A Skin Stretch Tactor for Sensory Substitution of Wrist Proprioception*

Oguz Kayhan, A. Kemal Nennioglu, and Evren Samur, *Member, IEEE*

***Abstract*—This paper presents a novel sensory feedback device and an original method aiming to provide skin stretch feedback of three degree-of-freedom wrist movements, which are extension-flexion, radial-ulnar deviation and pronation-supination, to prosthetic hand users. In order to evaluate the performance of the device, a test setup is built. A user study with able-bodied participants is conducted. Confusion matrices are created from the experimental data, and the results are analyzed in terms of correct identification of the intended stimulations. Analysis shows that the proposed design together with the sensory feedback method is a viable option for proprioceptive feedback lacking in robotic prosthetic hands.**

I. Introduction

There has been a significant effort to provide sensory feedback to persons with an amputation since they lack these information [1]. However, one of the main reasons for prosthesis rejection is still lack of realistic sensory information [2], [3]. It has been proved that proprioception plays a key role in body coordination [4]. Furthermore, the role of proprioceptive feedback in prosthesis control has been shown by Blank et al. [5]. Proprioceptive feedback enables prosthesis users to determine approximate, or for some cases exact, position of the prosthesis when visual feedback is limited. According the study of Pistohl et al. [6], addition of an artificial proprioceptive feedback to visual feedback, increases the accuracy of myoelectric control. Despite these benefits, only few studies have provided this feedback for upper-limb robotic prosthesis [6]–[11]. In these studies, proprioceptive information was provided through sensory substitution, which is an easy and cost effective way to provide intuitive feedback about the motion of interest.

Sensory substitution for prostheses relies on providing feedback through a sensory modality at an intact part of the body. Two modalities become prominent among the solutions in the literature: vibration and skin stretch. The former is useful especially for situational awareness of motion. For example, Witteween et al. [7] investigated the efficiency of vibrotactile feedback on the extent of hand opening. Also they pointed out that vibrotactile feedback is more successful than electrotactile one. The second most preferred modality for sensory substitution of proprioception is skin stretch [9]. The main advantage of skin stretch is that it activates both the slow-acting and fast-acting mechanoreceptors, and naturally provides kinesthetic information [12]. Skin stretch can be created by shear deformation of skin [13]. For instance, Kuniyasu et al. [14] developed a device which could present stretch feeling in four directions (forward, backward, left and right) for teaching device handling skills. Similarly, a forearm-mounted directional skin stretch device was also proposed to communicate navigational cues [15]. An example of skin stretch feedback device for prosthetic hands is proposed by Battaglia et al. [16]. The device consists of a rubber pad, which is adjusted to a wheel, which stretches the skin to right and left for providing a feedback of the hand grip motion. The feedback motion is correlated with the respect to the grip aperture. Wheeler et al. [9] conducted a study that concentrated on the role of rotational skin stretch feedback on prosthesis control. Position of a virtual arm was provided through their skin stretch tactor. More recently, Chinello et al. [17], [18] came up with a design aiming at a feedback device based on skin stretch providing supination, pronation, dorsal and ulnar motions. The device is composed of four end effectors stimulating the skin on four different faces of the forearm. Motion of the cylindrical-shaped end effectors is actuated via four servomotors, which are linked by a bracelet around the upper limb. Although the primary purpose of the device is giving navigational feedback, it can also be used to provide feedback to prosthesis users.

Fig. 1.Wrist movements (flexion-extension, ulnar-radial deviations, and supination-pronation), and corresponding deformations of the forearm hairy skin. The arrows indicate the directions of deformations. The selected stretch areas for feedback are shown with the red spots.

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O. Kayhan, A. K. Nennioglu, and E. Samur are with the Department of Mechanical Engineering, Bogazici University, 34342 Bebek, Istanbul, Turkey (corresponding author: E. Samur; phone: +90-212-359-7294; fax: +90-212-287-2456; e-mail: evren.samur@boun.edu.tr).

