# Chapter 2

# A cutaneous stretch device for forearm rotational guidace

Within the ACANTO project, physical exercises and rehabilitative activities are paramount aspects for the resulting assistive living environment. A possible way to spur physical activities is to make available remote caring assistance from doctors and caregivers, or to arrange training programs, which can be displayed by the FriWalk and its accessories at any time. Body limb guidance is one of the core of this concept, and effective ways to induce this guiding directions are in the scope of T6.2 and T6.3. In what follows, we present a cutaneous skin stretch device for command a desired pronation/supination of the forearm (also referred to as rotational guidance).

## 2.1 Introduction

Haptic devices able to provide only cutaneous stimuli have recently gained great attention in the haptic and robotic research fields. Cutaneous stimuli are sensed by mechanoreceptors in the skin, and they are useful to recognize the local properties of objects such as shape, edges, embossings, and recessed features [5, 29]. The richness of information cutaneous receptors are able to detect, together with their broad distribution throughout the body, makes the skin a perfect channel to communicate with the human user [28]. Moreover, cutaneous force feedback provides an effective and elegant way to simplify the design of this type of haptic interfaces: the very low activation thresholds of cutaneous receptors [28, 14] enable researchers to design small, lightweight and inexpensive cutaneous haptic interfaces [43, 33, 46, 57].

An example of a cutaneous device exploiting these capabilities is the one presented by Prattichizzo *et al.* [46], developed to provide contact deformations stimuli at the fingertip. The device weights only 35 g, and it is composed of two platforms: one is located on the back of the finger, supporting three small DC motors, and the other is in contact with the volar surface of the fingertip. The motors shorten and lengthen three cables to move the platform toward the user's fingertip and re-angle it to simulate contacts with arbitrarily oriented surfaces. The direction and amount of the force reflected to the user is changed by properly controlling the cable lengths. Three force-sensing resistors near the platform vertices measure the fingertip contact force for closed-loop control. A similar device was also used to display remote tactile experiences [47] and unobtrusively interact with virtual and augmented environments [41].

In addition to the above mentioned type of cutaneous devices, there is also a growing interest in vibrotactile cutaneous feedback. Vibrations have been in fact successfully employed to provide navigation information and contact acceleration feedback in many scenarios. Erp *et al.* [15], for example, explored the possibility of presenting navigation information through a vibrating waist belt. Results indicate the usefulness of vibrotactile cuesfor navigation purposes as well as for situational awareness in multi-tasks environments. Traylor and

Figure 2.1: A prototype of the cutaneous device worn by the user. Two cylindrical rotating end-effectors provide the user with independent skin stretches at the palmar and dorsal sides of the arm.

Tan [65] presented a vibrating wearable device able to provide directional information on the user's back. The tactile display consists of a single tactor strapped to the volar side of the user's forearm. An accelerometer is placed on top of the tactor to record its displacement during signal delivery.
A third type of devices providing cutaneous stimuli are the ones able to apply lateral stretches to the user's skin. They exploit the high sensitivity of human skin to tangential stretches and can provide the user with directional information. Conversely to vibration, skin stretch stimuli can be used to activate both slow-acting (SA) and fast acting (FA) mechanoreceptors. Schorr *et al.* [59] evaluated the potential of skin stretch feedback for robotic teleoperation systems. They presented a fingertip skin stretch feedback device that imposes tangential skin stretch proportionally to the intended level of force feedback. The authors carried out an experiment to determine the ability of subjects in discriminating between virtual surfaces of different stiffness using skin stretch feedback. The cutaneous device was attached to the end-effector of a Phantom haptic device to track the position of the fingertip and provide additional kinesthetic feedback. Results show that users' stiffness discrimination capability using solely skin stretch was comparable to that of using kinesthetic feedback. Furthermore, larger skin stretch cues were perceived as portraying greater stiffness without any advance training. Provancher and Sylvester [48] presented a haptic feedback system composed of a Phantom Premium kinesthetic interface and a contact location display apparatus. The Phantom was used to render normal forces and kinesthetic resistance. The contact location display utilized a rubber-coated wood block of 1 cm radius to provide shear and skin stretch to the user's fingertip.

