Accelerating Skill Acquisition of Two-Handed Drumming using Pneumatic Artificial Muscles

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ABSTRACT

While computers excel at augmenting user's cognitive abilities, only recently we started utilizing their full potential to enhance our physical abilities. More and more wearable force-feedback devices have been developed based on exoskeletons, electrical muscle stimulation (EMS) or pneumatic actuators. The latter, pneumatic-based artificial muscles, are of particular interest since they strike an interesting balance: lighter than exoskeletons and more precise than EMS. However, the promise of using artificial muscles to actually support skill acquisition and training users is still lacking empirical validation.

In this paper, we unveil how pneumatic artificial muscles impact skill acquisition, using two-handed drumming as an example use case. To understand this, we conducted a user study comparing participants' drumming performance after training with the audio or with our artificial-muscle setup. Our haptic system is comprised of four pneumatic muscles and is capable of actuating the user's forearm to drum accurately up to 80 bpm. We show that pneumatic muscles improve participants' correct recall of drumming patterns significantly when compared to auditory training.

CCS CONCEPTS

• **Computer systems organization** → **Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability.

KEYWORDS

Force-feedback, motor learning, pneumatic artificial muscles (PAMs)

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1 INTRODUCTION

A skilled individual is characterized by their fine-tuned perceptual and motor capabilities. Acquiring a new motor skill requires intensive training, especially for complex skills that often involve coordination between several limbs and other senses (e.g., dodging obstacles while walking, tapping to a beat, etc.). A widely used example of a complex task is playing a musical instrument as it requires auditory and multi-limb coordination [28, 32, 38]. The process of acquiring a new physical skill is called motor consolidation (this is, also, sometimes referred to as "muscle memory") [17].

Recently, more and more haptic interfaces, such as robotic actuators and exoskeletons, gained enough power output to actuate the user's body—these technologies are able to move humans in an active form of motor training that is particularly useful for new skill acquisition [4]. While grounded haptic devices such as the *Phantom* or larger exoskeletons have been shown to improve movement [4] and even musical training [5], this is not the case for more recent developments in wearable haptic actuation technologies, such as pneumatic muscles [31]. These interfaces are extremely promising for the field of motor learning since they are lightweight and interfere less with the user's own movements when compared to exoskeletons, however, these devices have not shown to *actually* improve motor learning.

In this paper, we demonstrate that pneumatic artificial muscles improve motor learning. To demonstrate this, we first created a wearable haptic system using a specific type of Pneumatic Artificial Muscle (PAM) that requires low-pressure to be actuated. These are called pneumatic gel muscles (Pneumatic Gel Muscle (PGM)) [31] and offer a more promising single path towards miniaturization since they operate on small CO_2 canisters. Using our haptic system, we studied how novice drummers learned two-handed patterns, consisting of consecutive tuplets without rest, and short roll-combinations, which are a sequence of notes with short rest or ties. We found that participants not only preferred our artificial

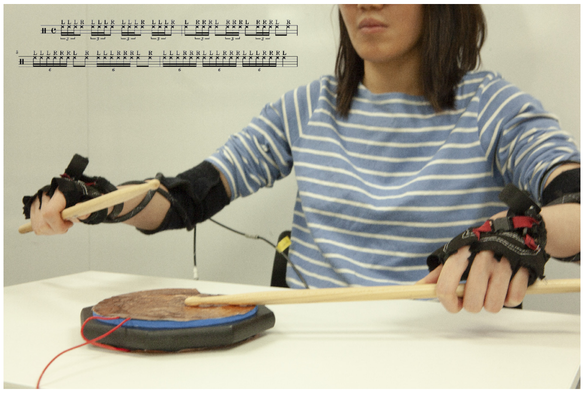

Figure 1: We investigated whether recently developments lightweight haptic actuation technologies, in particular pneumatic actuated muscles, promote motor learning for complex tasks. To explore this, we created a haptic system that actuates user's to automatically perform complex drumming patterns, as shown above. As we found out on our study two-handed drumming patterns was easier to acquire with our system than using the traditional auditory feedback approach that novice drummers use (musical score and metronome beeps signifying each note and hand).

muscles over the standard auditory training, they also incurred in less errors (missed beats).

