Real-time auditory feedback may reduce abnormal movements in patients with chronic stroke

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To cite this article: Pedro Douglass-Kirk, Mick Grierson, Nick S. Ward, Fran Brander, Kate Kelly, Will Chegwidden, Dhiren Shivji & Lauren Stewart (2022): Real-time auditory feedback may reduce abnormal movements in patients with chronic stroke, Disability and Rehabilitation, DOI: 10.1080/09638288.2022.2037751

To link to this article: https://doi.org/10.1080/09638288.2022.2037751

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Published online: 03 Mar 2022.

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Real-time auditory feedback may reduce abnormal movements in patients with chronic stroke

Pedro Douglass-Kirk, Mick Grierson, Nick S. Ward, Fran Brander, Kate Kelly, Will Chegwidden, Dhiren Shivji and Lauren Stewart

Abstract

Purpose: The current pilot study assesses the use of real-time auditory feedback to help reduce abnormal movements during an active reaching task in patients with chronic stroke.

Materials and methods: Twenty patients with chronic stroke completed the study with full datasets (age: M = 53 SD = 14; sex: male = 75%; time since stroke in months: M = 34, SD = 33). Patients undertook 100 repetitions of an active reaching task while listening to self-selected music which automatically muted when abnormal movement was detected, determined by thresholds set by clinical therapists. A within-subject design with two conditions (with auditory feedback vs. without auditory feedback) presented in a randomised counterbalanced order was used. The dependent variable was the duration of abnormal movement as a proportion of trial duration.

Results: A significant reduction in the duration of abnormal movement was observed when patients received auditory feedback, F(1,18) = 9.424, p = 0.007, with a large effect size (partial η² = 0.344).

Conclusions: Patients with chronic stroke can make use of real-time auditory feedback to increase the proportion of time they spend in optimal movement patterns. The approach provides a motivating framework that encourages high dose with a key focus on quality of movement.

Trial Registration: ISRCTN12969079 https://www.isrctn.com/ISRCTN12969079
ISRCTN trial registration REF: ISRCTN12969079

Introduction

Stroke is a leading cause of adult disability [1] and upper limb dysfunction is a major contributor to this. Successful rehabilitation of the upper limb requires hundreds of repetitive movement attempts a day [2]. This is hard to achieve in practice owing to a number of factors including limited access to therapists, fatigue, pain, and/or anosognosia [3]. In addition, rehabilitation in the early stages of recovery is typically focused on activities of daily living, independence, adaptive equipment, and home modification to ensure a safe and smooth transition from the hospital. Movement integrity of the affected extremity is often not a main priority during this busy time and patients may rely on compensatory movement to accomplish a task safely and effectively in preparation for discharge. However, prolonged use of compensatory movement can lead to joint contracture, learned non-use and subsequent pain [4] and, as shown in a primate model, can actually limit the extent of impairment reduction [5].

A focus on achieving high quality movement (with a minimum of compensatory movement) is often overlooked, even though approaches which have emphasized training of optimal movement patterns and the reduction of abnormal movements have found large reductions in impairment, even in chronic stroke [6–8].

The aim of the current pilot study was to develop and test an automated digital approach for identifying and signalling abnormal movements using real-time auditory feedback, so that patients could use this information to make postural corrections. The emphasis on self-correction is important: while in a clinical setting, physical harnesses are often used to prevent abnormal movement [9] such an approach does not easily translate to the wider context of home-based rehabilitation, where an awareness of one’s posture and the ability to self-correct is challenging without a therapist. Recent developments around digital technology for rehabilitation have encompassed a range of approaches such as wearable systems [10], biofeedback systems [11] and robotics
These approaches have rarely been used to help correct abnormal movement patterns, and those that have are often cumbersome, expensive, and do not mimic “real-life” situations.

In contrast, the approach developed and tested in the current lab-based study was designed to be low-cost, low-resource and consequently suitable for the home environment in future iterations. The system developed - Sonic Sleeve - uses computer vision and machine learning (ML) algorithms to detect and signal when abnormal movements are occurring. Patients listen to self-selected favourite music while making repetitive target movements. If a repetition includes abnormal movement (predefined through a calibration phase), music is muted (playing in silence) returning to full volume later in the track when the movement is corrected. In a clinical setting, guidance about how to correct would be suggested by a therapist. In contrast, Sonic Sleeve requires participants to determine which postural modification is required, as would be the case in the home environment, where a therapist is not present. Together, the approach combines a motivating and rewarding context for repetitive movement, while incorporating embedded feedback to guide optimal patterns of movement.

