Interactive Balance Rehabilitation Tool with Wearable Skin Stretch Device

Yi-Tsen Pan, and Pilwon Hur

***Abstract*— Physical interactions between human and machine are essential in facilitating effective physical therapy training programs. Nowadays, physical training largely involves robotic assistive devices or wearable haptics. In this study, we propose a lightweight wearable sensory augmentation device using skin stretch feedback to provide individuals with additional sensory cues during balance training. The goals of this study are i) to determine the effectiveness of the proposed novel system in improving the dynamic stability of healthy individuals and ii) to test the efficacy of additional cutaneous cues in substituting for missing visual feedback in said healthy subjects. The entire system comprises of a haptic wristband, a visual display, and a force platform. The haptic wristband provides real-time skin stretch feedback at the dorsal side of the wrist in response to user's postural sway. Center of pressure (COP) was displayed on a screen and users were asked to move the COP to a target position displayed on the screen by controlling their body posture in the sagittal plane. Results showed that subjects could complete the tasks when they received both visual feedback and skin stretch feedback by shifting their weights. When visual feedback was subsequently removed, subjects successfully interpreted the tactile cues at the wrist from the skin stretch device and completed the tasks. Larger sample size, diverse groups, and longitudinal studies are needed to demonstrate the effectiveness of the proposed device as a balance rehabilitation tool.**

I. Introduction

Balance rehabilitation involving exergames has been suggested as a more sustainable home-based training approach for all age groups [1]. From a human-centric perspective, a good physical training program should not only be thorough and effective but entertaining so that users can feel motivated and are more willing to be actively involved. In conventional balance training techniques, the ability to maintain the body center of mass (COM) within the base of support while dynamically performing secondary tasks has been the common target measure. In the past few years, the game-based approach has been introduced in balance training programs. For example, the Nintendo Wii Fit balance board was used along with a desktop PC to carry out exergames for balance rehabilitation purposes [2]. A Virtual Reality (VR) system is also incorporated into balance training programs to create a more realistic and diverse environment [3]. These exergame-based interventions have demonstrated their ability to improve individual's balance performance in the framework of traditional physical training programs while offering more flexibility and greater compliance.

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Positive effects of these balance training interventions are not only shown in exergames or VR trainings but also in haptic devices. Wearable haptic devices using vibrotactile instructional cues [4] [5] and skin stretch feedback [6] in response to trunk tilts have been shown to augment the impaired or unreliable sensory systems and improve standing posture. In [7], the effects of visual feedback, vibrotactile feedback, and multi-modal feedbacks on postural performance were also compared for potential home-based rehabilitation. For people with neurologic impairments such as stroke and spinal cord injury, the stimulus location is critical for the perception of cutaneous feedback. In this case, the arms, hands [6] [8], head [5]or tongue [9] seem to be more suitable than the torso [4] [7] in terms of available skin sites and wearability.

To facilitate a home-based balance training program for wider age groups and patients, we propose a novel interactive balance rehabilitation tool that combines both gaming technology and a wearable skin-stretch feedback device at the wrist. Wrist-worn devices such as a watch, or a fitness monitoring device have been widely used for tracking the user's movement. Most of these wrist-worn devices are based on sensor technologies. However, growing interests in wrist-worn "actuators" have been observed in recent studies for rehabilitation purposes. Wrist rotation guidance using vibration [10], skin stretch [11] and multiple haptic displays [12] are found to be intuitive and comfortable for achieving motor learning tasks. However, those devices are mainly for the upper limb posture guidance; there have been no studies investigating the wrist-worn device for balance training.

In this study, we propose a skin stretch device that is worn on the wrist that can deliver directional sensory cues in response to individual's postural sway. The mapping between skin stretch cues and postural sway movement is designed to be natural and easily understood by the wearer. Additionally, the gaming aspect is added to the visual display system. The objectives of this study are to i) determine the feasibility of the novel system in improving dynamic stability for healthy subjects and ii) test the efficacy of additional cutaneous cues in substituting for missing visual feedback in said healthy subjects.

