The design and evaluation of electromyography and inertial biofeedback in hand motor therapy gaming

Alexander Macintosh, Nicolas Vignais, Vincent Vigneron, Linda Fay, Alain Musielak, Eric Desailly, Elaine Biddiss

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### The design and evaluation of biofeedback in motor therapy gaming

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#### Abstract:

This article details the design of a co-created, evidence-based biofeedback therapy game addressing the research question: is the biofeedback implementation efficient, effective, and engaging for promoting quality movement during a therapy game focused on hand gestures?

First, we engaged nine young people with Cerebral Palsy (CP) as design partners to co-create the biofeedback implementation. A commercially available, tap-controlled game was converted into a gesture-controlled game with added biofeedback. The game is controlled by forearm electromyography and inertial sensors. Changes required to integrate biofeedback are described in detail and highlight the importance of closely linking movement quality to short- and long-term game rewards.

After development, 19 participants (8-17 years old) with CP played the game at home for four-weeks. Participants played 17±9 minutes/day, 4±1 days/week. The biofeedback implementation proved efficient (i.e. participants reduced compensatory arm movements by 10.2±4.0%), effective (i.e. participants made higher quality gestures over time) and engaging (i.e. participants consistently chose to review biofeedback). Participants found the game usable and enjoyable.

Biofeedback design in therapy games should consider principles of motor learning, best practices in video game design, and user perspectives. Design recommendations for integrating biofeedback into therapy games are compiled in an infographic to support interdisciplinary knowledge sharing.

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Keywords: assessment; developmental disability; knowledge translation; neurorehabilitation and brain computer interfaces; pediatrics; recreation; usability; biofeedback
Introduction

Cerebral palsy (CP) is a disability due to brain injury or abnormality near birth and persists through the lifespan (Rosenbaum et al., 2007). CP can impact a person’s motor control, perception, intellectual function, ability to perform daily activities and participate in society (Novak et al., 2013). Persons with CP can have impaired hand or arm function affecting motor activities. Improving performance in motor activities requires frequent and intense practice (MacIntosh, Lam, Vigneron, Vignais, & Biddiss, 2018). Understandably, much research has focused on designing engaging activities to promote practice and improve function. Integrating technologies and games into rehabilitation therapies is an approach of great interest to children, their families and clinicians (Howcroft et al., 2012). Previous work has explored the use of entertainment gaming systems such as the Nintendo Wii and Sony EyeToy as well as custom-designed therapy systems for motor rehabilitation with varying success (Kanitkar et al., 2017). One limitation of many technologies used to promote engaging practice of therapy activities is the poor quality or lack of feedback provided by the system to inform task performance (James, Ziviani, Ware, & Boyd, 2015). In previous studies, young people with CP and their families have reported a desire for more accurate feedback that can inform both real-time performance (i.e. “am I doing the movement right?”) and progress over time (i.e. “are my abilities changing?”) (James, Ziviani, King, & Boyd, 2015).

Feedback impacts how well tasks are learned, a person’s focus and their motivation (Wulf, Shea, & Lewthwaite, 2010). Biofeedback, where a person receives information about their body state (e.g. heart rate, foot speed, muscle activity), can help increase awareness and control by informing the individual to how their body is functioning (Timmermans, Seelen, Willmann, & Kingma, 2009; van Dijk, Jannink, & Hermens, 2005). Biofeedback in motor activities can be used to provide (i) “knowledge
of performance” (KP) indicating the quality of a movement (e.g., compensatory movements performed while throwing a ball) as well as (ii) “knowledge of results” (KR) indicating how successful an action was with respect to the desired outcome (e.g., whether the ball hit a target). An evidence-based biofeedback strategy: a) offers autonomy, making people active contributors to their practice by building a sense of ownership (Taylor, Dodd, McBurney, & Graham, 2004), b) is proportionate to the person’s ability, and c) varies in presentation (e.g. visual, audio) (Biddiss, Chan-Viquez, Cheung, & King, 2019; MacIntosh et al., 2018). These attributes fuel a person’s interest in their own performance and helps them refine their movements ultimately enhancing motivation, independence and self-efficacy (MacIntosh et al., 2018; Wulf, 2006).

However, a recent review found that biofeedback strategies used in motor interventions for people with CP are rarely based on motor learning principles or clinical evidence (MacIntosh et al., 2018). Traditionally, biofeedback has been given in a way that may slow motor learning by forcing the person into a passive role in their practice, building dependence on the feedback (Timmermans et al., 2009). Improving the quality of biofeedback in therapy games may positively impact functional outcomes by increasing engagement and efficiency of home-based practice (Howcroft et al., 2012).

