

Effects of Passive Haptic Learning in Music-Supported Therapy on Sensorimotor Performance in Older Adult Hands: A Randomized Crossover Trial

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Abstract

Background: Music-supported therapy (MST), a type of biofeedback therapy with multi-sensory information input, has been proposed as an effective approach to improving motor control in people with sensorimotor deficits. However, currently, MST training is restricted to being extensively applied for patients with various levels of defects in fine motor skills and cognitive functions. Therefore, the integration of passive haptic learning (PHL) with MST has been adopted as a motor training strategy intended to enhance “motor memory” learning through the use of vibration stimuli. The current study was designed to investigate differences in the sensorimotor performance of older adults’ hands under baseline, a single session of standard MST, and PHL-based MST conditions.

Methods: Thirty healthy older adults were recruited and randomized to receive either the single session of 30-minutes of PHL-based MST or 30-minutes of standard MST at the beginning of the experiment. After a one-week washout period, they switched their treatment programs and then were assessed to study the training effects of both approaches through measuring precision pinch performance, hand function, and sensory status.

Results: The results of the Pinch-Holding-Up Activity test revealed a statistically significant difference in the FR_{peak} parameter ($F = 14.37, p < 0.001, \eta^2 = 0.507$) under the PHL-based MST condition compared to the baseline and standard MST conditions. In addition, significant beneficial effects were found on the results of the barognosis ($F = 19.126, p < 0.001, \eta^2 = 0.577$) and roughness differentiation subtests ($F = 15.036, p < 0.001, \eta^2 = 0.518$) in the Manual Tactile Test for the participants in the PHL-based MST group. In addition, the participants under both the standard MST and PHL-based MST conditions exhibited better performance in the three subtests of the Purdue Pegboard Test as compared to under the baseline condition ($p < 0.016$).

Conclusions: The findings indicated that PHL-based MST potentially improves the precision pinch performance of hands in healthy older adults. In addition, the add-on effect of vibrotactile stimulation to the MST condition provides beneficial effects on the sensory functions of the upper extremities.

Clinical Trial Registration: NCT04802564

Background

The number and percentage of the older population is rapidly increasing worldwide. Aging declines skill performance related to physiological changes in skeletal muscles [1] as well as reduced functional integration of the sensory-motor system [2]. It is worth noting that manual dexterity of the hand has long been known as an early indicator of age-related functional decline [3]. A previous study revealed that aging strongly impacts motor performance such as fingertip force modulation requiring online sensory input [4]. Specifically, because many activities of daily living comprise major components of fine motor skills, the elderly population typically is found to be suffering from a loss of functional independence [5].

Thus, activities for maintaining and even promoting the sensorimotor control capabilities of an aging hand should be given attention.

Sensory-augmented therapy has been proposed as a helpful adjunctive strategy that can be used to enhance the effects of motor retraining when integrated with conventional rehabilitation programs for patients with sensorimotor deficits [6, 7]. Vibrotactile sensation caused by a mechanical stimulus characterized by an oscillating motion has been reported to enhance muscular function as well as neuronal activity [8]. A recent study revealed that the activity of the primary sensorimotor area is increased significantly during processing of high-frequency vibrotactile information [9]. In addition, light touch sensation has been shown to be improved in patients' hands when performing a specific task with vibrotactile stimuli on the dorsum of the wrist [10]. This effect may be due to the enhancement of the excitability of sensory neurons through interneuronal connections during task execution [11].