II. Methods

A. Overview of the Wearable Skin Stretch System

The whole system consists of a wrist-worn skin stretch device operated by a DC motor, a motor driver, a microcontroller for driving the DC motor and data acquisition, a monitor displaying an interactive program, and a force plate. Fig. 1 shows a schematic of the system and what feedback modalities are provided to the user. Each component is described in the subsequent sections.

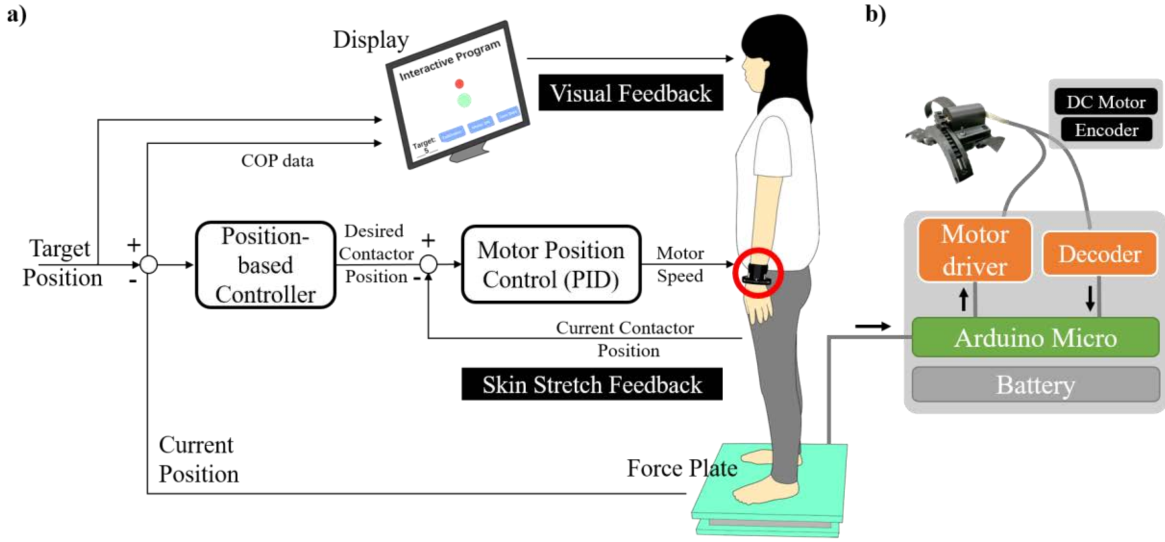

Fig. 1. a) A schematic of the proposed system. The system consists of both visual feedback and skin stretch feedback (circled in red) of the individual's COP. A subject swaying back and forth to reach the target defined by the experimenter. For skin stretch feedback, contactor moves on the top of the wrist, providing position error cues of the current COP. The subject needs to try moving the contactor back to the wrist center point to reach the target. b) A schematic of the electrical hardware.

B. Design of the Wrist-worn Device

The wrist-worn device comprises six major components, as shown in Fig. 2. All parts have been designed using Solidworks and fabricated in ABS material with a 3D printer (Replicator 2X, Makerbot, Brooklyn, NY) to develop a proof-of-concept device. A custom pinion (labeled as "A" in Fig. 2) and a curved rack (C) are designed to provide a one-dimensional shear force on the top of the wrist skin. A contactor with a rough surface is integrated into the curved rack (C). The design criteria of the contactor are to provide i) easily perceivable sensation to the skin, and ii) directional and intensity information of the reference inputs. Therefore, to effectively convey the cutaneous feedback and to avoid the desensitization and slipping, we have designed the contactor surface to be small (8×10 mm^2), and rough (notched surface). The rack and pinion mechanism is housed inside two combined curved bands with the embedded track (B). The custom track bounds the curved movement of the contactor which defines the range of motion of the contactor. Approximately 46 mm curved displacement can be applied to the skin of the wrist. A small DC motor (1524T009SR, Faulhaber, Germany) to drive the custom pinion is mounted inside a motor housing (D). To accommodate various sizes and shapes of wrists, two movable buckles (F) are attached at the end of both bands; the device is worn and tightened using two adjustable Velcro straps to ensure that users can feel the cutaneous sensation while minimizing their discomfort levels. The weight of the entire device is approximately 75 g. More details on how to actuate the rack and pinion mechanism by the DC motor are given in the next section.