This article describes the design and evaluation of a biofeedback therapy game for home-based motor rehabilitation. Note, this paper does not aim to describe clinical effectiveness, but rather to assess how the biofeedback implementation helps participants take interest in their practice and adjust their motor activities at home. The project was conducted in two phases. In phase 1, we engaged with young people with CP, clinicians, and a video game developer through a participatory design approach to answer the research question: how can user-centred biofeedback be integrated in an existing commercial video game to promote motor learning? In phase 2, the
biofeedback implementation is evaluated in-home for four weeks by 19 young people
with CP to answer the question: *is the co-created biofeedback implementation (i) efficient, (ii) effective, and (iii) engaging from the perspective of its users for promoting quality movement during a therapy game focused on hand gestures?* Specifically, we expect that participants will: i) adapt their movements immediately after KP biofeedback is presented informing on movement quality (*efficient*), ii) improve performance in the task over time (*effective*), iii) choose to review KR biofeedback informing on task performance when presented the opportunity (*engaging*).

**Methods**

**Phase 1: Design approach**

In line with the framework presented by (Druin, 2002), we recruited young people with CP (10-23 years old, with mild-moderately impaired use of one hand, Manual Abilities Classification System (MACS) level I-III (Eliasson et al., 2006) to participate as ‘design partners’ to integrate evidence-based biofeedback principles into a commercial video game. As design partners, participants were consulted throughout the process from ideation to final product (Druin, 2002). Participants tested game prototypes during 1-hour, one-on-one, sessions with a researcher. Three occupational therapists were also consulted and attended design sessions when required by participants. Biofeedback elements were added to the game and refined at each session. Researchers prompted participants to verbalize their thoughts related to biofeedback timing, aesthetic design, comprehension, and motivation during and after play-testing. Sessions were completed in an urban North American centre and a rural Western European centre to build biofeedback presentation receptive across cultures. After each design session, participant responses were synthesized, and changes were made to the game for the next
These changes were recorded in an audit trail to keep track of the decisions made and rationale. After the end of the design phase, the therapy video game with integrated biofeedback was ready for testing in-home.

**Gaming system description**

Biofeedback was added to the commercial game, ‘Dashy Square’ (KasSanity Inc.). The game objective is to navigate through 10 levels of increasing difficulty without touching obstacles. Example gameplay can be seen [here](http://mc.manuscriptcentral.com/uaty). In the game’s original form, players press a key to evade obstacles. Working with the developer, controls were changed from a single key press to a gesture-based controller using electromyography (EMG) and inertial sensors detected with the Myo Armband (Thalmic Labs). Participants wore the Myo Armband on the forearm of their affected side. Raw data from the armband’s eight-channel EMG and 9-axis inertial measurement unit (IMU) were processed through custom scripts developed in MATLAB 2017b to interpret gestures and command the game. Development of the classification algorithms for detecting these gestures will be described in a parallel paper, *in prep.* (MacIntosh, Biddiss, Vignais, & Vigneron, 2019). Participants and therapists were consulted to determine the desired gesture with which to control the game. Gestures were one of: wrist extension- active fingers, wrist extension- relaxed fingers, finger-thumb pinch, supination. The biofeedback was designed to reward completion of the therapeutic goals identified by clinicians and participants: making the gesture at the correct time and having high quality movement (i.e. low co-contraction and fewer compensatory movements).

Specifically, co-contraction was quantified as the ratio between extensor and flexor muscle activity. High forearm extensor activity while keeping flexor activity low was associated with less co-contraction and higher quality movement. Compensatory arm movements were detected by the IMU. Fewer arm movements, quantified by the
resultant angular velocity variability of the forearm, were associated with more isolated hand movements and higher quality movement. During design sessions, participants tested the custom gesture-controlled version of Dashy Square with added biofeedback elements. In summary, the biofeedback elements added to the game because of the co-design process were (full details in Results, Table 1):

1. **Dodge points** given for avoiding obstacles, linked to correct timing of a gesture.
2. **Style points** were linked to quality of movement, specifically the extent of co-contraction. Higher ‘Style Points’ means greater extensor and lesser flexor activity (less co-contraction).
3. **Speed-change** biofeedback events were linked to quality of movement, specifically the extent of compensatory arm movements. When compensatory arm movements were detected beyond an individualized threshold, game speed was reduced to give participants more time to perform gestures.
4. **Practice panels** were shown after consecutive poorly timed or executed movements. The practice panel offered a simplified game environment without obstacles wherein participants could practice the movement.
5. **End-of-level rewards**: Trophies were rewarded at the end of each level in accordance with the number of dodge and style points achieved. One trophy indicated a lower level of mastery while three trophies was associated with the highest level of mastery. Additional rewards such as unlocking characters and leader board standings could also be reviewed as end-of-level KR biofeedback.

Sample play with the game adapted with biofeedback can be seen [link removed for blinding].
Phase 2: In-home evaluation

Usability and impact of the biofeedback were evaluated in a 4-week home-based intervention. Inclusion criteria were: persons 8-18 years old with CP, MACS I-III, ability to co-operate, understand, and follow simple instructions, and, typical or corrected to typical vision and hearing. Exclusion criteria were: history of unmanaged epilepsy that may be triggered by video game play, having received a botulinum toxin treatment within 3 months or constraint-based movement therapy within 6 months of the study enrolment, visual, cognitive or auditory disability that would interfere with gameplay. The protocol was approved by the [names removed for blinding] Research Ethics Boards. Caregivers and participants gave written informed consent or assent as appropriate.