We present here a novel cutaneous haptic device able to provide navigation cues through lateral skin stretch force feedback. This kind of device is not yet included in the FriWalk prototype. The device focus of this Section is shown in Figure 2.1 and Figure 2.2. Two cylindrical rotating end-effectors, placed on the forearm of the human user, can generate independent skin stretches at the palmar and dorsal sides of the arm. When the two end-effectors rotate in opposite directions, the cutaneous device is able to provide cutaneous cues about a desired pronation/supination of the forearm (see Figure 2.3).

## 2.2 The Skin Stretch Haptic Device

The proposed skin stretch cutaneous device is able to provide independent skin stretches at the palmar and dorsal sides of the arm. The device is composed of two static platforms (namely A in Figure 2.2) that accommodate the housing of two servomotors (B), and two cylindrical shaped end-effectors (C) that apply the requested stimuli to the skin. The two static platforms are connected by fabric straps, forming a bracelet. The actuators used for the prototype are HS-422 servomotors (Hitec, Republic of Korea). The maximum stall torque of one motors is 0.41 N·m at 6.0 V. The pulley end-effectors and the mechanical support are made with a special type of acrylonitrile butadiene styrene, called ABSPlus (Stratasys, USA). The end-effectors are then covered with a rubber layer to improve grip and reduce slipping while in contact with the skin. The device is powered at 5 V by an external adapter.

### 2.2.1 Kinematics

If no slip occurs between the mobile end-effector and the user's skin, the displacement $\Delta_S$ of the end-effector can be considered as the skin stretch provided by our cutaneous device onto the user's skin. This displacement can be evaluated as

$$\Delta_S = \alpha \cdot r, \tag{2.1}$$

where $r = 20$ mm is the radius of the end-effector (see Figure 2.4) and $\alpha$ is the commanded angle expressed in radians.

## 2.3 Perceptual thresholds

In the ACANTO project, and in particular in WP6, it is crucial to understand how and where the wearable devices produced within the project are producing the less impact to the user, bringing the maximal result in terms of efficacy.

To understand how to correctly modulate the reference input of the device, as well as where to locate and how to wear it on the forearm to evoke the most effective cutaneous sensations, we carried out two preliminary experiments aiming at evaluating its absolute and differential thresholds.
We decided to test these two metrics in eight different working conditions, changing the position of the device along the arm and the normal force exerted on the skin, i.e., how tight it was. We tested the metrics with the device worn either 4 cm proximal to the lunate bone (see Figure 2.8) and 10 cm proximal to the lunate bone (see Fig. 2.8). Moreover, we tested the metrics when the end-effector applies a normal force $f_n$ to the skin of 2 N, 4 N, 6 N, and 8 N (see Figure 2.4).
The experimental setup is shown in Figure 2.5 and Figure 2.8. We modified the device to consider only the end-effector placed on the dorsal side of the arm. A six-axis force/torque sensor (ATI Mini 25, ATI Industrial

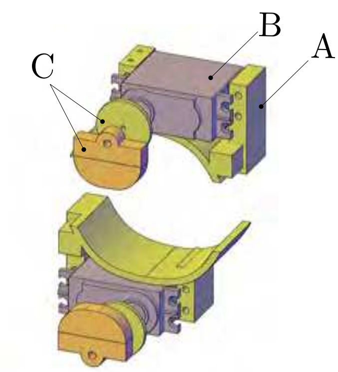


Figure 2.2: CAD design. The device is designed to provide independent skin stretches at the palmar and dorsal sides of the wrist. The device is composed of two static platforms ("A") that house two servomotors ("B"), and two output pulleys ("C") that apply the requested stimuli to the skin.