C. Skin Stretch Feedback Actuation

A 9V DC motor that actuates the contactor is controlled by an Arduino Micro microcontroller board which is light (13 g) and small (48×18 mm^2). An h-bridge type motor driver (L298N, STMicroelectronics, Italy) was used to provide appropriate control signals to the DC motor. The unloaded maximum speed of the DC motor was about 1183 rpm (equivalent to about 1 m/s). To control the position of the motor, the angular position was measured with its embedded encoder at 9728 counts per revolution of the pinion (512 counts per revolution with 1:19 gear reduction ratio). To increase the resolution of encoder inputs for the Arduino, a 32-bit quadrature counter LFLS7366R (LSI Computer Systems, Inc., Melville, NY) was attached to the Arduino Micro through a serial port interface. The desired angular

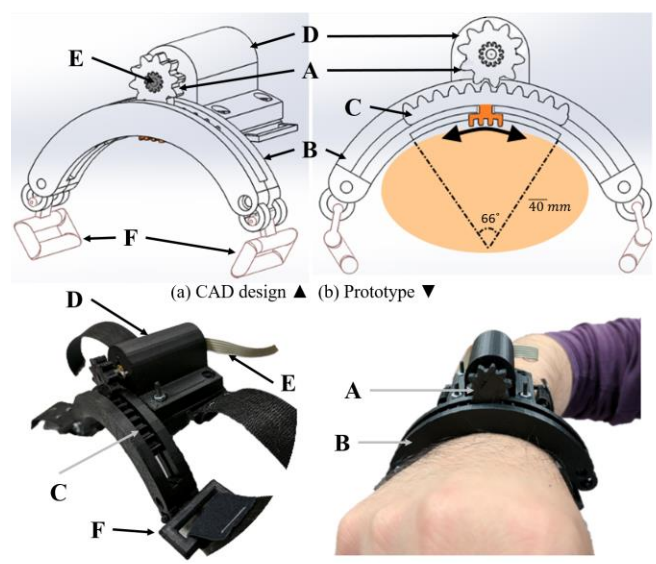

Fig. 2. Wrist-worn skin stretch device. Skin stretch feedback is provided by the contactor connected to a curved rack (C). The rack is driven by a DC motor (E) with a custom pinion (A) attached (D: motor housing). The rack and pinion mechanism is housed inside two combined curved bands with the embedded track (B). Two movable buckles (F) are attached at each end of bands to accommodate various wrist sizes. User can wear and tighten it using two adjustable Velcro straps.

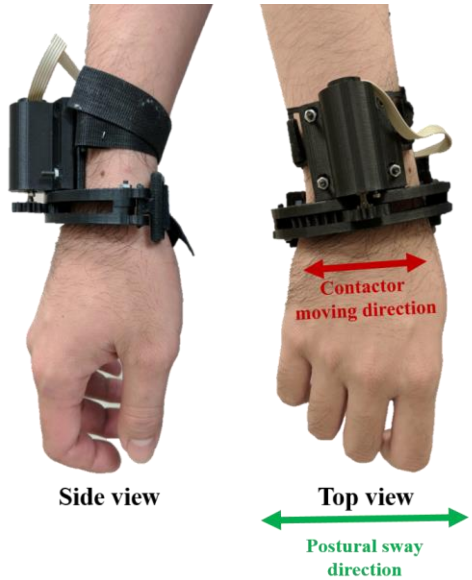

Fig. 3. Skin stretch device worn by subject viewed from the side and the top. The contactor moves along the top of wrist surface in response to the subject's postural sway direction.