Each participant took home a laptop with the game software and a Myo Armband to play for four weeks. Before playing alone, the researcher gave one or two training sessions to ensure participants could operate the system and understood the objectives and controls of the game. Participants created a self-defined practice schedule with the assistance of their caregiver and an occupational therapist (the suggested goal was 3-5 times per week, 30 minutes per day) (Golomb et al., 2009). At home, participants selected which level to play, but more difficult levels were unlocked only after finishing easier ones. Once per week, the researcher visited the participants to evaluate their motivation, adherence, collect system logs, and to record subjective biofeedback-related observations.

Outcome Measures

The system automatically logged biofeedback usage data (e.g. dodge points, style points, practice panels presented) and physiological data (i.e. EMG, arm kinematics) for
post-hoc analysis. At the end of the four-week trial, participants completed a semi-structured interview and a custom game-feedback questionnaire with the researcher. These were used to understand how the added biofeedback impacted the participants’ experience with the game. The questionnaire was based on validated questionnaires for measuring usability (System Usability Scale (SUS) (Brooke, 1996) and enjoyment (Flow Short (Engeser & Csikszentmihalyi, 2012)) and questions developed during a previous study of interactive computer play games for young people with CP (Hernández, Khan, Fay, Roy, & Biddiss, 2018). Examples of open questions used to facilitate conversations during the semi-structured interview include: ‘How did the score change how you played the game?’ and ‘What helped to make the game easier to play?’ (Appendix A).

Data Analysis

To resolve the Phase 1 research question: ‘how user-centred biofeedback can be integrated into an existing commercial video game to promote motor learning?’ an audit trail was generated that integrated participant feedback, researcher observations, and clinician input. This audit trail was reviewed, and a list of design specifications was tabulated to guide the integration of biofeedback into video games for motor therapy.

To evaluate the Phase 2 research question: is the biofeedback implementation (i) efficient, (ii) effective, and (iii) engaging from the perspective of its users for promoting quality movement during a therapy game focused on hand gestures?, the following variables were analysed:

1. Efficiency: The system was considered efficient if participants reduced the use of compensatory arm movements immediately after a speed-change biofeedback event. The difference in resultant angular velocity variability of the forearm
between the five seconds before and five seconds after the speed-change biofeedback event was calculated. We refer to this variable as the “change in arm movement.”

(2) Effectiveness: The system was considered effective if task performance improved over time. Three indicators of task performance are the “dodge point rate” (dodge points accumulated per minute of play, linked to correct timing of a gesture) and “style point rate” (style points accumulated per minute of play, linked to co-contraction quality). The number of “practice panels shown per minute” was calculated as an indicator of the need for biofeedback. Note: practice panels are presented when consecutive poorly timed or executed movements are performed. As such, indicators of improved performance are: increasing dodge point rate, increasing style point rate, and decreasing number of practice panels shown per minute.

(3) Engagement: The system was considered engaging if participants chose to review the KR biofeedback provided at the end of each level reporting on their success in the game (e.g., the trophies awarded). This variable, ‘review choice’ is the proportion of opportunities participants took to see end-of-level KR biofeedback.

To evaluate the efficiency of the biofeedback for promoting higher quality movement, the change in arm movement before and after a speed-change biofeedback event was compared using a dependent-samples t-test with alpha risk set to 0.05 (Chu et al., 2009; Müller & Sternad, 2009). Engagement is described as the percentage of instances participants chose to review end-of-level feedback. Effectiveness is described as the practical changes in performance (dodge points, style points, practice panels) in playing a typical 2-minute level at the beginning and end of the intervention. To
understand how the efficiency, effectiveness, and engagement with the biofeedback system changed over time, a generalized linear mixed-effect model (GLMM) was constructed for each of the above-described variables. The model takes into consideration variations between participants and the game levels. Specifically, all models included practice time (cumulative minutes spent playing the game) as a fixed effect, a random intercept for participants and a random participant*game level interaction effect since individuals self-selected which levels to play. Adjusted odds ratios (aOR), for binomial responses, and coefficients per unit increase from the mean observed value and their 95% confidence intervals (CIs) were calculated for each covariate. Alpha risk set to 0.05 was considered significant (see Supplementary Material A for full GLMM model specifications) (Casals, Girabent-Farrés, & Carrasco, 2014).

Lastly, post-intervention gameplay questionnaire data were used to further assess the impact that added biofeedback had on the game experience and usability. The 5-point Likert scale data from the questionnaire were reported via descriptive statistics (median, inter-quartile range (IQR)). Demographic characteristics and volume of practice are described first for each phase to provide context.

