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Design of a Sensory Augmentation Walker with a Skin Stretch Feedback Handle

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***Abstract*— Mobility aids such as canes, crutches, and walkers are widely used among the elderly and people with poor balance as a means for physical support to improve balance during walking. Advances in technology have led to the development of robotic walking aids which can provide active physical support and navigation by incorporating sensors and actuators in conventional walking aids. These devices have shown great potentials in enhancing mobility; however, few studies have employed the functionality to detect user's posture or have investigated the feedback approaches to augment this information. Thus, it is important for those with impaired balance not to just be passively supported by mobility aids but to also actively be engaged in correcting their posture. In this paper, we introduce the concept of a sensory augmentation walker that can provide real-time directional information via skin stretch feedback to the user. The design and the user study of perceiving directions on a novel skin stretch handle are presented. Results show that the directional cues rendered by skin stretch feedback can be accurately perceived by all healthy young subjects (n = 8) at their fingertips, while the palm is shown to be a less effective location for perceiving this kind of feedback. Positive feedback about the benefits in helping people with improper posture is also reported. Based on the results of this pilot study, a full system for improving balance performance in elderly or people with impaired balance will be undertaken.**

Fig. 1. A standard front-wheel walker with the sensory augmentation system that includes: (i) a skin stretch feedback device embedded into the right handgrip and (ii) a control unit together with the power source packed at the lower part of the walker.

I. INTRODUCTION

Population aging due to increasing life expectancy is a global challenge in the twenty-first century. In 2015, the population aged 65 and above represented approximately 8.5% of the global population and is projected to double (16.7%) by 2050 [1]. Therefore, it is crucial to have well-established health systems that can provide assisted-living environments, high-quality health care services and assistive devices to help seniors living independently and to improve the healthy life expectancy. Mobility aids such as canes, crutches and walkers are widely used to enhance balance and to prevent falls during daily activities [2] [3]. Such devices can partially support the body weight, increase postural stability, and may provide somatosensory feedback from the ground reaction forces and the environment. This boosts the confidence of the elderly individual in balance and raises the level of independence in their daily living.

Beyond the conventional mobility aids, canes or walkers equipped with additional sensors and actuators were investigated in several studies [4]–[11]. These devices were developed to provide better assistance than conventional ones during walking. Key functionalities offered by these robotic devices include: (i) detection of users intents, (ii) navigation, (iii) obstacle avoidance, and (iv) additional sensory feedback. An example for detecting users intention is the embedding of force sensors into the handgrips of the walker. In [4], both the push and pull pressures on the handgrips can be detected in controlling of the speed of a robotic walker. The study [5] also presented a robotic walker that determines the intended travel direction of the user by measuring forces on the handgrips. Another example is the detection of the lower limb position by applying infrared sensors to the lower part of a robotic walker, and thus the walkers motions can be adjusted to follow that of the users [6]. Users are able to actively control the direction and speed of these walking aids with the walkers motions augmented by the electronic components. Another type of robotic walking aid focuses on the navigation and obstacle avoidance by detecting the surrounding environment using ultrasound, infrared sensors or computer vision techniques. For example, [7] and [8] both presented white canes that detect obstacles and alert users via sensory feedback (e.g., auditory or vibrotactile). A similar concept is also found in a robotic walker that provides the surrounding obstacle information through haptic feedback on the joystick [9]. More advanced robotic walkers integrate all aforementioned key functionalities, and the assistance from the robotic device is adjustable based on the degree of disability of the user [10]. Detailed reviews on the functionalities of smart walking aids can be found in [11]. While these smart mobility aids have demonstrated great potentials in improving the quality of life of seniors

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and the disabled, most of them focused on developing the algorithm for changing the walkers behavior based on the users intention or the surrounding environment. Some devices monitor the real-time balance or gait performance of the user, but this information could not be accessed by the users. Without access to real-time balance information, a backward fall may occur due to lack of attention or impaired sense of balance among users of the walker, which could lead to serious injuries. The study [10] presented a safety feature that prevents falling in the anterior-posterior (A/P) direction by detecting the distance between the user and walker and the forces on the handgrips. The walker will stop immediately once it detects possible falls. This feature provides some mechanical support for fall prevention, but it is still important for users to learn and actively correct their balance or gait rather than to be passively assisted by the walking aids.

