DigituSync: A Dual-User Passive Exoskeleton Glove That Adaptively Shares Hand Gestures

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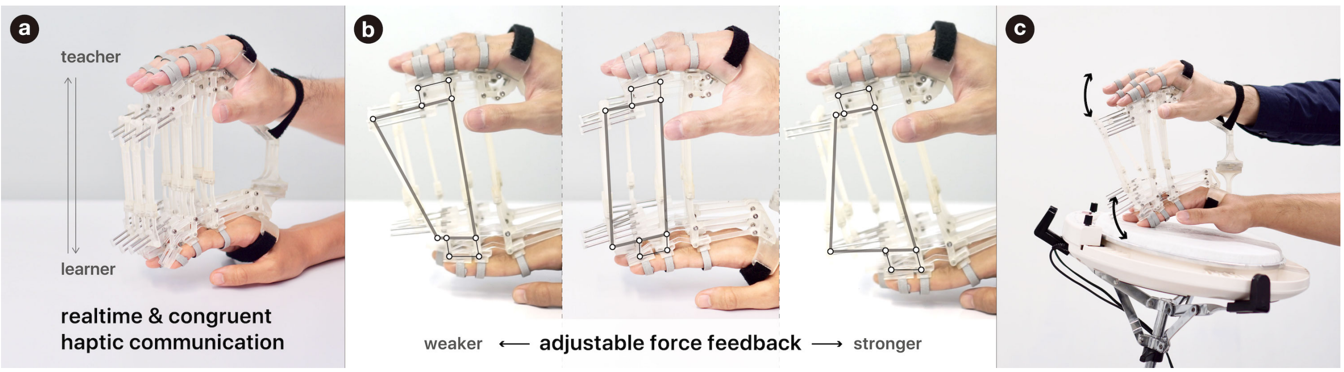

Figure 1: (a) We engineered DigituSync, a passive exoskeleton that allows two users to share the same hand pose. DigituSync requires no electronics to transmit forces and has virtually no latency, making it ideal for fine-motor skill transmission. In addition, (b) each finger mechanism features variable-length linkages that allow adjusting the amount of force to be conveyed. (c) Taken together, DigituSync is useful and safe to deploy in a variety of settings, such as between students and teachers in a music classroom.

ABSTRACT

We engineered DigituSync, a passive-exoskeleton that physically links two hands together, enabling two users to adaptively transmit finger movements in real-time. It uses multiple four-bar linkages to transfer both motion and force, while still preserving congruent haptic feedback. Moreover, we implemented a variable-length linkage that allows adjusting the force transmission ratio between the two users and regulates the amount of intervention, which enables users to customize their learning experience. DigituSync's benefits emerge from its passive design: unlike existing haptic devices (motor-based exoskeletons or electrical muscle stimulation), DigituSync has virtually no latency and does not require batteries/electronics to transmit or adjust movements, making it useful and safe to deploy in many settings, such as between students and teachers in a classroom. We validated DigituSync by means of technical evaluations and a user study, demonstrating that it instantly transfers finger motions and forces with the ability of adaptive force transmission, which allowed participants to feel more control over their own movements and to feel the teacher's intervention was more responsive. We also conducted two exploratory sessions with a music teacher and deaf-blind users, which allowed us to gather experiential insights from the teacher's side and explore DigituSync in applications.

CCS CONCEPTS

• **Human-centered computing**; • **Haptic devices**;

KEYWORDS

Exoskeletons, Mechanics, Haptics, Skill sharing

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1 INTRODUCTION

Learning dexterous hand skills plays an important role in our lives, from using highly dexterous interfaces (e.g., keyboards, touch screens), playing musical instruments [32, 33, 35, 49, 76, 106], performing surgical procedures [11], and even assisting others with their movements, such as in hand rehabilitation [1, 18, 82, 92]. These interactions require precise and stable finger pose, force, speed, and timing (rhythms) control over individual fingers and their coordination [33, 49, 53, 69, 81, 108]. Given the complexity of these activities, learning them takes a substantial amount of time due to the need to acquire many fundamental skills (e.g., simultaneous control of finger pose, force, speed, rhythm) that are hard for a novice user to understand by just passively watching a skilled user.

As such, a significant amount of research in interactive systems has been dedicated to creating devices that can support transferring skills. Popular examples of such devices include those that share visual perspectives using either head-mounted displays (HMD) [4, 44, 45, 47, 52, 101] or projection mapping systems [50, 76, 106], both of which allow a student to view the teacher's hand movements from the teacher's perspective. While these approaches scale up well, they do not transmit all the rich information that underlies skilled movement, such as force control. As a response, many researchers have focused on designing wearable devices that provide the missing haptics by leveraging exoskeletons with active motors [6, 25, 31, 56, 61, 62, 78, 94], electrical muscle stimulation [29, 55, 66, 68, 89], or even pneumatics [22, 87]. Providing haptic feedback directly to a novice user's body has often proven to be effective in motor learning scenarios such as learning rhythmic activities [22, 24] or recovering grasping capability after injuries [6, 13, 30, 99].

