect muscle activity. We believe that this would help sustain the patient's motivation to "self-administer" the required rehabilitation protocols in both outpatient and/or home settings. In this work, we make the following **key contributions:**

- Design, modification and assessment of games for upper limb amputation rehabilitation based on feedback from clinicians and experts in game design. Two existing games were modified and improved to be suitable for our purpose by: (i) making it directly playable using forearm muscle contractions, detected by an EMG arm sleeve, (ii) applying design principles from educational game design such as segmenting the game into different modes and difficulty levels, integrating active feedback to the users on the endurance and quality of muscle contractions during the game, (iii) incorporating engaging and challenging elements that improve intrinsic motivation of subjects to play the games and (iv) tracking quantitative outcomes of game play.
- Evaluation of how well initial versions of the games address the needs of providing enjoyable training experience by conducting play test sessions. Qualitative studies performed with 16 non-amputee participants show that training using the games led to higher engagement and helps in improving muscular control.
- Using the EMG data collected, we are able to (i) detect if the subject is getting fatigued during the game play with

*Work done while on exchange at Carnegie Mellon University.



(a) Muscle contractions (b) Flappy Bird Game (c) Space Invaders Game

Fig. 1: (a) Three main muscular contractions (flexion, extension, co-contraction) used to control a robotic prosthetic arm and Game screens of (b) Flappy Bird and (c) Space Invaders in our training tool.

an accuracy of 93% and detect the time of fatigue with a latency of ± 15 seconds using an HMM and (ii) study the quality of muscle isolation (i.e., proper flexion and extension of muscles) using covariance values.

II. Related Work

Though serious-game based therapy and training have been explored well in the area of upper-limb rehabilitation for patients with stroke [20], cerebral palsy [22], there has not been much work that targeted upper-limb prosthesis patients. Game-based therapy and training for upper-limb prosthesis amputee rehabilitation was introduced with the commercial product, Paula software from Otto Bock [6]. However, the software is complex (requires the involvement of a clinician to use it) and provides limited game play experience and feedback [17]. Anderson et al. [2] presented an augmented-reality based interface with a simulated virtual arm for training muscle control for trans-humeral amputees. It uses the same game as in Paula software and pose similar limitations.

Recent works [12], [13], [18], [21] have focused on developing more engaging game-based myoelectric training tools for patients with upper-limb extremities. Phelan et al. [12] explored the use of virtual reality environment to decrease the training time taken by transradial amputees to use a prosthetic arm. In our work we develop more engaging games that include elements that can sustain long-term motivation compared to simulation of actions in a kitchen environment, which can be monotonous.

Van et al. [19] employed a simple 'catching-game' to show that games integrated with ADL-relevant feedback can help in easier transfer to use of a prosthetic arm. But the game developed did not have any elements to make it engaging to sustain patient motivation. Similar to our proposed idea, a myo training game that engages forearm muscles is introduced in [18]. Other works [13], [21] have also shown that overall usability and motivation for prosthesis training can be improved using game-based approaches. However, these games still lack active feedback to the user during the training process and do not quantitatively assess their performance.

Compared to existing works, we use engaging games, devise novel performance metrics and evaluate using EMG data collected during the game play. We also ensure that the game inputs are properly mapped to the required prosthesis control actions and have a logical sequence. Using machine learning models trained on features extracted from EMG data, we assess the performance of users during the game play based on two key quantitative metrics: *muscle fatigue* and *muscle isolation*.

III. Designing Games for Prosthesis Training

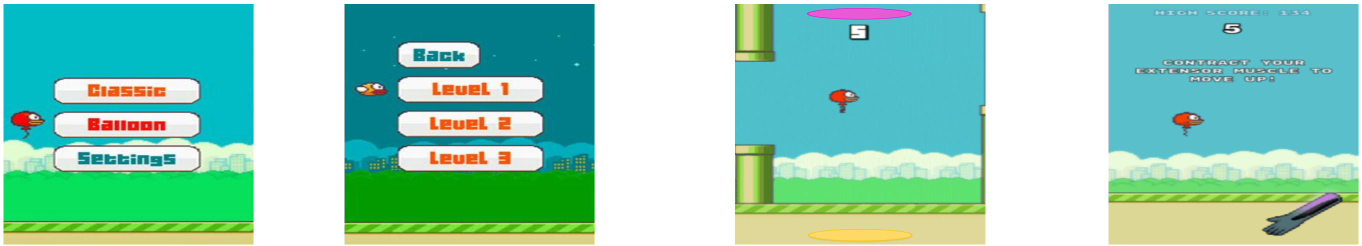
In this section, we discuss in detail the design principles, choice and modification of two games for prosthesis training.

