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A Novel Pneumatic Stimulator for the Investigation of Noise-Enhanced Proprioception

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***Abstract*— Executing coordinated movements requires that motor and sensory systems cooperate to achieve a motor goal. Impairment of either system may lead to unstable and/or inaccurate movements. In rehabilitation training, however, most approaches have focused on the motor aspects of the control loop. We are examining mechanisms that may enhance the sensory system to improve motor control. More precisely, the effects of stochastic subliminal vibratory tactile stimulation on wrist proprioception. We developed a device — based on a novel soft pneumatic actuator skin technology — to stimulate multiple sites simultaneously and independently. This device applies vibratory stimulation (amplitude ≤ 0.50 mm, bandwidth 20-120 Hz) to the skin overlaying the tendons of a joint to target the receptors in charge of position and movement encoding. It achieves high spatial resolution (< 1 mm^2), uses a soft and flexible interface, and has the potential to be used in combination with additional rehabilitation interventions. We conducted a feasibility study with 16 healthy subjects (11 younger - 6 females; 5 older - 2 females) in which a robotic manipulandum moved the subject's wrist to defined positions that had to be matched with a gauge. Comparing trials with and without stimulation we found that stochastic stimulation influenced joint position sense. The device we developed can be readily used in psycho-physical experiments, and subsequently benefit physiotherapy and rehabilitation treatments.**

I. INTRODUCTION

Controlled movement of the upper extremities requires that motor, sensory, and cerebral systems cooperate to achieve a motor goal [1]. However, when the sensorimotor system is injured or impaired, most approaches to rehabilitation focus on the motor system. Therefore, we seek to investigate mechanisms that include stimulation and training of the sensory system for potential use in neurorehabilitation therapies.

To generate controlled and stable movements, the neuromuscular system must adjust motor commands continuously based on sensory information. This information includes responses to stimuli produced within the body that relate to position, movement, balance, and effort, i.e. proprioception [2]. Our investigation focuses on the first two aspects: position and movement.

The peripheral and central mechanisms involved in proprioception remain unclear [2]. Experimental and theoretical examinations of movement and position sense indicate that muscle spindles are the primary encoder of muscle length and its rate of change, and, therefore, of joint position [3]. Muscle spindles are located inside the muscle, in parallel to the muscle fibers [2]. Proprioceptive information is derived in the central nervous system from the combined signals of spindles in synergistic and antagonist muscles [4], [5], and further supplemented by signals coming from cutaneous receptors [6]. The proprioceptive sense is thus based on the interplay of processes in the peripheral and central nervous system [7], [8].

One promising approach to enhance sensory function, and one that has gained popularity in recent years, is the use of stochastic stimulation. The application of subliminal mechanical or electrical stochastic stimulation has been shown to improve tactile sensation, balance, and motor control, both in the lower [9], [10] and upper extremities [11]–[14]. The underlying theoretical concept is called Stochastic Resonance (SR). According to SR theory, subliminal noise can improve the detectability and quality of a signal in an imperfect system prone to errors. However, these studies have often relied on electromechanical devices to deliver the vibratory stimulation [9]–[15]. These devices tend to be bulky, stiff, and offer limited spatial resolution.

We developed and validated a novel pneumatic stimulator system to investigate the effects of stochastic stimulation on proprioception. Our goal was to create a device that provides subliminal, vibratory stimulation with high spatial resolution and can be combined with conventional rehabilitation therapy and functional assessment methods (e.g. EEG or MRI).

We tested the safety and feasibility of using this device in a pilot study focused on enhancing wrist proprioception. We hypothesized that subliminal stochastic stimulation improves wrist position estimates. We further hypothesized that, since proprioception decreases with age [16]–[18], and SR theory predicts that the SR effect is only present if the underlying system is nondeterministic — i.e. driven by random factors — or imperfect, older subjects will benefit more from SR stimulation than younger subjects.