However, active haptic devices (e.g., motor-based exoskeletons) are not without limitations. This includes limitations such as **(1) end-to-end latency**, which is problematic in skill-sharing [71]—in fact, even assuming a collocated system (no network; teacher and learner see each other), just 200ms of haptic latency (very fast for motor-based exoskeletons) will be detrimental to the learning experience [28, 71], the sense of agency [5, 17, 79, 98], and the learning [46, 98]; **(2) prohibitive cost**, a pair of exoskeletons, such as Dexmo [25], might sell anywhere between 2400-45000 USD (actual quotes from vendors), which prevents exoskeletons and other active haptic devices from being widely used in school or home settings; **(3) adaptive feedback**: the challenges of the manufacturing cost and the setup effort in active haptic devices made researchers explore simpler and direct techniques such as "hand-over-hand guidance" [8, 82]—a technique in which the therapist assists a user in performing a task by physically grabbing the user's hands or wrists, or even using simple knitted joined-suits or gloves to synchronize two bodies' movements [100]; while these simple techniques can provide instant haptic feedback, these are not designed to transmit complex gestures (e.g., knitted joined-gloves have a lot of mechanical slack) nor these provide adjustable force feedback, which plays a critical role in skill acquisition and learning experience including the feeling of agency and the motivation [2, 23, 32, 42, 80, 96, 111].

In this paper, we take a different approach to realizing finger-skill transfer, one that is inspired by the precision and dexterity of exoskeletons but that circumvents their adjustability, latency, and prohibitive cost. To achieve this, we engineered DigituSync, a completely passive dual-user hand-exoskeleton. DigituSync allows two users to share the pose, force, speed, and timing of their finger movements on all fingers via mechanical linkages. Because the core of DigituSync is entirely 3D printed and has no electronics, its cost is as low as 40 USD, which we hope will enable such devices to be adopted in large classrooms. Moreover, as DigituSync is designed for providing adaptive feedback to a learner, we engineered it with end-user customization in mind, i.e., the teacher or the student can change the force transmission ratio to adjust the level of intervention in proportion to their learning progress.

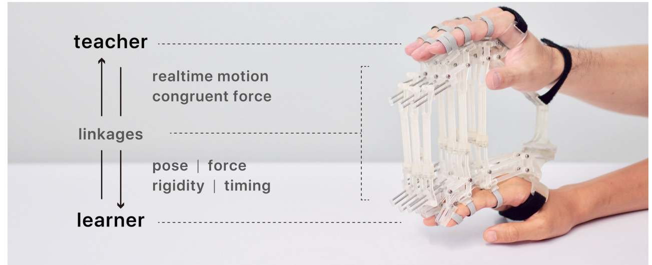

Figure 2: Sharing real-time finger motion and force through linkages between two users

2 OUR APPROACH: SHARING DEXTEROUS HAND GESTURES THROUGH PHYSICAL LINKAGES

Our key contribution is the design, engineering, and evaluation of a dual-user passive exoskeleton that allows users to share their hand postures in dexterous activities, as depicted in Figure 2. Our approach has the following benefits: **(1) adaptive, real-time, and congruent haptics**: unlike active exoskeletons which require sensors and actuators, our passive exoskeleton users can experience real-time haptics (e.g., pressure, rigidity) without any perceptual delay and much loss of fidelity. This is a direct benefit of our physical link. More importantly, our custom mechanics allow users to change the amount of force feedback, while preserving the nature of real-time and congruent feedback, enabling customization of their learning experience; **(2) safe to use**: our exoskeleton is entirely controlled by the users, without forces from motors, making it extremely safe and easy to deploy; **(3) wearable, walk-up-use, and low-cost**: our device literally fits the user's hands like a glove, it is easy to understand and use without any explanations, which we confirmed in our user studies. It also features magnetic linkages that allow to attach and detach two users together, enabling students to receive haptic assistance just when needed. Lastly, thanks to the passive form factor the cost is drastically reduced (40 USD), making it easy to equip a classroom with dozens of DigituSync.

Naturally, our exoskeleton design is not without its limitations: **(1) hand-over-hand guidance**: the teacher can guide the learner by positioning their hand over the learner's hand, while this suits applications such as piano, pegboard rehabilitation, occupational therapy, etc.; it restricts the space of applications when compared to motor-based decoupled exoskeletons; **(2) finger motion**: our current mechanism solely transmits vertical finger motion, while a teacher can rotate a learner's hand through the wrist linkage. It also places linkages on the finger's dorsal side, which interfere with the user's palm, this prevents full grasp gestures; **(3) the weight of the other**: since both users' hands are physically connected, users feel the weight of the other user, which might impact the performance; yet, in our studies, no participant mentioned this limitation. Lastly, note that we are not proposing to replace all existing haptic devices; instead, we tend to think of DigituSync as a unique passive device that is particularly useful for situations that require no latency, high accuracy, and easily deployable in safe settings.

3 RELATED WORK

3.1 Hand Skills and Dexterity

Hand interactions are of one the central abilities of human beings [43]. A dexterous interaction, such as playing the piano or interacting with a computer keyboard, requires precise control of one's individual fingers' pose, force, speed, and timing [33, 49, 53, 69, 81, 108]—usually in synchronization with one's hands and eyes. Dexterity played such a major role in evolution that much of our brain's capacity is dedicated to understanding the state of our hands. As such, there is a lot of research in interactive systems that can allow the learner to *see* from the teacher's perspective.

3.2 *Seeing* from the teacher's perspective

One popular and effective way to convey a person's physical interactions to another is by visually depicting what the other sees from their perspective. This has been realized by visually projecting their gestures [50, 76, 106] or by switching/blending both user's views using head-mounted displays (HMD) [4, 44, 45, 101]—these approaches allow, for instance, a teacher to transfer rhythmic hand movements [47, 52]. These techniques have been further extended by using virtual reality (VR) which also allows two persons to share a virtual body [19, 26, 88]. While these visual-based approaches allow for tele-learning, they do not transmit all the *rich haptic cues* that underlie skilled movements, such as pose, force, speed, and timing control. While visual-based methods might apply for a subset of these skills, other cues are not being conveyed, such as force control.