In addition to vibrotactile stimuli, sensory-based interventions to improve hand function also include visual and auditory strategies. Music supported therapy (MST), which has been utilized in the last two decades, is a type of biofeedback therapy that integrates multiple types of sensory information through the use of rhythmic stimuli in order to improve sensory and motor functions in patients [12] [13]. Clinical utility of MST applications include the use of auditory stimuli intended to improve movement quality and the use of rhythmic cuing intended to affect motor planning and execution [14]. Playing keyboards and drums have been reported as the most popular training regimes used to improve fine motor and gross motor coordination, respectively [15]. MST is currently considered to be a practical framework based on neuroscience used for motor relearning and shaping, audio-motor coupling, and evoking emotional effects [16]. Recent evidence revealed that the finger dexterity of subacute stroke patients was improved through providing diverse sensory rewards for sequential finger movements based on keyboard playing programs [17]. Specifically, MST increased the activity and connectivity between the auditory and motor cortical regions by providing individuals with auditory feedback for errors and real-time movement adjustments, which consequently boosted motor recovery of the upper limbs of stroke patients [18]. In addition to patients with neurological deficits, a recent study also revealed that active music therapy has effects on improving upper limb muscle power in community dwelling older adults [19]. However, the effects of MST on the sensorimotor control capacity of an aging hand closely related to lifestyle and living quality are as yet not well known.

Music-supported therapy mainly focuses on movement relearning and shaping through training in the use of musical instruments or specifically-designed electronic devices. Despite the fact that positive findings have been reported [20, 21], the current training MST protocol has limitations related to widespread application in patients with different or varied levels of fine motor skills and cognitive functions. Therefore, the concept of passive haptic learning (PHL) has been adopted recently as a novel strategy, where subjects can acquire "motor memory" through vibration stimuli [22]. The participants acquire motor skills by receiving properly sequenced and timed vibrotactile stimuli on the finger pulps. In addition, vibrotactile feedback has been reported to enhance the performance of the affected arm in stabilization and reaching tasks given to patients suffering from neurological diseases [23]. However, the

difference in the training effects between the standard MST and PHL-based MST on hand functions has not been appropriately investigated. Thus, the purpose of this study was to analyze the difference in the effects on the sensorimotor control capacity of a hand across baseline, standard MST, and PHL-based MST conditions. For this purpose, a PHL-based MST system was designed to assist with performing MST in this study.

Methods

Study design

An assessor blinded, randomized controlled, crossover design was used in the study. The participants were randomly assigned in a 1:1 ratio into either a one-session standard MST group or a PHL-based MST group. After a one-week washout period, they switched treatment programs. The assessments were conducted with the time of pre-treatment as the baseline (T_b), immediately followed by one-session of the standard MST (T_s) and PHL-based MST (T_p).

Participants

Thirty community dwelling healthy older adults were recruited based on an estimation of the effects obtained regarding hand performance using a previous sensory augmented rehabilitation program estimated with a 2-tailed alpha of 0.05 and a power of 0.95 [24]. The inclusion criteria for all the participants in this research group were as follows: (1) right-handed; (2) age ranging from 55 to 85; (3) no history of neurological or psychiatric illness, no severe vision or hearing loss, no abnormalities in the upper extremities, (4) the capacity to perform and maintain a pinch task with the thumb and index finger without support from the upper extremities, (5) no previous musical instrument education, and (6) a score of 24 or more on the Mini Mental State Examination. Participants with difficulty following instructions, diagnosed with neuro-musculoskeletal disorders, or having a poor attention span were excluded. Prior to participation, each participant was asked to sign a consent form after being informed of the objectives and the related research procedures.

Equipment

The PHL-based MST system (Fig. 1) is a custom-made training apparatus composed of three distinct parts: (1) A laptop computer: This computer produces music output integrated with visual information in the form of a color bar moving on the screen display corresponding with the rhythmic elements of the music. (2) Haptic feedback component: To establish the haptic interface, an Arduino UNO microcontroller board was used as a microprocessor, which controlled and worked with five coin-shaped micro vibration motors (Model #1027, TAIWAINIOT™, Taiwan) to achieve the function of providing vibrotactile feedback in the system. The motor was driven at a voltage of $5 V_{DC}$ (direct current) with sinusoidal vibration applied to the fingertip at a frequency of approximately 200 Hz. The pulp of each digit was securely positioned in a specially designed 3D printing base as a reinforced structure with Velcro-fastenings. (3) Image classifier: The artificial intelligence deep residual network (ResNet50) was used for precise image recognition and

the integration of the visual information from the moving color bar and vibrotactile stimuli in a timely manner.

