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Proprioceptive Gaming: Making Finger Sensation Training Intense and Engaging with the P-Pong Game and PINKIE Robot

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Abstract— **Proprioceptive deficits are common after a stroke and are thought to negatively impact motor learning. Despite this, there is a lack of practical robotic devices for assessing proprioception, as well as few robotic rehabilitation techniques that intensely and engagingly target proprioception. This work first presents the design of a simple robotic device, PINKIE, developed to assess and train finger proprioception. PINKIE uses low-cost actuators and sensors and is fabricated completely from 3D printed, laser cut, and off-the-shelf components. We then describe the design and testing of a gamified proprioceptive training technique, Proprioceptive-Pong (P-Pong), implemented with PINKIE. In P-Pong, players must continuously make game decisions based on sensed index and middle finger positions, as the game robotically moves their fingers instead of screen pixels to express the motion of the ball and paddle. We also report the results of a pilot study in which we investigated the effect of a short bout of P-Pong play on proprioceptive acuity, and quantified user engagement and intrinsic motivation of game play. We randomly assigned 15 unimpaired human participants to play 15 minutes of P-Pong (proprioceptive training group) or a similar but video-only version of Pong (control group). We assessed finger proprioception acuity before and after game play using the Crisscross assessment previously developed by our laboratory, engagement using the User Engagement Scale, and motivation using the Intrinsic Motivation Inventory survey. Following game play, there was a significant improvement in proprioceptive acuity (2.2 ± 2.6 SD mm, $p = 0.023$) in the proprioceptive training group but not the control group (0.5 ± 0.9 SD mm, $p = 0.101$). Participants rated P-Pong highly on all survey subscales, and as highly as visual Pong, except in the Perceived Usability and Competence subscales, a finding we discuss. To our knowledge, this work presents the first computer gaming approach for providing intense and engaging finger proprioception training, by splitting the feedback of game elements between the visual and proprioceptive senses. The pilot experiment indicates that the human sensory motor system has the ability to at least temporarily improve proprioception acuity with such game-based training.**

I. INTRODUCTION

Upper limb motor and sensory deficits are common in stroke survivors [1], [2] and limit the ability to perform activities of daily living [3]. Proprioception has been identified as an essential input for learning [4] and a strong behavioral predictor for motor gains in the hand following constrain-induced therapy [5] and robotic hand therapy in chronic stroke [6], [7], suggesting that the training and improvement of proprioception could improve motor learning and recovery [8]. However, investigating the role of proprioception in motor learning is limited by a lack of reliable, sensitive assessments to classify and grade proprioceptive deficits [9], and by the lack of training interventions to reduce those deficits [10].

Considering the large number of practice repetitions required for sensory [11] and motor [12], [13] learning, the current model of clinical care may limit functional recovery since studies show few repetitions are practiced during therapy sessions [14]. Further, due to the relatively short patient-clinician therapy durations [14], home-based therapy is presently a major aspect of stroke rehabilitation. And yet, the adherence rate for home-based rehabilitation is low [15], potentially due to reduced motivation [16], [17]. Home-based therapy outcomes may be ameliorated by game-based therapy, which has been shown to increase motivation and repetitions [18], [19]. We interpret these shortcomings as indicating a need for practical, patient-accessible, motivating, proprioception training interventions, and developed the Phalange traINer for KInesthesia and Extension (PINKIE) as well as a proprioceptive gaming paradigm as a potential solution.

PINKIE is a simplified, compact version of the FINGER robot [20]. We implemented the Crisscross proprioception assessment, previously developed for FINGER [21], on PINKIE and created Proprioceptive Pong (P-Pong), a computer game that specifically targets proprioceptive acuity training. While games have been developed that incorporate simultaneous sensory feedback (vision, touch, proprioception) of game elements [22]–[24], previous approaches do not integrate proprioception sensing as a required input to game decisions the player makes to succeed. As we describe next, we designed P-Pong to bring the benefits of gamification to finger proprioception training, with the goal of provoking somatosensory learning with motivating, high-intensity training that is continuously and explicitly focused on finger position sensing in order to successfully play the game.