3.3 *Feeling* from the teacher's perspective

As a response, researchers turned to engineer wearables that provide the missing haptics. For instance, even just sharing vibrotactile cues allows us to teach rhythms [18, 34], melodies [35], and gait [63]. While vibration is exceptional in providing temporal and tactile information, it leaves out kinesthetic cues, such as *forces*, etc. To this end, researchers often rely on force-feedback devices with sufficient force to move the user's body (typically with motors), including large surgical telerobots that provide enhanced dexterity to doctors or wearable robotic arms, such as *Fusion* [78] or *Naviarm* [56], which allow two users to transfer upper-limb motions, and electrical muscle stimulation (EMS—a technique that directly stimulates the muscles with electrical pulses, causing them to feel force feedback [14, 51, 70, 89–91, 109]. While EMS has been used to share simple movements across multiple users [27, 29, 66, 68] and to teach drumming [15], it still remains a key challenge to *precisely* actuate multiple fingers simultaneously [86]. Aside from *active* actuators or EMS, researchers have been also exploring the other side of the spectrum: *passive mechanisms*. These mechanisms, such as linkages or hydrostatic transmissions, are increasingly popular since they achieve safer, accurate, and direct bi-directional interaction. Examples include: a humanoid robot controlled by hydrostatic tubes from a remote location [103], sharing remote users' presence through mechanical rollers [12], changing the dimensions of the user's hand [59, 64, 65, 67] and body [3] via mechanical linkages, or even computation using microstructure [36–38]. While passive devices excel in safety, they dispense some advantages from active devices, such as dynamic adjustments, etc. As such, researchers have been exploring designs that supplement the passive exoskeletons with additional mechanisms, such as active brakes [16, 25, 31, 54], adjustable dampers [95], or variable-length linkages [110]. We take inspiration from these semi-passive mechanisms to engineer our exoskeleton that allows bidirectional and adaptive transmission of individual finger motions.

3.4 Adaptive and interpersonal haptic learning

There is substantial evidence that supports the role of adaptive and interpersonal haptic learning, coming from HCI and neuroscience. Adaptive training is a training paradigm in which the task or the feedback is varied as a function of how well the learner performs [48], leading to *better performance* as well as more *motivation* [2, 23, 32, 42, 80, 96, 111]. One way to provide adaptive feedback to a learner is to establish an interpersonal haptic communication—the teacher responds to the learner's action *directly*. Researchers have shown that interpersonal motor learning is effective as it can provide more responsive feedback to a learner's action [7, 21, 41, 58, 72–74, 102]. For instance, connecting two users' wrists via a physical linkage, allows them to achieve higher performance in a target tracking task when compared with doing the task alone [20, 83–85]. Therefore, these suggest that feeling the physical movements of the other user (e.g., teacher) play a positive role in skill transmission. This is precisely the inspiration for our work, in which we explore how even a passive exoskeleton can achieve adaptive and interpersonal transmission of new finger skills.

4 IMPLEMENTATION

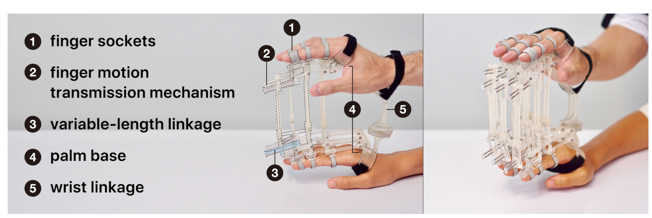

Figure 3: DigituSync consists of finger sockets, variable-length linkages that transmit motion, palm bases, and a wrist linkage.

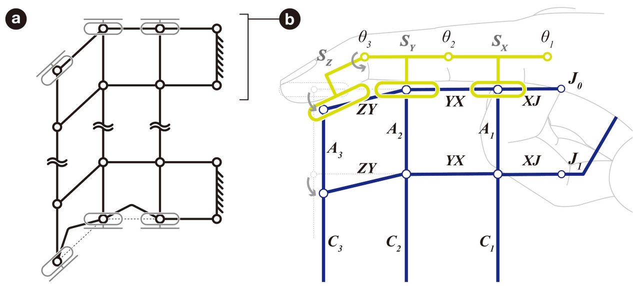

Figure 4: (a) Linkage structure of the transmission mechanism. (b) Overview of the finger socket and the pin-slot behavior.

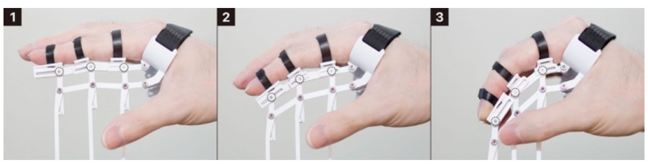

Figure 5: The pin slots successfully absorb the distance displacement of the inner joints and transmit finger motion.

As depicted in Figure 3, DigituSync consists of: finger sockets, a finger motion transmission mechanism with variable-length linkages, palm bases, and a wrist linkage. To accelerate replication, we provide all 3D files and bill of materials of our implementation[1].

4.1 Finger motion transmission mechanism

To transmit the movement of individual fingers between two users, we designed a transmission mechanism, depicted in Figure 4 (a). The core of the mechanism is comprised of multiple four-bar linkages, allowing bi-directional interaction *without motors and with no delay*.