Results

Phase 1: Design approach

Participatory design partners were nine young people with CP, 9-23 years old. Four were at MACS level II and five at level I. There were three female and six males. Participants engaged in gameplay for 30±11 minutes of a typical 60-minute session. Three participants completed three sessions, two participated in two sessions and four did one session. Feedback collected during these design sessions was compiled and changes in five key areas were identified: game flow/objectives, feedback elements,
adaptive difficulty settings, aesthetic considerations and technical issues were identified. Table 1 below details the changes made based on participant comments.

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Table 1. Design changes to integrate biofeedback into a commercial game (Dashy Square)

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Phase 2: In-home evaluation

Nineteen participants played the biofeedback-enhanced therapy game at home for four weeks. There were ten females and nine males, 8-17 years old (11.7±2.5 years). Seven participants were considered MACS level II and 12 were at level I. Seven had mixed tone, one had mild dystonia and 11 had spastic hemiplegia. During the four-week intervention, participants played an average of 17±9 minutes/day, 4±1 days/week. Total practice time ranged from 37-333 minutes across the 19 participants. Participants averaged 2815±2202 repetitions over the course of the intervention.

Efficiency. All participants adapted their movements immediately after biofeedback as evident in Figure 1. On average, participants reduced arm movement by 10.2±4.0% in response to biofeedback ($t_{18} = 7.68$, $p<0.001$, 95% CI=-11.9 - -8.5%). Participants continued to respond to the speed-change biofeedback across the intervention as practice time was not a significant predictor in the model ($p=0.330$, 95% CI -0.738 – 0.246). A participant*level interaction random effect was not observed and was therefore removed from the model ($\Delta$AIC (akaike information criterion) =0.809, $p=0.275$, see Supplementary Material A).

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Figure 1. Participant specific box plots of task performance response to feedback

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**Effectiveness.** After accounting for participant and game level variance in the GLMM, practice time was associated with: i. scoring points faster (p<0.001, 95% CI 0.963 - 1.093, increase in *dodge point rate* per 60-minutes practice), ii. doing gestures with higher quality co-contraction (p<0.001, 95% CI 22.555 - 30.042, increase in *style point rate* per 60-minutes practice), and iii. seeing fewer *practice panels* (p<0.001, 95% CI -0.047 - -0.025, fewer practice panels shown per minute of play for every 60-minutes of practice). See Supplementary Material A for full model output including random effects of participant and participant*level interactions.

Practically this means that the average participant playing a 2-minute level for the first time could expect 23 dodge points, 1598 style points and 5 practice panels. At the end of the 4-week intervention, on a similar level, the same participant could expect 32 dodge points, 1729 style points and 4 practice panels.

**Engagement.** Participants chose to view their end-of-level KR biofeedback 65.4±22.4% of the time. Based on results of the GLMM, the *choice to view* end-of-level KR biofeedback was not dependent on practice time (p=0.557, aOR = -0.061, 95% CI -0.265 – 0.261). This suggests that participants continued to engage with the end-of-level KR biofeedback throughout the 4-week intervention. There was a small variance across participants (random intercept aOR standard deviation = 0.841, 95% CI 0.552 - 1.282), but including this as a random intercept improved model performance (ΔAIC = 778.03, p<0.005) suggesting that engagement with end-of-level KR biofeedback was, to some extent, person-dependent. To this point, 16/19 participants remarked that they decided to review their achievements as they aimed to get all the rewards in each level.

Lastly, Figure 2 shows the frequency distribution from the usability and enjoyment questionnaire completed after four weeks of play. Overall, participants found the game highly usable (Median=5, IQR=3-5) and partially-to-highly enjoyable.
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Semi-structured interviews with participants and caregivers revealed participants used different personal success indicators. For instance, one participant, Dylan (pseudonym) noted that he “[didn’t] care about trophies, [and it was] more about points”. While Tina “first tried to get three trophies, to get all characters, then tried to beat top scores”. Of the 19 participants, nine were motivated primarily by long term rewards (e.g. collecting trophies), seven focused on the immediate score, and three on their game rank relative to others. Participants and caregivers also remarked on the technical performance of the system and its impact on engagement. “When the system crashed, it made her frustrated and not want to play” – Anna’s mom. Conversely when the system worked well, it provided an immersive experience: “it felt like my hand was actually speaking to the computer” – Geoffrey.

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Figure 2. Usability and enjoyment questionnaire responses.

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Discussion

Biofeedback interventions for people with CP historically have not implemented biofeedback in line with motor learning theory (MacIntosh et al., 2018). They generally provide information too frequently and offer the person little choice. This study aimed to integrate evidence-based and co-created biofeedback strategies into a home-based therapy video game. Required changes for a commercial game were identified through a participatory design framework. In-home evaluation of the new technology showed that evidence-based biofeedback could be integrated to create a highly usable system (i.e. efficient, effective and engaging). Key findings suggest that the biofeedback implementation in the therapy game was:

Median=4, IQR=3-5. Of the 19 participants, nine were motivated primarily by long term rewards (e.g. collecting trophies), seven focused on the immediate score, and three on their game rank relative to others. Participants and caregivers also remarked on the technical performance of the system and its impact on engagement. “When the system crashed, it made her frustrated and not want to play” – Anna’s mom. Conversely when the system worked well, it provided an immersive experience: “it felt like my hand was actually speaking to the computer” – Geoffrey.
(1) efficient – participants responded immediately to in-level KP biofeedback
isolating hand movements while practicing at home,

(2) effective – participants used KP biofeedback to improve their movement timing,
quality and mastery of the game,

(3) engaging – participants often chose to review their end-of-level KR biofeedback
(e.g. trophies awarded) demonstrating autonomy and active engagement with the
system.