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II. METHODS

A. Physiological and Practical Requirements

Our goal is the development of a device that stimulates the sensory system to promote rehabilitation of the upper extremities when affected by sensory deficits. As a first step, we focused on the wrist joint. To target the distal tendons of the muscles involved in wrist flexion and extension, we needed a system that could deliver focalized stimulation across multiple locations of the wrist joint. At the wrist, the tendons that move the hand and fingers are located very close to each other. Tendon diameters at the wrist are typically less than $10\ \mathrm{mm}$.

Physiologically, we sought to apply simulation that is compatible with the frequency response bandwidth of muscle spindles (0-120 Hz, [19]). In accordance with SR theory, the stimulation's amplitude needed to be below subjects' threshold of perception. Because human skin is very sensitive to vibratory stimulation, our setup must deliver very low stimulation amplitudes. Muscle spindles in the ankle muscles start to respond to tendon vibrations of 0-120 Hz at amplitudes below $0.01\mathrm{mm}$ [20]. Vibration perception thresholds at the wrist are not described precisely in the literature, however from pilot testing we estimated these amplitudes to be in the range of 0.05-$0.50\ \mathrm{mm}$ peak-to-peak.

Since tactile perception thresholds vary between individuals, within an individual's different skin sites and with frequency [21], it is necessary to adjust the stimulation intensities — i.e. the vibration amplitudes — for each individual. In view of an application of this approach for rehabilitation, we further considered the necessity of short setup times and a simple design that does not interfere with the therapy's goals, for example restrict the patient's movements.

B. Technical Requirements and Stimulator Design

To meet the spatial requirements of the upper limb's anatomy, we based our design on the novel Soft Pneumatic Actuator (SPA) skin [22]. The size and shape of these silicone-based actuators is highly customizable, allowing for inflatable structures as small as $1\ \mathrm{mm}$ in diameter. The actuators are readily biocompatible because of the material used in their fabrication (Dragon Skin 30® silicone, KauPo, Spaichingen, Germany). The SPA design was guided by the following requirements: inflation amplitudes of 0.05-$0.50\ \mathrm{mm}$; frequency bandwidth: 0-120 Hz, i.e. fast inflation/deflation of at most $4\ \mathrm{ms}$; tendon sizes in the wrist, i.e. a stimulation area of about $\sim 100\ \mathrm{mm}^2$. We expected that the viscoelastic properties of the material would lead to a decrease in the inflation amplitude with increasing frequencies, thus transforming the white noise input signal into a colored noise spectrum. Colored noise has the potential of increasing the SR effect [23] and is naturally present in healthy functioning organisms [11], [24]. We therefore assume that this type of noise benefits our design. Furthermore, to ensure that subjects were blinded to the stimulation during the experiment, the stimulator casing needed to shield auditory cues during operation.

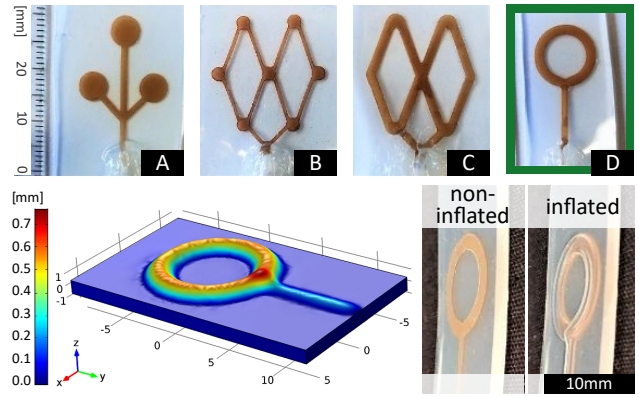

Fig. 1. Soft Pneumatic Actuator (SPA) principles. Top: bubble-tree (A), bubble-duct (B), channel (C) and ring (D) structures. In the final application, we implemented the latter design. Bottom-left: Static inflation simulation of the ring structure for a pressure of $p = 50\ \mathrm{kPa}$ above ambient. Material properties were approximated as linear elastic with Young's modulus $E = 500\ \mathrm{kPa}$, Poison's ratio $\nu = 0.49$ and density $\rho = 1080\ \frac{\mathrm{kg}}{\mathrm{m}^3}$. Bottom-right: Non-inflated (left) and inflated (right) state of the ring actuator shape. Our design supports very uniform and small inflation amplitudes covering a large area.