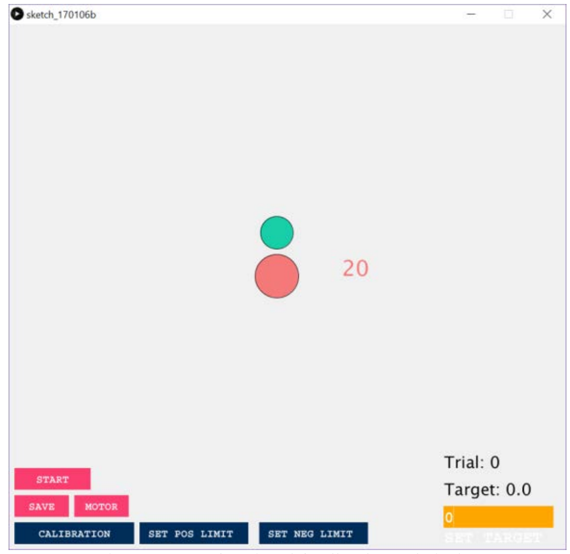

Fig. 4. Interactive program for visual feedback. Red circle represents the subject's current position along with the text on the right. Green circle represents the target position. Target positions are entered by the experimenter in each trial. Subjects are blind to the target position indicated in the lower right corner.

position of the motor was regulated using a proportional-integral-derivative (PID) controller. The maximum angular displacement of the custom pinion (attached on the motor) is limited to ± 150˚ to match the designated range of motion of the contactor. The contactor's position was always initiated at the center that corresponds to the angular position of 0˚.

D. Control Algorithm

The amount of skin stretch rendered to the user is determined by the user's center of pressure (COP) movement along the anterior-posterior (AP) direction. Before actuating the skin stretch device, its motion is calibrated based on each subject's COP equilibrium and the limit of stability. The limit of stability is determined by the maximum COP displacement in both forward and backward directions. The contactor location (θ_C) is therefore defined to be proportional to the user's current COP (x_{COP}) in anterior-posterior direction:

$$\theta_C = \theta_L \cdot \chi_{COP} / \chi_{FL}, \text{ if } \chi_{COP} \geq 0.$$
$$\theta_C = \theta_L \cdot \chi_{COP} / \chi_{BL}, \text{ if } \chi_{COP} < 0. \quad (1)$$

where θ_L is the limit of the pinion angle (i.e., 150˚), x_{FL} and x_{BL} are the absolute value of COP limits at front and back respectively. Since users are asked to rest their arms naturally (see Fig. 3), the movement of the contactor is aligned with users' COP movements as they sway back and forth. The proposed controller can be defined as position-based control, i.e. when user stands still at his/her equilibrium position, the contactor would move back to the center of the device (θ_C = 0°); if s/he leans forward and reach the front limit, the contactor would move "forward" and close to the device limit at one side.

Similarly, if the COP target position is set to other than the user's equilibrium position, the contactor's initial position (i.e., the center of the device) will correspond to the target position. Therefore, by applying the same position-based control, the contactor's location is then mapped to the error between the target and current COP position within the COP range; (1) can be slightly modified as:

$$\theta_C = \theta_L \cdot \Delta\chi / \chi_{FL}, \text{ if } \Delta\chi \geq 0.$$
$$\theta_C = \theta_L \cdot \Delta\chi / \chi_{BL}, \text{ if } \Delta\chi < 0. \quad (2)$$

where $\Delta x = x_{COP} - x_T$ and x_T is the pre-defined target position.