This paper presents a novel skin stretch tactor design for sensory substitution of wrist proprioception. The main objective is to provide feedback about wrist movements having three degrees of freedom (DOF). These movements, which are flexion-extension, ulnar-radial deviation, and supination-pronation, are illustrated in Fig. 1. The target application is sensory feedback for users of myoelectric prosthetic hands.

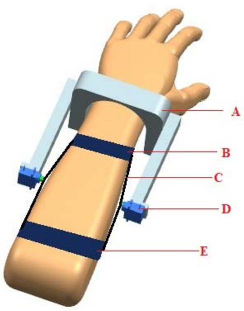
II. Methodology

A. Skin Stretch Tactor

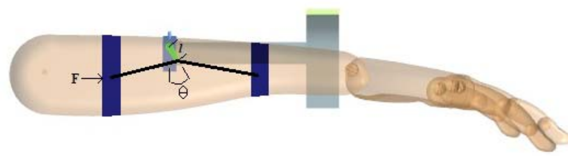
Design Considerations: In order to find appropriate stimulation areas on the forearm for sensory substitution of wrist proprioception, we have investigated which area of the forearm skin stretch most with respect to the six motions shown in Fig. 1. While compression is observed during extension, flexion stretches the forearm hairy skin. Radial deviation simultaneously stretches the medial side and compresses the lateral side of the forearm hairy skin. The opposite happens in ulnar deviation. During supination and pronation movements, there are torsions stretching the forearm skin crosswise. Therefore, we hypothesized that providing corresponding skin stretches at the red spotted areas shown in Fig. 1 leads to intuitive wrist movement feedback. The red spotted areas were considered as target areas to stretch. Extension and flexion motions should create front-to-back and back-to-front tensions at the target areas, respectively. Feedback of ulnar and radial deviations should stretch the two points in the corresponding direction as shown with the arrows in Fig. 1. Finally, the red spotted areas should be stretched diagonally for supination and pronation movements.

Since it has been decided to use skin stretch to create a feedback, the physical properties of skin have to be considered to determine required actuator torque for a certain skin stretch. Tregear [19] conducted a study in order to find the elastic properties of skin. He took several animal skins including human, and subjected them to tensile tests. His study showed that human skin shows both nonlinear and viscoelastic behavior when it is subjected to a tensile or compressive force. Although Tregear's studies lead to very valuable information, they were not in vivo measurements. In 2009, Bark [20] conducted a series of experiments for her PhD thesis at Stanford University. Her experiments consisted of a grid drawn on the forearm. Human skin was subjected to linear and rotational skin stretch in vivo. According to Bark's study, when the skin is subjected to a 0.5 N force, it stretches approximately 7 mm. In order to determine the actuator torque in our study, the skin was modeled as a spring with constant stiffness for the sake of simplicity. Thus the constant stiffness of the skin was taken as 0.071 N/mm. In our system, one-centimeter stretch of the skin is assumed to be sufficient for a comfortable feedback. In order to stretch the skin one centimeter, 0.71 N force must be applied.

Prototype: We have designed a skin stretch tactor (see Fig. 2) and developed a prototype to realize the considered feedbacks. The prototype consists of a 3-D printed main body, two servomotors, four fishing lines, two bracelets, and a microcontroller (see Fig. 3). The main body, made of PLA, carries the servomotors and the microcontroller unit. Handmade bracelets are attached to the servomotors with four fishing lines to transfer mechanical force of the actuators to the skin. To increase skin grip, inside of these bracelets are covered by plastic pads. Outside of these bracelets are covered by velcro to have easy adjustability. The fishing lines are pinned to small links at the servomotors side, and the other sides of the line are stitched into small velcro fasteners. Using fishing line as a force transfer medium is selected not only because it is durable but also its flexibility satisfies the design requirements in terms of intended motion (e.g. while pulling one bracelet, the other one is not pushed).