2 ACQUIRING SKILLS WITH ARTIFICIAL MUSCLES

Our haptic system is designed to foster motor learning by providing actuation forces to the human body. Figure 1 illustrates how we used pneumatic-gel artificial muscles (PGM) as soft exoskeletons for learning two-handed drumming. It has been argued that force-feedback devices provide substantial proprioceptive feedback that could enhance motor learning. Our study was the first to confirm this hypothesis, for the case of two-handed drumming, which we believe is a canonical example of a physical skill requiring non-trivial multi-sensory coordination.Our haptic device actively rotates the user's forehand to realize pronation and supination motions by contracting the corresponding PGMs. These motions were designed to create the appropriate stimuli to foster learning.

Figure 1 shows also the core components of our haptic system, i.e., a set of four PGM actuators, two per forearm. These actuators are soft, flexible and lightweight. Therefore, they can be easily wrapped around the user's forearm, mimicking the pattern of human muscles; hence, these are called artificial muscles. Each PGM actuates one type of motion for either left or right forearm. These PGMs are driven by solenoid valves, controlled by a microcontroller with compressed air supplied from a mini CO_2 canister. The one of the end points of the actuators were attached to the dorsal side of the hand (near the knuckles) through plastic buckles. The other end of the actuators was attached to a supporter worn on the elbow through hook and loop fasteners. This end was used by the user to adjust the tension on the forearm by changing the deflated elongation of the soft actuators as per their comfort.

3 BENEFITS AND CONTRIBUTION

Our main contribution in this paper is the validation that pneumatic artificial muscles foster skill acquisition. Our user study also suggests that haptic approach is beneficial for pattern recall. Our haptic system demonstrates that even an exoskeleton with a small form factor, such as one based on pneumatic muscles, can be transformative in haptic learning. The benefits of our findings are widespread, these inspire new thrusts of research in haptics for skill acquisition, especially using pneumatic artificial muscles such as PGMs.

On the other hand, while our device can actuate wrist drumming patterns, more complex motions, such as full-arm, shoulder rotations or feet that are required in other drumming abilities (e.g., cymbals) are outside the capabilities of our device. Furthermore, like any other haptic device capable of producing enough force for limb actuation, our device must be calibrated prior to use.

4 RELATED WORK

The work presented in this paper builds on previous work related to force feedback using rigid and soft exoskeleton approaches, embodied learning, and general haptic systems for learning musical instruments.

4.1 Force Feedback

There is a range of haptic actuation technologies capable of producing sufficient force to displace a user's limbs; these are the so called force feedback devices, these range from robotic arms, exoskeletons, electrical muscle stimulation and pneumatic actuators (just to cite a few). In our work we are especially focused on wearable approaches for force feedback as these do not require users to be grounded to a robotic arm or motion platform. When it comes to wearable haptic systems, the most common approaches are exoskeletons [11], electrical muscle stimulation (EMS) [24, 38] and artificial muscles [3].

4.1.1 Exoskeletons. Exoskeletons are mechanical systems that push /pull against the user's limbs using electric motors and linkages. These are some of the most promising and precise haptic systems, as demonstrated by their wide spread applications, ranging from haptics for VR/AR [11], restoring motor function [13], to supporting a payload [43]. A disadvantage of current exoskeletons is their weight [9], which often is approximately equal to the human body part it supports or even larger [1]. Consequently, one aim of current exoskeleton research and innovation is system weight reduction. While DEXMO [11], for example, is a portable exoskeleton that weighs only 270 grams, it is only able to apply force to fingers. Hence, the use cases light-weight exoskeletons, such as DEXMO, currently support are limited and light systems for wrist joint manipulation, needed e.g. for drumming, do not exist.

4.1.2 Electrical Muscle Stimulation. Electrical muscle stimulation is a technique originated in medical rehabilitation, in which electrical impulses create an involuntary contraction on the user's muscles—causing it to produce force feedback. Its usage in HCI is more recent but important as, unlike the aforementioned exoskeletons, EMS devices can be made very small and wearable [21, 22]. For instance, Tamaki *et al.* engineered an Electrical Muscle Stimulation (EMS)-based haptic device to assist playing a musical instrument (the *Koto*, a Japanese traditional stringed instrument) [38]. EMS was also embedded into the affordance++ system to assist users in manipulation everyday objects they are not familiar with [23]. In addition, it was used to emulate the force of obstacles or objects in VR [24] and AR [25].