To this end, we propose a new functionality for a conventional walker that monitors real-time balance performance and provides this information to the user as a means of improving the postural stability. The reasons for choosing a walker over other walking aids are the ease of use and its consistent orientation frame compared to canes or crutches. The sensory feedback for posture is augmented via a skin stretch device embedded into the handgrip of a walker. Studies have shown that skin stretch feedback about the applied forces or direction of postural sway at fingertip can be useful for balance control [12]. Significant physical stabilization is also observed with touch contact of a cane at low force levels [13]. It has been suggested that touch contact on those mobility aids could be used to improve balance performance at a sensory level [14], [15]. However, the effects of light touch on gripping a handle while using those mobility aids are not clear; Therefore, we hypothesize that applying artificial skin stretch feedback could achieve similar effects to that of light touch, and persons with impaired balance can still be provided physical supports with a mobility aid.

Artificial skin stretch has been shown to be effective in conveying direction and intensity cues [16]–[18]. Its applications can be seen in controlling body movements using fingertip [19] and wrist [20] devices; teleoperation [21]; controlling a prothesis using a forearm device [22], [23], and driving an autonomous car using a feedback wheel [24]. This kind of feedback can provide richer information such as multiple degrees of direction with fewer motors compared to conventional tactile feedback approach using vibratory motors. Tangential skin displacement is also shown to be more easily perceived by users with around half of the normal skin displacement [25]. This is beneficial in developing a compact device.

In this paper, we present the design and implementation of a skin stretch device embedded into the handgrip of a conventional walker. Our aim is to provide directional cues in the anterior and posterior directions for the purpose of postural control. Candidate locations for skin stretch feedback are the palm and the fingertip as these two are the main contact areas while holding a handgrip ergonomically. The objective of this study is to evaluate how intuitive are the directional cues delivered via a handheld device and to compare the performance of the two skin sites for perceiving the directional cues. The complete system which integrates the mapping between skin stretch feedback and posture adjustment along with the final device will be presented in a future study.

II. SENSORY AUGMENTATION WALKER

A. *Skin Stretch Feedback*

To provide intuitive and realistic cues associated with the interpretation of directions, we have chosen to employ cutaneous feedback because the sense of touch plays an important role for humans to interact with each other and their environments. It is also broadly accepted among all populations. For example, physical therapists tap on the shoulder of stroke patients to inform them the correct side for weight shifting during walking. Individuals with impaired vision use touch sensation as a sensory substitution, e.g., braille. Our skin, the largest organ in the human body, contains a variety of sensory receptors that allows human to perceive different kinds of physical stimuli. There are four different types of mechanoreceptors characterized by adaptation speed to mechanical stimuli: fast-adapting (FA) I & II and slow-adapting (SA) I & II. The density of FA I and SA I units in the skin is highly correlated with the capacity for spatial discrimination [26]. In the hand, the density of type I units at the fingertip is about five times higher than at

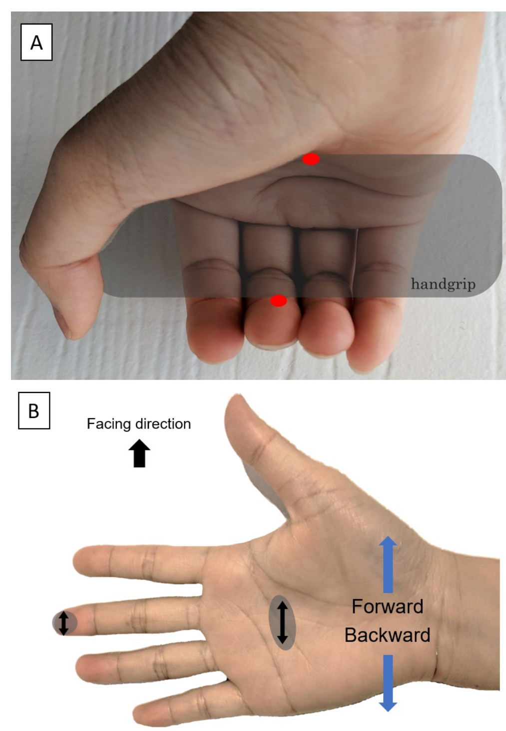

Fig. 2. (A) The two primary skin contact areas (red dots) while holding a handgrip. (B) Mapping of the 1-DOF skin stretch direction at fingertip/ palm (gray shades) with the body orientation.