Qualitative reports supported the above conclusions. Overall, participants
perceived the game as usable and enjoyable after playing for one month.

Recommendations for the effective design of biofeedback in therapy gaming
technologies

Learning from our co-design and evaluation process, we present the following key
recommendations to consider when delivering biofeedback in therapy games:

Link game rewards to movement goals

There can be multiple short-, mid-, and long-term rewards that provide KP and KR
biofeedback in video games. The value that a player places on these different rewards
can vary greatly and different people may be motivated by different aspects of the
game. To be effective, it is crucial that each game reward is directly impacted by and
linked to the targeted therapeutic aim. Involving the end-user in the development and
testing phase to ‘stress’ the system is a valuable approach to uncover ways that
individuals may achieve game rewards while circumventing the therapy goal. For
example, in this project, initial design sessions revealed that participants could achieve
game rewards by pronating and flexing instead of extending at the wrist. Working
through this led to changes in the controller, which helped ensure participants were
required to do the intended therapeutic movement to collect rewards and succeed in the
game. Linking game goals to movement goals ensures that biofeedback is in fact
accurate, informative, and reinforces practice of therapeutic movement strategies.

Provide a safe space

Video games are immersive environments where it is easy to get carried away in the
excitement. In therapy games, this can lead to poor quality movement execution. In
design sessions, we found that increases in game difficulty could result in participants
trying a flurry of low-quality gestures, straying away from the therapeutic aim. In
response, we introduced a practice panel which was intended to be a safe space in the
game to practice the high-quality therapeutic movements that would help them succeed.
Stopping the game, minimizing sounds and graphics, and eliminating the potential for
any negative in-game consequences, gave participants the opportunity to focus on
movement quality and adjust to the increasing difficulty of the game. Tutorials are
ubiquitous in video games. They usually help people learn contextual controls when
starting games (e.g. Press ‘A’ to jump over the wall). A therapy game can leverage the
established logic of traditional game tutorials by incorporating prescriptive feedback
towards the therapy aim. Instead of presenting tutorials mainly in the beginning of a
new situation, presentation can be dictated by how ‘well’ (e.g. how frequently or how
accurately) participants do the therapeutic movement. Continued opportunities for
prescriptive feedback in a safe space, when it is needed, can enable participants to build
competency in the game and in the therapeutic movements. However, it is important to
ensure these practice elements do not detract from immersion and game flow. If they
occur too frequently or take too long to complete, it may indicate an inappropriate
challenge for the participant. During design sessions we modified the frequency and
timing of the practice panel to find a balance that was perceived to be optimal by our
users.

**Minimize presence to maximize impact**

In traditional biofeedback interventions, when information is constantly given, the person can develop a dependency (Taylor, Dodd, McBurney, Graham, & Kerr Graham, 2004). Literature suggests that certain techniques can improve performance and retention, including: varying the modality (e.g. visual, audio), providing a ‘fading’ biofeedback schedule as a person improves, and only offering biofeedback when players are in a ‘target zone’ (Muratori, Lamberg, Quinn, & Duff, 2013; Timmermans et al., 2009). These techniques were employed in this therapy game intervention. Participants track their immediate score with a counter and a progress bar accompanied by audio cues with each successful movement. This feedback was supplemented with a ‘bonus’ score that appeared when players were in a ‘target zone’ (achieving high quality co-contraction for extended periods). Then, as the participant’s achieved mastery of the game, the progress bars were removed, the ‘bonus’ was shown less frequently, and participants were able to choose whether to review their scores and rewards at the end of a level or skip directly to the next level. This type of autonomy can build investment in an activity (Bingham & Calhoun, 2015).

We have further summarized our learnings in an infographic ([link removed for blinding], and in Supplementary Material B). This infographic may serve multi-disciplinary teams building technologies to help people practice motor activities. It may be particularly useful to support engagement with mainstream game developers. Researchers should consider adapting professional games, especially when artistic and developer resources are limited. In this project, the company we partnered with was small (2-5 members) which allowed greater flexibility to make changes in the game. While adapting an existing game with demonstrated popularity has many advantages...
with respect to the quality of gameplay achieved, considerable time was invested educating and working with the company to appropriately integrate biofeedback elements. It is our hope that the infographic will facilitate these collaborations and accelerate development of higher quality biofeedback therapy games.