4.1.3 Artificial Muscles. Artificial muscles are interesting with respect to wearability because they strike a useful balance between the accurate force control of exoskeletons and the portability of EMS. Most artificial muscles are based on pneumatics; these are often referred to as Pneumatic Artificial Muscle (PAM) [40]. These artificial muscles work by contracting as compressed air fills up a pneumatic bladder. They mimic human muscles as they only contract. Subsequent expansion to original form is slow and passive. Therefore, to move a limb in two directions, two opposing PAMs are used (one acts as a flexor, the other as an extensor; just like human muscles). The first design of PAMs was unveiled by McKibben in the 1960s [40]. Most PAMs are precisely variations on McKibben's design and require high-pressure air to trigger a powerful contraction. This has limited their applicability to wearable form-factors as it requires a powerful air compressor.

More recently, a wearable design for pneumatic muscles emerged: Pneumatic Gel Muscle (PGM). These also share McKibben's structural design but requires less pressure (operates PGM from 0.05 MPa to 0.30 MPa) to initiate the contraction, making it more suited for wearable applications [2, 31]. Yamamoto et al. used PGMs for a wearable balance exercise device by connecting several artificial muscles to a small CO2 canister [42]. Ogawa et al. developed a motion assist suit without any electric source to reinforce hitting a tennis forehand [30]. Sakoda et al. also proposed the use of PGM for sport, and they used it as hitting training equipment for baseball in VR world [33]. Kishishita et al. developed a wearable force-feedback suit for upper extremity for VR/AR gamification [16]. Thakur et al. developed the wearable suit for lower limb for reducing muscle effort in walking [39]. Higuchi et al. applied a similar design of the wearable suit to assist walking of Parkinson's disease patients [14] Similarly, Das *et al.* utilized PGM for force feedback in a haptic glove form factor [3]. Lastly, PGMs have several benefits compared with EMS and rigid exoskeletons: (1) PGMs are soft and they do not restrict our body movement as much as rigid exoskeletons, (2) PGMs do not contract the user's muscles, leaving the user's with agency and sufficient force to move against the PGM; on the contrary, EMS devices make it harder to resist because they activate the user's own muscles.

4.2 Skill Acquisition (Motor Learning)

Learning a new physical skill, especially one that involves multi-sensory coordination, is a demanding task even for individuals with high dexterity. The key to learning a physical skill is a process that involves *repetition.* Over time the repetitive attempts to perform the task start to consolidate into the user's physical skill —this process is called motor consolidation [17].

Drumming is often used by neuroscientists that study motor learning because it requires a great amount of coordination between limbs and auditory/visual information [6]. Learning how to drum on both hands, requires learning asymmetric drumming patterns that are very hard to coordinate between both hands. The more skilled a drummer is, the faster they can perform these two-handed drumming patterns, especially those that require asymmetric hand coordination [8].

4.2.1 Haptic-assisted skill acquisition. One strategy that has been proven successful in facilitating skill acquisition is the addition of haptic feedback. Several studies have investigated what type or what frequency of haptic feedback facilitates the retention of a new motor skill. Researchers have shown, countless times, how haptic assistance can promote learning of new skills [19, 29, 41]. The caveat here is that the *guidance hypothesis* [34, 35] postulates that interleaving trials with haptic feedback, and no-assistance is superior to constant haptic assistance. Researchers confirmed that users start to acquire consolidation of motor skills in the trials (without haptic assistance) that follow the haptic-assisted trial.

Researchers in Human Computer Interaction (HCI) have greatly leveraged the potential of haptics for assisting with motor learning. For example, Feygin *et al.* demonstrated that using PHANToM, a grounded haptic device, was beneficial for learning a 3D trajectory, particularly in timing-related aspects [4]. Similarly, vibrotactile feedback was used to foster rhythm skills and multi-limb coordination through a drumming task in [15]. Many researchers tried to accelerate the learning process of musical instruments, *e.g.*piano, and they presented multiple interactive systems for this purpose. Takahashi et al. developed soft exoskeleton glove with 20 DOFs for VR applications and intuitive guidance in motor skill acquisition [37]. Fujii et al. performed a study using two grounded haptic robots to teach how to play theremin between an expert and a beginner [5] However, none of these previous studies provides insights that extend to pneumatic artificial muscles—this is precisely the focus and contribution of our paper.

Our system is completely wearable (is self contained and can be activated by a mobile CO2 cylinder for about 500 - 800 times, total weight: 413g). It does not require a compressor (as for other related work and the PGM used is also flexible).

5 IMPLEMENTATION DETAILS

To help readers to replicate our design, the necessary technical details are provided in this section.