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II. METHODS

A. *PINKIE Device Development*

We developed PINKIE as a practical, low-cost device for the assessment and training of finger extension and proprioception. Like a typical video gaming system, it has a console (PJRC *Teensy 3.6*), display (Excamera Labs *Gameduino 3X*), and handheld controller (Nintendo *Wii Nunchuk*). Proprioception is engaged through the manipulandum (Fig. 1), which can act as a user input device, sensing active finger movement, or output, actuating the fingers in unfurling/furling trajectories. With such a system we can substitute visual states for proprioceptive ones, i.e. we move fingers instead of screen pixels to express the motion of game elements.

The index and middle fingers are each guided by a prismatic-revolute mechanism. For passive finger movements, the linear degree of freedom is coupled to a lead screw actuator (Actuonix Motion Devices *P16*) through a simple magnetic clutching system. For low-resistance active movements the position dependent clutch is disconnected: the actuator retracts past the range of motion of the mechanism, thereby pulling the mechanism against its flexion hard stop and separating the magnets affixed to the mechanism and actuator, leaving the mechanism free for patient driven movements.

Donning involves rotating the entire device about its long axis to the left- or right-hand orientation, taping magnetic rings to the fingers, and adjusting support straps at the hand and wrist with ratchet dials (BOA *S2*). The magnetic finger "rollers" (Fig. 1) attract the rings to simplify donning, act as mechanical fuses to protect against over-extending the fingers, and sense ring presence to enable the actuators through an embedded switch. The device is covered with electrically switchable PDLC film (Smart Tint *LV-SF*) to control hand visibility with no moving parts; the microcontroller can instantaneously switch the film from transparent to opaque. Of note, we fabricated all custom components solely using 3D printing and laser cutting.

B. *Proprioceptive Pong Development*

P-Pong is based on the popular Atari arcade game. We modified the input-output structure of the ball and player's paddle to require proprioceptive sensing for game play and changed the mechanics of the match-style play to progressively challenge proprioceptive acuity.

To require proprioception for play, feedback of game elements (player paddle, ball, and opponent paddle) is divided between the screen and manipulandum (Fig. 2). The manipulandum drives the player's middle finger according to the ball's position in the virtual field. The player then moves the index finger, trying to match the position of the index "paddle" finger with that of the middle "ball" finger to hit the ball. From a traditional psychometric perspective, the game is akin to a joint position reproduction task [25]: overlapping the index with the middle finger in physical space corresponds to aligning the paddle with the ball in virtual game space. Differing from a typical joint position reproduction task, the middle finger target position is dynamic, constantly presented (requiring no memorization from the player), and reproduced with an ipsilateral finger [25].

We replaced the ping pong match-style play with a survival style mechanic. At the start of the match the player paddle is wide, and the ball speed is slow. As the player "survives" by continuing to return the ball, the ball speed increases, and the paddle width decreases, until reaching preset limits. The game-controlled opponent always returns the ball, and the game ends when the player misses the ball. From a proprioception perspective, the game difficulty ramps up from start: decreasing the paddle width corresponds to decreasing the allowable separation distance, or position error, between the fingers. We found this mode more engaging than traditional match play and adaptation has been