The SPAs are manufactured by embedding a customized mask between two silicone layers (for a detailed description see [22], [25]). This results in an inflatable cavity. We developed and tested four candidate geometries (Fig. 1, A-D) and analyzed their inflation dynamics — amplitudes in terms of pressure and frequency — across the desired 0-120 Hz range. We simulated the static inflation behavior (see Fig. 1, bottom left) and measured the amplitude of the SPA displacement experimentally with a laser distance sensor (OWLF 4007 FA S1, Welotec, Laer, Germany). During the measurements, one side of the SPAs was fixed to a table whereas the other side was free to move.

To control the air delivery to the SPAs we designed a pneumatic actuation setup that was fed with compressed air regulated at $200\ \mathrm{kPa}$. Safety was ensured using a double-regulator system and continuous pressure monitoring (MPXH6250A, Freescale Semiconductor, Inc., Austin, USA). Three pressure regulators then reduced the pressure to 0-$100\ \mathrm{kPa}$ (MS4, Festo AG & Co. KG, Berkheim, Germany). The stochastic frequencies were generated using a microcontroller (Arduino Mega2560, Arduino LLC, USA) that controlled three high-frequency valves (MHE2, Festo AG & Co. KG, Berkheim, Germany); two for the SPAs, and one to imitate the noise generated by the air flow during stimulation and thus blind the subject about the state of the system. Fig. 2 shows a flow chart of the pneumatic actuation setup. To ensure that the stimulation was consistent at all locations around the wrist, we covered the subject's wrist using a pressurized cuff (OMRON Healthcare Europe B.V., Hoofddorp, The Netherlands). An additional valve and regulator controlled the pressure of the cuff at $4\ \mathrm{kPa}$ above ambient pressure.

C. Subjects

We conducted a study to test the safety and feasibility of the device. We tested 16 subjects divided into two age

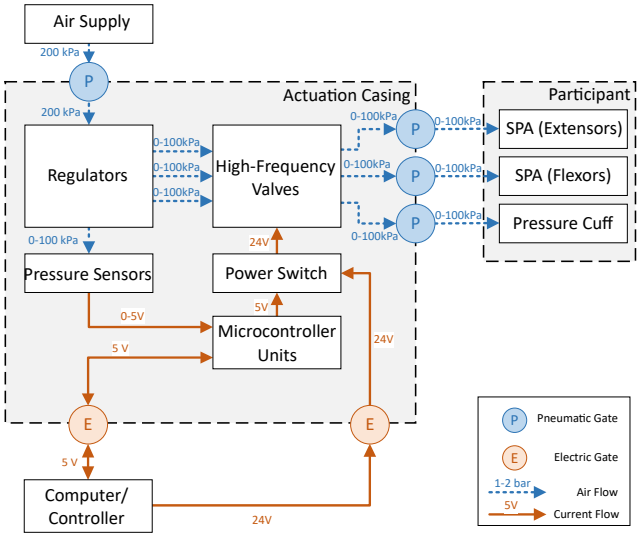

Fig. 2. Flow chart of the energy (current) and mass (air) flows in the pneumatic actuation setup. Here, 0kpa complies with ambient pressure.