The motion of our mechanism is illustrated in Figure 4 (b). When the teacher bends the first joint of their index finger (distal interphalangeal joint), their fingertip pushes down the bridge link A_3, which in turn pushes down the connection link C_3 and the bridge link A_3 of the learner's side. Thus, the teacher's finger motion is replicated on the learner's finger, and vice versa, moving the users *together*, preserving all haptic cues. The bridge links ZY and YX of the learner's side are angled preventing interreference with the learner's finger joints when bent.

Since the distance between each socket S_X, S_Y, S_Z and between socket S_X and Joint J_0 will change when fingers are bent or extended, a pin slot was attached to the sockets S_i to permit translating movement from each joint to the bridge links ZY, YX, and XJ. These pin slots absorb the distance displacement of the inner joints while transmitting finger motion continuously (Figure 5). To calculate the length of this pin slot, we first measured the angular displacement of each finger joint using a motion capture system (OptiTrack, V100 R2) for a grasping motion. Then, using a simulation in Autodesk Fusion 360, we obtained the minimum pin length required to achieve this motion range. While this mechanism

[1]http://lab.plopes.org/#digitusync-files

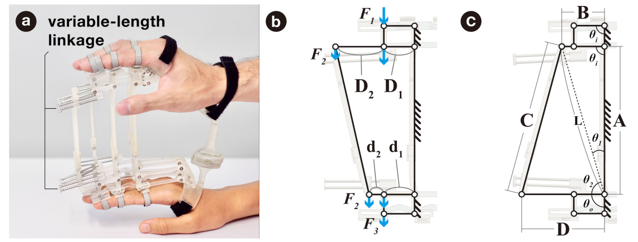

Figure 6: (a) The linkage has two pairs of variable-length mechanisms to dynamically change the transmission. (b) It allows an input force F_1 to be scaled up/down as F_3. (c) It also allows an input angle θ_i to be scaled up/down as θ_o

accommodates various finger poses, it restricts the transmission of fully-clenched grasping gestures (the maximum range of angle of the first and second joints are 40 degrees and 47 degrees, respectively).

4.2 Variable transmission mechanism

Furthermore, we added a variable-length linkage, as shown in Figure 6 (a), that allows for changing the lengths of the four-bar linkage (not for generating haptic feedback to a user) to optimize the learning experience.

Force Transmission. Figure 6 (b) shows the model of the moment of force. D_1 and d_1 represent the linkage length of the connection link ZY. D_2 and d_2 represent lengths of length-adjustable linkage. F_1 and F_3 represents an input and output force respectively. These can be described using F_2, $d_{1,2}$ and $D_{1,2}$ as follows: $\begin{cases} F_1 D_1 = F_2(D_1 + D_2)\ [N \cdot m] \\ F_3 d_1 = F_2(d_1 + d_2)\ [N \cdot m] \end{cases}$. Therefore, the output force F_3 can be described as: $F_3 = tF_1\ [N \cdot m]$, in which ($t = \frac{D_1}{D_1 + D_2} \cdot \frac{d_1 + d_2}{d_1}$). We defined these linkage distances as $D_1 = d_1 = 23mm$. Thus, resulting in: $t = \frac{23}{23 + D_2} \cdot \frac{23 + d_2}{23}$. Since we allow the lengths D_2 and d_2 to be changed from 5 to 35mm, we obtain: $0.44 \leq t \leq 2.29$. This value t indicates that the teacher's finger force is reduced by half when the variable-length linkage is at its minimum (when $d_2 < D_2$) and is doubled when the variable-length linkage is at the maximum (when $d_2 > D_2$). As we will see later, we confirmed the relationship between this value t and the force transmission ratio F_3 / F_1.

Angle Transmission. Figure 6 (c) shows the model of the joint angles θ_i and θ_o, which represent the input angle of the teacher's second finger joint (proximal interphalangeal joint) and the output angle of the learner's, respectively. An additional line L, angle θ_1, and θ_2 can be represented as follows: $L = sqrt(A^2 + B^2 - 2ABcos\theta_i)$ in which $\theta_1 = cos^{-1}(\frac{A - Bcos\theta_i}{L})$ and $\theta_2 = cos^{-1}(\frac{A^2 + B^2 - C^2 + D^2 - 2ABcos\theta_i}{2DL})$. Therefore, the output angle θ_o can be calculated as: $\theta_o = \pi - \theta_1 - \theta_2$. In our implementation, we defined linkage lengths as $A = C = 109mm$, $D = d_1 + d_2$, $B = D_1 + D_2$. We used this model to calculate the angular transmission ratio $\Delta\theta_o / \Delta\theta_i$, which we evaluated in the later section.

Variable-length linkage. Our default method is to provide users of DigituSync with a manual configuration for the transmission ratio. Users simply adjust the intended level of transmission via a slide-joint, as depicted in Figure 7. This mechanism, consisting

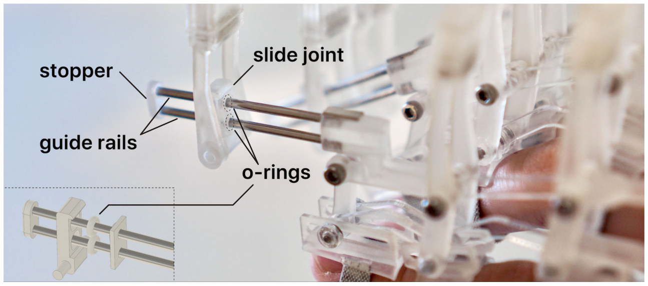

Figure 7: Users can manually adjust the transmission ratio. Positions can be fixed by the rubber O-rings in the slide.