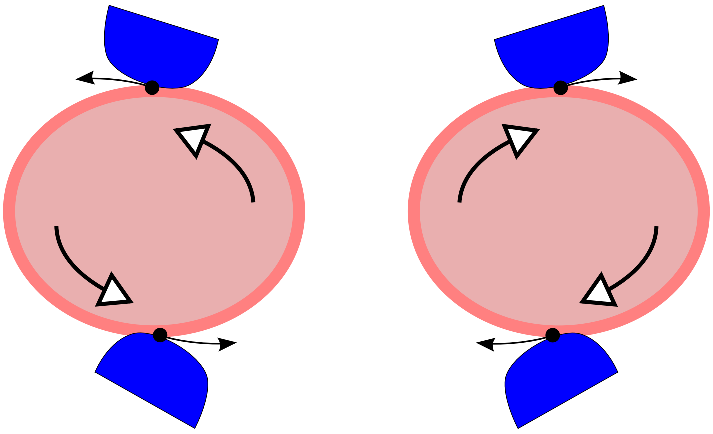

Figure 2.3: Working principle. When the two end-effectors rotate in opposite directions, the cutaneous device can convey information about a desired rotation of the forearm.

Automation, USA) was mounted between the static platform (namely A in Fig. 2.2) and an external structure in order to measure the interaction forces between the device and the skin, associating the normal component of these forces to how tight the device was fastened to the user's arm. A screw enabled the experimenter to easily modulate the force exerted by the device. The sensor was also used to detect any slippage of the end-effector on the skin through the monitoring of the lateral force $f_l$. A white cardboard prevented the subjects from seeing the device.
The force $\boldsymbol{f}$ applied by the device to the skin can be evaluated as

$$\boldsymbol{f} = \left[f_l,\ f_n\right]^T = \left[-\frac{\tau_z}{d},\ -\frac{\tau_y}{d}\right]^T, \qquad (2.2)$$

where $\tau_y$ and $\tau_z$ are the torques registered by the ATI sensor w.r.t. the reference frame $s_0 = \langle x, y, z\rangle$ placed at the base of the sensor, $f_l$ and $f_n$ are the lateral and normal forces exerted by the mobile end-effector to the skin,

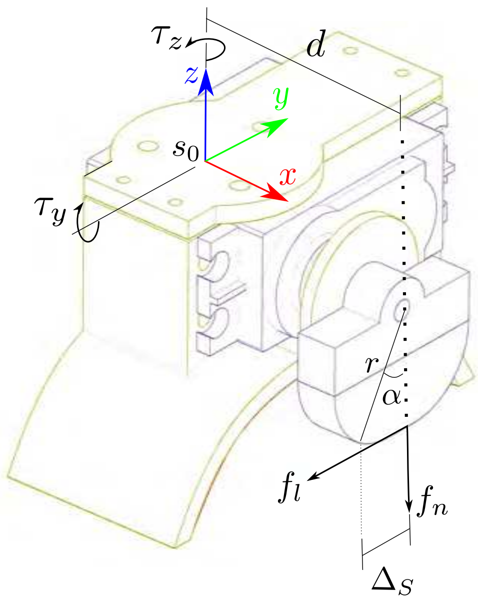


Figure 2.4: Kinematic scheme of the skin stretch device.

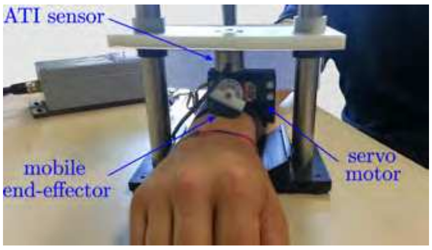


Figure 2.5: Absolute and differential threshold experiments.. Front view (4 cm proximal to the lunate bone).

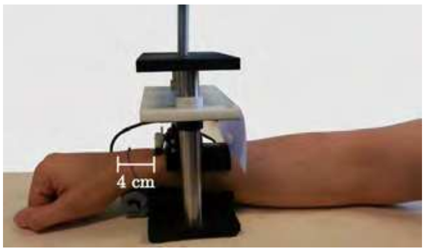


Figure 2.6: Side view (4 cm proximal to the lunate bone).