Intervention

Two training regimes, the MST and PHL-based MST regimes, based on a crossover study design with a one-week washout phase were applied for all the participants. The standard MST is aimed toward improving the participants' fine motor skills through a 30-minute "active practice" session. The participants were instructed to play music by pressing the keyboard with the corresponding digits guided by auditory and visual feedback displayed as a moving color-bar on the computer screen. The hand was allowed to perform different kinds of pressing activities, such as single and multiple digits pressing in a specific rhythm. In the PHL-based MST, the system provided 30-minutes of vibrotactile stimuli synchronized with audio and visual information to each digit via small, coin-shaped vibration motors fitted on the pulps of the digits while the music was played. Different from the standard MST, the participants receiving the PHL-based MST program were asked to receive multiple sensory information, including visual, auditory, and vibrotactile stimuli, but did not actively perform piano key pressing tasks.

Outcome measures

Primary outcome measures

The pinch-holding-up activity (PHUA) test is a task-based assessment used for detecting the precision pinch performance of a hand. A 480g-weight pinch apparatus with two load cells and one accelerometer used to detect the pinch force exertion of a hand and acceleration of the apparatus in space, respectively, were used to examine the pinch and load force coupling related to lifting performance of the upper extremity. The testing procedures comprised two phases, a holding phase and a lifting phase. The participants were instructed to pinch and lift the apparatus to a 5 cm height above the table and then asked to hold the device in this position for 5 seconds (holding phase). Afterwards, the pinch-apparatus was lifted from 5 cm to the height of 30 cm (lifting phase) above the table and then slowly lowered to the initial position. The total duration of data collection was approximately 15 seconds, where the maximum upward acceleration of the apparatus and peak pinch force exerted by the digits during the lifting phase of the test were recorded. The peak pinch force during the lifting phase was defined as FP_{peak} , and the maximum load of the object was defined as FL_{max} . FR_{peak} , the ratio between FP_{peak} and FL_{max} , indicated the ability of a hand to adjust to the pinch force related to changes in the inertial load of the lifted object. FR_{peak} is a sensitive parameter used to assess the sensorimotor control of the hand in the form of a dynamic coordination model [25].

Secondary outcome measures

The manual tactile test (MTT) is a timed evaluation tool used to determine the discriminative sensation involved in active exploration of a hand with reported reliability, accuracy, and validity [26]. Three subtests in the MTT, barognosis, roughness differentiation, and stereognosis, were conducted for evaluating the hand perceptions of a participant related to distinguishing object characteristics - weight, roughness, and

shape, respectively, with active touch while blindfolded. The test procedures for each subtest were repeated three times for each hand. The average time required to perform each test was calculated to arrive at the final score of that test.

The Semmes-Weinstein monofilament (SWM) test is the most responsive touch-pressure sensory test [27]. It also has reliability and specificity for identifying a loss of protective sensation in seniors [28]. A full set of SWM contains 20 monofilaments, and each monofilament is labeled with a numerical marking, which is a log to the base ten of force in tenths of a milligram. When conducting the SWM test, the filaments are applied perpendicular to the pulp of each digit with a constant force onto the skin area for 1-1.5 seconds.

The Purdue Pegboard Test (PPT) is a test of the uni-manual and bimanual dexterity of the hands. It has been demonstrated to have high testing validity and reliability [29]. The test was carried out using a procedure in which pins are inserted into small holes with the dominant hand and both hands simultaneously in 30 seconds, as well as an assembly task that was performed for 60 seconds.

Statistical analysis

SPSS 19.0 for Windows (Statistical Package for Social Sciences Inc. Chicago, IL, USA) was used for the statistical analyses. The descriptive statistics were used to describe the means and standard deviations of the characteristics data and outcome measurements. Normality in the data distribution was examined with a Shapiro-Wilk's test. Differences in the outcome assessments for the following three conditions, the baseline, one-session of the standard MST, and one-session of PHL-based MST, were calculated using a repeated measure ANOVA. Statistical significance was set at $p < 0.05$. A post hoc test was used to examine whether any differences existed between the different conditions as the main ANOVA is significant. After the Bonferroni correction, the statistical threshold was adjusted to $p < 0.016$.