**Limitations**

This study does not discuss the transfer of experiences in-game to daily activities. Rather, it reports the direct biofeedback implications observed when performing motor activities to control a video game. The customized feedback questionnaire was not a validated measure but merely addressed key domains of usability and enjoyment. Further, participants used self-directed practice schedules to maximize ownership and motivation at home. Certain participants played infrequently some weeks (e.g. due to school assignments or competing interests). Finally, changes in biofeedback thresholds and game difficulty were manually adjusted in some cases by the researcher based on their evaluation of the participant’s competency and motivation. Future work should further standardize how feedback is modulated as player competency increases at home.
References

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https://doi.org/10.1371/journal.pone.0112653


Appendix A. Open questions used to facilitate conversations during the semi-structured interview after 4-week in-home evaluation

a. Usability
   i. Ease of play
      1. What helped to make the game easier to play?
      2. What helped to make the game harder to play?
      3. Did you feel like you were in control of the game?
      4. Did anything hold you back from playing the way you wanted?
   ii. Strategy
      1. Was there anything that you used when playing the game to help you succeed?
      2. How did the score change how you played the game?
      3. Did the characters change how you played the game?
      4. What was your strategy to avoid the obstacles?
      5. Name the game you have played that is most similar to this game.
   iii. Focus
      1. What was the most important part of the game for you?
      2. If you could change any aspect of the game or your experience, what would it be? Unlimited budget and time.

b. Fun
   1. What parts of the game did you find most fun?
   2. What was your favorite moment or interaction?
   3. What was your least favorite moment or interaction?
   4. Which game mode do you like the best? (Jump, Dash, Fly), Why?
Table 1. Design changes to integrate evidence-based biofeedback into a commercial game (Dashy Square)

<table>
<thead>
<tr>
<th>I. Game flow/ objectives</th>
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<tbody>
<tr>
<td>a. Added calibration game to get session baseline for movements and biofeedback</td>
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<tr>
<td>b. Changed from pass/fail to score-based objectives</td>
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<tr>
<td>c. Linked reward schedule (unlocking trophies and characters) to movement performance</td>
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<tr>
<td>i. Completing movement at correct time (dodging obstacles) and with high movement quality*</td>
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<tr>
<th>II. Feedback Elements</th>
<th>Feedback modulation schedule†</th>
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<tr>
<td>1. In-level</td>
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<tr>
<td>a. Visual and sound effects indicating successful movement</td>
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<tr>
<td>i. successful dodge</td>
<td></td>
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<tr>
<td>ii. movement quality score achieved</td>
<td></td>
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<tr>
<td>b. Increment</td>
<td></td>
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<tr>
<td>i. Dodge score counter and progress bar</td>
<td></td>
</tr>
<tr>
<td>ii. Movement quality score counter and progress bar</td>
<td></td>
</tr>
<tr>
<td>c. Visual effect on unsuccessful movement</td>
<td></td>
</tr>
<tr>
<td>d. Reduce game speed on unsuccessful event with excess arm movement (poor hand movement isolation)</td>
<td></td>
</tr>
<tr>
<td>e. Added movement-based animation ques to improve player timing</td>
<td>i. Movement quality score counter and progress bar are shown when performance status is ‘great’</td>
</tr>
<tr>
<td></td>
<td>ii. Dodge score progress bar is hidden after person develops competency</td>
</tr>
<tr>
<td>2. Practice panel</td>
<td></td>
</tr>
<tr>
<td>a. Pause game and show practice environment</td>
<td>i. Appears when performance status is ‘poor’ at in-level checkpoint or at end of level</td>
</tr>
<tr>
<td>i. Remove excess animations/sound and simplify background</td>
<td></td>
</tr>
<tr>
<td>ii. Show prescriptive animation and written que of how to improve movement</td>
<td></td>
</tr>
<tr>
<td>b. Person completes two successful movements as practice</td>
<td>ii. Appears when person reaches threshold number of consecutive unsuccessful movements (3-10)</td>
</tr>
</tbody>
</table>
c. Bonus movement quality score awarded with visual and sound effect

3. *End-level*

| a. Show icon to view or skip end-level feedback | i. Person has option to view or skip feedback when performance status is ‘good’ |
| b. Show dodge score counter and progress bar | ii. Movement quality score counter and progress bar are shown when performance status is ‘great’ |
| c. Show movement quality score counter and progress bar | iii. Person always views feedback after developing competency |
| d. Run animations and sound effects for unlocked rewards (trophies and characters) |

†Modulating feedback according to performance and competency

a. Performance thresholds
   i. Determine when feedback elements are shown or hidden.
   ii. Based on percent of successful movements in-level.
   iii. Performance status:
      1. *Poor* - < 25% successful movements
      2. *Good* - 25% - 65% successful movements
      3. *Great* - >65% successful movements

b. Competency
   i. After the person shows competency in the movement and game, certain feedback elements are hidden
   ii. Researcher determined competency at weekly evaluations
   iii. Usually after the person completes most levels on the easiest mode