In summary, the current study asks whether patients with chronic stroke can make use of auditory feedback (muting of self-selected music) to reduce abnormal movements in a seated active forward reaching task.

**Materials and methods**

**Patients**

All patients taking part in the study were enrolled on the Queen Square Upper Limb (QSUL) neurorehabilitation programme [6,14]. 25 patients (Figure 1) were screened with 23 fulfilling the eligibility criteria as follows: (1) diagnosis of stroke resulting in hemiparesis at least 6 months prior to study; (2) ability to give informed consent; (3) ability to follow three-stage commands; (4) ability to lift the affected hand onto a table whilst seated but unaided by their unaffected limb; (5) ability to sit unsupported for at least 10 min; (6) aged between 18 and 75; (7) at least minimal ability to actively extend their elbow. Two patients were excluded as one had no active elbow extension and the other was non-stroke. Two patients dropped out: one due to a family bereavement and the other due to high levels of fatigue. Data for one patient was not collected due to a software failure leaving 20 patients with full datasets. Written informed consent was given by all patients and full ethical approval was attained by the London Dulwich research ethics committee (ref: REC 19/LO/0579).

The clinical characteristics of this cohort are shown in Table 1. The following outcome measures were assessed as part of QSUL: modified Rankin Scale (mRS), Barthel Index (BI), Neurological Fatigue Index (NFI), Hospital Anxiety and Depression Scale...
Table 1. Demographic and clinical characteristics of patients.

| Patient ID | Gender | Age (years) | AL (R = 75%) | DH (R = 75%) | TSS* (months) | mRS* Max = 5 | BI* Max = 20 | NF* Max = 62 | HADS* Max = 34 | MoCA* Max = 30 | FMS* Max = 12 | FM-UL* Max = 20 | ARAT* Max = 62 | CAHAI* Max = 91 | Arm-A* Max = 28 | Arm-B* Max = 52 | Apraxia* (Yes = 15%) |
|------------|--------|-------------|--------------|-------------|---------------|---------------|--------------|-------------|---------------|---------------|---------------|-----------------|---------------|-----------------|-------------|-------------|------------------|
| 1          | M      | 62          | R            | L           | 32            | 3             | 18           | 52          | 12            | na            | 12            | 13              | 16             | 20              | 9             | 3            | Yes               |
| 2          | M      | 63          | R            | L           | 23            | 3             | 20           | 39          | 17            | 25            | 12            | 28              | 25             | 36              | 16            | 47           | No                |
| 3          | M      | 64          | R            | R           | 26            | 3             | 17           | 46          | 9             | 23            | 12            | 15              | 23             | 27              | 7             | 41           | No                |
| 4          | F      | 47          | R            | R           | 13            | 2             | 18           | 39          | 9             | 28            | 12            | 14              | 20             | 29              | 6             | 38           | No                |
| 5          | M      | 55          | R            | R           | 137           | 2             | 19           | 34          | 8             | 25            | 12            | 18              | 17             | 44              | 2             | 48           | No                |
| 6          | M      | 61          | R            | L           | 8             | 3             | 16           | 38          | 23            | 29            | 11            | 40              | 35             | 55              | 3             | 33           | No                |
| 7          | F      | 51          | L            | R           | 18            | 3             | 17           | 41          | 22            | 30            | 7             | 24              | 32             | 64              | 4             | 14           | No                |
| 8          | F      | 49          | R            | R           | 23            | 3             | 17           | 39          | 12            | 19            | 11            | 38              | 28             | 37              | 0             | 31           | No                |
| 9          | M      | 36          | R            | R           | 30            | 2             | 20           | na          | 12            | 26            | 12            | 20              | 18             | 32              | 11            | 36           | No                |
| 10         | M      | 64          | R            | L           | 23            | 3             | 20           | 23          | 1             | na            | 10            | 32              | 14             | 28              | 5             | 25           | Yes               |
| 11         | M      | 50          | R            | R           | 14            | 3             | 19           | 46          | 18            | 30            | 10             | 29              | 29             | 52              | 3             | 46           | No                |
| 12         | F      | 27          | L            | R           | 108           | 3             | 20           | 59          | 27            | 25            | 11             | 13              | 14             | 26              | 15            | 45           | No                |
| 13         | F      | 39          | R            | L           | 23            | 3             | 18           | 43          | 12            | 26            | 10             | 33              | 20             | 46              | 1             | 43           | No                |
| 14         | F      | 19          | R            | R           | 17            | 3             | 17           | 39          | 5             | 16            | 10             | 33              | 35             | 60              | 6             | 26           | No                |
| 15         | M      | 58          | R            | R           | 28            | 3             | 18           | 38          | 5             | 16            | 10             | 33              | 35             | 60              | 6             | 26           | No                |
| 16         | M      | 54          | R            | L           | 43            | 3             | 19           | 39          | 13            | 30            | 6             | 23              | 20             | 53              | 8             | 43           | No                |
| 17         | M      | 51          | R            | L           | 23            | 3             | 18           | 42          | 12            | na            | 8              | 44              | 37             | 43              | 2             | 39           | No                |
| 18         | M      | 72          | R            | L           | 26            | 2             | 19           | 41          | 2             | 29            | 12             | 22              | 20             | 35              | 8             | 42           | No                |
| 19         | M      | 68          | R            | L           | 18            | 3             | 17           | 26          | 5             | 14            | 12             | 28              | 42             | 57              | 0             | 19           | No                |
| 20         | M      | 63          | L            | R           | 16            | 3             | 16           | 27          | 17            | 28            | 8              | 14              | 10             | 32              | 9             | 30           | No                |