A. Background, Game Design Requirements and Principles

The main focus of pre-prosthesis training for transradial amputees is to engage them to activate their forearm muscles and to teach them to properly isolate and control two opposing muscles. The three main muscle movements that are used to control a robotic prosthetic arm are flexion, extension and co-contraction (see Figure 1(a)). On consultation with physical therapists and game-design experts, we obtain the following insights on game-based myoelectric prosthesis training:

- Amputees start off with very little strength and control of their forearm muscles and it is challenging for them to contract muscles [5]. Therefore, it is important that appropriate difficulty in game levels are maintained so as to not frustrate or cause pain to the subjects.
- Learning to isolate flexion and extension muscles is important to properly control a robotic prosthetic arm. This requires that the game should include opportunities to practice with isolating muscles and feedback to allow the player to correct themselves and improve.
- The repetitive tasks of contracting and relaxing different muscles are often monotonous and boring. So, the game needs to be engaging and have motivating elements to sustain player's motivation.

An educational game will be more effective when it tightly integrates the following three components: precisely specifying educational objectives, considering and relating a game's mechanics, dynamics, and aesthetics (MDA framework), and applying principles for instructional design grounded in the learning sciences [1]. As rehabilitation exercises can be stressful due to their slow, repetitive and often painful movements, it is important to sustain patient motivation. A game-based training environment can increase intrinsic motivation through elements involving challenge, curiosity, control, and fantasy [11]. Through our interactions with two game design experts, we also learned there is a much greater opportunity



(a) Main Screen Menu (b) Difficulty levels in each mode (c) Feedback with glowing orbs (d) Feedback with hand model

Fig. 2: Difficulty modes and Feedback Module for Flappy Bird game

to create a compelling experience for the users in modifying existing popular games, as opposed to creating new games.

B. Game Selection and Play Experience

The educational objectives of our games include improving strength and isolation of forearm muscles with the long-term goal of applying these skills to control a robotic prosthetic arm. We chose two simple but popular games – *Flappy Bird* and *Space Invaders* (see Figure 1(b) & Figure 1(c)) for including in our training tool. Both the games had its open source implementation available in Unity framework.

These games were specifically selected because their MDA framework matched our educational requirements. Requiring only two directional movements forces the player to properly isolate the flexion and extension muscles. With the time pressure of obstacles or lasers coming at the player, the player is forced and therefore highly motivated to contract their muscle correctly. Additionally, strength develops over time as the games require the player to make many movements within just a few minutes to survive. This tight integration between the games' learning objective and core mechanics should lead to better learning and greater motivation in the player [1].

For *Flappy Bird*, the mechanics include moving a bird up (by flexion) and down (by extension) to avoid incoming obstacles as long as possible. Co-contraction is used to navigate the initial menu and to speed forward. For *Space Invaders*, mechanics include moving a spaceship left (by flexion) and right (by extension) to avoid getting hit and shooting lasers at aliens using co-contraction.

The aesthetic goal of both games is that of challenge and fantasy. Players get immersed in the whimsical world of Flappy Bird or the retro world of Space Invaders, and often they will want to keep playing in order to reach higher scores and avoid more obstacles or defeat more enemies.

C. Redesign and Modification of Games

In this work, we used a custom-made wearable EMG-controlled arm sleeve [10]. The hardware has its in-built pattern recognition system that detects flexion, extension and co-contraction based on the myoelectric signals recorded. We modified the two games to be playable using these actions.

To collect data, we configured the custom EMG sleeve hardware to stream data from the EMG sensors and to perform pattern recognition of muscle contractions from up to 8 EMG channels. We also modified the game to record logs from the Unity framework to capture information such as contraction type detected, strength of each contraction and mean absolute values of signals from each channel.

