Motion Guidance Sleeve: Guiding the Forearm Rotation through External Artificial Muscles

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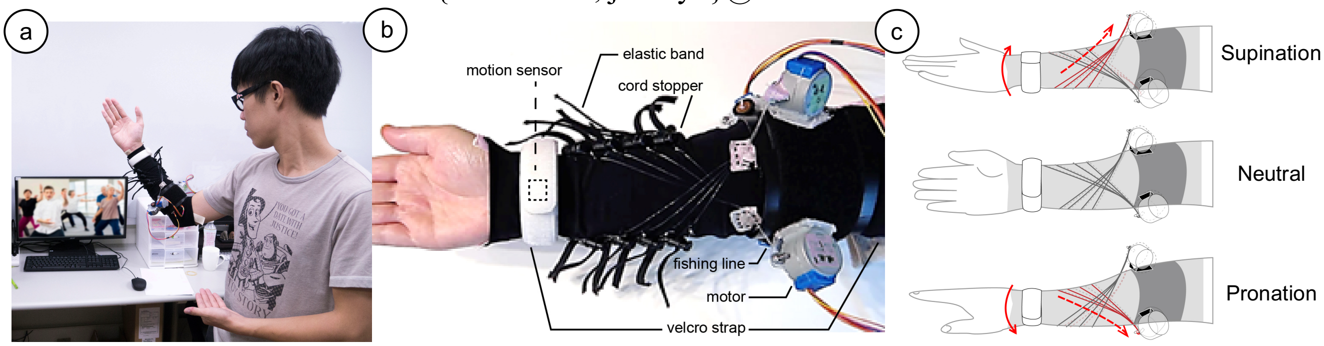

Figure 1: (a) Motion guidance sleeve worn on right arm to guide subtle motion of forearm in *tai chi* training scenario. (b) Hardware overview of motion guidance sleeve. (c) Contracting different artificial muscle groups can be a guide to a forearm pronation or supination (i.e. internal or external rotation).

ABSTRACT
Online fitness videos make it possible and popular to do exercise at home. However, it is not easy to notice the details of motions by merely watching training videos. We propose a new type of motion guidance system that simulates the way that the human body moves as driven by muscle contractions. We have designed external artificial muscles on a sleeve to create a pulling sensation that can guide the forearm's pronation (internal rotation) and the forearm's supination (external rotation). The sleeve consists of stepper motors to provide pulling force, fishing lines and elastic bands to imitate muscle contraction to drive the forearm to rotate instinctively. We present two preliminary experiments. The first one shows that this system can effectively guide the forearm to rotate in the correct direction. The second one shows that users can be guided to the targeted angle by utilizing a tactile cue. We also report users' feedback through the experiments and provide design recommendations and directions for future research.

Author Keywords
Motion guidance; external artificial muscle; haptic feedback.

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INTRODUCTION
Doing exercise and fitness at home have become more and more popular in recent years. Exercises and practice such as *tai chi*, yoga and aerobics are among the types of physical training that can be performed anywhere and at anytime. This kind of training is traditionally instructed on-site to guide practitioners through the correct movements for different levels. For example, *tai chi* coach would hold the practitioner's arm and guide its rotation to achieve optimal training results. However, many people who do exercise through self-study video cannot perform these movements well since the subtle changes of rotation are difficult to perceive merely by visual observation. So our goal is to design a wearable device that can provide motion guidance by an instinctive tactile feedback from a virtual coach.

After comparison with other tactile feedback techniques, we have designed a wearable artificial muscle that provides simple and instinctive pronation/supination cues for guiding a user's forearm movements. Our main contributions are: (1) we apply the concept of external artificial muscles to motion guidance and a prototype of motion guidance sleeve, and (2) we have conducted two preliminary experiments to show that our system effectively guides users to perform accurate directional responses and angle-targeting tasks of forearm rotation.

RELATED WORK
There are many research projects that have focused on tactile motion guidance. To convey the subtle movement when learning dancing through video, Nakamura et al. [10] designed a mobile screen robot and a bracelet with a vibrotactile feedback that alerts user when to initiate body movements. Spelmezan et al. [14] designed a set of full-body

vibrotactile patterns to assist in guiding correct postures during physical activities or sports training. In order to improve the learnability of tactile feedbacks, some projects focus on vibration patterns and rhythms. For example, spatio-temporal patterns [14] and sequential triggering of vibrotactors [5] can be used to indicate speed and direction of motion, and the stimulus should be presented at the side of the hand that corresponds with the direction [6, 9, 12, 17]. However, these vibrotactile feedbacks require users' extra cognition load to translate the tactile information into appropriate movements.