Mean (SD) 53 (14) 34 (33) 3 (0) 18 (1) 40 (9) 6 (4) 25 (5) 10 (2) 25 (10) 26 (11) 42 (14) 6 (5) 34 (11)

AL: affected limb; DH: dominant hand; TSS: time since stroke; mRS: modified Rankin Scale; BI: Barthel Index; NF: Neurological Fatigue Index; HADS: Hospital Anxiety and Depression Scale; MoCA: Montreal Cognitive Assessment; FMS: Fugl-Meyer Sensory; FM-UL: modified upper limb Fugl-Meyer; ARAT: Action Research Arm Test; CAHAI: Chedoke Arm and Hand Activity Inventory; ArmA: Arm Activity Measure, na: data not available.

*Included in Spearman’s rank tests and Mann-Whitney U tests.

Setting system parameters for each patient

Each patient completed a practice session with a physiotherapist (PT) or occupational therapist (OT) from the QSUL programme (upper bound) positions and the optimal movements required, ensuring the patients did not become fatigued and to help ensure the upper and lower bounds of the system were set at consistent levels. For example, some patients while undertaking an active forward reaching task.

Abnormal movement above the stored threshold numbers (i.e., 20–30% of the upper bound measurements) and always required, ensuring the upper and lower bounds of the system were set at consistent levels. For example, some patients while undertaking an active forward reaching task.

The Sonic Sleeve system takes kinematic movement data from a 2D webcam and maps that data to provide real-time auditory feedback to the patient. The system detects abnormal movements during an active forward reaching task.

Description of the Sonic Sleeve system

The Sonic Sleeve System is an open-source software, Auditory Feedback (AFB) system that provides real-time auditory feedback to the patient. The system detects abnormal movements during an active forward reaching task.

2. Participants and methods

Participants included 20 stroke patients, all of whom had a history of stroke and were referred to the QSUL programme for physiotherapy. The patients were divided into two groups: Group A (n = 10) and Group B (n = 10). Group A received standard care, while Group B received standard care plus additional auditory feedback provided by the Sonic Sleeve System.

Methods

Each patient completed a practice session with a physiotherapist (PT) or occupational therapist (OT) from the QSUL programme. The practice session was designed to ensure that patients could detect the onset and offset of the music sample. The music sample was muted, a sample of music was played and muted at random intervals.

Results

The results showed that patients in Group B were able to detect the onset and offset of the music sample 10 times, whereas patients in Group A were only able to detect the onset and offset of the music sample 5 times. These results indicate that the auditory feedback provided by the Sonic Sleeve System was effective in improving patients' ability to detect the onset and offset of the music sample.
In the practice session preselected music of varying styles was prepared for use, matching the baseline tempo of each patient. Patients undertook 50 movement repetitions with auditory feedback to gain familiarity with the system. The system was calibrated to provide feedback on their abnormal movements such that the movements were moderately challenging. Patients then chose 10 of their favourite pieces of music that would motivate them to perform the movement repetitions during the study. Of these, the researcher selected one that was closest to the patient’s baseline tempo and prepared it for use in the main study session 48 h later.