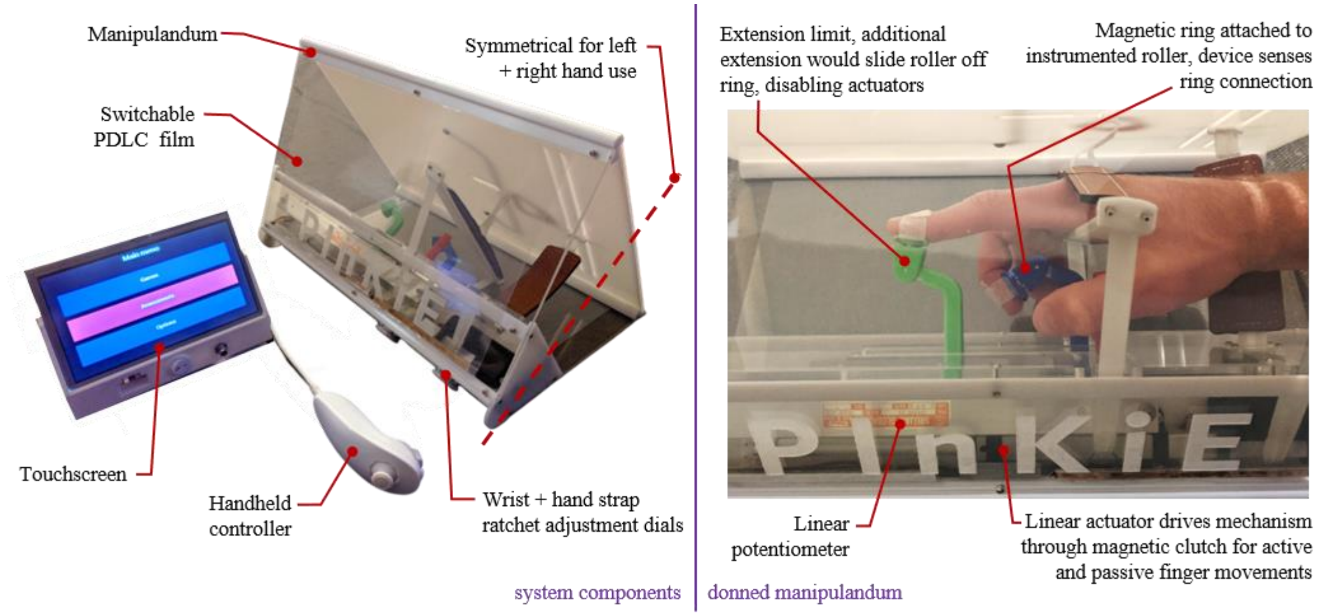

Figure 1. Layout of PINKIE system components (left) and closeup of the donned manipulandum (right). In both images the PDLC film that covers the top and bottom of the manipulandum is transparent. All device functionality such as user settings, assessments, and training games are controlled via the touchscreen.