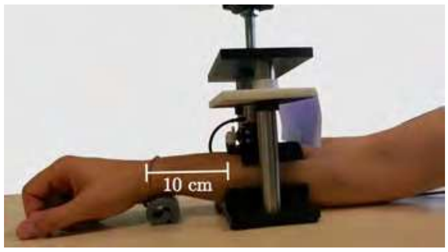


Figure 2.7: Side view (10 cm proximal to the lunate bone).

Figure 2.8: Absolute and differential threshold experiments.

respectively, and $d = 30$ mm is the distance between the end-effector and the origin of $s_0$ (see Figure 2.4).

### 2.3.1 Absolute threshold

The absolute threshold can be defined as the "smallest amount of stimulus energy necessary to produce a sensation" [21], and provides information about the smallest displacement we need to generate with the device to produce a skin stretch sensation perceivable by the human user.
Ten participants took part in the experiment. Two of them were women. Six of them had previous experience with haptic interfaces. None of the participants reported any deficiencies in their visual or haptic perception abilities, and all of them were right-hand dominant.
We evaluated the absolute threshold using the simple up-down method [35]. We used a step-size $\alpha = 1°$, that corresponded to a stretch of $0.35$ mm on the skin (see eq. (2.1)). We considered the task completed when six reversals occurred. Subjects were required to wear the cutaneous device as shown in Figure 2.5 and Figure 2.8 and tell the experimenter when they felt the stimulus, i.e., when they felt the stretch on the skin.
Each participant performed sixteen trials of the simple up-down procedure, with two repetitions for each of the four force values considered (2 N, 4 N, 6 N, 8 N) and each of the two position considered (4 cm and 10 cm proximal to the lunate bone). Figure 2.11 introduces the absolute thresholds registered in the eight working conditions. By examining the lateral forces registered through the ATI F/T sensor it was verified that no slippage effect took place during these trials. As expected, when the device is well tight and, therefore, the mobile end-effector exert a higher pressure on the user's skin, the absolute threshold is lower. Moreover, it seems that the position further from the wrist provides a better performance (i.e., a lower threshold).

### 2.3.2 Differential threshold

The differential threshold can be defined as "the smallest amount of stimulus change necessary to achieve some criterion level of performance in a discrimination task" [21]. This gives us information about how different two

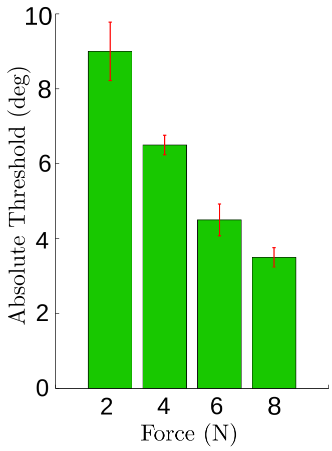


Figure 2.9: pos. 4 cm

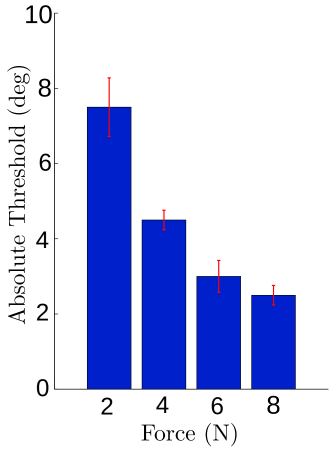


Figure 2.10: pos. 10 cm

Figure 2.11: Absolute thresholds for the eight working conditions. Means and standard deviations are plotted. We tested the metric with the device worn either 4 cm proximal to the lunate bone (data in 2.9) and 10 cm proximal to the lunate bone (data in 2.10). Moreover, we considered the cases of the end-effector exerting a normal force to the skin of 2 N, 4 N, 6 N, and 8 N.

displacements provided with our device need to be in order to be perceived as different by the human user. This threshold is often referred to as just-noticeable difference, or JND. The differential threshold of a perceptual stimulus reflect also the fact that people are usually more sensitive to changes in weak stimuli than they are to similar changes in stronger or more intense stimuli. The German physician Ernst Heinrich Weber proposed the simple proportional law $JND = kI$, suggesting that the differential threshold increases with increasing intensity $I$ of the stimulus. Constant $k$ is thus referred to as "Weber's fraction".