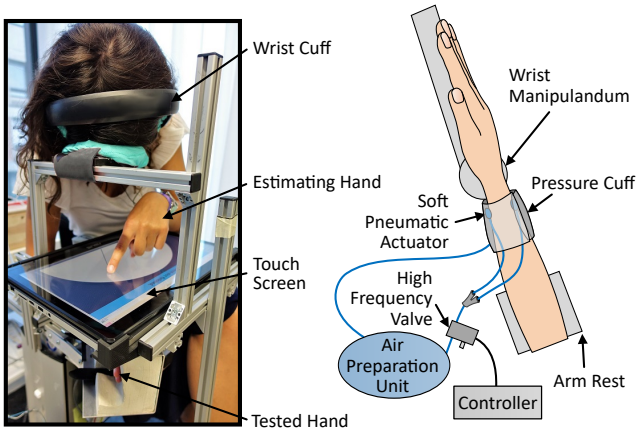

Fig. 3. Study setup. Left: A subject estimates her wrist position on the touchscreen using a gauge. The touchscreen occludes any visual hints of the wrist's position. To prevent auditory cues that might affect the estimation, subjects wore headphones while white noise was played at a comfortable volume. Right: The subjects' arm rests comfortably on an arm rest covered with foam. The wrist's position is manipulated by the ReFlex robot. The Soft Pneumatic Actuators (SPAs) are actuated with high frequency valves that generate the desired stochastic stimulation. To ensure uniform conditions around the wrist, the SPAs are covered with a pressure cuff.

groups: younger (26.5±4.2 years, 11 subjects, 6 females) and older (64.4±6.6 years, 5 subjects, 2 females). Subjects were excluded if they had any pathologies that affected the right upper limb. To avoid effects from limb asymmetry [26], only right-handed individuals were included. Handedness was assessed using the Edinburgh Inventory [27]. All subjects participated voluntarily and gave their written consent. The protocol was approved by the Ethics Commission of ETH Zurich.

D. Study Protocol

To assess the influence of SR on wrist position sense we used a reliable robotic assessment of wrist proprioception based on a gauge position matching paradigm (see Fig. 3, left) [28]. Each subject participated in two sessions on two different days. During each session, the stimulation perception threshold — in terms of the amplitude — was determined. The stimulation amplitude was then set to approx. 80% of the absolute threshold to ensure subliminal stimulation. Four blocks of proprioception assessment followed. This short assessment consisted of 21 trials (for details see [28]). In each trial, one wrist position was imposed by the robot and estimated by the subject. The range of positions assessed in each block was 10° to 30° in increments of 1°, presented in random order.

Two of the four blocks were done in the direction of wrist flexion and two in wrist extension. On session day A, stochastic stimulation was applied during the last two blocks, whereas no stimulation was applied during the first two blocks. This order was reversed on session day B. The subjects had no knowledge of the stimulation condition. Between blocks, subjects took two-minute breaks to minimize possible after effects of the stimulation [29]. Fig. 4 gives an overview over the experimental protocol. To reduce order effects, movement directions and the order of session days A and B were randomized. At the end of each day, subjects completed a questionnaire to report on their activity, fatigue, and product consumption.

We attached four SPAs to the subject's wrist: two SPAs for wrist flexors, two for wrist extensors. The SPAs were fixed on the skin above the respective tendons with medical tape (Micropore 25 mm×5 m, 3M (Schweiz) GmbH, Rüschlikon, Switzerland) and covered with the pressure cuff. The SPA setup is schematically shown in Fig. 3 (right).

The ReFlex robot [30] was used to control the tested wrist's position. The robot was adjusted to each subject's body anthropometry. A touchscreen covered the tested wrist and thus eliminated visual feedback. Subjects also wore headphones to prevent auditory cues from the robot movement and stimulation.

Subjects were instructed to use a gauge in the touchscreen to match the position of their wrist after the robot had moved the wrist to the target position. To prevent subjects from basing their position estimations on the duration of the movement, the robot moved the subject's wrist with a constant duration (2 s). To eliminate visual distortion of the wrist angle due to parallaxes, we instructed subjects to align their axis of vision with the axis of wrist rotation and the origin of the gauge based on a reflective marker placed between their eyes. The subject's head was supported with a head rest, and body positions were visually checked by the experimenter to ensure consistent postures throughout testing.