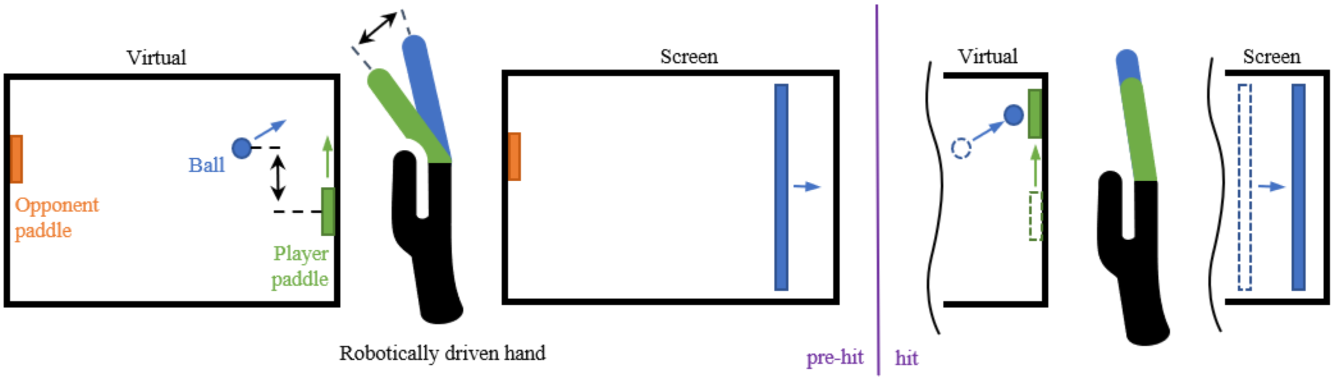

Figure 2. Proprioceptive Pong play at two timepoints "pre-hit" (left) and "hit" (right). At pre-hit (left) the ball is travelling toward the player's paddle, shown in the virtual game state, where by "virtual" we mean the internal game state that is not displayed on the screen but is instantiated in code. The player senses the positions of game elements through separate modalities, either proprioceptively from their robotically-driven hand or visually from the screen. The robotically-driven hand conveys the vertical position of the ball by moving the middle finger and vertical position of the paddle by moving the index finger. The screen conveys the vertical position of the opponent paddle and the horizontal position of the ball as vertical lines. To successfully hit the ball, the player must drive the paddle finger to overlap with the ball finger (pre-hit to hit timepoints). The overlap generates a hit (right) and returns the ball. The paddle, vertical ball position, and player's robotically-driven hand are visually hidden while the ball travels toward the player, and all reappear when the ball reverses. The paddle can be controlled via active movements of the index "paddle" finger which backdrive the robot, or with the contralateral thumb and joystick using the handheld controller, which controls the robot paddle finger motor. The clutch is disconnected for the former and coupled to the finger mechanism for the latter passive "paddle" finger movement scheme. The joystick input mode is intended to make gameplay accessible to people with a stroke who cannot actively move their fingers and was the mode evaluated in this study.

reported to improve reinforcement learning [26].

C. Participants and Experimental Design

The study was approved by the UCI Institutional Review Board and subjects provided consent. We assigned 15 healthy subjects, 7 female, 2 left-handed, ages 20-51 to either the proprioceptive training (8 subjects) or control (7 subjects) group. The proprioceptive training group played P-Pong with their dominant hand in the manipulandum and their non-dominant hand holding the controller. The control group played a traditional, visually-driven version of P-Pong. Unlike for the proprioceptive training group, the ball and paddles were always displayed on screen and the dominant hand was not driven by the robot like the traditional video game. The dynamics of the ball and paddle were the same for both groups.

Each participant attended one session comprised of a Crisscross baseline assessment of finger proprioception acuity, 15 minutes of game play (P-Pong for the proprioceptive training group or visual Pong for the control group), and a Crisscross post assessment. We confirmed participants understood Crisscross and their assigned Pong version with an introductory practice period. To account for differences in adapting to the rules and controls of each activity, participants practiced until they verbally acknowledged that they understood the activity. We implemented Crisscross in the same way as described in [21] with a total of 36 finger crossings at both the baseline and post-training assessments. For each crossing, the robot moved the fingers from opposite flexion and extension positions towards one another with random movement start delays, and the participant indicated when they believed their fingers were overlapped by pushing a button on the handheld controller. We administered UES and IMI surveys after game play for both groups, the full UES Short Form per [27] on a 5-point Likert scale and select IMI statements on a 7-point Likert scale. For the IMI, we selected 10 statements from the four subscales Effort/Importance, Perceived Competence, Interest/Enjoyment, and Pressure/Tension [28]. We assigned subjects to their training group using an adaptive randomization technique based on their mean baseline Crisscross crossing error to attempt to match mean baseline proprioception acuity between the two groups.

D. Data Analysis

We used crossing error, defined as the unsigned difference in position between the two finger mechanisms, to quantify finger proprioception acuity. For Crisscross, we calculated crossing error from the finger positions at the moment when the participant indicated that their fingers were overlapped. For P-Pong and visual Pong, we calculated crossing error at the moment when the ball reached the player's paddle.

We tested three research questions. First, does P-Pong gameplay improve finger proprioception acuity? To answer this question, we evaluated the change in mean Crisscross crossing error (baseline to post) using Student's t-tests. We compared both experiment groups using the 2-sample t-test and performed 1-sample t-tests on each group to check for significant Crisscross change (versus no change). We also evaluated whether the P-Pong crossing error decreased over the course of game play.

Second, does P-Pong performance predict proprioceptive acuity? To answer this question, we performed correlation to identify whether the mean of the final 36 P-Pong crossing errors predicted the mean of the post-training Crisscross crossing errors across subjects.

Third, is P-Pong motivating and engaging? We evaluated engagement and motivation by comparing post-play UES and IMI survey scores of P-Pong and video Pong using the 2-sample t-test. Following analysis, we converted IMI scores to the 5-point scale used for UES for reporting purposes.