Schorr *et al.* [59], in order to evaluate the potential for skin stretch feedback to be used as a sensory substitute for kinesthetic feedback in robotic teleoperation systems, measured the ability of users to discriminate environment stiffness using varying levels of skin stretch at the finger pad. Results showed a mean Weber fractions of 0.168. Similarly, Guinan *et al.* [25] found a mean Weber fraction of 0.2 for their skin stretch sliding plate tactile device.

The experimental setup was the same as described in Sec. 2.3.1. The same ten participants participated also in this experiment. We evaluated the differential threshold using again the simple up-down method [35]. We used again a step-size $\alpha = 1°$, that corresponded to a stretch of 0.35 mm on the skin. We considered the

| | Normal force $f_n$ at the skin | | | |
|---|---|---|---|---|
| standard stimulus | 2 N | 4 N | 6 N | 8 N |
| 10° | 0.225 | 0.200 | 0.150 | 0.125 |
| 20° | 0.137 | 0.125 | 0.112 | 0.087 |
| 30° | 0.108 | 0.092 | 0.083 | 0.075 |

4 cm proximal to the lunate bone

| | Normal force $f_n$ at the skin | | | |
|---|---|---|---|---|
| standard stimulus | 2 N | 4 N | 6 N | 8 N |
| 10° | 0.150 | 0.125 | 0.100 | 0.075 |
| 20° | 0.112 | 0.087 | 0.075 | 0.062 |
| 30° | 0.091 | 0.083 | 0.075 | 0.067 |

10 cm proximal to the lunate bone

Table 2.1: Weber fractions registered in the eight working conditions for each reference stimulus.

task completed when six reversals occurred. Subjects were required to wear the cutaneous device as shown in Figure 2.5 and Figure 2.8 and tell the experimenter when the two stretches provided felt different. We tested the JND at three standard stimuli: 10°, 20°, and 30°, which corresponded to stretches of 3.5 mm, 7 mm, and 10.5 mm, respectively. Similarly to Sec. 2.3.1, each participant performed sixteen trials of the simple up-down procedure, with two repetitions for each of the four force values considered (2 N, 4 N, 6 N, 8 N) and each of the two position considered (4 cm and 10 cm proximal to the lunate bone). Figure 2.18 shows the differential thresholds registered for each reference stimulus in the eight working conditions, while Table 2.1 shows the corresponding Weber fractions. By examining the lateral forces registered through the ATI F/T sensor it was verified that no slippage effect took place during these trials.
Immediately after the experiment, participants were asked to fill in a 5-item questionnaire using bipolar Likert-type seven-point scales. The questions evaluated the comfort of the cutaneous device when tight at the four levels of force considered. A score of 7 described wearing the device as "very comfortable" and a score of 1