In general, the major modifications and redesigns we implemented for both the games include the following:
Simple and direct interactions for meaningful game play: The required movements of the exercises and game actions were mapped directly with logical consequences.
Better Aesthetics and Dynamics: The overall interface, game menu, game elements were customized for better look and feel. Figure 2(a) & (b) shows examples of modified screens for Flappy Bird. In Flappy Bird, we tweaked the height and spacing of the pipes to to ensure that (i) it is never impossible to pass through, and (ii) players have time to rest in between more challenging parts of the game.
Proper Segmentation: We separated the game into different modes and difficulty levels to allow the player to progress through at their own pace. For Flappy Bird, this includes an additional "balloon mode" that utilizes simpler controls. In Space Invaders, the difficulty of the game gradually increases with the aliens starting to move left and right instead of remaining at a static position, which makes it more challenging to shoot them. Separating the game into short bite-sized levels also helps to reduce frustration.
Extrinsic motivation through rewards and progress scores: We added floating coins to the games to encourage the player to extend and flex properly and to increase the feeling of reward. In addition, after certain levels, players could use "co-contraction boosts" to speed forward for a few seconds.
Increased Challenge: Random sequences of muscle contractions are displayed during the game for the player to follow. This is to ensure that each action is performed and not one is always repeated. Following the sequence help to earn more points and create immersion with the time pressure.
Active Feedback: We included active feedback to indicate the strength and isolation of players muscle contractions via glowing orbs representing each muscle (top one for flexion and bottom one for extension) as shown in Figure 2(c). The orb glows based on the current muscle contraction type and the glowing intensity depends on strength of the contraction. Also, when the users co-contract, both the orbs are glowed simultaneously. We also designed a version that involves an actual graphic of an arm with glowing muscles (Figure 2(d)), with similar functionality.

IV. Study Methodology

We next describe the data collected and the methodology used to answer the two questions: (i) can we identify if the user is getting fatigued during the game play?, (ii) can we study their muscle isolation quality during the game play?

Most of the existing works [12], [18] that focus on myoelectric game-based prosthesis training conduct only qualitative assessment of the games. We believe that it is also important to gather insights about the actual performance of the subjects when using this training tool (i) to provide them appropriate feedback, (ii) to give a summarized as well as detailed report to the occupational therapists on how the subjects are performing.

A. Digital Playtesting & Data Collection

We conducted a user study (approved by our Institutional Review Board) with 16 student volunteers. Our study with non-amputee subjects is supported by existing work [15] that has shown that the learning capabilities of motor tasks by amputees using body-powered upper limb terminal devices were similar to those of able-bodied subjects.

At the beginning of the study, each participant was given instructions about the game controls and mechanisms. The participants wore the arm sleeve that recorded raw EMG data during the game play. To begin with, we asked the subject to perform each of the three contractions (flexion, extension, co-contraction) with their maximum strength in order to measure Maximum Voluntary Contraction (MVC) value. The MVC value is used to normalize EMG data recorded across all users.

The participants were asked to play both *Flappy Bird* and *Space Invaders* one after the other in randomized order. All game play sessions were video recorded for the ground truth of mapping muscle contractions to game play interactions (i.e., if the muscle contractions are detected and getting mapped correctly to game controls). For Flappy Bird, the subjects played varying difficulty modes of the game. After each game was completed, the subjects filled in a questionnaire. This was to assess their subjective opinion and experience during the game play, gather feedback on what they liked or disliked about the game and suggestions on what can be improved. The ground truth of whether the subject felt fatigued or not during the game play is also obtained from this questionnaire. Out of the 16 subjects, 14 of them reported that their forearm muscles felt fatigued while playing both the games. The entire session per subject lasted for about 30 minutes on average. Table I shows the summary of the dataset collected.

We also collected a secondary dataset specifically for the evaluation of muscle fatigue. We collected data from two out of the 16 subjects playing Space Invaders for five trials each. During this study, we asked the subject to keep playing until their muscles felt fatigued and also marked the total game play time and exact time at which they started feeling fatigued. Our goal was to use this data to study the latency of our model in detecting fatigue by comparing against the ground truth marked time. Within this dataset, individual game trial duration ranged from a minimum of 140 seconds to a maximum of 263 seconds. On an average, both the subjects reported to feel muscle fatigue after about 100 seconds.