E. Interactive Program

We developed an interactive program using Processing, an open source software for the development of the graphic user interface (GUI). This program allows users to visually check their current COP_{AP} in an intuitive way and records their movements for each trial. Target position setup and motor actuation are also controlled by this program. Using Processing is beneficial for sending/receiving data to/from Arduino due to the built-in library for a serial communication between Arduino. The COP_{AP} data recorded from a force plate can be easily collected and displayed on a monitor. Fig. 4 shows a screenshot of the program. User's current COP_{AP} position is shown as a red circle, along with its absolute value recorded from the force plate. The target position is set by the experimenter and shown in the green circle in Fig. 4. The purpose of this GUI is to i) evaluate users' postural control performance by shifting their weight on a force plate to reach the target with visual feedback only or both visual and skin stretch feedback, and ii) provide convenient ways of data-logging and test management by clicking the custom buttons. Additionally, the calibration of the user's posture equilibrium and measurement of front/back limit are performed using the GUI.

F. Experimental Protocol

Five healthy young subjects (age ± s.d.: 25.2 ± 2.9, two females) were recruited to participate in the pilot test of the proposed wrist-worn device prototype. The aims of this test are to i) identify the effect of skin stretch feedback on postural

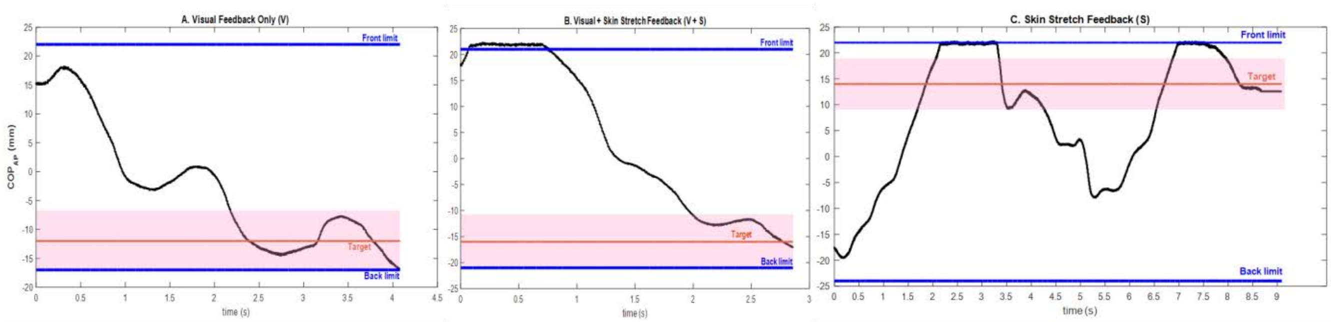

Fig. 5. Results of COP_{AP} trajectories from subject No. 2 on postural control tasks: A. Visual Feedback Only (V), B. Visual + Skin Stretch Feedback (V + S), and C. Skin Stretch Feedback (S). Front/back limits of the subject, target position of selected task are shown in blue and red lines respectively. 5 mm dead band is shaded in red. The subjects are considered to have completed the trial if they successfully reach within the dead band of the target (rectangle area) and stay within it for 1 sec.

control when visual feedback is available, and ii) determine if subjects can still perform the same postural control task and reach the target by using only skin stretch feedback after a short learning phase.

This pilot test is composed of three parts and conducted in the following order: visual feedback only (V), visual + skin stretch feedback (V + S), and skin stretch feedback only (S). In each part, subjects were asked to stand on a force plate in their normal stance, wear the skin stretch device on their right wrist, and let their arm hung naturally by their sides. No talking was allowed during the test. Subjects were required to perform postural control tasks by moving their body back and forth. In each part, six subtasks were performed in a randomized order (see Table I). First, the experimenter instructed the subject to return to the initial position and set the target position (subjects were blind to the target position at the lower right corner of the display). When the target position was set, the experimenter double checked if the subject is in the right position, and informed the subject to start the task. Subjects were considered finishing one trial if they successfully reach the target with errors less than 5 mm (i.e., dead band) for 1 sec. When the task was completed, either the text “You have reached the target!” was displayed on the monitor or the experimenter verbally informed the subject if subject’s eyes were closed. If the subject cannot reach the target within 3 mins, the trial would be considered fail and s/he would be asked to try one more trial.