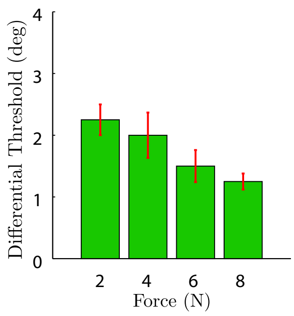


Figure 2.12: pos. 4 cm, stand. stim. 10°

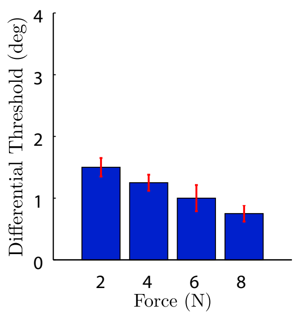


Figure 2.13: pos. 10 cm, stand. stim. 10°

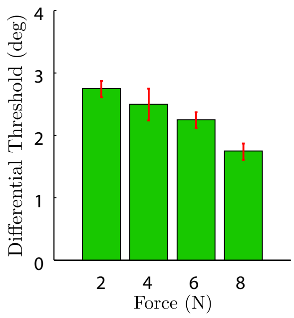


Figure 2.14: pos. 4 cm, stand. stim. 20°

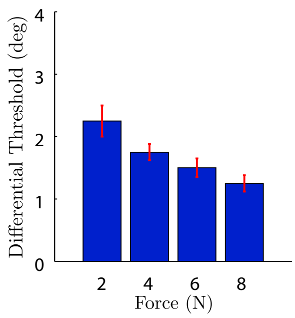


Figure 2.15: pos. 10 cm, stand. stim. 20°

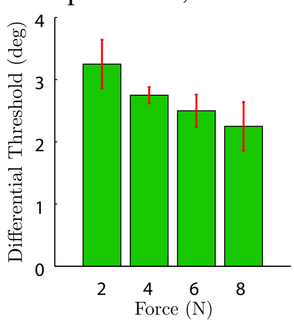


Figure 2.16: pos. 4 cm, stand. stim. 30°

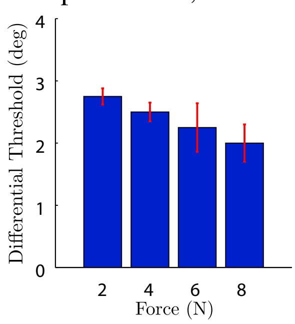


Figure 2.17: pos. 10 cm, stand. stim. 30°

Figure 2.18: Differential thresholds for the eight working conditions and for each reference stimulus considered. Means and standard deviations are plotted.

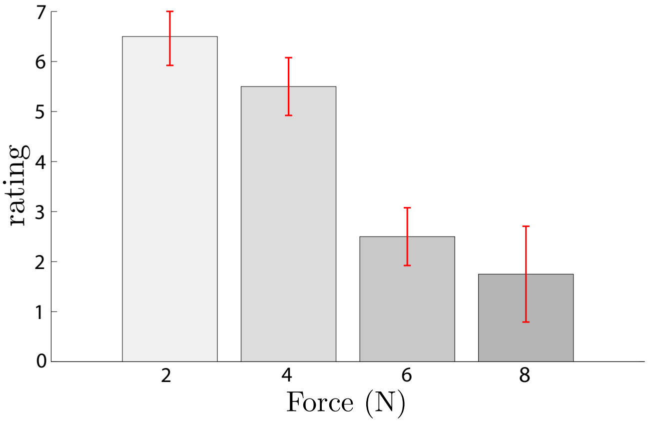


Figure 2.19: Comfort level. Participants rated the comfort level at the four different levels of tightness of the device on the arm (1 = very uncomfortable, 7 = very comfortable). Means and standard deviations are plotted.

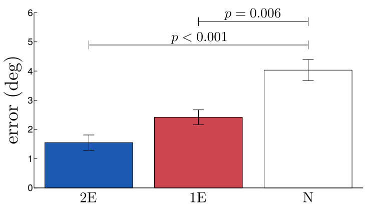


Figure 2.20: Rotation error

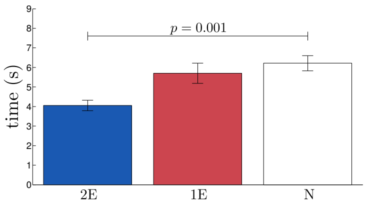


Figure 2.21: Completion time

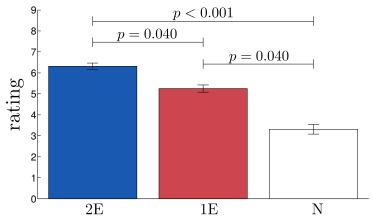


Figure 2.22: Perceived effectiveness

Figure 2.23: Navigation task. The task consisted in rotating the forearm accordingly to the navigation information provided by the device, being as accurate as possible. In condition 2E the two end-effectors rotate in opposite direction, applying two opposites stretches to the dorsal and palmar sides of the arm. In condition 1E only the end-effector placed on the dorsal side of the wrist is active. In condition N both end-effectors are not active and the experiments communicate verbally to the subject the desired rotation. Absolute rotation error and task completion time provided a measure of performance. Finally, users were asked to rate the perceived effectiveness of each condition. Mean and Standard Error of the Mean (SEM) are plotted.

as “very uncomfortable”. Figure 2.19 shows the evaluation of each question. In addition to this questionnaire, subjects were also asked which position of the bracelet they preferred. Seven out of ten preferred when the device was placed 10 cm proximal to the lunate bone.