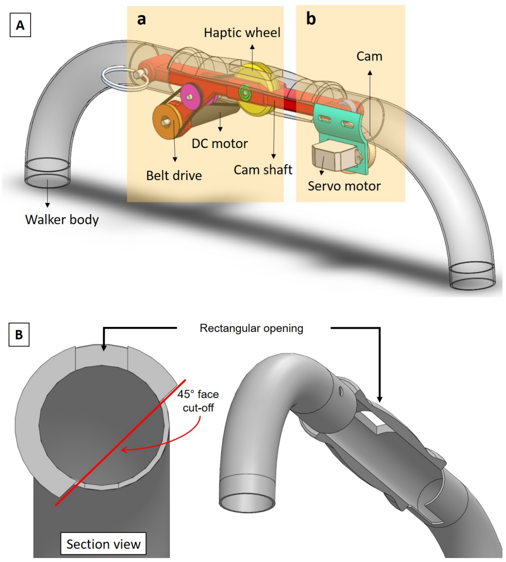

Fig. 3. (A) CAD design of the skin stretch device embedded into the right-hand side handgrip of a walker. The mechanism consists of two parts for producing lateral skin stretch using a DC motor (a) and normal skin displacement using a micro servo (b). (B) Section view and bottom front view of handgrip tube. Two sites including a rectangular opening on the top and a 45° face cut-off along the tube were fabricated for the installation of the skin stretch device.

the palm. The average two-point threshold for fingertip and palm are about 1.6 mm and 8 mm respectively [26]. This implies a minimum skin contact area at both locations.

Fig. 2 (A) shows the two skin contact regions while holding a handgrip which are the fingertip of the middle finger and the center of the palm (displayed as red dots in Fig. 2 A). To render the one degree-of-freedom (DOF) directional cues at these two locations, we have chosen to apply skin stretch feedback in which body orientation in the sagittal plane can be mapped directly from the skin stretch direction (Fig. 2 B). That is, when user senses a stretching of the skin from regions back to front, it represents a forward directional cue, and vice versa. An initial prototype was developed as a proof-of-concept. The next section details the device design.

B. Device Design

A conventional front-wheel walker made in aluminum was re-engineered as a fundamental structure to develop the initial proof-of-concept prototype (Fig. 1). The design comprises two parts for conveying (i) lateral skin stretch and (ii) normal skin displacement, labeled as (a) and (b) in Fig. 3 (A) respectively. All parts, except for the mechanical components (e.g., bearings and fasteners) that were purchased, were designed using DS SolidWorks and printed in PLA material with a 3D printer (Dreamer, Flashforge, USA, City of Industry, CA).

First, for the installation of the main part that provides lateral skin stretch, several geometrical modifications were made on the right handgrip. They include a 45° face cut-off along the tube, a rectangular opening on the top, a slot on the bottom and a M5 through-hole on the sides (Fig. 3 B). Skin stretch feedback is conveyed through a haptic wheel (diameter: 30.5 mm, width: 8 mm) and belt-drive

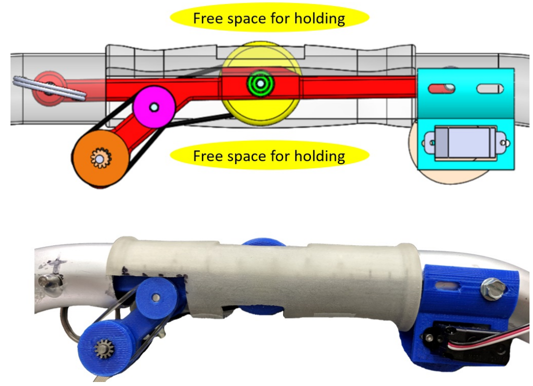

Fig. 4. CAD design (top) and the prototype (bottom) of the skin stretch device from the left-side view.

systems operated by a small DC motor with a gear ratio 19:1 (1524T009SR, Faulhaber, Germany). The DC motor, pulleys, and the haptic wheel are attached to a camshaft. The camshaft is fixed on the walker body using a quick-release pin. The speed ratio of the DC motor and the haptic wheel was set to be 1:1. The pulleys and the routing of the round belts within the unit were well-positioned to ensure the handle can be gripped easily by the users. A handgrip cover printed in flexible material was made to improve comfort while gripping. For motion control of the DC motor, a Teensy 3.6 microcontroller, an h-bridge type motor driver (L298N, STMicroelectronics, Italy) and a 9V battery are used and packed in a small box on the lower part of the walker. The normal skin displacement is controlled via a custom cam rotated by a servo motor (Futaba S3114 Micro High Torque Servo) connected to the same control unit (Teensy 3.6) and fixed on the walker body. By rotating the cam, the shaft can move vertically allowing a normal skin displacement of 5 mm at the palm. The normal skin displacement is by default set to 2.5 mm. The entire mechanism weights approximately 40 g. A close-up view of the skin stretch part and the physical prototype can be seen in Fig 4.