No. of subjects	16 (11 males, 5 females)
No. of game trials	Total:132 Flappy Bird (84); Space Invaders (48)
Game play time per trial	Flappy Bird – Average time: 38.6 secs, Std Dev.: 29 secs; Space Invaders – Average time: 131 secs, Std Dev.: 59 secs
No. of contractions detected	Flexion – 1282; Extension – 1409; Co-contraction – 2134

TABLE I: Summary of dataset collected

Time Domain Features	Frequency Domain Features
Mean Absolute Value (MAV)	Median Frequency (MDF)
Root Mean Square (RMS)	Mean Frequency (MNF)
Variance of EMG (VAR)	Modified Median Frequency (MMDF)
Waveform Length (WL)	Modified Mean Frequency (MMNF)
Zero Crossings (ZC)	Frequency Ratio (FR)
Simple Square Integral (SSI)	

TABLE II: Features extracted on EMG signal

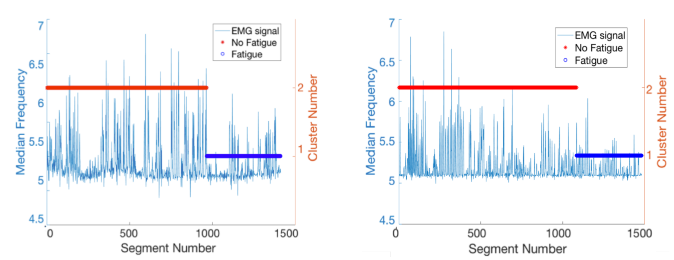
B. Data Pre-processing & Feature Extraction

From the EMG arm sleeve, we obtained data corresponding to channels from flexion and extension muscles. The best channel for both flexion and extension muscles per individual subject is calibrated initially.

We first normalized the EMG data based on the maximum value of MVC values recorded per channel. The raw EMG signals from each of the chosen channels were divided into multiple frames of 100 samples each. We then extracted time-domain and frequency-domain features (as explained in [14]) on individual frames for each channel of EMG data. The features extracted are listed in Table II. For each frame, a feature vector with 11 features is computed per channel.

C. Detecting Muscle Fatigue

Continuously contracting the forearm flexion and extension muscles during the game play would cause the subject to get fatigued and thus, reduce the muscle activity. Thus, detecting fatigue is important to signal the subject to take appropriate breaks during the training sessions.



(a) Flappy Bird game play (b) Space Invaders game play

Fig. 3: Variation in median frequency of EMG data during (a) Flappy Bird and (b) Space Invaders game and the no-fatigue (red line) and fatigue (blue line) clusters identified by HMM.

We study muscle fatigue of users based on features extracted from raw EMG data collected from the game play sessions. In this work, we conduct offline analysis of the EMG data collected to understand (i) if we could detect that the person is getting fatigued during the game play and (ii) study how close to the actual time of fatigue is the prediction of our fatigue detection model. Existing work [9] have proposed the use of characteristic indicators of the frequency spectrum of the EMG signal such as the *Median Frequency* and *Mean Frequency* to understand muscle fatigue. Our approach builds upon this prior work that have established that the *median frequency* of the EMG signal decreases as the person gets fatigued. Figure 3 shows the variation of the median frequency of the EMG data for one trial each of Flappy Bird and Space Invaders game play. We observe the decreasing trend of median frequency indicating decrease in muscle activity and thereby, muscle fatigue.

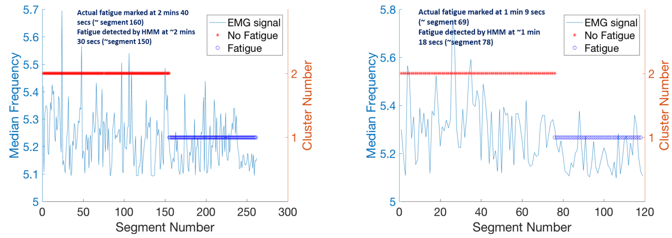
We used an unsupervised clustering approach to detect if the subject was fatigued during the game play. For this purpose, we trained a Hidden Markov Model (HMM) as it works well with sequential time series data in identifying hidden states from it. HMM was trained on the discretized median frequency feature (MDF) extracted on EMG data collected from each game play session, to cluster it into *No-Fatigue* and *Fatigue* clusters. For training the model, we first compute the transition and emission probabilities of the HMM for each sequence with known initial states ('No Fatigue'). With the estimated probability distributions, the most likely path or sequence of states is obtained using the *Viterbi algorithm*.

D. Understanding Quality of Muscle Isolation

For the amputees to properly control the robotic prosthetic arm it is important that they learn to isolate the contraction of flexion and extension muscles. i.e., there should be minimal interference of signals from opposing muscle groups.