For the last two parts that involve the skin stretch device, each subject was asked to do the calibration before activating the devices. During the calibration phase, the subject was instructed to i) stand still to calibrate for the posture equilibrium and ii) lean as far as they can in both anterior and posterior directions to calibrate the front/back limit. Each subject was given 5 to10 mins practice session to familiarize themselves to the device and understand how the feedback relates to their body movements. After the practice session, the same procedure as in the previous paragraph was repeated.

For the last part, subjects were asked to close their eyes after they were at the right initial position and tried to complete the task based on haptic cues from the device only. A break was provided upon request and the whole experiment lasted about 30 mins.

TABLE I.

SETTINGS FOR THE POSTURAL CONTROL TASKS

	Initial position	Target position
1	Center	Near front limit
2	Center	Near back limit
3	Tilt forward a bit[a]	Center
4	Tilt forward a bit[a]	Near back limit
5	Tilt backward a bit[a]	Center
6	Tilt backward a bit[a]	Near front limit

a. Level of body tilt was adjusted by subjects themselves

G. Data Collection and Analysis

COP_{AP} data, desired motor angular position, actual motor angular position, PWM signal and time spending for each trial were recorded and post-processed using MATLAB (R2016b, MathWorks, Natick, MA). Postural control performance for each subject was evaluated based on the movement time and the postural sway mean velocity (i.e., the ratio of total COP_{AP} excursions to movement time). Time series of COP_{AP} data and the actual motor angular position was compared, and their correlation coefficient was calculated using MATLAB.

For statistical analysis, a one-way ANOVA was performed to study the effect of skin stretch feedback and availability of sensory modality on postural control. The significance level was set to α=0.05 (SPSS, v21, Chicago, IL).

III. RESULTS AND DISCUSSION

Table II shows the mean (SD) of movement time required to complete the task and the mean velocity of trials from all five subjects under the three sensory conditions. Representative COP time series of the three sensory conditions from subject no. 2 are shown in Fig. 5.

A. Motor skill acquisition

All subjects could map visual and skin stretch feedback cues to their standing position and reach the desired target positions with available sensory feedback(s) (V, V + S, and S). Only one trial in S was found failed in the subject no. 4 because of a lost contact with the device that prevented the perception of haptic cues. The average time to complete the trial for all five subjects are 5.94 ± 0.34 s for V, 5.38 ± 0.65 s for V + S, and 11.45 ± 2.62 s for S, respectively. Based on

TABLE II.

POSTURAL CONTROL PERFORMANCE MEASURES

Subject No.	Sensory Modality	Movement time (s) Mean (SD)	Mean velocity (mm/s) Mean (SD)
1	V	5.70 (0.80)	53.08 (10.88)
	V + S	6.25 (2.25)	50.87 (6.79)
	S	7.61 (5.16)	46.59 (16.9)
2	V	5.59 (1.52)	30.95 (8.36)
	V + S	4.49 (1.78)	35.02 (6.82)
	S	11.40 (4.49)	40.05 (6.27)
3	V	6.45 (1.09)	60.11 (16.2)
	V + S	5.10 (2.01)	68.01 (20.21)
	S	14.01 (11.51)	66.34 (19.12)
4	V	6.04 (2.37)	92.13 (34.81)
	V + S	5.38 (2.9)	85.48 (32.94)
	S*	13.73 (3.65)	80.29 (31.26)
5	V	5.93 (2.72)	68.87 (21.36)
	V + S	5.65 (1.8)	75.35 (32)
	S	10.50 (7.02)	80.94 (26.16)