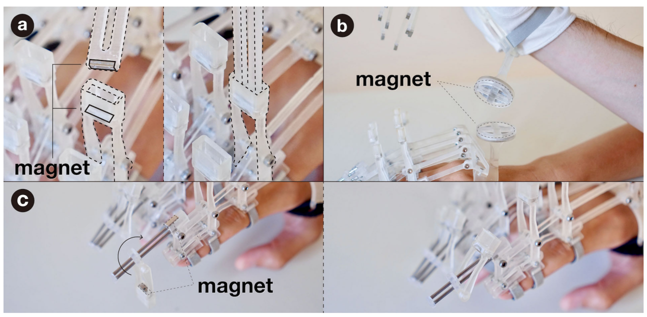

Figure 8: Magnets embedded in the linkages enable quick attachment and detachment of (a) two hands and (b) wrists. (c) They also fix floating linkages when detached.

of using metal shafts (2mm diameter, 45mm length) and O-rings (4mm diameter), was designed with sufficient friction that it does not un-adjust itself but will still be easy to move at the push of a finger.

Detachable linkage mechanism. To transition between the coupled and decoupled state of the dual-exoskeleton, we designed a magnetic attachment mechanism. Small magnet slates are embedded as shown in Figure 8 (a). Those can be detached easily yet can keep them connected while transferring finger poses. Larger magnets, depicted in Figure 8 (b), were used for the wrist connection linkage since this is subject to more force. We also added small magnets near the linkages of the first joint to avoid having moving joints when detached, as shown in Figure 8 (c). Attaching and detaching action require 20s and ~4s to complete, respectively.

Fabrication. DigituSync is manufactured from methacrylate resin on a Formlabs Form3 printer. The total weight of the exoskeleton is 240g (learner's side: 118g, teacher's side: 122g). The rest of the linkages are manufactured using a laser cutter with a 1.5mm thick acrylic plate. Each of those has Velcro tapes to fit each finger's depth.

5 TECHNICAL EVALUATION: LINKAGE TRANSMISSION

To validate the force and angular transmission ratio of DigituSync, we measured the changes in output force and the angle at arbitrary combinations of D_2 and d_2, and then compared them with the

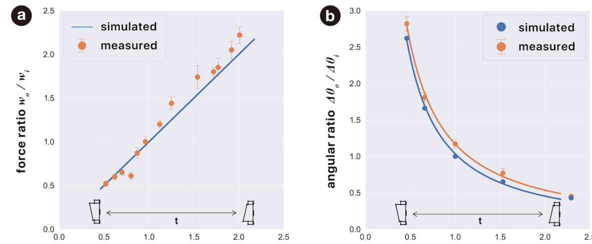

Figure 9: Comparison between measured and simulated results of (a) the force and (b) angle transmission.

previously derived theoretical model. The linkage length D_2 was determined according to d_2 by using the minimum and the maximum length of the variable-length link L_{min} and L_{MAX}, which were 5 mm and 35mm respectively, as follows: $D_2 = L_{MAX} - d_2 + L_{min}$ $[mm]$.

Force transmission evaluation. A dummy weight (AAA battery, w_i = 11g) was used instead of an actual finger to provide a more repeatable load. A load-cell sensor (TAL220) was placed underneath the learner's finger socket S_Z. The output weight (w_o) was measured three times for thirteen different combinations of D_2 and d_2. Figure 9 (a) shows the measured ratio of the input and output force (in orange), plotted alongside the simulated function (in blue). With a known constant weight when $t = 1.0$ (ratio between D_2 and d_2), by increasing the linkage's ratio t, the force transmission ratio also increases linearly, thus it allows variable force transmission from half up to double the input force (fitting function: $y = 1.15x - 0.13$, $R^2 = 0.98$).

Angular transmission evaluation. We also evaluated the relationship between the input and output angles of the finger motion transmission. We used the motion capture system (mean calibration error=0.27mm) and placed reflective markers on the teacher's and the learner's index fingers to measure the second joint (middle interphalangeal joint) angles. The angles were measured five times with five different combinations of D_2 and d_2. Then, we calculated the angular ratio ($\Delta\theta_o/\Delta\theta_i$). Figure 9 (b) shows the result of the t value, measured ratio (fitting function: $y = 1.17x^{-1.12}$), and simulated ratio (fitting function: $y = 1.03x^{-1.19}$). We observed that the measured angular ratio follows the simulated ratio, suggesting that our linkage allows variable angular transmission from half up to double the input angle.

6 USER STUDIES

Our studies were approved by our Institutional Review Board (IRB19-1431).

6.1 Initial study: piano learning

Goal. We first confirmed that the DigituSync exoskeleton *does not degrade the learner's performance* when compared to a traditional learning setting. There are many piano learning settings one can compare against, such as using a screen-based [114], projection mapping [76, 106], vibration [34, 35, 60], force-feedback [22, 24] including EMS [15], and so forth; however, as a preliminary evaluation, we first compared with this *visual demonstration* setting as it is the more traditional and widely used method in piano classes to confirm the DigituSync can be applied to this scenario.

Task & apparatus. Participants were asked to replay a melody with correct timing and volume after it was performed by an experimenter. This task design was modeled after prior studies on drumming skill acquisition [15,22]. We used a force-sensitive MIDI keyboard (MiDiplus, Classic 25). Apple Logic Pro X and Apple Script were used for recording and playing with consistent timings between the demonstration and the replay.