Electrical Muscle Stimulation (EMS) has been applied to motion guidance by the placing of electrode pads to stimulate and cause the contraction of specific muscles to induce a user to perform required movements without or beyond visual hints [7, 8, 11, 16]. EMS, however, as a form of force feedback, overwrites a user's intentions and forces users' muscles to react involuntarily. This may against the original purpose of fitness training.

Skin Stretch excites slowly adapting receptors (SA1, SA2) to deliver rotational stretch cues that causes users to feel the location and directional hints on the skin [1, 2]. Stanley et al. [15] present a wrist motion guidance system that aims to direct the user's movement toward a target pose or trajectory by delivering tactile cues through five wearable actuators, capable of tapping, dragging across, squeezing, twisting, or vibrating against the wrist. They found users move most quickly when the cue's direction is conveyed through the location of the tactile stimulus. Our external muscles provide similar cues as these devices but stretch different area of the skin.

Pneumatic artificial muscles (PAMs) have been used as robotic actuators and as a way to empower the human body to enhance movements and postures [3]. Exoskeleton [4] also adopts the idea of artificial muscles. This kind of device shares the same concept as our motion guidance system but it's heavy and mainly focuses on augmenting human abilities.

Our aim is to develop a system that surpasses the aforementioned research projects by providing clear tactile cues, while decreasing the cognition load by giving minimal interference [13]. To develop a system that can provide distinct motion guidance, we applied the concept of artificial muscles to our approach, reconsidered the human anatomical system of muscles, and simulated the contraction and relaxation of muscles in this study.

WEARABLE MOTION GUIDANCE SYSTEM

We have designed external artificial muscles on a motion guidance sleeve to function as the human muscle, in order to achieve a clear and intuitive stimulus. As shown in Figure 1a, the motion guidance sleeve is currently designed to be attached around the arm, and envisioned to be utilized when located on other limbs. It is 216g in weight, 38cm in length, wrapping the entire forearm and part of the upper arm. This system is developed based on an elastic sleeve, using Velcro® straps on the elbow and wrist to stabilize the device. We set a row of cord stoppers on both side of the arm, in order to adjust the tightness of the elastic bands to fit various diameters of arm. As shown in Figure 1b, an external artificial muscle consists of a 2cm elastic band connecting to a fishing line. The fishing lines are 14, 13, 12, 11 cm in length respectively; the closer that the connecting point is to the wrist, the shorter the line has been made. The material of the cords and its pulling force were empirically tuned through several iterations of preliminary testing, from which users commented that there was a weaker contraction when using the prototype with only elastic bands. We inferred that band-stretching caused force loss. Thus an inelastic material, fishing line, was stitched together with elastic bands to provide more uniform pulling force throughout the contraction phase and to facilitate the return to default position in the relaxation phase.

Sixteen artificial muscles cover the entire arm. There are eight artificial muscles in both the inner and outer side of the arm with each of four artificial muscles crossed, simulating the position where human muscle contracts. The pulling force increases as the number of functioning artificial muscles is increased. Artificial muscles are driven by stepper motors (28BYJ-48 5V, which weigh 34g and have an output of a maximum torque of 34.3Mn-m when not loaded) attached to the sleeve near the elbow. When the forearm rotates, the elbow rotates at a relatively lesser angle than the wrist; therefore, the motor attached near the elbow stays fixed. In the pilot study, we experimented on different radiuses of stepper motor axle and found that a greater radius leads to faster and more remarkable feedback; thus, the radius is set to 1.2cm. The artificial muscles are powered by a ULN2003 driver chip and a 5V/1.2A individual power supply; these are connected to an Arduino Uno communicating with a PC using a USB cable. All subjects' forearm rotations were recorded with a 6-axis motion sensor, MPU-6050, which is attached to the wrist covered by a Velcro® strap, as shown in Figure 1b.

Tactile Feedback

As shown in Figure 1c, pulling different artificial muscles can cause different muscular contractions, leading to forearm supination or pronation. By changing the speed of motor and the time each cue lasts, the artificial muscle provides varied sensations that resemble pulling force, which can cause different tactile feedback.

USER STUDY AND RESULTS

To validate the concept of artificial muscles, we conducted two experiments. First we measured the clarity of tactile feedback that communicates the desired direction of forearm rotation. Second, we tested whether the device can guide a user to rotate to a certain angle. In all trials, the device was worn on the subjects' right arm as shown in Figure 1a. During the experiment, the subjects were required to keep the right arm stretched forward, and were not allowed to see the device. The system performed with the sleeve prototype connected to an OSX 10.10.4 MacBook Air with 1.4 GHz Intel Core i5 with 8GB of RAM.