5.1 Pneumatic Control System

We depict the diagram of system we engineered in Figure 2. Our haptic system uses four pneumatic gel muscles (PGM) as soft actuators worn by the user on their forearm. Total weight of the system excluding the air pressure source is 413g (including four PGMs of weight 86g). All together these four actuators PGM can induce four types of movement in the forearm (flexion, extension, pronation and supination) [3, 10]. Each PGM is either actuated or deflated through a dedicated 3/2 solenoid valve, operated in normally-closed configuration. The solenoid valve used in our device is the SYJ312M-SLZD-M3 (SMC) with an operating pressure range of 0-0.7MPa. Our device does not required to use a stationary air compressor, instead we can opt for a NTG mini CO_2 gas cylinder (with a gas volume of 74 grams). The cylinder is attached to a regulator used to maintain an input air pressure of 0.2MPa to the solenoid valves. Our device is controlled via a python-based system. The actuation of the artificial muscles is then directed according to those patterns by our software. Therefore, the microcontroller receives instructions from our software and actuates the corresponding channels to energize or de-energize the solenoid valves. The system also offers a stand-alone mode, in which the drumming programs can be loaded directly into the microcontroller. We utilize this version in our user study. Our pneumatic system can provide forces starting from a slight "drag" or "pull" (haptic feedback) to a strong actuation of user's body depending on the selected input air pressure. For drumming, we utilize strong actuation forces that are capable of moving the user's forearm involuntarily.

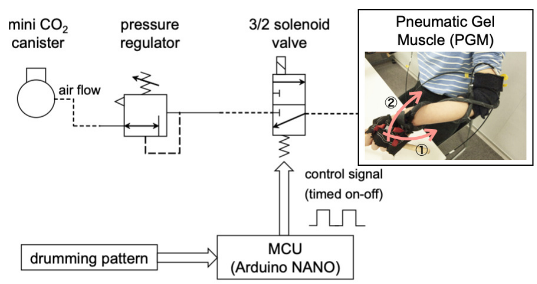

Figure 2: Schematic representation of the pneumatic control system.

5.2 Measurement of force profile of PGM

The force profiles generated through the actuation of a PGM of maximum stretched length of 35.8cm have been shown in Figure 3. This data was recorded by keeping the input air pressure fixed at 0.2MPa. The actuation was controlled using the same control system as in the user study. Rising and falling behaviour of the resultant force at three different stretched lengths can be seen. It was evident from the data that the resultant force increased with an increase in the tension applied to the artificial muscle. In addition, there was a decrease in the rise time and deflation time as the tension applied to the artificial muscle was increased.

5.3 Motion Design

Drumming movement consists of wrist flexion/extension movement and we designed a drum stroke based on forearm pronation-supination movement by our soft exoskeletons [7]. Figure 4 shows how our designed drumming movements work. In user study, which described later, all tasks were performed at 80 BPM (signifying one beat every 750 milliseconds) as the basic tempo. Hence before hitting a single note, one PGM actuates for around 100 milliseconds to supinate users' forearm and another PGM actuates for around 200 milliseconds to pronate the forearm.

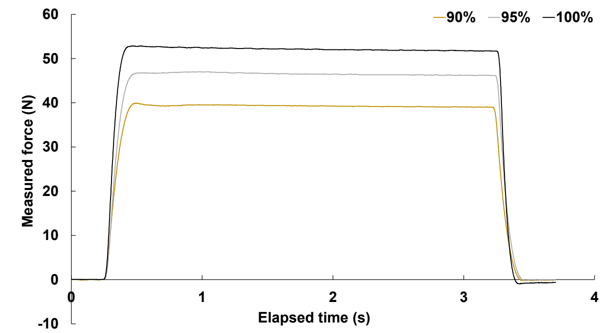

Figure 3: Comparison of force profile with respect to elapsed time for different stretched lengths of PGM (in terms of % of maximum stretched length).

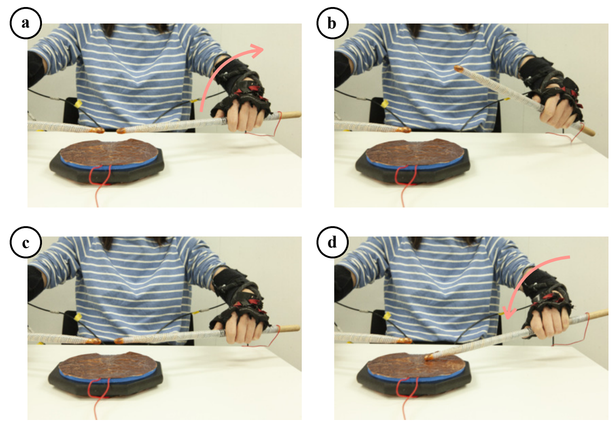

Figure 4: Movements for drumming based on pronation and supination caused by our soft exoskeletons: (a) supinate users' forearm for 15 % length of time of one beat, (b) stop supination, (c) start pronation for 25 % length of time of one beat, (d) pronate users' forearm to hit drum pad by the drum stick and wait the rest of time until next beat.