### 2.3.3 Discussion

The highest levels of performance (lower thresholds) were obtained when the bracelet was tightly fasten to the arm and placed more distant from the wrist. However, we can see from Figure 2.19 how fastening the device too tight results in a great discomfort for the user. In order to find a trade-off between performance and comfort, we decided to place the device 10 cm proximal to the lunate bone, and to fasten it to the arm until the end-effector applies a force of 4 N normal to the skin.

## 2.4 Experimental Evaluation

To evaluate the effectiveness of our device in providing informative and intuitive shear cutaneous stimuli at the user’s arm, we carried out an experiment of remote haptic navigation. In fact, when the two end-effectors rotate

in opposite directions, the cutaneous device is able to provide the human operator with navigation feedback about a desired rotation of the forearm (pronation/supination) (see Figure 2.3).
The experimental setup was composed of our skin stretch device in its complete two-end-effectors configuration, as shown in Figure 2.1. As discussed in the previous Section, we placed the device 10 cm proximal to the lunate bone, and to fastened it to the arm until the end-effector applied a force of 4 N normal to the skin. We also equipped the bracelet with a 3-axis accelerometer (ADXL335, Analog Devices, MA, USA), able to easily detect pronation and supination rotational movements of the wrist.
The task consisted of rotating the wrist accordingly to the navigation information provided by the device, being as accurate as possible.
Sixteen participants took part in the experiment, including two women and fourteen men. Ten of them had previous experience with haptic interfaces. None of the participants reported any deficiencies in their visual or haptic perception abilities, and all of them were right-hand dominant. Each participant made nine randomized trials of the navigation task, with three repetitions for each condition proposed:

- navigation feedback about the desired rotation employing two end-effectors (condition 2E),
- navigation feedback about the desired rotation employing the dorsal end-effector only (condition 1E),
- no navigation feedback at all (condition N).

In condition 2E, at the beginning of each repetition, the two end-effectors rotate in opposite direction, applying two opposites stretches to the dorsal and palmar sides of the arm. The end-effector on the dorsal side rotates clockwise, while the other one rotates counterclockwise (see Figure 2.3). Subjects are required to rotate the wrist accordingly to the reference rotation indicated by the device. The more the subject rotates the wrist toward the target, the less stretch the device applies to the skin. When the subject reaches the desired wrist rotation, the device applies no stretch to the skin. This simple proportional control policy is summarized in Fig. 2.24.
In condition 1E, the same feedback control strategy described above is employed. However, this time only the end-effector placed on the dorsal side of the wrist is active.
In condition N, both end-effectors are not active. The experimenter communicates verbally to the subject the desired rotation.
Subjects were required to wear noise-canceling headphones and were blindfolded. Reference rotations were randomly chosen in the range 10° – 50°.
Absolute rotation error and task completion time provided a measure of performance. A low value of these metrics denotes the best performance. Figure 2.20 shows the average absolute rotation error at the end of the task. All the data passed the Shapiro-Wilk normality test and the Mauchly's Test of Sphericity. A repeated-measure ANOVA showed a statistically significant difference between the means of the three feedback conditions (F(2,30) = 22.297, $p < 0.001$, a = 0.05). Post hoc analysis with Bonferroni adjustments revealed a statistically significant difference between conditions 2E and N ($p < 0.001$), and 1E and N ($p = 0.006$). Moreover, although condition 2E was not found significantly different from condition 1E, comparison between them was very close to significance ($p = 0.061$). Figure 2.21 shows the average task completion time. All the data passed the Shapiro-Wilk normality test and the Mauchly's Test of Sphericity. A repeated-measure ANOVA showed a statistically significant difference between the means of the three feedback conditions (F(2,30) = 7.522, $p = 0.002$, a = 0.05). Post hoc analysis with Bonferroni adjustments revealed a statistically significant difference only between conditions 2E and N ($p = 0.001$). Moreover, although condition 2E was not found significantly different from condition 1E, comparison between them was very close to significance ($p = 0.054$).
In addition to the quantitative evaluation reported above, we also measured users' experience. Immediately after the experiment, subjects were asked to report the effectiveness of each feedback condition in completing the given task using bipolar Likert-type seven-point scales. Figure 2.22 shows the perceived effectiveness of the three feedback conditions. A Friedman test showed a statistically significant difference between the means of the four feedback conditions ($\chi^2(2)$ = 27.034, $p < 0.001$). The Friedman test is the non-parametric equivalent