*one trial failed

Turkey HSD post-hoc test, S is significantly different from V and V + S ($p < 0.01$). The results indicated that without visual inputs, subjects needed more time to precisely move the contactor back to the center of the wrist. Fig. 5 shows that in all three trials, the subject could easily find the correct direction of the target within around 2 s, whereas in S condition (no visual feedback), more COP fluctuation was observed. The reason might be that more time was needed for locating the current contactor position and hence subjects were actively correcting their posture before they were informed the task completion. It is also known that vision dominates other senses for spatial tasks. With only tactile feedback, the training duration could also significantly affect the performance outcomes. For mean velocity of completed trials, the average for all five subjects are 61.07 ± 22.34 mm/s for V, 63.13 ± 19.77 mm/s for V + S, and 62.82 ± 18.88 mm/s for S. There are no significant differences among three sensory feedback conditions. Since the mean COP velocity may reflect the regulatory balancing activity for postural control [13], it suggested that postural stability remained similar among these sensory feedback conditions while performing weight-shifting tasks.

B. Effects of skin stretch feedback

One of the goals of this research is to see if the additional skin stretch feedback can aid postural control performance while reaching the target position. From the results, even though no significant differences were found between V and V + S conditions, it could be observed in most trials that COP fluctuation seemed to decrease more in V + S trials (for example, see Fig. 5 A and B). This implies that when additional skin stretch feedback was provided, it could feed the dynamical information such as relative position or rate change back to the subjects and therefore helped them stabilize their movements. However, in the self-reported questionnaire from each subject, all subjects stated they relied mainly on the visual feedback to complete the task, and it is uncertain that to what extent did the haptic feedback contribute to each task. Future work may include more complex postural control tasks to evaluate the effectiveness of additional tactile cues.

C. Skin stretch feedback perception

To effectively provide skin stretch cues to users, the contact location, wearability of the device and tactile pattern have been fully considered when developing the skin stretch device. All subjects found that skin stretch cues provided by our device was easy to be perceived as the contactor moved across the surface of the wrist. The moving direction was also easily differentiated. No desensitization or uncomfortable feelings were reported throughout the whole procedure by subjects. However, one subject reported he could barely feel the contactor when it stopped moving. Therefore, it was difficult to position the contactor accurately which forced him to slightly move his body every time to move the contactor to find the current contactor position. A possible solution is to change the controller that only stops moving when the desired position is reached, instead of using position-based control only.

D. Limitations

One challenge for wrist-worn device design is to accommodate the different shapes and sizes of the human wrist. To avoid a twisted track while rotating the curved rack along with it, the prototype housing has been made using the rigid material. Using flexible material may resolve the sizing problem but also generate mechanical issues. Further studies on device design using flexible material and different mechanisms are currently being investigated. A small number of subjects may have prevented accurate statistical results. More subjects are being recruited to have robust statistical interpretations. The force plate system we used for capturing COP data is expensive and bulky for personal use and in-home training. The potential low-cost replacement tool could be a Nintendo Wii Balance Board. Even though the lower accuracy and higher variability of COP measurements might be expected, it can still be used for the purpose of rehabilitation.

IV. CONCLUSION AND FUTURE WORKS

In this study, we have presented an interactive framework incorporating both visual and skin stretch feedbacks to assist users in reaching certain target positions by shifting their weights back and forth. An innovative, lightweight, and portable wrist-worn skin stretch device has been designed to provide position and directional cues for the desired position. The proposed system has been demonstrated to be easily understood that all test subjects were able to complete the tasks by the aids of the provided feedbacks. All subjects could complete the motor tasks by successfully interpreting the skin stretch cues at their wrists after a short-term training. This points out the potential use of wearable haptics in balance/walking rehabilitation for people with visual impairments. The wearable haptic device can also serve as an interactive tool to encourage and attract people who are in the long-term rehabilitation program. Future work includes implementation of a new control scheme for rendering skin stretch feedback, an improved wearable wrist device design that uses flexible materials, and incorporating different postural control tasks along with long-term retention tests.

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