For all t-tests, we first tested for normality and variance homogeneity with the Anderson-Darling and 2-sample F-test, respectively. We performed all analyses in MATLAB R2021a.

III. RESULTS

A. *Does P-Pong play improve finger proprioception acuity?*

Proprioceptive game play significantly reduced crossing error as robotically measured with the Crisscross assessment (one-sided, t-test, p = 0.023), but visual game play did not (one-sided t-test, p = 0.101) (Fig. 3). The mean crossing error decreased by 0.5 ± 0.9 SD mm for the proprioceptive training group, and 2.2 ± 2.6 SD mm for the control group from baseline to post Crisscross, a difference that approached significance (one-sided t-test, p = 0.058). In addition, the P-Pong crossing error (proprioceptive training group) decreased over the course of gameplay (linear regression, p = 0.00 and slope -0.11 mm/min) (Fig. 4).

B. *Does P-Pong performance predict proprioception acuity?*

The Crisscross crossing errors measured post-training were not significantly correlated with the crossing-errors during the last 36 ball hits of P-Pong play (p = 0.82).

C. *Is P-Pong motivating and engaging?*

Participants rated all subscales > 3.0, except IMI Pressure/Tension ≤ 2.0 which is theorized to be a negative marker for intrinsic motivation [28], indicating that user engagement and experience were positive for all activities (Table 1). Scores on two of the eight subscales were significantly less for P-Pong than for Visual Pong – the Perceived Usability (UES) and Perceived Competence (IMI) subscales (2-sample t-test, p = 0.00).

IV. DISCUSSION

This paper first described the design of a practical robotic device for measuring and training finger proprioception. We then introduced the concept of a proprioceptive computer game that splits game feedback between vision and proprioception for the intense and engaging training of proprioception acuity. Finally, the pilot experiment with P-Pong indicated that the human sensory motor system has the ability to at least temporarily improve proprioception acuity with such game-based training.

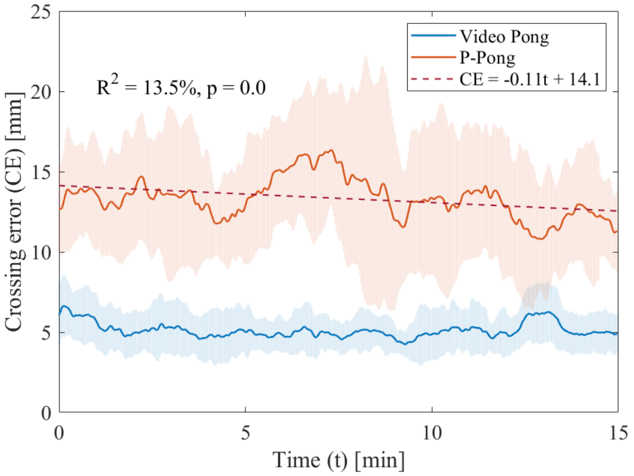

Figure 4. Mean video Pong (control) and P-Pong (proprioceptive training) crossing error over play time. For each subject, we calculated a moving mean of the crossing error over a 60 sec window. Video Pong and P-Pong lines are means across subject moving means, shaded regions are ± 1 SD. The dashed line shows the best fit line using linear regression.

A. *PINKIE: A practical robotic device for measuring finger proprioception*

Clinical techniques for measuring finger proprioception typically rely on crude tests, such as having the patient close their eyes and respond when the therapist moves their finger up or down. Currently, there are few practical robotic technologies for quickly quantifying finger proprioception. We had previously developed the FINGER exoskeleton as a way to provide high fidelity control and good backdriveablity for finger movement studies [20], [21]. We modeled PINKIE after the FINGER exoskeleton [20] in that it incorporates mechanisms for a furling/unfurling motion of the index and middle fingers. Unlike FINGER, however, we simplified the mechanism to a finger-contacting roller and linear slide instead of an 8-bar linkage, we used low-cost actuators and sensors, and we fabricated custom components with 3D printing and laser cutting. Also unlike FINGER, PINKIE has the disadvantage that it can only implement two finger mechanism impedances: either low impedance, in which it is very backdriveable but can't actively drive the finger, or high