To understand if the muscle contractions are properly isolated during the game play, we computed the *covariance values* between the signals from respective EMG channels for flexion and extension. In order to observe proper isolation of the muscles, there should be a *negative correlation* between the EMG channel values corresponding to flexion and extension. Also, as the muscles are co-contracted (contracting both the muscle groups together) we expect to observe positive correlation between the signals from these two muscle sites.

The covariance based studies are performed on the Mean Absolute Values (MAV) of EMG signals. The EMG data obtained from one game play session is a continuous stream interspersed with data corresponding to multiple muscle contractions. Therefore, we first classify the continuous data stream into groups that corresponds to varying muscle contraction types (flexion, extension, co-contraction and rest) performed at different instances during the game play. We implemented a simple threshold-based approach to classify the contraction types. Based on the data classified into different contraction types, we computed the covariance matrix between data from flexion and extension channels for each user's game trials.



(a) HMM detects fatigue at 150 secs on Subject 1's Space Invaders game. Ground truth marked time=160 secs.

(b) HMM detects fatigue at 78 secs on Subject 2's Space Invaders game. Ground truth marked time=69 secs.

Fig. 4: Comparison of time of detection of fatigue against ground truth time for the two subjects. Red line represents 'No-Fatigue' cluster and blue line represents 'Fatigue' cluster.

V. Evaluation

We next evaluate the performance of our approach and describe the qualitative feedback obtained for the two games.

A. Performance of Detecting Muscle Fatigue

As described in Section IV, we trained an HMM on the EMG data to detect if the subject is getting fatigued during the game play. We first trained an HMM on per-person data – i.e., for each user, we trained a model on their Flappy Bird game data and tested on their Space Invader's game data. Using this approach, we obtained 93% accuracy with a precision of 0.932 and recall of 0.931 in detecting fatigue in subjects while playing Space Invaders game. The model couldn't detect fatigue for one subject's game. When we analyzed the particular subject's EMG data from both games, we observed that the average strength of muscle contractions were much lower in the case of Flappy Bird compared to Space Invaders. This affected the model's estimated probability distributions and the state sequences.

We also performed a leave-one-subject-out cross validation to see if a generalized model would work in detecting fatigue in users. This model achieved an accuracy of 85.7% with a precision and recall of 0.858 each.

For evaluating how precisely we could detect the time at which the subject started to get fatigued, we used the secondary dataset collected (for Space Invaders game) with ground truth marked for time of fatigue.

For each subject, we performed a leave-one-episode-out (here, one episode is one game trial) cross validation – i.e., HMM trained on 4 game trials of data and tested on fifth game trial. The decreasing trend in median frequency when the person was getting fatigued was evident and the HMM could accurately demarcate the data sequence into 'no-fatigue' and 'fatigue' clusters for all 10 game trials. Figure 4(a) and Figure 4(b) shows examples of accurately detecting fatigue at almost similar time as the ground truth for the two subjects. Across all the 10 game trials, the average latency in detecting time of fatigue was ± 15 seconds (std. dev of 4 seconds), compared to the ground truth marked time of fatigue.

Statement	Average response value for Flappy Bird	Average response value for Space Invaders
I enjoyed the (Flappy Bird/Space Invaders) game very much	4.12 (1.10)	3.86 (1.23)
I liked the various difficulty levels in this game.	3.71 (1.27)	3.14 (1.10)
I liked the aesthetics of the game	3.93 (0.92)	3.57 (1.28)
I put a lot of effort into playing this game	3.93 (0.47)	4.07 (0.99)
The feedback provided during the game play was useful to me	2.71 (1.33)	3.0 (1.17)
I would prefer some feedback during the game play compared to no feedback at all	3.86 (1.17)	3.92 (1.20)
I think this game would help me to improve my forearm muscular control	4.14 (0.66)	4.35 (0.74)
I would be motivated to play this game again	3.86 (1.23)	4.07 (1.26)

Values in brackets are the standard deviation of response values.

TABLE III: Summary of Survey responses for both games

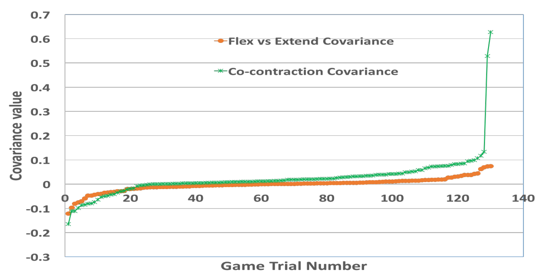


Fig. 5: Covariance value between EMG signals indicating overall quality of muscle isolation during each game play trial. Negative covariance values between flexion and extension channels indicate good quality of muscle isolation.