Results

15 male and 15 female older adults between the ages of 55 and 85 (65.7 ± 5.6 years old) were recruited in this study. All of the participants completed all the outcomes measurements for the three conditions.

Table 1 summarizes the descriptive statistics and the results of the repeated measure ANOVA for the precision pinch performance, hand function, and sensory status under the three conditions of interest. A statistically significant difference was detected for the FR_{peak} parameter ($F = 14.37$, $p < 0.001$, $\eta^2 = 0.507$) and FP_{peak} ($F = 7.295$, $p = .003$, $\eta^2 = 0.343$) using the PHUA test, across all three conditions. Based on the post-hoc examination, the participants under the PHL-based MST condition had better capacity to modulate their pinch force according to the fluctuated load of the lifted object in terms of their dynamic pinch-lifting performance compared to the baseline and standard MST conditions (Table 1). However, there were no statistically significant differences for the precision pinch performance between the baseline and standard MST condition ($p = 0.304$ and $p = 0.165$, respectively, for FR_{peak} and FP_{peak}).

Table 1

The descriptive statistics and the results of the repeated measure ANOVA used to determine the precision pinch performance, hand function, and sensory status under the three conditions.

		Conditions			Difference across conditions		
		Baseline	Standard MST	PHL-based MST	F	<i>p</i>	partial η^2
PHUA	FP _{peak} (N)	13.19 ± 1.54	12.91 ± 1.15 [‡]	12.40 ± 1.01 ^{†‡}	7.295	.003	.343
	FR _{peak}	2.98 ± .33	2.94 ± .30 [‡]	2.76 ± .23 ^{†‡}	14.370	< 0.001	.507
MTT (seconds)	Barognosis	3.18 ± .10	3.10 ± .09 [‡]	2.81 ± .09 ^{†‡}	19.126	< 0.001	.577
	Roughness differentiation	31.12 ± 6.40	28.56 ± 4.13 ^{*‡}	27.49 ± 3.60 ^{†‡}	15.036	< 0.001	.518
	Stereognosis	24.86 ± 2.65	23.46 ± 2.71 [*]	22.40 ± 4.39 [†]	9.057	0.001	.393
SWM test (gm)	Thumb	.181 ± .211	.156 ± .206	.130 ± .205 [†]	4.389	.022	.239
	Index finger	.161 ± .170	.124 ± .153 ^{*‡}	.083 ± .111 ^{†‡}	6.373	.005	.313
	Little finger	.123 ± .143	.093 ± .109 [‡]	.060 ± .073 ^{†‡}	4.700	.017	.251
PPT	Pin insertion-DH	14.1 ± .4	15.0 ± .3 [*]	15.2 ± .3 [†]	8.454	0.001	.377
	Pin insertion- BH	11.3 ± 1.6	12.1 ± 1.2 [*]	11.9 ± 1.4 [†]	.11.932	< 0.001	.460
	Assembly	31.8 ± 5.9	35.6 ± 5.6 [*]	34.6 ± 5.2 [†]	18.458	< 0.001	.568

A repeated measure ANOVA was used to compare the effects of the different interventions. The level of significance was set at $p < 0.05$. A post hoc test was used to examine whether any differences existed among the different conditions. After the Bonferroni correction, the statistical threshold was adjusted to $p < 0.016$.

*: Significant difference between Baseline and Standard MST. †: Significant difference between Baseline and PHL-based MST. ‡: Significant difference between Standard MST and PHL-based MST.

FR_{peak}: Force ratio (FP_{peak}: FL_{max}); FP_{peak}: maximum pinch force during the lifting phase

MTT: Manual tactile test.