Evaluation 1: Directional Response Task

The directional response task measured the clarity with which the artificial muscles were guided to the desired direction of forearm rotation, and examined how different motor speeds affected tactile feedback. We also examined the effects of muscular contraction and releasing of artificial muscles. The within-subject evaluation enrolled N=10 subjects. (5 female and 5 male, right-handed, averaging an age of 35.4 years) Each participant was given 600 rpm and 900 rpm motor speed tests, and asked to rotate their forearm based on the tactile cues that they perceived. Each speed test consisted of 2 rotational directions × 6 trials, counterbalanced among subjects. Every trial started with the subject's forearm rotated to neutral position. Subjects then waited for cues to start after a random delay. Directional cues started with 2.8 cm muscular contraction of artificial muscles, hold for 0.5 seconds and end with muscle relaxation. Subjects are required to indicate what the rotational direction was verbally as they perceive the directional guidance. After completing each trial, participants were asked to report their level of confidence in the rotational guidance given.

The accuracy rates of the directional response task are 100% for 900 rpm and 98.33% for 600 rpm. Two-way ANOVA was performed which shows a significant effect of motor speed on response time ($F=25.02$; $p<.001$). It specifically shows that a speed of 900 rpm (1.55 sec) can lead to a faster directional response than a speed of 600 rpm (1.09 sec). Also, a significant effect of contraction time on the angle by which users were guided to rotate ($F=17.77$; $p<.01$) is shown. According to responses given during the user interviews conducted, users can clearly feel a difference between two stimuli, contraction and relaxation, of the artificial muscles. When feeling the relaxation, users' forearm would turn backward a bit.

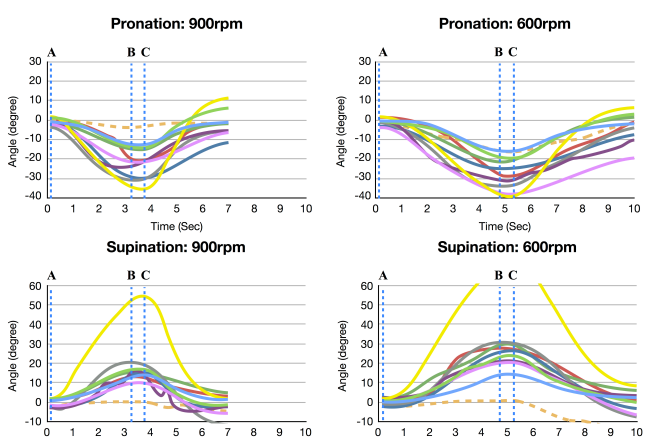

Figure 2: Directional response task with two motor speed of pronation and supination. The vertical dotted line showed the different action phase: (A) contraction start, (B) hold, and (C) release, of the artificial muscles.

Evaluation 2: Angle Targeting Task

Based on the results obtained by evaluation 1, we further integrated the effect of motor speed and contraction time, and designed three stages of tactile cues to provide different cues based on the rotational status. As shown in Table 1, a directional cue given at a speed of 900 rpm is provided once at the beginning of the trial, aimed to imply a fast directional hint that leads to a preliminary forearm rotation. Every subject's rotation angle was being tracked during the experiment. When the subject stopped rotation, angle targeting cues were given to imply "keep rotating the forearm." Since users distinguish contraction and relaxation of artificial muscles, we paired the relaxation to the hint of "reaching the target angle."

Stage	Tactile Cue	Contraction Time
Directional Cue	Directional Guidance, given once at the beginning	2s
Angle Targeting Cue	Directional Guidance, given when user stops rotation	0.5s
Setting Alert	Releasing, given when user reaches target angle	

Table 1: Three stages of tactile cues in each trial of angle targeting task, integrating the effect of contraction time and motor speed.

This evaluation enrolled N=10 subjects from a general university, none of whom had participated in previous studies. (5 female and 5 male, right-handed, averaging an age of 21.9 years) Each participant was given 2 rotational directions × 15 trials (5 target angles including 15°, 30°, 45°, 60°, 75°, each randomly given 3 times), counterbalanced among subjects. The subjects were asked to "rotate the forearm to a particular angle when you feel the tactile cues" In addition, the subjects were instructed that "when you are given the settling alert it means that you have just reached the targeted angle, hold still for at least one second." Figure 3 shows the rotational status of a sampled subject; directional cues can lead to a 10-degree preliminary rotation, followed by several angle-targeting cues before reaching the targeted angle. The subject commented that the angle-targeting cue was an obvious and intuitive hint to continue to rotate the forearm. The number of angle targeting cues is affected by directing pronation or supination to different targeted angles. As shown in Figure 3, participants were not aware of a single cue until several cues had been applied. After continuous cues were applied, participants rotated to a greater angle because they felt tighter contractions. An ANOVA test shows a significant difference between targeted angles ($F=25.32$; $p<.001$). As shown in Figure 4, a greater targeted angle requires a greater number of angle targeting cues. Overall, pronation requires fewer cues than supination (F=6.38; p=.0325).