Metrics. We calculated the percentage of correct notes and the percentage of correct intensities using MATLAB and *MIDI Toolbox 1.1* [93]. A note was considered correct if it was played within 150ms of the experimenter's timing, which is also typically used in the studies of drumming [22] or piano [76]. We calculated the intensity score by averaging the intensity error of all notes from those of the experimenter.

Melodies. We created two different melodies (see scores in *Appendix*) with comparable level of difficulty by flipping the order of the note sequence, which generates a melody that untrained participants cannot identify as a flipped-melody.

Procedure. The study consisted of 10 sets of *demonstration* and *replay* phases. There were two demonstration conditions: *visual* (Figure 10a) and *DigituSync* (Figure 10b). In a demonstration phase, participants were instructed to relax their hands and acquire the melody (using one of the two conditions). Immediately after the demonstration, the participant was asked to replay the melody without the exoskeleton attached to that of the teacher. Our two melodies and two interface conditions were presented using a balanced Latin-square across participants.

Participants. We recruited twelve right-handed participants from our organization (six identified as female; six as male; mean age=22.9 years old, SD=2.7), who were compensated with 10 USD. No participant had tried an exoskeleton and had no dexterity impairments. Eleven out of twelve participants had some experience in learning any musical.

Results. Figure 10 (c) shows the error in notes with DigituSync (mean=5.04, SD=1.59) and the visual demonstration (mean=6.63, SD=1.25). Figure 10 (c) also shows the error in intensity with DigituSync (mean=18.84, SD=1.51) and the visual demonstration (mean=23.84, SD=6.86). A paired t-test revealed a significant difference in both notes and intensity error between the two demonstration conditions (notes; $t(11) = -2.68$, $p = 0.02 < 0.05$, intensity; $t(11) = -2.47$, $p = 0.03 < 0.05$).

Participants' feedback. A participant stated "The [DigituSync] feedback actually helped a lot more than after experiencing the condition with just the teacher [visual] (. . .) [in the visual condition] I had to utilize much more memorization to get the volume right compared to when I had the [DigituSync] feedback" (P12). No participant reported negative feedback regarding our device's form factor or weight thanks to the detachable mechanism.

Study conclusion. These results suggest that using the DigituSync exoskeleton in a piano learning setting does not degrade their learning performance. Based on these results, we conducted an exploratory session in a piano class, which we describe later.

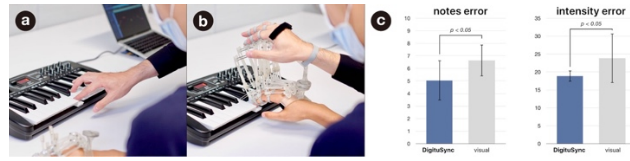

Figure 10: Conditions: (a) visual and (b) DigituSync. (c) We found that using DigituSync does not degrade their learning.

6.2 User study: learning with variable-length linkages

In this study, we investigate whether DigituSync's variable transmission linkages can be used to optimize the learning experience. As such, we compare the users' feeling of control over their own movements and how a teacher was responsive to users' actions that are critical for preserving their learning motivation, in acquiring a rhythm taught by the experimenter in two conditions: *(1) variable transmission*, in which our variable linkages provide a transmission directly correlated to the participants' accuracy while playing the rhythm (i.e., the better their score, the lower the transmission force will be—this is just one of the many possible strategies one could implement, we chose it as it is the simplest in order to explore the role of the variable-length linkages); and *(2) static transmission* (baseline) where the same level of force feedback is provided in all trials, which emulates conventional hand-over-hand guidance or using a knitted joint-glove. We collected subjective feedback on their learning experience as well as measured music performance.

Task. Participants learned a rhythm (in one of two conditions) from an experimenter then replayed it with correct timing and volume. To allow participants to compare the two conditions easily, we simplified the rhythms to use just the index finger. This study focuses on rhythmic patterns with a shorter range for evaluating timing (100ms). The same apparatus from preliminary study was used.

Procedure. The study consisted of a block of 15 trials. Each trial was comprised of two phases: (1) *demonstration*, in which the experimenter leads and plays the rhythm, and (2) *replay*. Note that, in this study, we asked participants to try to *play together* with the experimenter during the demonstration phases (except the very first one, in which they were asked to relax). At the end of each condition, they were asked to answer a 7-point Likert questionnaire and comment at the end of the study regarding their learning experience. Our two interface conditions and two rhythms were presented using a balanced Latin-square.

Variable transmission. While in the baseline condition we kept the linkage transmission at a fixed ratio, as shown in Figure 11 (a), in the variable transmission condition, the experimenter manually adjusted the linkage ratio t between 0.44 to 2.29 in five increments based on the accuracy difference of the participants' current and last replay trial. The idea behind this simple strategy is that the participants receive less haptic feedback from the teacher as their accuracy improved, or vice-versa. In other words, in the case where the score improves by 1-50%, we decreased by one increment of t value (=0.46). In the case where the score improves by more than

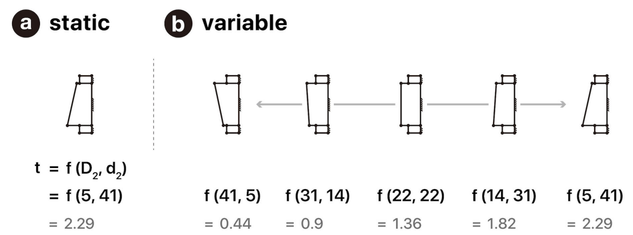

Figure 11: Experimental setup used to explore learning experience with: (a) static linkage or with (b) variable linkage.