III. USER PERCEPTION STUDY

The purpose of this user study is to evaluate the functionality of our skin stretch device on rendering directional cues. Two candidate locations, i.e., palm and fingertip, were tested to assess and compare the perception of direction in the sagittal plane. The final design of the skin stretch device will be based on the preliminary results gathered from this experiment.

A. Experiment Setup

A graphical user interface (GUI) was created to control the rotation direction of the haptic wheel (referred to as the tactor) and to record the user data. The device was connected to a PC via a USB port. Motor commands were operated using Arduino IDE and the motor driver was used to provide appropriate PWM signals to the DC motor. The DC motor rotates clockwise or counter-clockwise in order to deliver skin stretch cues in either the forward or backward direction.

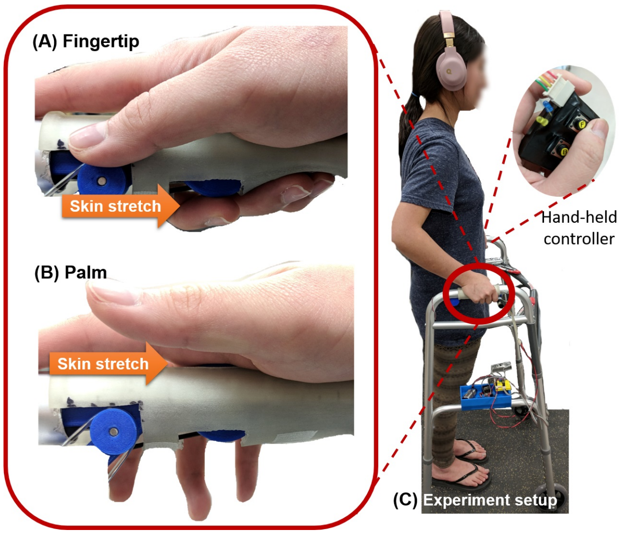

Fig. 5. Experiment setup. During the experiment, skin stretches are applied at different locations in the fingertip session (A) and palm session (B). (C) The participant stands quietly while holding the handgrip using her right hand and a controller using the left hand to toggle between two directions.

The output cues are combinations of multiple speeds and durations of stimulus. Four speeds: (i) 55mm/s (ii) 85mm/s (iii) 130mm/s (iv) 205mm/s and three durations: (i) 0.1s (ii) 0.25s (iii) 0.5s were chosen to determine a baseline for our device. These parameter ranges were selected based on the pilot tests conducted by the researchers. The effects of speeds were examined to investigate the minimum threshold on perceiving the direction and to determine whether users are more sensitive at the slow, medium or fast speed. The effects of durations were studied to determine how quickly the users can react to a directional cue and to detect potential habituation problems from a long-duration cue. A small hand-held portable controller with two buttons (F and B) was made for the users to toggle between forward or backward directions (Fig. C). The controller was held by the users left hand while the device delivered cues at their right hand. Two front wheels on the walker were locked to provide a static standing environment.

B. Experiment procedure

A total of eight subjects were recruited (age ± s.d.: 26.6 ± 4.57, 2 females). The experiment consisted of three sessions: (i) practice (ii) perceptual study at palm and (iii) perceptual study at fingertip. In the first session, participants were instructed on the functionality of the skin stretch feedback device and on how to perceive the cues at the two skin sites. Participants were also given time to familiarize themselves with the hand-held controller. The experimenter provided several practice trials and checked if the participants could respond to the cueing sensation and were comfortable with wearing the device. A maximum period of ten minutes was given to prevent any learning effects on one or both locations.