E. Statistical Analysis

We developed a linear mixed model using R (version 3.3.1) with the *lmer()*-function and the *lme4* and *lmerTest* packages to analyze the constant error of estimation [31], [32]. The constant error describes the deviation from a target value, taking into account the direction and magnitude of the error [28]. We set the level of significance for all

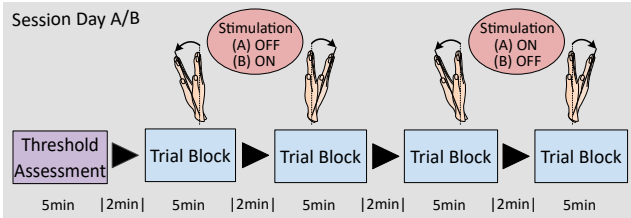

Fig. 4. Experimental Protocol. Participants took part in two sessions on two different days; stimulation was applied during the last two (day A) or first two blocks (day B). Following the assessment of the perception threshold, subjects estimate their wrist positions in four blocks of 21 trials. The order of day A and day B was randomized; two-minute breaks were held between each assessment block to mitigate stimulation after-effects.

tests at $\alpha = 0.05$ and determined statistical significance of our covariates by calculating confidence intervals with the *confint(∼, level=0.95)*-function, i.e. based on the likelihood-ratio test, and the respective p-values based on Satterthwaite's approximation. Model quality was evaluated using QQ-plots and Tukey-Anscombe (residual vs. fitted values) plots.

We reduced our analysis to the statistically significant covariates and those covariates related to our hypotheses to prevent overfitting and used random effects to account for correlations in the data coming from the same subject.

III. RESULTS

The device met all the requirements for spatial resolution, amplitude, and frequency for stochastic vibratory stimulation. It covered the required amplitude range (0.05-0.50 mm) when inflated at 0-50 kPa above the ambient pressure (Fig. 5 (top)). The device generated perceptible vibrations up to 120 Hz at a pressure of 35 kPa above ambient pressure.

The geometry that best met our requirements was the ring design shown in Fig. 1 (bottom right). The static inflation simulation in Fig. 1 (bottom left) shows the uniform distribution of inflation amplitudes.

As expected, the amplitude response over the required frequencies resembled a colored noise frequency spectrum (Fig. 5 (bottom). Inflating the SPAs with low-pressure air (10-50 kPa above ambient pressure) produced the required vibration amplitudes. The use of the Soft Pneumatic Actuators (SPAs) allowed us to customize the stimulator to meet the anatomical requirements. The casing around the valves reduced the noise during experimental conditions by 7 dB to 54 dB. At these noise levels, and in combination with the headphones, subjects were not able to determine from auditory cues whether the stimulation was applied or not.

In the feasibility study, the device was safe and easy to interface with the robotic device used. The pressure cuff with the embedded SPA's did not interfere with the movement or measurements of the robot and did not induce any discomfort at any point during or after the experiment. Although the desired range of target positions was 10° to 30°, a calibration error of 9° on the robot's position meant that subjects instead were exposed to ranges between 1° to 21° in flexion and 19° to 39^0 in extension.

The covariates in the linear mixed model which were set as categorical variables were the stimulus setting (on/off),

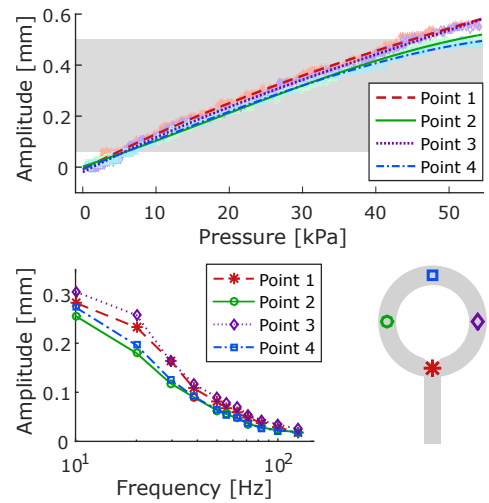

Fig. 5. Top: Amplitude as a function of pressure during static inflation of a ring bubble measured at four different points (indicated on the bottom right); the required amplitude range is shaded; here, 0kPa complies with the ambient pressure. Bottom left: Frequency response; pressure was held constant at 35 kPa above ambient pressure.