5.4 Detecting a drum pad hit

Firstly, the drumming practice is arranged using a pair of regular wooden drumsticks and a two-sided practice pad as shown in Figure 5. For the user study, which will be described later, we added a few components to the basic drumming set-up to detect the timing of drumming. The surface of the drum practice pad and the tips of the drum sticks were covered with copper sheet. The copper sheet on the drum pad was connected to 5V. The drumstick tips, were pulled down to ground in conditions without contact to the drum pad. Whenever a contact between any one of the drumsticks and the drum pad was detected, an interrupt signal was sent to the microcontroller, which in turn kept a log of the contact timings. Each drumstick (left and right) was monitored separately through two interrupt pins. To prevent chattering effect, the system was

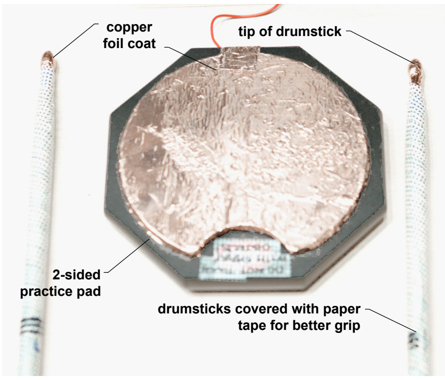

Figure 5: Materials used for setting up the drumming practice and timing detection.

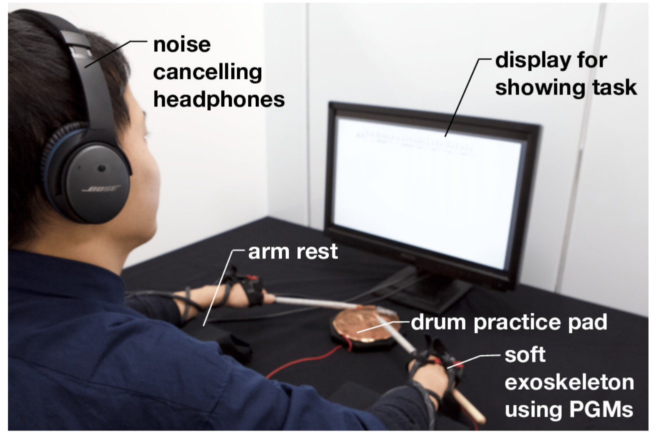

Figure 6: Experiment Settings.

set to halt the reception of interrupt from a specific pin for 150 milliseconds after the detection of a hit or contact.

5.5 Limitation of air tank capacity

The setup in our user study consisted of air compressor to provide compressed air into the PGM. We mentioned our setup works with a very small gas cylinder, which is 13 cm long with 74 g compressed CO_2 gas, however, this introduces also a limitation of for how long we can actuate. Naturally, the operational duration depends on how frequently and how strongly we activate PGM, therefore, the relationship between the working time and the number of activations depicts the capacity-duration trade-off. This CO_2 gas cylinder (74g) at a constant maximum drumming rate of 80 bpm, and with all actuators at maximum force, lasts around 10 minutes.

6 USER STUDY

We conducted a study to understand the impact of pneumatic artificial muscles on skill acquisition. We conducted our investigation at the example of two-handed drumming with novices. In our study, we asked participants to learn and play a series of two-handed drum patterns, in two conditions: using our PGM-based haptic system or auditory feedback (baseline).

6.1 Apparatus

Figure 6 shows our apparatus. Participants wore our PGM-based haptic system (described in Implementation). This system was calibrated per each participant to perform robust pronation and supination of the participant's wrists. The calibration was performed once before the participants start to train at the PGM-conditions in the user study and we did not calibrate the setup per each trial. Furthermore, we prepared the aforementioned drum practice pad and two sticks with copper sheet to detect when participants' stroke the pad. The practice pad was placed in front of the participants. To minimize fatigue effects, we added armrests under each arm. Furthermore, participants wore noise-cancelling headphones which play white noise in the PGM-condition, to eliminate potential confounds caused by the actuator's sound.