(a) Oblique view



(b) Side view

Fig. 2. Illustrations of the prototype. A: main body, B: distal bracelet, C: fishing line, D: servomotor, and E: proximal bracelet.

Force (F) that can be applied by the tactor can be formulated as follows,

$$F = \int_0^{\frac{\pi}{2}} \frac{T}{l} cos\theta d\theta \quad (1)$$

where T is the torque that the motor can supply, Θ is the angular position of the servomotors, and l is the length of linkage at the end of which the fishing lines are attached. These variables are shown on the side view illustration of the tactor given in Fig. 2.b. The limits of integral are defined by the initial and final positions of the motors. It should be noted that this force is in the axial direction of arm and the force in the radial direction is neglected since length of the linkage is smaller than length of the fishing lines and this makes the radial component of the force very small. Rearranging equation 1 yields to,

$$T = 2Fl \quad (2)$$

where T is the minimum torque needed, F is the horizontal force which is required to be 0.71 N, and l is the length of linkage which is 7 mm. The required torque yields to be 9.94 Nmm. Many mini servomotors can satisfy this value, thus, the limiting constraint was dimensions.

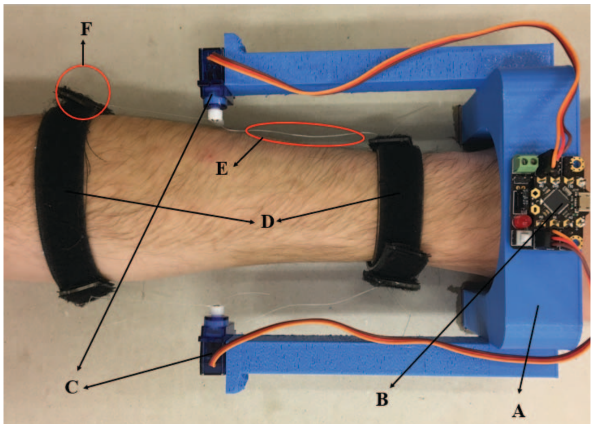
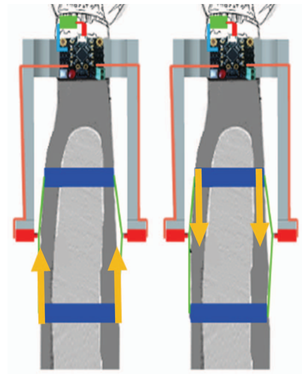


Fig. 3. Prototype of the skin stretch tactor. A: main body, B: Arduino Beetle and motorshield, C: servomotors, D: proximal and distal bracelets, E: fishing line, and F: bracelet holder.

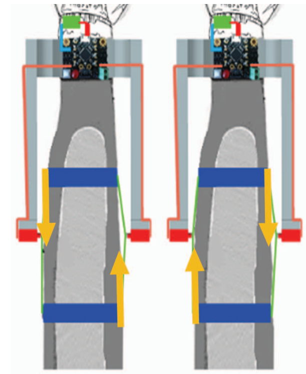
Tower Pro SG90 servomotors were selected as actuators of the system. Two motors are located at both sides of the arm. Using servomotors provide some critical advantages, such as having smooth movements, and being lightweight. Most importantly, it has angle control and this feature can be used to give more intuitive feedback to user. In order to drive the skin stretch tactor system, an Arduino Beetle was used with an appropriate motor shield. This tiny microcontroller was used because of physical restrictions.

Working Principle: Movements of the bracelets provide the indented feedback. The working principle is visualized in Fig. 4. While moving the proximal bracelet forward provides the feedback for flexion, moving the distal bracelet backwards provides the extension feedback. In addition, the feedback for ulnar deviation is provided by pulling the distal bracelet from left towards backward, and the proximal bracelet from right towards forward. The feedback for radial deviation is the opposite of the one of ulnar. Finally, pulling the proximal bracelet forward from right and left provides the feedbacks for supination and pronation, respectively. This feedback method is for left prosthetic hands. If the system is to be implemented to right prosthetic hands; ulnar-radial deviation, and supination-pronation feedback should be fed differently.