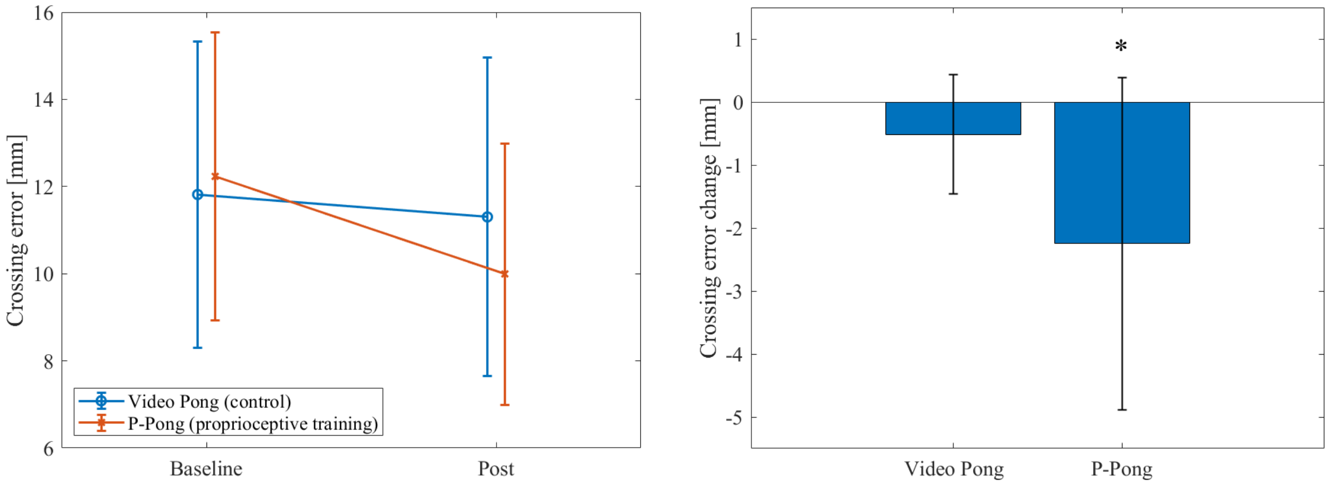

Figure 3. Finger proprioception acuity for each group, measured by the mean crossing error with the Crisscross assessment, at each timepoint (left) and change from baseline to post-gameplay (right). Error bars show ± 1 SD. * indicates significant, one-sided, t-test (p = 0.023) of change compared to zero.

TABLE I. UES AND IMI MEAN SURVEY RESULTS PER SUBSCALE.

Group	**UES**				**IMI**			
	FA	***PU***	***AE***	***RW***	***IE***	***PC***	***EI***	***PT***
Video Pong	4.0	4.2*	4.4	4.1	4.3	3.8*	3.7	1.7
P-Pong	4.5	3.1*	4.2	4.4	4.6	2.2*	4.4	1.9

IMI results were converted to the 5-point scale used for UES. The UES subscales are Focused Attention (FA), Perceived Usability (PU), Aesthetic Appeal (AE), and Reward (RW). The IMI subscales are Interest/Enjoyment (IE), Perceived Competence (PC), Effort/Importance (EI), and Pressure/Tension (PT). *P<0.01.

impedance, in which it is not user backdriveable but can actively drive the finger. We made the impedances switchable via a simple, automatic, magnetic clutch. While this design limits the capability of PINKIE to provide active assistance, these are the two impedance modes essential for most proprioceptive testing paradigms.

B. P-Pong: Implementing a proprioceptive computer gaming paradigm

While games have been developed for proprioception training [22]–[24], previous approaches do not integrate proprioception as a required input to the player's decision making process. Here we presented the concept of a proprioceptive computer game. In the paradigm we propose, players must continuously make game decisions based on sensed finger position as the game robotically moves the fingers, instead of screen pixels, to express the motion of game elements. We implemented this paradigm on the classic arcade game Pong, but it could be applied to many other existing video games. Our intent is to use this proprioceptive gaming paradigm to increase the intensity and motivation for proprioceptive training.