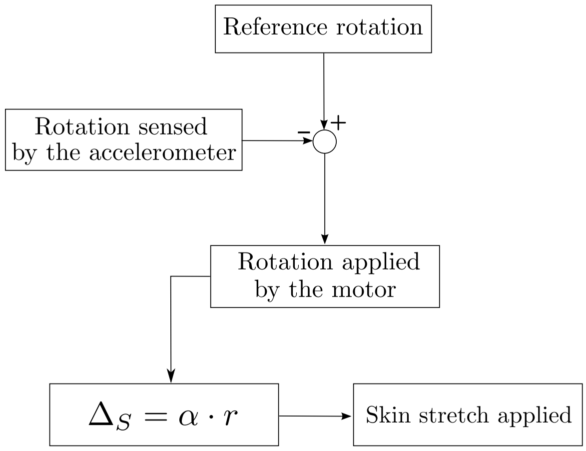


Figure 2.24: Experimental evaluation. Given the random reference rotation for considered repetition, the system evaluates the current rotation of the motor by subtracting the rotation sensed by the accelerometer. From the rotation we can easily calculate the applied skin stretch from eq. (2.1). The reference rotations were randomly chosen in the range $10° – 50°$.

of the more popular repeated measures ANOVA. The latter is not appropriate here since the dependent variable was measured at the ordinal level. Post hoc analysis with Bonferroni adjustments revealed a statistically significant difference between all the conditions (2E vs. 1E, $p = 0.040$; 2E vs. N, $p < 0.001$; 1E vs. N, $p = 0.040$). Finally, subjects were asked to choose the condition they preferred the most. Condition 2E was preferred by twelve subjects, condition 1E was preferred by two subjects, and condition N was preferred by two subjects.

## 2.5 Discussion and Conclusions

We presented a cutaneous device able to provide independent skin stretches at the palmar and dorsal sides of the arm. The device is composed of a bracelet housing two servomotors installed and used to power two cylindrical shape end-effectors. While in contact with the skin, the two end-effectors are able to generate modulated rotations that can effectively produce controlled stretches at the skin of the user. We have presented the details of the device implementation, together with the results of a number of experiments performed to evaluate and demonstrate the performance and effectiveness of the proposed device.

In particular, in order to examine how to generate appropriate control signals as well as how and where to install the device on the forearm, we carried out perceptual experiments to evaluate the absolute and differential thresholds of our device. Moreover, we performed an experiment in which the device was used to provide haptic navigation about a desired orientation of the user forearm (pronation/supination motion). In the best feedback condition (when both motors were active) the average error was as little as $1.55°$. Moreover, 87% of the subjects found our device effective in conveying navigation information.

The above results effectively demonstrated the performance and efficacy of the proposed device to render high fidelity skin stretch stimulations, allowing its use in higher level tasks as a haptic navigation feedback device. In the near future, we plan to add two more end-effectors, equidistant from the ones we already have, so to be able to also provide pinching sensations. This may enable us to convey directional information in addition to the current rotational cues.