B. Determining Quality of Muscle Isolation

For studying the quality of muscle isolation, we computed the covariance matrix between the flexion and extension channel data for all the game trials across 16 subjects. Figure 5 shows the covariance value computed for flexion vs extension and for co-contraction per each game trial. For 60 out of 132 game trials, a negative covariance value was obtained, indicating proper isolation of the flexion and extension muscles. Remaining 72 game play trials had a positive covariance value ($\approx$0.05) showing some reduction in the quality of isolating the two muscles. However, covariance values less than 0.3 suggest that the signals from two muscle groups contain little crosstalk [4]. Therefore, most subjects could properly isolate their forearm muscles during the game play. We anticipate that actual amputees may have more difficulty in properly isolating the muscles and the feedback on the strength and quality of muscle contraction would be more helpful for them.

C. Subjective Evaluation

We also conducted subjective evaluation based on a post game play questionnaire to determine the perceived usefulness, enjoyment, ease of use, ability to sustain motivation of the games. We modified the IMI questionnaire [7], which is the most common instrument used for assessing subjective opinion about games. The questionnaire included 18 statements and 4 open-ended questions. Participants' responses were recorded on a 5 point Likert-type scale with the anchors varying from 'Strongly Disagree' to 'Strongly Agree'.

Based on the responses to the questionnaire, we found that majority of the participants enjoyed the experience of playing the games. All except two subjects reported that they think these games would help to improve their forearm muscular control. Table III summarizes the response ratings to the key questions in the questionnaire for both the games. The subjects also reported that it took a lot of effort for them to play the game and it was tiring. Some of the key suggestions/feedback included integrating more controls for game play, including audio feedback, ability to pause during the game as to relax their muscles and to include more bonus points or rewards.

VI. Discussion

While our game-based training tool for prosthesis rehabilitation shows great promise in terms of the experience it provides as well as the outcome measures derived, there are still some challenges and open questions that are yet to be answered.

One of the major limitation is that we have only conducted preliminary evaluation of the training tool with able-bodied subjects. Although as supported by prior work [15], we believe that the results obtained would be representative of the learning capabilities of motor tasks that can be achieved by amputees. However, to validate the robustness and performance of our tool, it is important to conduct testing and evaluation with transradial amputees and also gather feedback from them.

Another limitation is that sometimes during game play, different contractions are mis-detected (as precise measurement of fine movements based on strength of contraction was difficult), and this negatively affects the game play experience. We are exploring ways to improve the accuracy of the pattern recognition algorithm that detects muscle contractions. We are also improving the existing games (e.g., by adding rest period in between game play, including more rewards and feedback) based on the feedback obtained from the subjects.

There are also a variety of additional approaches and possibilities that we are addressing in ongoing work. At present, the detection of muscle fatigue and assessment of muscle isolation is performed offline and in future we intend to perform it in real time during the game play. This will be more helpful in providing real time feedback to the users based on their performance. We also intend to study other performance metrics such as gain in muscular strength, ease of muscular activation and controls. We are also exploring additional games (e.g., virtual reality games that can provide a more immersive and engaging experience to the users) that can be integrated into a desktop and/or mobile-based training tool.

VII. Conclusion

In this work, we present the design and evaluation of myoelectric games for transradial upper limb amputees to improve their muscular control during the pre-prosthesis phase. We modified the Unity open source implementation of *Flappy Bird* and *Space Invaders* games for this purpose. User studies conducted with 16 able-bodied subjects show that these games are engaging and fun to play. About 80% of the participants responded that they think both these games would help in improving their forearm muscular control. Results from our quantitative evaluation also show that using an HMM, we can understand if a person is getting fatigued during the game play with an accuracy of over 93% and the time of fatigue with a latency of only ± 15 seconds. We are also able to derive the quality of muscle isolation during the game play.

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References

[1] Aleven, V., Myers, E., Easterday, M., and Ogan, A. Toward a framework for the analysis and design of educational games. *Proc. of DIGITEL'10*.

[2] Anderson, F. and Bischof, W. F. Augmented reality improves myoelectric prosthesis training. *International Journal on Disability and Human Development*, 13(3):349–354, 2014.