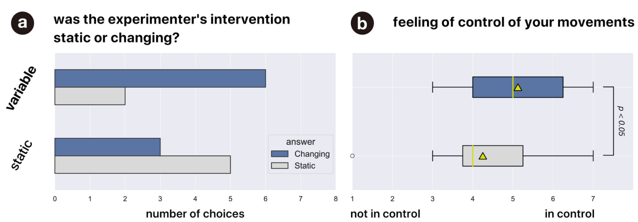

Figure 12: (a) Subjective reporting on the intervention (b) feeling of control. (average(△), median(|), IQR, outlier(◯))

50%, we decreased by two increments of t value (=0.93), as shown in Figure 11 (b). The same logic was applied when the score decreased.

Rhythms. We created two rhythms with comparable difficulty by shuffling the order of note segments; see scores in *Appendix*).

Questionnaire. Participants were asked to answer the following after each condition: (Q_1) Did you feel that the experimenter's intervention was static or changing as a response to your mistakes? (static or variable); and (Q_2) Please rate how much you felt in control of your movements in this condition (1: not in control, 7: in control). Finally, at the end of the study, we asked participants "in which condition you felt that the teacher was able to react better to your mistakes". It is noted that we always referred to conditions as "in this condition" rather than using "static" or "variable" words to avoid bias.

Participants. We recruited eight right-handed participants from our local organization (four self-identified as female; four as male; mean age=22.9 years old, SD=2.7), who were compensated with 10 USD. Five out of eight participants had an experience of learning any musical instruments (mean duration=8.5 years, SD=3.2). The experimenter has 10 years of experience with piano and practiced rhythms beforehand.

Results. While we found there is no difference in the participants' performance between both conditions (timing; $t(7) = -0.83$, $p = 0.43$, intensity; $t(7) = 0.517$, $p = 0.62$), we did find differences in their *learning experiences* across both conditions. First, as depicted in Figure 12 (a), the participants more often reported feeling the experimenter's intervention as responsive in the variable transmission condition than in the static transmission. Secondly, participants reported a higher sense of finger control over their movements (mean=5.1, SD=1.4) in the variable transmission than that of the static transmission (mean=4.3, SD=1.7), which was confirmed using a paired t-test ($t(7) = 2.97$, $p = 0.02 < 0.05$). At the end of our study, Six out of eight participants chose the variable condition for a condition in which "the teacher was able to react better to your mistakes".

Participants' feedback. When asked to justify their preference for the variable transmission, comments included "weaker linkage [trials] gives me the freedom to practice more on my own" (P2), "While I just start learning, the teacher can lead more; while I nearly learn the rhythms, the teacher can provide less force." (P4), and, "I had a different experience. I also felt much more comfortable (. . .) since the sound (. . .) was being impacted by me and provided variability and leeway when I repeat the sound" (P8). Some participants also stated limitations of the variable condition, including "[it] changed my perception of the general dynamic range" (P7), and "sometimes it provided better feedback, but other times it felt like the inconsistency in intervention pressure caused confusion" (P6). When asked to justify their preference for the static condition, two of the participants commented "I liked (. . .) since the intervention felt more consistent" (P6) and "it consistently stimulates my touching sense" (P5). When interviewed regarding their learning experience with the variable transmission, comments included "the first linkage length [high force ratio] have a stronger power to lead (. . .) the second one [low force ratio] is relatively weaker" (P5). With the static transmission, comments included "I let the teacher play (. . .) I found (. . .) it would interfere with the rhythm and pressure (. . .) also my perception" (P3), "I tried to follow the teacher (. . .) and I felt like the teacher and I clashed" (P5), and, interestingly, "I do believe I got better (. . .), as time went on, I got closer to the melody yet I kept doubting myself" (P8).

Study conclusion. These results suggest that our variable transmission impacted positively, while not compromising performance. It is also worth noting that learning a new skill has many challenges beyond improving one's performance, such as keeping oneself motivated [96, 97], which, again, the variable transmission seemed to support better. Yet some participants preferred a static transmission, the real benefit to note regarding the variable transmission is that it can also be static and they can choose. There are more advanced learning strategies that can be coupled with our variable linkage mechanism, such as [20, 23, 77, 104] as well as additional sensors, such as electromyography, eye tracking devices [39, 40], or brain-computer interfaces [111, 112], enabling more accurate estimation on the user's state.

Discussion on usability. We also received feedback on the exoskeleton design such as absorbing personal differences in hand dimensions and applying this to other parts of the body. These could be achieved by incorporating computational techniques for mechanical design [57, 64, 107, 113].

6.3 Exploratory session: feedback from music teacher

In this session, we explored teaching experience with a professional pianist in an actual piano class. We asked a tenured music professor (45 years old, +20 years of teaching) at music college to use DigituSync anytime during their one-on-one piano class. In this class, the student was an advanced student (20 years old and more than 10 years of experience) and had no prior experience in using the exoskeleton. We provided no instructions whatsoever to the

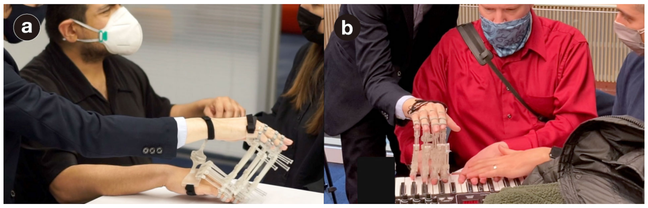

Figure 13: (a) A deaf-blind user (middle) is testing the usability of DigituSync while receiving instruction from a protactile sign interpreter and (b) playing a rhythm together.

teacher as we wanted to understand if DigituSync affords "walkup use".