Subjects commented that they could feel the apparent relaxation of the artificial muscles, but when targeting a lesser angle, e.g., 15 degrees, relaxation is less obvious. Figure 5 shows the data for the error in angle when the settling alert is given one second later. Mean error angle is 2.69 degrees. (SD=4.25 degrees)

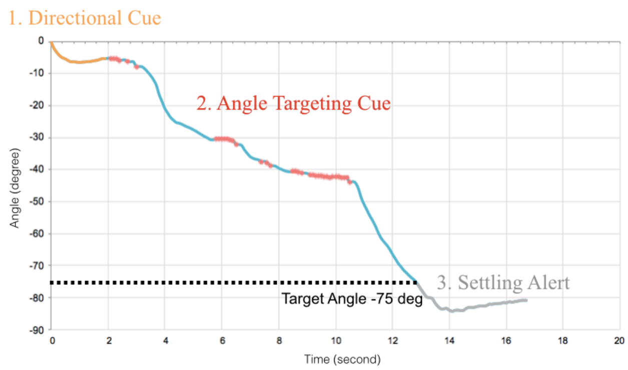

Figure 3: Sampled normalized plot for angle targeting task of 75-degree pronation. Orange line is the directional cue, red dots are angle targeting cues, and gray line is settling alert.

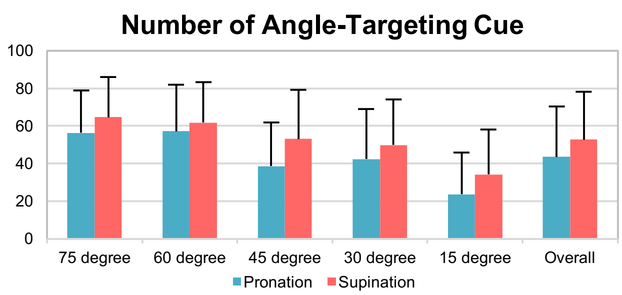

Figure 4: Number of angle-target cue. Error bars show the SD.

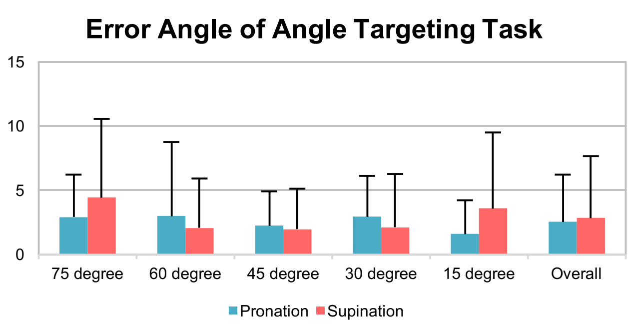

Figure 5: Error when given settling alert 1 second later.

CONCLUSIONS & DISCUSSION

The concept of the external artificial muscle described herein simulates the contraction and relaxation of the human muscle and applies a natural cue to the human body to provide a clear and intuitive feedback. In this study, we proposed a device of artificial muscles to gently guide pronation and supination, i.e., internal and external rotation of the forearm, driven by stepper motors on the forearm. The weight of the system can be reduced by replacing heaver motors with lighter ones allowing for smooth user movement and integration within a more practical environment. This approach allows a user to perform movements via their free will while discerning the guidance of the sleeve which is thus far unique among EMS and vibrotactile feedback systems. Two evaluations were conducted in this study. We explored the effect of the external artificial muscles and how users' forearms were being pulled. Our prototype provided a distinguishable rotational direction cue with 99.87% accuracy in average. Secondly, we applied the results of the first evaluation and designed three-staged tactile cues to guide rotation to specific targeted angles, aiming to provide more precise motion guidance. The results of this study clearly imply that the human forearm can be precisely guided by angle-targeting cues to a targeted angle (mean error is within 3 degrees). The current system design allows for giving users angle-targeting cues continuously, with a 0.5s contraction when the user ceases rotational motion, until the targeted angle is reached. However, there is a limited number of cues; the motor no longer provides cues if the arm is over-tightened. The current limit is 80 times for angle-targeting cues and 7 out of 300 trials reflected this limitation.

This current study explored the use of artificial muscles on the forearm. We envision that in future studies, the concept of the external muscle can be applied to other limbs, such as the thigh, upper arm, shoulder, *etcetera* by changing the direction and position of pulling force, according to the differing muscular anatomy of various human limbs. We will conduct an experiment in a realistic training scenario with our system and state-of-the-art tactile techniques. Future applications include utilization within the context of a VR *tai-chi* or yoga class, assisting in the tactile feedback simulating a coach's guidance, and mimicking of the on-site training experience.

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