SWM test: Semmes-Weinstein monofilament test

PPT: Purdue Pegboard Test; DH: Dominant hand; BH: Both hands;

In terms of sensory function, there was a statistically significant difference in the results of the MTT and SWM test for the participants across all three conditions (Table 1). The SWM results under the PHL-based MST condition was better than that under the baseline condition ($p = 0.010$, $p = 0.001$, and $p = 0.004$, respectively, for the thumb, index finger, and little finger). However, the SWM results under the standard MST condition revealed no statistically significant differences compared to the baseline condition ($p = 0.069$, $p = 0.038$, $p = 0.063$, respectively, for the thumb, index finger, and little finger). The difference in the results of SWM between the PHL-based MST condition and standard MST condition was not statistically significant for the thumb, index finger and little finger ($p > 0.016$). Similar to the SWM results, the sensory assessment evaluation using three MTT subtests under the PHL-based MST condition revealed statistically better performance compared to the baseline condition ($p < 0.001$, $p < 0.001$ and $p = 0.002$, respectively, for barognosis, roughness differentiation, and stereognosis). In addition, compared to the standard MST, the participants spent relatively less time completing the barognosis ($p < 0.001$) and roughness differentiation ($p = 0.014$) subtests under the PHL-based MST condition. Different from the SWM results, better results were found in the roughness differentiation subtest ($p = 0.006$) and stereognosis ($p = 0.001$) following the standard MST as compared to the baseline condition; however, there was lack of statistical difference in the results for barognosis between the baseline and standard MST conditions ($p = 0.077$).

The results of the pin insertion subtests using the dominant hand, both hands, and the PPT assembly task revealed statistically significant differences across the three conditions (Table 1). The participants in both the standard MST and PHL-based MST conditions had faster performance in the three PPT subtests as compared to under the baseline condition.

Discussion

The aim of the present study was to evaluate the differences in the effects on the sensorimotor control capacity of a hand across conditions including baseline, standard MST, and PHL-based MST conditions. A passive haptic learning-based music-supported therapy system suitable for sensorimotor control training was developed in this study. The findings partially supported the premise that the PHL-based MST would enhance the sensorimotor performance of a hand in healthy older adults. Participants in the PHL-based MST group exhibited better performance in a pinch-holding task that required online sensory feedback, as compared to those in the standard MST and the baseline groups. In addition, the results also showed that there were better effects of the PHL-based MST on improving sensory functions related to barognosis and roughness differentiation, as compared to those under the baseline and standard MST conditions. This result clearly demonstrated the effectiveness of the PHL-based MST on the sensorimotor performance of healthy older adults.

The FR_{peak} under the baseline condition in the current study was higher when compared with data obtained from young subjects [30]. A higher pinch-to-load force ratio, which indicated inaccurate pinch force modulation to the momentum-induced load changes [31], might have been due to the decline in the sensorimotor functioning of the hands. In the case of healthy participants, pinch force predictions and adjustments during execution of a functional task is an automatic motor response corresponding to the dynamics of arm movement [32]; however, recent evidence suggested that sensory deficits of a hand appear to remarkably decrease the capacity of momentary motor adjustment [33] because task-based sensorimotor processing depends on not only a feed-forward control mechanism but also on peripheral sensory events [34]. Since aging leads to slowing of sensorimotor functions [35], an intervention program involving the use of passive sensory stimulation drives plastic reorganizational changes in the sensorimotor cortex based on the Hebbian forms of plasticity [36], which promotes precision pinch performance in the hands of healthy seniors. The better performance in precision pinch performance when receiving the PHL-based MST intervention was supported by recent studies based on sensory augmentation systems used to explain the potential mechanisms of sensory restoration, sensorimotor integration, and substitution in motor control [37, 38]. That is, integration of afferent vibration signals in the form of haptic feedback in hand therapy contributes to enhancing hand performance [39].

In addition, the results of the SWM test and MTT test obtained under the baseline condition in the older adults examined in the present study revealed lower sensitivity in both the touch threshold [40] and discriminative sensory function [26]. The PHL-based MST had superior training effects on the results of the SWM test and the MTT barognosis subtest. Compared to the standard MST, the sensitivity related to both tactile and proprioceptive sensation increased through activation of sensory receptors during the transmission of vibrotactile stimulation to the finger tips, which enhanced sensory restoration in the participants receiving the PHL-based MST intervention. A recent report indicated that the vibrotactile component of the haptic feedback that occurs when playing a musical instrument leads to increased quality of hand perceptions [41]. Due to central mechanisms, vibrotactile stimulation on the fingertips results in not only activating cutaneous mechanoreceptors, but it also enhances the mechanical coupling between the contacted skin, tendons, and bones, which significantly improves the of touch-pressure threshold, as tested by Semmes-Weinstein monofilament [42] and the capacity of active force perception as measured when participants manipulate objects [43].