Teacher's feedback: The teacher stated "glove was interesting for my piano classes (. . .) I chose to use it with a more advanced student, who plays well but does not articulate well yet [articulate refers to the length of its sound and the shape of its attack and decay] (. . .) while we were playing a contemporary piece, I put on the glove and demonstrated how to articulate legato [playing notes smoothly and connected] and portato [playing notes smoothly pulsing] to sound distinct [these are two different articulations], as my student tends to slur these in the same way, [this] was visibly exciting." The teacher also elaborated on limitations, "[it] did not work for any interval, as it was difficult for me to extend their hands via the glove to play a voice doubling [informal language to playing the same note an octave above], perhaps a future glove could permit this and have some more flexibility on the curl position too".

Participants' feedback on walkup use: The teacher stated "surprisingly, I found it easy to use. When I first saw it, I thought I would never be able to get inside the glove alone, but I was able to do it and the student too (. . .) after we used this for articulation, the student played the remainder of the piece with the glove and I was surprised by it, [student] said it feels very different, but he quickly was getting used to it".

Reversing roles: Surprising to us, teacher and student decided to reverse roles (again, we gave no prompts or even instructions). Teacher explained "this time I also let my student control my hand, which was a fun exercise, but also when we broke it – perhaps having too much fun.".

6.4 Exploratory session: feedback from deaf-blind users

We also explored using DigituSync with deaf-blind users in a workshop, depicted in Figure 13. While these sessions did not carry the rigor of our controlled experiments, they allowed us to gather insights into how deaf-blind users reacted to DigituSync in a looser setting. We gave a brief introduction to the protactile sign language interpreters. After the interpreters communicated with the deaf-blind participants, the deaf-blind participants either touched, grabbed, or moved the exoskeleton without attaching it to their hands. In this session, three deaf-blind participants (P1, P2, P3) tried the DigituSync for 15 minutes each.

Participants' feedback. P1, who was born deaf-blind, attached the exoskeleton, then received rhythms from the experimenter on the table, as shown in Figure 13 (a). P1 stated that "[when] move those different knuckles [as they felt all the fingers move] (..) they could be stronger so that I can feel it much better". After I asked whether this can be used for, P1 stated that "I think this kind of device would be good for (. . .) supporting a person to change a specific habit [of fingers, referring to erroneous finger poses]". We also received opposite reactions regarding the feedback strength. P2 tried the exoskeleton with a MIDI keyboard as shown in Figure 13 (b). P2 stated they would prefer to receive feedback on a targeted part of a finger (alluding to the movements being too strong, conversely to P1). Lastly, a P3 used the exoskeleton in midair, similar to signing, and stated "I think it has a great potential (. . .) such as teaching cooking for children (. . .) because it would support memorizing the position of cooking utensils". P2 and P3 were born Deaf and lost vision over time.

7 FURTHER OPPORTUNITIES FOR DIGITUSYNC

We believe there is a range of interesting motor learning scenarios where users can leverage the benefits of DigituSync: adaptive, real-time, and congruent haptic communication with walk-up-use and low-cost form factor.

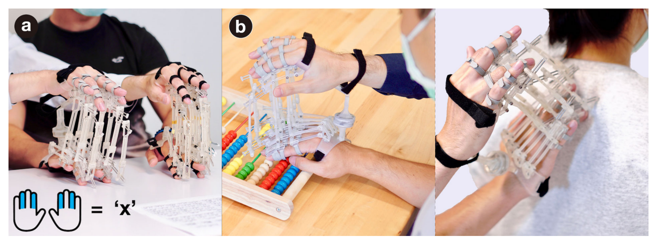

Figure 14: Application scenarios: (a) Finger braille training; (b) Hand-over-Hand Guidance; visually impaired persons receive manual manipulation during therapy or performing massage.

One such example is in teaching languages based on complex and fast finger gesture combinations, such as finger braille, an important tactual communication language used by deaf-blind people, as depicted in Figure 14 (a). Highly skilled interlocutors and interpreters, not only just tap with their fingers to spell letters, but can also express emotion and attitude with the *tapping pressure* and rate [10, 105]. Another interactive space is in physical therapy for patients who lost some degree of motor function. Physicians make often use of direct "hand-over-hand guidance" [82], which is extremely similar to how DigituSync operates. Given the adjustability of feedback, it might improve patients' learning experience including their motivation as we found in our user study. These could also include, for instance, teaching how to operate an abacus and learning acupressure techniques for blind users [9, 75], as depicted in Figure 14 (b).

8 CONCLUSION

We engineered DigituSync, a passive-exoskeleton that physically links two hands together, enabling two users to adaptively transmit finger movements in real-time. We conducted a user study and two exploratory sessions to evaluate the benefits and challenges of the DigituSync in potential scenarios: In our user study on adaptive learning experience, we examined the role of the variable-length linkages on the learning experience; we found that while it did not compromise performance, participants felt more control over their own movements and felt the teacher's intervention was more responsive. Then in our exploratory sessions, we gathered insights from participants (a piano teacher and deaf-blind people), which provided inspiration for future development. Finally, we discussed further opportunities to use DigituSync in haptic communication, such as assisting the learning of finger braille or how to use tools including an abacus that would benefit from the passive form factor of DigituSync.

9 APPENDIX: SCORES OF THE MELODIES & RHYTHMS

Figure 15: Our two 7-second melodies with comparable difficulty (blue notes in pianissimo, red notes in fortissimo).

Figure 16: Our two 7-second rhythmic patterns with comparable difficulty (with a *crescendo* section in the middle).

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