By connecting the drum pad with a microcontroller, we were able to precisely measure: the timing of the user's beats (also denoted as a sinter-beat interval), the number of missed/extra beats, and coordination errors (using the wrong hand).

6.2 Interface conditions

We performed an experiment in the following condition:

PGM: force feedback by means of PGM, which caused the participants' arms to drum involuntarily.

Audio (baseline): audio feedback heard over the participants' headphone. Participants received auditory cues, such as "left" or "right", for each beat (many drum teachers, tutorials and apps use precisely this approach). In a small pre-study, we included music score (with and without audio), a video with sound and audio as potential base lines. The music score was eliminated as it was hard especially for novice learners. We were using audio as a learning modality as it has been shown in other related rhythm feedback studies to be helpful and no significant improvement using visuals could be achieved [20].

These conditions were displayed in a counterbalanced order. Every participant concluded the task in each condition (within-subjects)

6.3 Participants

We recruited 12 participants (8 self-identified as female, 4 as male, aged from 23 to 31 years old) through university. We recruited only participants who had never trained for any musical instrument. They received a coupon, which corresponds to about $ 20 in the local currency, for completing the 90-min experiment.

6.4 Task

The study is a typical trial and recall. Participants experienced a trial aided by one of the conditions (haptic or auditory feedback) and attempted performing the pattern in the next trial. We informed participants that they were allowed only to attempt each target

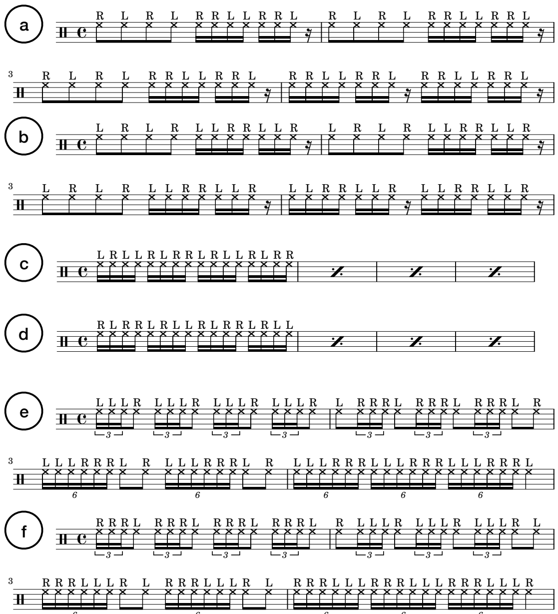

Figure 7: Our three tasks with two patterns per task. These were prepared by a professional jazz drummer for our study. The tasks range in difficulty levels.

pattern for 10 times. There were three tasks, varying in level of difficulty: **easy**, **medium**, **hard**. Participants were always shown the pattern in musical notation in a screen in front of them; this setup mimics precisely how novices learn drumming (auditory beeps and score)

6.5 Tasks: Three Drumming Patterns

We prepared six two-handed patterns, two for each difficulty level. These pattern pairs (per difficulty level) are comparable in that they exhibit the same number of beats and rests, same tempo, etc.; they simply have different patterns to prevent learning effects between conditions.

The patterns used for this user study are shown in Figure 7. The **easy** pattern pair, depicted in Figure 7(a,b), consists of eighth, sixteenth notes, and rests; this pattern is a modified version of a standard drumming exercise, also known as *paradiddle*[1]; the second one is a hand-inversion of the first. The **medium** pattern pair, depicted in Figure 7(c,d), consists of the standard unmodified *single paradiddle* at a fast pace of continuous sixteenth notes; likewise, the second one is a hand-inversion of the first. Lastly, the **hard** pattern pair, depicted in Figure 7(e, f), is a sixteenth notes variation of the standard *single stroke four* exercise; likewise, the second version is a hand-inversion of the first. The latter two of three pattern pairs were created based on the classic instructional drumming book [36].

[1]Percussive Arts Society, "Rudiments Online" https://web.archive.org/web/20110718234202/http://www.pas.org/Learn/Rudiments/RudimentsOnline.aspx.

6.6 Error metrics

In analysis of haptic coordination tasks it is important to define the error metrics. We defined a mistake as a beat of the pattern that the user skipped, or drummed too late (more than ±62.5 milliseconds, given our target BPM and note duration), or in the presence of double strokes instead of a single stroke.

6.7 Procedure

Participants were introduced to the drumsticks and drum pad; then, participants completed the aforementioned three tasks for each of the two interface conditions. After completing the three tasks for one condition, participants were asked to answer whether they perceived if they improved using the feedback in this condition. Then, participants switched to the remaining condition. Before the PGM-condition participants were equipped with our haptic system with the help of an experimenter. Lastly, after experiencing both conditions, participants were asked to choose which condition they preferred.