The standard MST in this study also presented some training effects on improving hand functions, which might concur with the findings of a previous review report regarding MST training used to enhance the motor functions of stroke survivors [44]. MST provides visual and auditory information intended to guide the temporal and spatial organization of sequential motor responses based on rhythmic keyboard pressing and enhances the coordinated actions of the hand [45]. Furthermore, the predictability of motor sequences serve as a facilitative factor for motor control based on a cognitive processing mechanism that occurs during the preparation and execution of movements such as keyboard pressing during MST [46]. Therefore, music-based paradigms have been suggested to be an effective strategy for motor learning and rehabilitation. Also, the results of the roughness differentiation and stereognosis after the

standard MST revealed statistically significant changes compared to the baseline condition in the current study, which might have been correlated with the enrichment of the sensorimotor network through functional motor training in a multisensory environment [47].

This may be the first study examining the effects of an intervention using a music-supported therapy with multiple sensory feedback on sensorimotor performance of the hands of healthy senior participants. The present study established a passive haptic learning-based music-supported therapy (PHL-based MST) system acting as a sensory augmentation approach to dealing with impaired motor control capabilities. It is noteworthy that better training results in precision pinch performance, hand function, and sensory function of healthy older adults have been obtained for participants even when only receiving the PHL-based MST intervention once comparing with receiving the standard MST. Also, both the PHL-based MST and standard MST interventions had beneficial effects on hand performance and sensory function compared to the baseline condition. However, several limitations exist in the present study. First of all, the protocol only provided immediate outcome measures, which make it impossible to clearly understand the delayed effects on the sensorimotor performance that occurred in both the PHL-based MST and standard MST interventions. The other limitation was that the design of current study was only a single session intervention, which did not permit us to observe effects of a longer training period of music-supported therapy on the sensorimotor performance of hands. In spite of these limitations, the results indeed have merit related to supporting future studies investigating the impacts of PHL-based MST and standard MST on hand sensorimotor performance or sensory functioning in participants with marked sensorimotor deficits.

Conclusions

In summary, a single session of a passive haptic learning-based music-supported therapy (PHL-based MST) was shown to provide potential training effects on ameliorating the declined sensorimotor performance in the hands of healthy older adults, especially for in the case of motor skills requiring online sensory feedback. Future studies are needed in order to optimize the training protocol of music-supported therapy by examining the effects of intervention intensity or time periods required for executing PHL-based MST and standard MST training in individuals with age-related sensorimotor deficits or neurological impairments.

List Of Abbreviations

MST
Music supported therapy
PHL
Passive haptic learning
PHUA
Pinch-holding-up activity
FP_{peak}

Peak pinch force

FL_{max}

Maximum load force

FR_{peak}

Ratio between peak pinch force and maximum load force

MTT

Manual tactile test

SWM

Semmes-Weinstein monofilament

PPT

Purdue Pegboard Test

SPSS

Statistical Package for Social Sciences

ANOVA

Analysis of variance

Declarations

Ethics approval and consent to participate

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The procedures and consent form were approved by the Institutional Review Board at National Cheng Kung University Hospital.

Informed consent: Informed consent was obtained from all individual participants included in the study.

Consent for publication

Not Applicable

Availability of data and materials

Not Applicable

Competing interests

The authors wish to declare no known conflicts of interest associated with this study, and there has been no significant financial support for this work that could have influenced the outcome.

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Author contributions

HYH, FCS and LCK were the main contributors in the determination of unmet clinical needs, the study design, and data collection. HYH, CWL, FCS, HK and LCK carried out the development of the Passive Haptic Learning and Music-Supported Therapy system and technical problem solving for the system. HYH, YCL, PTW and LCK participated in the registration, screening, and examinations of the participants. HYH, PTW, and LCK participated in the data interpretation, analysis, and interpretations. HYH, CWL and LCK helped to draft the manuscript. All authors read and approved the content and format of the final manuscript.