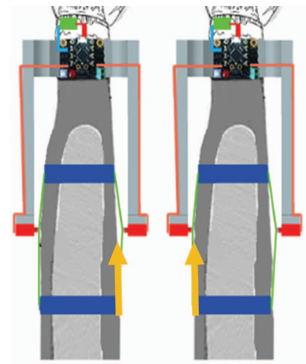
Application Scenario: Implementation of the skin stretch tactor on prosthetic hands is visualized in Fig. 5. The control units are attached on the main body and it is directly powered by the prosthetic hand. Moreover, input of the control unit comes from the prosthetic hand controller to create direct feedback of the desired motion. Prosthetic hands have a rigid part that is worn by the user. This part will include the main body with the motors and the microcontroller fixed on it. There must be two stretchable parts (the blue bands in Fig. 5) in order to provide the skin stretch. Servomotors will be connected with fishing lines to these parts that will give the sensation of skin stretch.



(a) Flexion-Extension

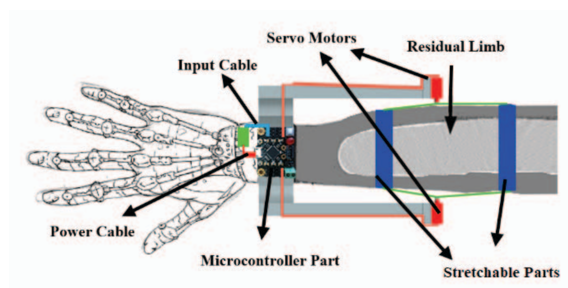


(b) Ulnar-Radial Deviation

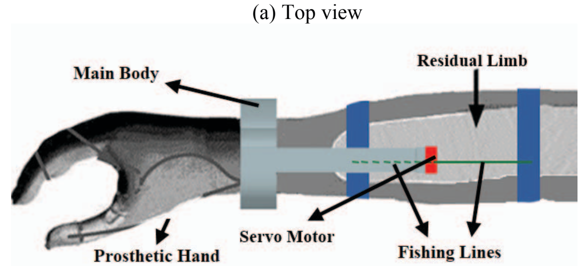


(c) Supination-Pronation

Fig. 4. Visualization of the skin stretch feedback. The selected stretch directions of the corresponding movements are shown with the arrows.



(a) Top view



(b) Side view

Fig. 5. Application scenario of the skin stretch tactor for prosthetic hands.

B. User Study

In order to examine the level of intuitiveness of the design, a psychophysical experiment, which was approved by the Institutional Review Board of Bogazici University, was conducted. 11 participants, three of whom were women, gave their written consents before the experiment. Only right-handed participants were involved due to the experimental setup (see Fig. 6). Only one of them had a prior experience with haptic devices. Participants ranged between the ages 19 and 33, and had a mean age of 24.5 years old.

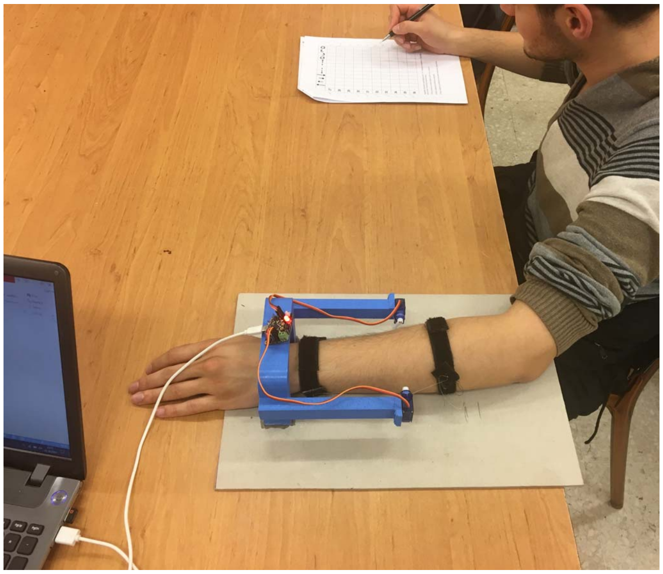


Fig. 6. Experimental test setup. The tactor prototype was worn on the left hand. Subjects answered the questions with their right hands. Predetermined randomly ordered inputs were given via a code running on a laptop.