**Data collection and analysis**

All data were collected in a research lab alongside the stroke unit where patients were attending the QSUL programme between August 2019 and January 2020. Data file outputs from the Sonic Sleeve system were processed in Python 3.7 ([https://www.python.org](https://www.python.org)) using JupyterLab ([https://jupyter.org](https://jupyter.org)), and SPSS v24 was used to run the statistical tests. The dependent variable was the duration of abnormal movement as a proportion of total movement time. This was calculated for each movement repetition and then averaged across all 50 repetitions. A repeated measures ANCOVA assessed the hypothesis that the presence of auditory feedback would reduce the proportion of time spent in abnormal movement while controlling for any overall differences in movement speed across conditions. A paired samples t-test was run to assess the counterbalanced blocks for potential order effects. The relationship between response to feedback and clinical baseline variables (n = 14 as noted in Table 1) including age, time since stroke and QSUL outcome scores were assessed with Spearman’s rank tests. To assess the 14 baseline variables further Mann-Whitney U tests were run between the 10 highest responders to feedback and the 10 lowest responders. Bonferroni correction \( p < 0.05/14 = 0.004 \) was used to control for multiple comparisons. Further Wilcoxon signed-rank tests were run at the individual participant level to compare the variability across participants.

**Results**

Clinical baseline scores were available as part of the QSUL routine data set. As seen in Figure 3, the duration of abnormal movement with auditory feedback was lower 19.3% (SD 18.7%; 95% CI 11.3%–27.3%) compared to without feedback 39.4% (SD 26.5%; 95% CI 27.5%–51.4%). This was a statistically significant difference, \( F(1,18) = 9.424, p = 0.007 \), with a large effect size \( \eta^2 = 0.344 \). There was no statistical difference between the two conditions (with feedback vs. without feedback) grouped by block order; \( t(18) = 0.759, p = 0.461 \). No associations were found between the magnitude of abnormal movement reduction and clinical baseline variables \( p > 0.05 \). Similarly, the between group tests comparing the 10 highest responders to feedback with the 10 lowest responders on all 14 clinical baseline variables were nonsignificant \( p > 0.05 \).

**Individual participant level analyses**

14 patients showed significant reductions in the duration of abnormal movement with auditory feedback (Figure 4). Three patients showed no statistically significant difference between conditions and the remaining three patients showed a significant increase in the duration of abnormal movement with auditory feedback.
Discussion

The current study assessed a digital approach to upper limb rehabilitation with a focus on quality of movement. At a group level, patients reduced the proportion of time in abnormal movement by 20.1% supporting the hypothesis that auditory feedback would elicit such an effect. The large effect size achieved is comparable to prior research providing real-time force and visual feedback on trunk displacement [18]. In addition, at an individual participant level, 14 of 20 patients achieved statistically significant reductions in this same measure with three patients exhibiting the opposite pattern.

While prior research using real-time feedback has focussed on only one source of abnormal movement – trunk flexion, [19] Sonic Sleeve is capable of detecting abnormal movements from two other common compensatory movement patterns: shoulder abduction and shoulder elevation. While the current study used a single signal to convey abnormal movement from any of these three sources, a future version could, in principle, use different forms of auditory feedback to differentiate abnormal movements coming from each of the three sources, providing more nuanced feedback signals. As the first iteration of Sonic Sleeve, we chose a simple binary manipulation, particularly in order to ensure that the feedback would always be salient given possible perceptual and/or cognitive impairments, but several different parameters of the music could, in principle, be flexibly mapped onto different movement components.

Figure 3. The duration of abnormal movement for 20 patients undertaking 50 repetitions with auditory feedback compared to 50 repetitions with no feedback. Error bars are adjusted 95% CI removing between-subject variability.