C. Pilot Results with P-Pong

Playing 15 minutes of P-Pong caused a significant reduction in Crisscross crossing error, a measure of finger proprioceptive acuity, while playing visual Pong did not. This indicates that finger proprioceptive acuity can be improved at least temporarily using a proprioceptive gaming paradigm. We also found that P-Pong crossing error decreased over time, which may be due in part to improved proprioception, although other factors influence crossing error during P-Pong gameplay as well (see below).

We have shown previously that crossing error measured with the Crisscross test is sensitive to the proprioceptive decline known to occur with aging [21] and is predicted by a combination of neural function (connectivity between ipsilesional secondary somatosensory cortex and ipsilesional primary motor cortex) and neural injury (total sensory system injury) [29]. In addition crossing error measured at baseline predicts the amount of functional benefit attainable with robotic finger training [6], [7]. The finding that crossing error can be reduced with training is intriguing, given the significance of this maker of proprioception.

Surprisingly, we did not find a significant correlation between Crisscross and P-Pong crossing errors across subjects. This may be because our sample size was small. It may also be because additional physiological mechanisms influence P-Pong performance. Unlike Crisscross, P-Pong required interhemispheric coordination, was dependent on non-dominant hand motor control ability, and involved controlling an unfamiliar entity (i.e. the "paddle" finger, for which the transfer function between the joystick input and paddle finger movement exhibits nonlinear dynamics). Also, unlike in Crisscross, in P-Pong players could potentially use visual information to recalibrate their proprioceptive estimates of their finger positions [30]. Specifically, each time the ball and player paddle appeared on screen (which was only while the ball was traveling away from the player paddle), the player could use simultaneous visual and proprioceptive information to update their belief of their current finger position. One implication of the non-significant correlation between Crisscross and P-Pong crossing errors is that it may be better to define and implement a dedicated finger proprioception assessment (such as the Crisscross Test), rather than trying to infer proprioception acuity from gameplay metrics, as the latter involves other physiological mechanisms that add noise to proprioception assessment.

Participants rated P-Pong positively for all queried engagement and intrinsic motivation subscales. While this result may seem unsurprising since P-Pong is based on a successful and ubiquitous game, we changed the input-output structure through which the player interacted with game elements, which is a key ingredient of the player's experience. We also found small but significant differences between P-Pong and visual Pong subscores on some rating elements that most likely are attributable to the input-output structure. Participants scored P-Pong significantly lower than visual Pong on both the Perceived Usability UES subscale and Perceived Competence IMI subscale. The UES subscale queries whether the activity was frustrating, confusing, and taxing, and the IMI subscale probes feelings related to performance satisfaction and skill level. As the input-output structure was the defining difference between P-Pong and visual Pong play, it could be that the combination of moving the paddle with the non-dominant controller hand, sensing movement with the manipulandum hand, and tracking remaining game elements on screen introduced cognitive burden that was somewhat more confusing and taxing, which in turn led to decreased perceived skill. Perhaps with a longer duration of proprioceptive game play users would rate usability and competence higher. A key direction for future work is to assess the effects of different control scheme designs on proprioceptive improvement. A simplified alternative scheme could be to replace the joystick held in the contralateral hand with an unactuated, stripped down version of the manipulandum, and a "mirror-match" control law where the manipulandum matches the position of the paddle finger with the position of the contralateral input finger.

V. CONCLUSION

These results support the potential value of the proposed proprioceptive computer gaming paradigm for improving finger position sense, and of the simple robotic device PINKIE for delivering proprioceptive assessments and gamified training. Our goal is to translate that value to different rehabilitation settings, including the clinical setting where finger proprioception assessment is crude and few methods are available for intense proprioceptive training, and the home setting where rehabilitation adherence is low.

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