In the main sessions, i.e., (ii) and (iii), participants were asked to put on headphones while holding the handgrip with their right hand in an upright stance. Headphones playing white noise were used to minimize distractions from the sound of the DC motor. Participants were also asked not to look down at the device and focus on the cue sensation at their hand. A series of forward and backward directional cues was given in a randomized combination of speeds and durations; for example, a 0.5 s cue was given in the forward direction with speed of 130 mm/s. The trials included 12 combinations of speed and duration with 5 repetitions in both the forward and backward directions. In total, 120 cues were tested in a randomized order in each session. Upon request, the participants were allowed to retry up to one additional trial on the same cue. If the skin stretch actuation was blocked due to normal hand gripping strength, the participant was asked to adjust the hand position and to release their hands slightly. For perceiving skin stretch at palm, the participants were instructed to touch lightly on the tactor with the palm while avoiding the fingertip contact at the opposite site of the tactor (Fig. 5 B). Similarly, in the fingertip session, subjects were instructed to touch the tactor lightly with one fingertip (e.g., middle finger) while avoiding skin contact between palm and the tactor (Fig. 5 A). The participants used the portable controller to select either forward or backward direction by pressing the F or B button respectively after receiving the cues operated by the experimenter. The entire procedure, including break, took around one hour to complete.

C. Post-experiment Questionnaire

After completing the previous sessions, a questionnaire was provided to the participants for them to rate the overall performance using the semantic differential scales (1 - 7 rating scales). The level of comfort (1 = very uncomfortable, 7 = very comfortable), intuitiveness (1 = very difficult to understand, 7 = very easy to understand), preferred speed (low, medium, and high) and duration (short, medium, and long) at both palm and fingertip were surveyed. They were also asked to choose a preferable location other than the palm and fingertip, and provide comments on the design of the device, haptic feedback and experimental protocol.

IV. RESULT AND DISCUSSION

A. Perception of direction

Fig. 6 shows the mean percentage of perceiving the correct direction across all eight subjects for each of the combinations. Perception of direction at the palm yields an accuracy rate in the range from 65 - 80%. Six of the twelve conditions have accuracy rate over 75% (stippled boxes). Perception of direction at the fingertip yields a range of accuracy rate from 91% to 99%. Four out of nine conditions obtained no significant deviation from the 100% maximal result by Student's t test ($p > 0.05$).

B. Effects of the speed and duration on discerning direction

One-way repeated-measure analysis of variance (ANOVA) was performed to evaluate if the perception of direction changes significantly among different speeds or durations.

Palm

Speed (mm/s)	Duration 0.1 s	Duration 0.25 s	Duration 0.5 s
205	66	76	75
130	66	68	75
85	74	65	78
55	66	80	77

Finger

Speed (mm/s)	Duration 0.1 s	Duration 0.25 s	Duration 0.5 s
205	93	98	98
130	91	95	93
85	96	94	99
55	94	99	95

Fig. 6. Mean percentage of perceiving the correct direction at palm and fingertip under twelve speed-duration combinations. The shaded cells correspond to accuracy, with darker color representing higher accuracy.

Speed (mm/s)	Palm	Fingertip
205	0.73 ± 0.043	0.95 ± 0.003
130	0.70 ± 0.031	0.93 ± 0.003
85	0.72 ± 0.043	0.96 ± 0.003
55	0.74 ± 0.046	0.96 ± 0.002

Duration (s)	Palm	Fingertip
500	0.75 ± 0.045	0.96 ± 0.001
250	0.71 ± 0.032	0.96 ± 0.001
100	0.68 ± 0.047	0.94 ± 0.007

Fig. 7. Accuracy rates for discerning the correct direction at different speeds (top row) and different durations (bottom row). 95% confidence intervals are provided.

Fig. 7 shows the mean accuracy and its 95% confidence interval for speeds and durations of stimuli for palm and fingertip. The results show that no significant differences were observed among different speeds, for both locations. Similarly, no significant differences were observed among different durations for both locations. While no statistical results were found, perception of 130 mm/s (medium-high) cues yield the lowest accuracy rates for both palm and fingertip. The reason for this trend is unclear since this speed profile is characterized as medium to high in this study. It will be worthwhile to investigate in a future study whether directional cues are better operated at either low or high speeds. Similar trends without statistical significance are also found in perception of 0.1 s (short) cues. A possible explanation is that the response time for each user differs, hence the pulsing duration less than 0.1 might be more difficult to be processed in time, which identify a lower bound of duration for delivering such directional cues. These results also imply that the ranges of speeds and durations chosen in the experiment can be used in our device with no significant difference in perception of direction. Further experimentation is needed to investigate whether these two factors can be used for rendering skin stretch cues of different magnitudes.