III. Adaptive difficulty settings

a. Added adjustable game speed
b. Added adjustable performance status thresholds
c. Added settings for binary switch or multiple gesture control
d. Edited obstacles size and spacing to let players control with gestures
IV. Aesthetics

a. Simplified backgrounds, options and level difficulty  
b. Fixed camera window orientation  
c. Reduced animation and sound after unsuccessful movements

V. Technical

a. Changed tap controller input to Myo Armband  
b. Added functionality to  
   i. Accept binary inputs based on movement thresholds  
   ii. Accept multiple inputs based on gestures  
   iii. Accept movement quality scores  
   iv. Store and synchronize game scores and rewards with movement data

Requirements were identified during participatory design sessions by young people with CP, occupational therapists, and researchers. These changes aimed to improve biofeedback comprehension and link biofeedback to game goals.

*Movement quality is based on physiological factors: forearm extensor/flexor co-contraction, resultant forearm angular velocity variability and predicted gesture
Figure 1. Participant specific box plots of change in task performance in response to biofeedback. Data left of the red vertical line indicates decreased arm movement (variance in resultant angular velocity) immediately after being given biofeedback. Left axis = participant ID. Bottom axis = percentage change in arm movement.
Figure 2. Usability and enjoyment questionnaire responses. Number of responses shown for each level of the 5-point Likert scale on all nine questions (N=19).

290x190mm (300 x 300 DPI)
Supplemental A: Generalized Linear Mixed-Effects Models Details

Analyses were performed with MATLAB 2017b, Fit generalized linear mixed-effects model package (fitglme).

- Tables 1 and 2 below show model estimates and fit with model properties detailed below.
- Fixed effects: minutes of practice (exp),
- Random effects: participant (id), game level (level).
- Response variables:
  - Measure 1: choice - The proportion of opportunities participants took to view their achievements.
  - Measure 2: ChgArmMvmt – The percent change in arm movement before and after showing biofeedback
  - Measure 3:
    - i. scrDodge – number of dodge points accumulated / minute of play
    - ii. scrStyle - number of style points accumulated / minute of play
    - iii. panelsperminute - number of practice panels shown / minute of play

<table>
<thead>
<tr>
<th>Table 1: Model Estimates</th>
<th>Estimate (95%CI)</th>
<th>SE</th>
<th>t</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measure 1: The proportion of opportunities participants took to view their achievements.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 1- response variable: choice (683 observations)</td>
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<tr>
<td>Fixed (2)</td>
<td>Intercept</td>
<td>0.83 (0.36-1.31)</td>
<td>0.242</td>
<td>3.447</td>
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<tr>
<td></td>
<td>practice time (60 min)</td>
<td>-0.06 (-0.26-0.14)</td>
<td>0.102</td>
<td>-0.588</td>
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<tr>
<td>Random covariance (std, 19)</td>
<td>Id</td>
<td>0.84 (0.55-1.28)</td>
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<tr>
<td>Measure 2: The change in arm movement before and after showing biofeedback</td>
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<tr>
<td>Model 2- response variable: ChgArmMvmt (515 observations)</td>
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<tr>
<td>Fixed (2)</td>
<td>Intercept</td>
<td>-10.18 (-12.32--8.05)</td>
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<td>-9.378</td>
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<td>practice time (60 min)</td>
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<td>0.251</td>
<td>-0.976</td>
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<tr>
<td>Random covariance (std, 153)</td>
<td>id</td>
<td>4.42 (3.09-6.31)</td>
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<tr>
<td></td>
<td>level*id</td>
<td>1.13 (0.41-3.11)</td>
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</tbody>
</table>
* Measure 3: Game performance

Model 3a - response variable: scrDodge (1959 observations)

<p>| | | | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Fixed (2)</td>
<td>intercept</td>
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<td>practice time (60 min)</td>
<td>1.03 (0.96-1.09)</td>
<td>0.033</td>
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<tr>
<td>Random covariance (std, 197)</td>
<td>Id</td>
<td>2.51 (1.8-3.49)</td>
<td>0.6 (0.51-0.71)</td>
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<td>level*id</td>
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</table>

Model 3b - response variable: scrStyle (1959 observations)

<p>| | | | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Fixed (2)</td>
<td>intercept</td>
<td>783.82 (724.5-843.14)</td>
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<td>practice time (60 min)</td>
<td>26.3 (22.56-30.04)</td>
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<tr>
<td>Random covariance (std, 197)</td>
<td>Id</td>
<td>130.36 (93.56-181.65)</td>
<td>39.39 (33.57-46.22)</td>
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<td>level*id</td>
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</tbody>
</table>

Model 3c - response variable: panelsperminute (1959 observations)

<p>| | | | |</p>
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<thead>
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</thead>
<tbody>
<tr>
<td>Fixed (2)</td>
<td>intercept</td>
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<td>practice time (60 min)</td>
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<tr>
<td>Random covariance (std, 197)</td>
<td>id</td>
<td>0.34 (0.24-0.47)</td>
<td>0.11 (0.09-0.13)</td>
</tr>
<tr>
<td></td>
<td>level*id</td>
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<td></td>
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</tbody>
</table>