age group (younger/older), gender (male/female), movement direction (flexion/extension), and consumption of perception altering substances such as coffee or alcohol prior to the study session (yes/no); the remaining numerical covariates were the target angle size (°), the squared target angle size, and their respective interaction with the movement direction. The data analysis showed that, both in flexion and extension, the constant error became more negative when the stimulation was applied (see Table I). This change, however, was not significant at the significance level of $\alpha = 0.05$ ($p = 0.058$). We did not see performance differences between age groups ($p = 0.151$). Moreover, movement direction and the magnitude of the target angle played a significant role ($p < 0.01$) on the estimation of constant errors (Fig. 6).

IV. DISCUSSION

We built a device to deliver stochastic vibratory stimulation to enhance proprioceptive sensory information. The design implements a novel technology that uses soft, skin-compatible materials in combination with pressurized air to deliver vibratory stimulation to the skin. The device is capable of delivering stimulation that meets the anatomical and physiological requirements for use in the wrist joint. This technology can be easily adapted for other joints of the body (i.e. larger stimulation areas for larger tendons). In addition, we conducted a study to ensure the safety and feasibility of the stimulator to be used in combination with other technologies for rehabilitation (i.e. robotic devices). The pilot study showed the compatibility of the device with safety requirements and with the use in combination with a robotic device designed for rehabilitation. The results were limited by the small sample size and a calibration error that increased the variability in our data.

The device delivers stimulation that meets the frequency bandwidth and amplitude range required for stochastic stimulation of the muscle spindles. Although the device covers

TABLE I

ESTIMATION ERROR RESULTS

	Stimulus	Median [°]	Mean [°]	Std. Dev. [°]
Flexion	ON	3.592	3.799	6.759
	OFF	4.028	4.009	6.128
Extension	ON	-3.885	-2.542	8.739
	OFF	-1.991	-1.481	9.367

the required frequency range at a pressure of 35 kPa above ambient pressure, it may be beneficial to adjust the design to increase the vibration amplitudes in the higher frequency range. This can be achieved by adjusting the thickness of the silicone layers or the length and diameters of the supply tubes. The current setup effectively attenuates the acoustic noise generated by the high-frequency valves during operation. However, the device is still dependent on an external pressurized air source, and the size of the actuation unit can be improved for portability.

The results of our feasibility study are limited by the small sample size and current setup. For example, we cannot be certain whether the stochastic stimulation is strong enough to increase the activity of the muscle spindles significantly or is limited to the activation of cutaneous receptors.

The primary hypothesis associated with the study is based on recent findings in experiments on noise-enhanced proprioception. These studies commonly used electromechanical stimulators that act mechanically on the skin [9], [10], [14], or stimulate the neuromuscular system electrically [13]. Combining these systems with EMG or EEG recordings, MRI imaging or transcranial stimulation is challenging due to effects such as electromagnetic interference. Electromechanically generated stochastic stimulation of distal joints has been investigated before with EEG recordings [14]. However, interferences are likely to occur when stimulation is applied to proximal joints (i.e. the shoulder). Pneumatic stimulators were used in a limited number of cases and not described in detail [5], [15]. Our approach introduces a novel way to deliver stochastic vibratory tactile stimulation. Among other applications, it allows the investigation of noise-enhanced proprioception with functional MRI imaging.

For analysis, we used the constant error, as we were interested in the direction (over-/underestimation) and magnitude of the error. However, this measure may masks certain effects such as the zero-crossing of the estimation errors in the extension direction.