C. Subjective Perception

Qualitative analysis was performed using the post-experiment questionnaire. All eight participants completed the survey and commented on the device performance. The levels of comfort for the palm and the fingertip were rated both at an average score of 5.3 (out of 7). One subject suggested to design a better enclosure for the device. Since the current prototype has an open structure, extra cognitive load may be required for avoiding skin contact on other areas of the hand. This can be improved in a future study. For the level of intuitiveness, the palm was rated easier in mapping the forward and backward orientations when compared to the fingertip (average scores of 5.3 for the palm and 5 for the fingertip). This is because of the opposite skin stretch direction with respect to the spatial orientation when touching the bottom side of the handgrip. Some subjects interpreted the direction cues based on the rotational motion of the tactor while others based on the direction of skin stretch at the fingertip. Three out of eight participants were confused about the right direction even though they could precisely perceive the direction change. Two types of interpretation were observed: (i) skin stretch direction and (ii) rotating direction of the wheel. In our default setting, users were asked to interpret the directionality of fingertip feedback using the skin stretch direction. One of the subjects stated that it was not natural for the subject to respond to such a strategy. An adequate learning time is required for correctly interpreting the directionality of the rendered cues. Some users suggested that the cueing strategy should be consistent among users while some other stated that strategies could be adapted to each user as long as the instruction was clear and enough practice was provided. The latter statement was supported by the quantitative evaluation showing high accuracy rates (approximately 95+%) for perceiving directional cues at the fingertip among all users

Comparing the preferable skin sites on which the feedback is applied, the fingertip is favored as six out of the eight participants chose this location while the remaining two indicated no preference, agreeing with the experimental results. For the speed and duration used to render cues (Fig. 8), seven out of eight participants chose medium to high speed paired with a medium to high duration for both locations. Only one participant chose a short-medium duration and mentioned a potential discomfort when perceiving strong cues at palm. All subjects stated that they can identify a set of three different durations (i.e., short, medium, long) whereas the varying speeds were not as distinguishable as durations. All subjects can identify two (low and high) out of four speed profiles used in the experiments but can hardly specify all of the speeds. This implies that stimuli of varying durations may be more suitable for representing cues of different magnitudes.

Overall, the participants were positive about the concept and believed that this device may be helpful for people needing walking aids. However, further improvement of the hardware is needed. For the elderly, it is important to provide a long and strong cue. A motor capable of generating enough torque is lacking in this design and will be investigated in the next prototype.

V. CONCLUSIONS AND FUTURE WORK

In this study we have presented an initial proof-of-concept prototype that can provide skin stretch feedback while hold-

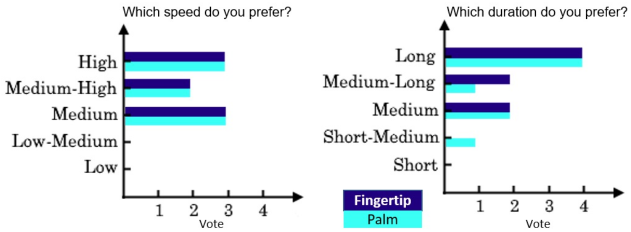

Fig. 8. Votes of preferable speed and duration from all test subjects (n=8).

ing the handgrip of a walker. Perceptual studies about how well users can discern the directions at two skin sites are assessed and compared. It is shown that the fingertip is an ideal location for perceiving the 1-DOF directional cues (forward and backward) supported by both quantitative and qualitative results. The accuracy rates for perceiving the correct direction at the fingertip achieved 95+% for all eight subjects whereas it fell down to around 70% for palm. No significant differences were found among stimuli speeds and among the stimuli durations with respect to perceiving the correct direction at the two hand locations. When discerning the direction, a long and strong stimulus is preferred by the subjects. To sum up, we introduced a new functionality for a walker that can provide directional cues via skin stretch feedback. Such directional cues can be used for augmenting the posture information and improving the postural stability at the sensory level.

In a future study a beta version of the skin stretch feedback device will be developed based on the preliminary evaluation of the current prototype. The fingertip will be the only skin site for rendering the directional cues. An enclosure that covers the whole skin stretch mechanism will be fabricated to improve user comfort. Motors that can generate larger torque than the current one will be explored and included during the design process. A full closed-loop system that detects users posture and provides feedback on balance with the skin stretch feedback device will be implemented. Further experimentation is needed to evaluate the efficacy of skin stretch feedback in improving the sense of balance among walker users.

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