Table 2: Final model fit characteristics

<table>
<thead>
<tr>
<th></th>
<th>AIC</th>
<th>BIC</th>
<th>LogLikelihood</th>
<th>Deviance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>778.03 ^2</td>
<td>791.61</td>
<td>-386.01</td>
<td>772.03</td>
</tr>
<tr>
<td>Model 2</td>
<td>3276.8 ^2</td>
<td>3298</td>
<td>-1633.4</td>
<td>3266.8</td>
</tr>
<tr>
<td>Model 3a</td>
<td>6895.1 ^2</td>
<td>6923</td>
<td>-3442.5</td>
<td>6885.1</td>
</tr>
<tr>
<td>Model 3b</td>
<td>22780 ^2</td>
<td>22807</td>
<td>-11385</td>
<td>22770</td>
</tr>
<tr>
<td>Model 3c</td>
<td>21.54 ^2</td>
<td>49.436</td>
<td>-5.77</td>
<td>11.54</td>
</tr>
</tbody>
</table>

AIC = Akaike Information Criterion, BIC = Bayesian Information Criterion
Model 1 properties: Binomial distribution, logit link function and Laplace fit method. Model formula: choice ~ 1 + exp + (1 | id).
Model dispersion = 1.
Theoretical Likelihood Ratio Test showed non-significant addition of random id*level interaction effect (df = 4, ΔAIC = 1.31, p = 0.406).

Model 2 properties: Normal distribution, identity link function and REMPL fit method. Model formula: ChgArmMvmt ~ 1 + exp + (1 | id) + (1 | level:id). Model dispersion = 5.36, 95% CI = 5.00-5.74.
Theoretical Likelihood Ratio Test showed significant addition of random id*level interaction effect (df = 5, ΔAIC = 0.809, p = 0.275).

Model 3a-c properties: Normal distribution, identity link function and REMPL fit method. Model formula: [scrDodge or stylerDodge or panelsperminute] ~ 1 + exp + (1 | id) + (1 | level:id). Model dispersion = a) 1.309, 95% CI = 1.267-1.352, b) 75.354, 95% CI = 72.941-77.847, c) 0.226, 95% CI = 0.219-0.234.
Theoretical Likelihood Ratio Test showed significant addition of random id*level interaction effect for models 3a-3c (3a. df = 5, ΔAIC = -269.7, p = <0.001, 3b. df = 5, ΔAIC = -309.5, p = <0.001, 3c. df = 5, ΔAIC = -200.3, p = <0.001).
Making a rehab video game takes input from clinicians, developers and players. Here are helpful tips for teams looking to add biofeedback into their video games.

**What is biofeedback?**

Biofeedback gives people information about their body. People use biofeedback to learn how to control their body better. Biofeedback can help in learning new skills.

**Biofeedback in games**

Games can deliver biofeedback to promote learning:

- Player does a rehab activity
- Feedback informs the player’s rehab
- Feedback based on activity is generated
- Sensor records activity
- Activity controls game
- Feedback based on activity is generated

Well integrated biofeedback closely links game feedback with the rehab activity.

**Biofeedback design characteristics**

**Feedback can be about:**

- movement (speed, accuracy, distance)
- performance (good or poor)
- health data (heart rate, muscle activity)

**Feedback can be delivered in different ways:**

- audio
- visual
- tactile

**Feedback can be given at different times:**

- during or after a game
- when the player performs well or poorly
- with decreasing frequency as the player improves
Feedback should match the player’s needs:

**Overview**

**Player goal**
- Practice: Goal: increase repetitions
  - feedback
  - error tolerance
- Mastery: Goal: improve technique
  - feedback
  - error tolerance

**Skill difficulty**
- Simple skills: Give instructional feedback
- Complex skills: Give success/failure feedback

**Player skill level**
- Novice: detail in feedback, instructions
- Expert: detail in feedback, instructions

**Tutorial Tips**

**Feedback should match the player’s needs:**

**Player needs can be determined by a clinician, themselves or a computer**

**Simple skills** are usually a single step
**Example:** wave hand up

**Complex skills** are usually many steps
**Example:** shooting a basketball

**Novices benefit from being shown how to do a movement**
**Example:** instructions

**Experts should explore and find what works best for them**
**Example:** thumbs up

Here are 3 approaches to feedback that are hardly used even though they can be effective.

**Build in choice**
Giving players choice can help motivate them to learn new skills. They might choose to:
- get feedback
- ignore feedback
- customize feedback

**Less is more**
As players get more skilled, they should rely on themselves more than on the feedback. Only give feedback when they need it:
- once a skill is learned, no longer provide instructions
- only provide feedback when the player succeeds/fails

**Mix it up**
Changing how feedback looks helps the player become more independent. Variations can be:
- giving feedback at the end of the level instead of during the level
- going from more detailed feedback (e.g. instruction) to less detailed (e.g. a sound)