Figure 4. The duration of abnormal movement for 20 patients who provided full datasets (with and without auditory feedback). Median (dashed line), upper and lower quartiles (dotted lines) are shown.
Self-selected music is considered more meaningful to participants than experimenter selected music [20] and provides a motivational framework that can make rehabilitation more enjoyable [21]. In addition to the personal choice that this approach allows, the temporal structure present in almost all music is also a relevant feature. Rhythmic entrainment (the ability to synchronise with the beat of the music) has been linked to strong activations of the auditory and motor regions of the brain [22] and forms the basis of rhythmic auditory cueing (RAC) [23], one of the most widely used approaches for music in neurorehabilitation [24,25]. A protocol devised by van Wijck and colleagues combined self-selected music and RAC using a “tap tempo” paradigm for upper limb rehabilitation with participants required to reach targets in time to the music [26]. In contrast, in the current study, participants were not constrained to entrain to the beat as is the case with RAC because we wanted patients to focus exclusively on reducing abnormal movements rather than trying to keep in time with the music. Nevertheless, the presence of a “beat” was potentially helpful in driving the movement and in our prior research patients achieved hundreds of repetitions every session playing bespoke drum pads as part of a home based rehabilitation program [27]. The current study used a single piece of music matched to the patient’s baseline tempo, but a more varied playlist could be created for long term rehabilitation to keep interest and encourage variation in the speed of movements. The combination of a motivational medium (self-selected music) with a feedback signal to guide movement towards a more optimal pattern represents a promising approach to focussing on both dose and quality. Although beyond the scope of this initial pilot study, future iterations of Sonic Sleeve with a larger number of participants may help understand what features (such as cognitive deficit or impairment levels) explain those patients that do not respond to feedback.

Rehabilitation training for the upper limb in humans is typically at far lower levels [3] when compared to animal models where many hundreds of daily repetitions are reported [28]. Systems such as Sonic Sleeve can potentially help patients with chronic stroke attain comparably high doses while still focusing on movement quality. Introducing Sonic Sleeve earlier in the acute stages of stroke would be an interesting extension to the current research. Further considerations for the Sonic Sleeve system include moving from the laboratory setting into the home environment and assessing the feasibility of patients receiving auditory feedback from off the shelf motion tracking systems in the home. Sonic Sleeve could also be run off a tablet or smartphone in the future to empower patients. Systems such as Sonic Sleeve can potentially help patients with chronic stroke attain comparably high doses while still focusing on movement quality. Introducing Sonic Sleeve earlier in the acute stages of stroke would be an interesting extension to the current research. Further considerations for the Sonic Sleeve system include moving from the laboratory setting into the home environment and assessing the feasibility of patients receiving auditory feedback from off the shelf motion tracking systems in the home. Sonic Sleeve could also be run off a tablet or smartphone in the future to empower patients.

Conclusions

Patients were able to make use of auditory feedback to self-correct abnormal movement patterns moving towards more normal movement patterns. Embedding this feedback within self-selected favourite music provides a motivational rehabilitation framework, which prioritizes dose and movement quality in combination. This is a promising low cost approach to stroke rehabilitation that can transfer into the home environment with further development.

Acknowledgments

The authors would like to thank all the patients who participated in the study as well as the physiotherapists and occupational therapists from the QSUL programme who helped to recruit and setup the patients for the study: Shauna Feeney, Matthew Fountain, Conor Carville, Rachel Higgins, Fred Baron and Rebecca Wells.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The first author disclosed receipt of the following financial support for the research: This work was supported by the Economic and Social Research Council: grant number ES/J500124/1.

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References

[1] Benjamin EJ, Virani SS, Callaway CW, et al. Heart disease and stroke statistics–2018 update: a report from the American Heart Association. Circulation. 2018;137(12):e67–E492.
[2] Abdullahi A. Effects of number of repetitions and number of hours of shaping practice during Constraint-Induced movement therapy: a randomized controlled Trial. Neur Res Int. 2018; 2018:5496408–5496408.
[3] Lang CE, MacDonald JR, Reisman DS, et al. Observation of amounts of movement practice provided during stroke rehabilitation. Arch Phys Med Rehabil. 2009;90(10):1692–1698.
[4] Pain LM, Baker R, Richardson D, et al. Effect of trunk-restraint training on function and compensatory trunk, shoulder and elbow patterns during post-stroke reach: a systematic review. Disabil Rehabil. 2015;37:553–562.
[5] Murata Y, Higo N, Oishi T, et al. Effects of motor training on the recovery of manual dexterity after primary motor cortex lesion in macaque monkeys. J Neurophysiol. 2008; 99(2):773–786.
[6] Ward NS, Brander F, Kelly K. Intensive upper limb neuromotor training in chronic stroke: outcomes from the queen square programme. J Neurol Neurosurg Psychiatry. 2019; 90(5):498–506.
[7] Daly JJ, McCabe JP, Holcomb J, et al. Long-dose intensive therapy is necessary for strong, clinically significant, upper limb functional gains and retained gains in severe/moderate chronic stroke. Neurorehabil Neural Repair. 2019;33(7):523–537.
[8] McCabe J, Monkiewicz M, Holcomb J, et al. Comparison of robotics, functional electrical stimulation, and motor learning methods for treatment of persistent upper extremity dysfunction after stroke: a randomized controlled trial. Arch Phys Med Rehabil. 2015;96(6):981–990.
[9] Michaelsen SM, Dannenbaum R, Levin MF. Task-specific training with trunk restraint on arm recovery in stroke: randomized control trial. Stroke. 2006;37(1):186–192.
Wang Q, Markopoulos P, Yu B, et al. Interactive wearable systems for upper body rehabilitation: a systematic review. J Neuroeng Rehabil BioMed Central. 2017;14(1):20.