Due to the calibration error of the robotic device, there was a mismatch between the position of the subject's wrist and the gauge needle on the touchscreen. We initially assumed that this would result in a consistent shift in our data and thus the initial position of the gauge needle (0°) was not adjusted. In our protocol, the instruction to the subjects was to use the gauge in the touch screen to estimate the posture of their wrist after the robot had finished positioning it. However, based on the analysis of the results, we believe that subjects used different estimation strategies: one of matching the position, and one of matching the magnitude

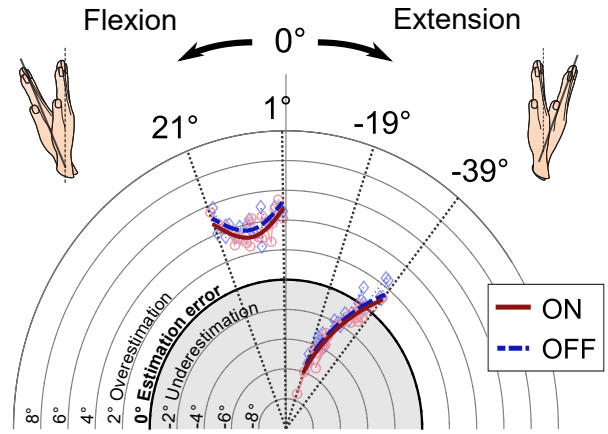

Fig. 6. Estimation Errors. The means of the recorded values for each target angle are plotted as circles (stimulation ON) and diamonds (stimulation OFF); the superimposed lines represent the fit of the linear mixed model. Data of trials without stimulation are indicated in blue (dashed line), data of trials with stimulation in red (solid line).

of the movement. When a subject matched the position, the results showed accurate position estimation. When they instead matched the size of the movement, the results showed a shift in the position estimation. Most subjects may have applied a mixed strategy, resulting in a nonlinear relationship between the estimation error data and the target angle size. We could not compensate for the calibration mistake, and thus testing of our hypotheses was limited.

The results from the feasibility study indicate that the stimulation affected the subject's estimation of the wrist position, a finding that supports the hypothesis that stochastic vibratory stimulation can enhance wrist position estimations. When the stimulation was applied, mean errors tend to decrease in the flexion direction. Due to the zero-crossing, interpretation of the means in extension is not straightforward. However, with stimulation, the smaller overshoot to overestimation at larger target angles indicates a higher estimation precision. We believe that our approach has the potential to show meaningful results, as found in similar studies [9]–[13], but we need to conduct the study with a larger sample size.

In our secondary hypothesis, we assumed that older subjects would show larger improvements in position estimation performance, mostly due to the decrease in proprioceptive acuity shown before [16]. Contrary to our hypothesis, the performance of older and younger subjects was similar. However, it is important to note that our sample of older subjects consisted of active and healthy individuals. Previous studies have shown that activity levels correlate with proprioceptive performance [17] and thus could attenuate the effect of aging.

V. CONCLUSION

We developed a device that can apply stochastic, subliminal, vibratory tactile stimulation to the skin above muscle tendons. This device can be readily used in psycho-physics or in behavioral experiments investigating the enhancement of proprioception.

A current limitation of the device is the lack of monitoring of the stimulation delivered to the skin during operation, i.e. the inflation of the SPA bubbles. In follow-up studies, we will implement SPAs with embedded piezoelectric sensors to quantify bubble inflation in experimental conditions.

In this feasibility study, we saw evidence that participants used different strategies to achieve the position matching task. From pilot tests, we expect that movement perception vanishes quickly after the robotic manipulandum has completed the movement. Introducing a 1-2 s pause between the robot's movement and the subject's wrist position estimation should promote position matching strategies and prevent movement matching.

Future studies with the device will also investigate the effects of stochastic stimulation on the ascending and descending pathways of the nervous system. Our device can be combined with techniques such as EMG, EEG, and MRI, to record central and peripheral activities while the stochastic stimulation is applied. These studies will also extend to neurological patients populations where we see potential for reducing sensory deficits and improving proprioceptive performance with stochastic stimulation.

These findings will enhance our understanding of the processing and generation of controlled and passive movement, and subsequently enhance rehabilitation treatments and physiotherapy.

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