[3] Biddiss, E. A. and Chau, T. T. Upper limb prosthesis use and abandonment: a survey of the last 25 years. *Prosthetics and orthotics international*, 31(3):236–257, 2007.

[4] Birdwell, J. A., Hargrove, L. J., et al. Quantification of isolated muscle compartment activity in extrinsic finger muscles for potential prosthesis control sites. *Proc. of EMBC'11*. IEEE, 2011.

[5] Bouwsema, H., van der Sluis, C. K., and Bongers, R. M. Learning to control opening and closing a myoelectric hand. *Archives of physical medicine and rehabilitation*, 91(9):1442–1446, 2010.

[6] Bouwsema, H., van der Sluis, C. K., and Bongers, R. M. Guideline for training with a myoelectric prosthesis. *Center for Human Movement Sciences/Department of Rehabilitation Medicine. University Medical Center Groningen, University of Groningen, NLD*, 2013.

[7] Cordova, D. I. and Lepper, M. R. Intrinsic motivation and the process of learning: Beneficial effects of contextualization, personalization, and choice. *Journal of educational psychology*, 88(4):715, 1996.

[8] Dawson, M. R., Carey, J. P., and Fahimi, F. Myoelectric training systems. *Expert review of medical devices*, 8(5):581–589, 2011.

[9] De Luca, C. J. The use of surface electromyography in biomechanics. *Journal of applied biomechanics*, 13(2):135–163, 1997.

[10] Kuiken, T. A., Li, G., Lock, B. A., Lipschutz, R. D., Miller, L. A., Stubblefield, K. A., and Englehart, K. B. Targeted muscle reinnervation for real-time myoelectric control of multifunction artificial arms. *Jama*, 301(6):619–628, 2009.

[11] Lepper, M. R. and Malone, T. W. Intrinsic motivation and instructional effectiveness in computer-based education. *Aptitude, learning, and instruction*, 3:255–286, 1987.

[12] Phelan, I., Arden, M., Garcia, C., and Roast, C. Exploring virtual reality and prosthetic training. *Proc. of IEEE Virtual Reality (VR)*, 2015.

[13] Prahm, C., Kayali, F., Vujaklija, I., Sturma, A., and Aszmann, O. Increasing motivation, effort and performance through game-based rehabilitation for upper limb myoelectric prosthesis control. *Proc. ICVR'17*.

[14] Rechy-Ramirez, E. J. and Hu, H. Stages for developing control systems using emg and eeg signals: A survey. *School of Computer Science and Electronic Engineering, University of Essex*, pages 1744–8050, 2011.

[15] Schabowsky, C. N., Dromerick, A. W., Holley, R. J., Monroe, B., and Lum, P. S. Trans-radial upper extremity amputees are capable of adapting to a novel dynamic environment. *Experimental brain research*, 188(4):589–601, 2008.

[16] Siewiorek, D., Smailagic, A., and Dey, A. Architecture and applications of virtual coaches. *Proc. of the IEEE*, 100(8):2472–2488, 2012.

[17] Tabor, A., Bateman, S., and Scheme, E. Game-based myoelectric training. *Adjunct Proc. of CHI'16 (CHI Play)*. ACM, 2016.

[18] Tabor, A., Bateman, S., Scheme, E., Flatla, D., Gerling, K., et al. Designing game-based myoelectric prosthesis training. 2017.

[19] van Dijk, L., van Sluis, C. K., van Dijk, H. W., and Bongers, R. M. Task-oriented gaming for transfer to prosthesis use. *IEEE Transactions on Neural Systems & Rehabilitation Engineering*, 24:1384–1394, 2016.

[20] Viriyasaksathian, B., Khemmachotikun, S., Kaimuk, P., and Wongsawat, Y. Emg-based upper-limb rehabilitation via music synchronization with augmented reality. *Proc. of ROBIO'11*.

[21] Winslow, B. D., Ruble, M., and Huber, Z. Mobile, game-based training for myoelectric prosthesis control. *Frontiers in bioengineering and biotechnology*, 6, 2018.

[22] Yoo, J. W., Lee, D. R., Sim, Y. J., You, J. H., and Kim, C. J. Effects of innovative virtual reality game and emg biofeedback on neuromotor control in cerebral palsy. *Bio-medical materials and engineering*, 24(6):3613–3618, 2014.