7 RESULTS

Drumming Performance. We performed a two-way ANOVA (2x3 independent variables, i.e. two feedback conditions and three task in the difference level of difficulty) and found significant main effects of task ($F(2, 714) = 173$, $p < 0.01$) and two feedback conditions ($F(1, 714) = 34.5$, $p < 0.01$) on the error ratio. We could not find significant interaction of task and feedback ($F(2, 714) = 0.922$, $p = 0.398$), however, this is not an issue because it means we cannot compare the audio and haptic feedback on the difference difficulty. For the accuracy of the timing, we did not find any significant difference with a two-way ANOVA ($p > 0.05$). As post-hoc test, we performed t-tests (Bonferroni adjusted p-values) and found a statistical significant different using, suggesting that PGM outperformed auditory feedback in terms of error ratio. Results of t-tests are following: the **easy** pattern ($t(238) = 3.74$, $p = .000200$), **medium** pattern ($t(238) = 2.51$, $p = .0130$), and **hard** pattern ($t(238) = 4.13$ $p = .000100$). Figure 8 depicts the results. For accuracy of timing for those right hitting, we did not find a statistical difference between interface conditions, which is depicted in Figure 9, as with the result of a two-way ANOVA. The data didn't confirm that they are normally distributed using Shapiro-Wilk test ($p > 0.05$), thus we performed these parametric tests after square-root transformation. As our sample size is quite small, we also performed a non-parametric analysis, the Scheirer–Ray–Hare test for the non-transformed data shows also significance between the audio and haptic feedback conditions ($p < 0.05$).

Preferences. 9 of 12 participants stated that they preferred the PGM-condition over the baseline. Furthermore, 11 of 12 participants stated that they felt an improvement immediately after the PGM-condition, while 7 participants stated a perceived improvement after the baseline condition.

7.1 Participants' commentaries and open-ended questions

Participants answered open-ended questions after each condition and all trials and we interviewed participants about their experience after finishing the experiments.

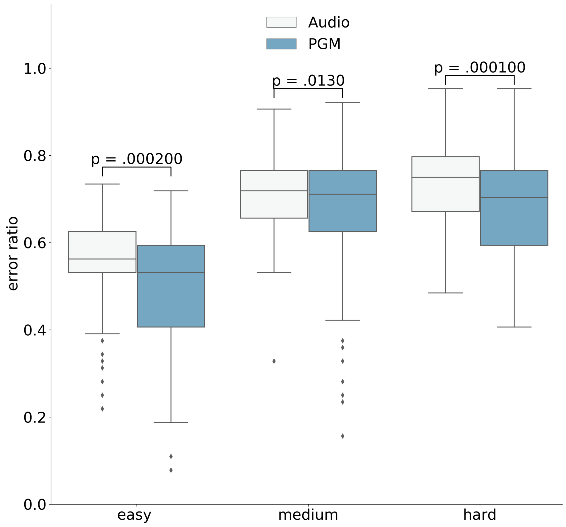

Figure 8: Results of error rate for each task.

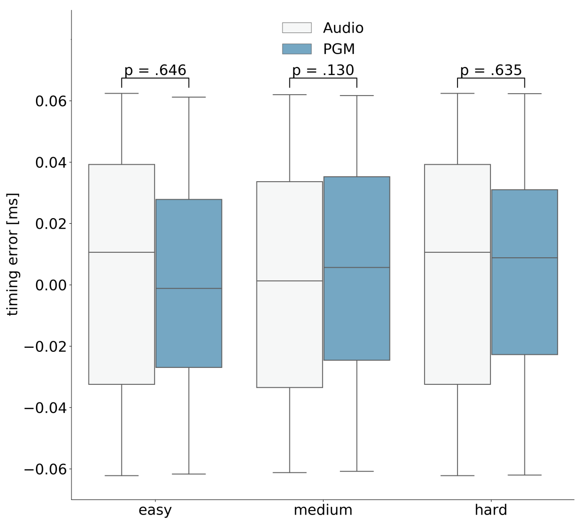

Figure 9: Results of timing error for each task when participants hit drum in right timing.

Several participants made specific comments comparing the two approaches. For instance, P3 commented "PGM makes me less tiring and enjoyable. I am a visual person, PGM is better for me. Audio is easy to miss when I was failed". Some participants (P5 and similarly for P8) stated: "it's less confusing and less pressure".