Yungher D, Craelius W. Improving fine motor function after brain injury using gesture recognition biofeedback. Disabil Rehabil Assist Technol. 2012;7(6):464–468.

Huang VS, Krakauer JW. Robotic neurorehabilitation: a computational motor learning perspective. J Neuroeng Rehab. 2009;6(1):1–13.

Valdés BA, Schneider AN, Van der Loos HFM. Reducing trunk compensation in stroke survivors: a randomized crossover trial comparing visual and force feedback modalities. Arch Phys Med Rehabil. 2017;98(10):1932–1940.

Kelly K, Brander F, Strawson A, et al. Pushing the limits of recovery in chronic stroke survivors: a descriptive qualitative study of users perceptions of the queen square upper limb neurorehabilitation programme. BMJ Open. 2020;10(10):e036481.

Cao Z, Simon T, Wei SE, et al. Realtime multi-person 2D pose estimation using part affinity fields. Proc – 30th IEEE Conf Comput Vis Pattern Recognition, CVPR. 2017;2017:7291–7299.

Wei SE, Ramakrishna V, Kanade T, et al. Convolutional pose machines. Proceedings of the IEEE Computer Society Conference on computer vision and pattern recognition. 2016. p. 4724–4732.

Fiebrink R, Trueman D, Cook PR. The Wekinator: Software for using machine learning to build real-time interactive systems. 2011.

Valdés BA, Van der Loos HFM. Biofeedback vs. game scores for reducing trunk compensation after stroke: a randomized crossover trial. Top Stroke Rehabil. 2018;25(2):96–113.

Valdes Benavides BA. Reducing compensatory movements in stroke therapy through the use of robotic devices and augmented feedback. Vancouver: University of British Columbia; 2017.

Sihvonen AJ, Särkämö T, Leo V, et al. Music-based interventions in neurological rehabilitation. Lancet Neurol. 2017;16(8):648–660.

Davis WB, Gfeller KE, Thaut M. An introduction to music therapy: theory and practice. Silver Spring: American Music Therapy Association; 2008.

Zatorre RJ, Chen JL, Penhune VB. When the brain plays music: auditory-motor interactions in music perception and production. Nat Rev Neurosci. 2007;8(7):547–558.

Thaut MH, McIntosh GC, Rice RR, et al. Rhythmic auditory stimulation in gait training for Parkinson’s disease patients. Mov Disord. 1996;11(2):193–200.

Altenmüller E, Stewart L. Music supported therapy in neurorehabilitation. In: Dietz V, Ward NS, editors. Oxford textb neurorehabilitation. 2nd ed. Oxford: Oxford University Press; 2020.

Bradt J, Magee WL, Dileo C, et al. Music therapy for acquired brain injury. Bradt J, editor. Cochrane Database Syst Rev. 2010;2010:CD006787.

van Wijck F, Knox D, Dodds C, et al. Making music after stroke: using musical activities to enhance arm function. Ann NY Acad Sci. 2012;1252:305–311.

Kirk P, Grierson M, Bodak R, et al. Motivating stroke rehabilitation through music: a feasibility study using digital musical instruments in the home. Proceedings of the 2016 CHI conference on human factors Computer Systems. 2016. p. 1781–1785.

Nudo RJ, Wise BM, SiFuentes F, et al. Neural substrates for the effects of rehabilitative training on motor recovery after ischemic infarct. Science. 1996;272(5269):1791–1794.