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Figures

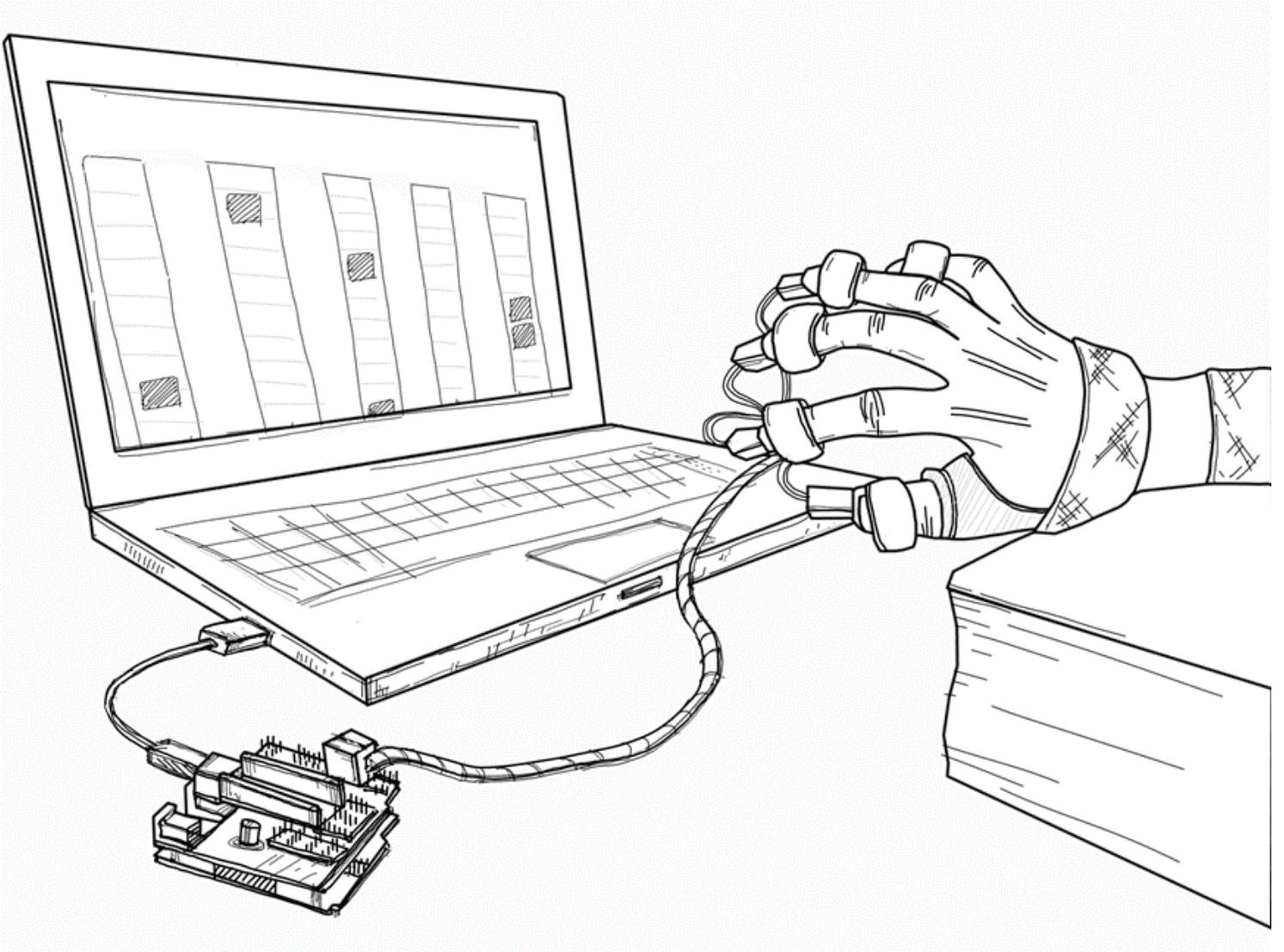


Figure 1

Illustration of the passive haptic learning-based music-supported therapy (PHL-based MST) system