With regards to embodiment, participants had mixed feelings, while the majority commented that PGM "worked!" and "felt right", some participants mentioned they did not feel that *they* were moving but that they *were being moved*; for instance, P9 mentioned "PGM pulls my arms when I need to hit the drum ". P4 commented about the feeling of actuation by PGM that compared with audio, "Audio is somebody teach me, PGM is just like control me to drum, It's not me, but it's internal". Furthermore, a few participants added that those sensation caused by PGM is quite new for them and actually, P5 mentioned that "I feel like the audio one had more pressure. The PGM has more of guidance feel to it albeit being quite fast-paced. Maybe one just has to get used to it". suggesting that indeed, there is a learning curve to this new sensation.

For fatigue, some participants confirmed that PGM makes them more tired, even if they have a good impression for the feedback. Actually, P7 mentioned: "PGM was good for me, it was playful. However, I was too tired, while PGM leads me to drum."

Some participants mentioned that audio is better than PGM. P3 stated "Because sometimes the force feedback by PGM confuses me with the rhythm. But for some melody, PGM helped." P9 added in an interview "Manipulation of hands disturb me to focus on drumming, and I felt my arms move to the opposite direction from right direction."

8 DISCUSSION

Our study results support our hypothesis, i.e., proprioceptive feedback using *PGM* did indeed enhance motor learning in case of drumming. Furthermore, we got participants' positive comments including "It feels like a bump which can teach you how to hit on the beat, and I recognize that this is related to learning by body cognition", which is the essence of why we used PGM to implement this functionality based on our embodiment.

One thing, we need to mention is that our study is limited for motor consolidation because our experiment has taken only for 90 min and it is a short-term experiment for motor learning. We cannot argue anything how that proprioceptive feedback affected long-term memory. However, we also observed that, proprioceptive feedback (e.g., the actuation of participants' hand) was easier to understand rhythm pattern. Several studies reported that haptic guidance including proprioceptive feedback brings greater benefit for initially less skilled subjects [26, 27]. Accordingly, P1 mentioned "I used a strategy, that is developed task using PGM beforehand, when I trained using audio feedback, but I think I can't develop the idea when the order is inverted. It was more clear for me how I should move my body (when I use PGM) because my body moves before my brain reacts". This suggesting that the feedback using PGM is also easier to understand for participants and is beneficial for beginners. On the other hand, P2 stated "PGM works for 1st and 3rd task, but for 2nd task (Figure 7(c,d)), it doesn't work because of too fast and continuous rhythm patterns", while some participants commented opposite. This happens because some people are faster than others in responding to tactile or auditory stimuli. Actually, a well-trained musician has a better perception for multisensory stimuli compared to non-musician[18]. Although participants in this study are people who never trained for any musical instrument, they might still have a variant of responding time. Hence, some participants could utilize proprioceptive feedback to train for faster and continuous rhythm patterns, while others could not. The challenge point theory, an influential motor learning theory, stated that optimal learning achieved when the difficulty of tasks fit the level of the performer[12]. As a recommendation for further use of proprioceptive feedback for motor learning, we suggest conducting the learning process step by step depending on participants' level of reaction time to foster motor learning.

9 CONCLUSION

In this paper, we unveiled how pneumatic artificial muscles impact skill acquisition of two-handed drumming. Pneumatic muscles are an emergent actuator of particular interest in haptics as they strike an interesting balance: lighter than rigid-exoskeletons and, certainly, more precise than electrical muscle stimulation. To understand the effect of pneumatic muscles on skill acquisition, we conducted a user study where we compared participants' drumming performance after training with audio or with our artificial-muscles. Our haptic system is comprised of four pneumatic muscles and is capable of actuating the user's wrist to drum accurately up to 80 bpm. We found in our study that pneumatic muscles improved participants' correct recall of drumming patterns when compared to auditory training.

We believe that our work is a step towards understanding the advantages of artificial muscles in HCI research. Many institutions, such as rehabilitation clinics or factories, employ exclusively rigid-exoskeletons to train their users, while researchers in assistive technology exploring the rigid-flexible-soft structure design of exoskeletons in their applications. We believe that soft actuators, such as pneumatic artificial muscles, have also an immense potential for motor learning in HCI as our findings revealed.

As future work, we plan to study the application of our artificial muscles to other locations, such as covered users' whole arm, to move their body in more bigger movements applicable for a wider range of tasks, beyond drumming.

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