Experiments were carried out with the test prototype, which could be worn on the left hand. Thus, the right-handed subjects could note their answers on the answer sheet. Test setup can be seen in Fig. 6. The prototype provides feedback in three degrees of freedom. In the experiments, each degree of freedom was divided into four levels in order to analyze the ability of device to provide feedback at different angular position of the wrist. Therefore we had 12 different inputs in order of 90^o flexion (F2), 45^o flexion (F1), 45^o extension (E1), 90^o extension (E2), 90^o ulnar deviation (U2), 45^o ulnar deviation (U1), 45^o radial deviation (R1), 90^o radial deviation (R2), 90^o supination (S2), 45^o supination (S1), 45^o pronation (P1) and 90^o pronation (P2). These degrees are the values given to the servomotors. The limits of the wrist movements are different for every person. Thus 90^o inputs corresponds to wrist movements that one can perform at verge. The amount of deformation is approximately 7 mm and 3.5 mm for 90^o and 45^o rotations, respectively.

Before the experimental trials, a training session was performed. In this session, participants were informed about the protocol and the wrist movements. Twelve inputs and which wrist movements they correspond to were explained in detail. The two bracelets were attached to subjects' left forearms. The bracelet holders, which were connected to the servomotors with the fishing lines, were attached to the bracelets. Subjects had the answer sheet, having visual information about the wrist motions, in front of them. Inputs were given to the tactor in the predetermined order. Thus, the subjects got familiar with the corresponding cutaneous feedbacks. An experimental trial consisted of 36 inputs in total (12 inputs randomly repeated three times) given in a random order. In the experimental trials, participants were asked to identify the corresponding wrist movement according to the feeling they had on their forearm. A barrier was placed between subjects and their left arms to block visual feedback. They recorded their answer by selecting a checkbox related to the identified wrist movement on the answer sheet. A total of 396 (11 subjects x 12 inputs x 3 repetitions) inputs were given at this point.

At the end of the experiment, subjects answered a questionnaire with three questions. They rated comfort, intuitiveness, and ease of learning by giving a score out of five for each of them, where five indicated the highest positive impression.

III. Results & Discussion

The results of the experiments are presented in three different confusion matrices (see Fig. 7, 8, and 9) in order to investigate three different aspects of the study. In these matrices, rows represent the given inputs, and the columns represent the answers of the subjects. In other words, element a_{ij} represents the number of questions answered as j where the input was i. Therefore, these matrices is expected to be diagonal for a perfectly transparent feedback system.

First aspect to investigate is the accurate identification of degrees of freedom. As mentioned above, different regions on the forearm hairy skin were selected as stretch areas for the desired feedbacks. A 3x3 confusion matrix is used to evaluate these selections (see Fig. 7). 132 (11 subjects x 4 motions x 3 repetitions) inputs were given for each degree of freedom. For flexion-extension inputs, 123 of them were correctly identified, which correspond to 93 percent success rate. This tells us that the stretch area selection for flexion and extension movements is accurate. On the other hand, out of 132 ulnar-radial deviation inputs, 103 answers were correct, which is 78 percent success rate. For supination-pronation movements, 97 of 132 inputs were identified correctly. This also leads a satisfying success rate of 73 percent. However, 33 inputs were answered as ulnar-radial deviation while supination-pronation was intended. This is due to intersection of the target skin stretch areas of supination-pronation set and ulnar-radial deviation set. As can be seen in Fig.1, the stretch areas of ulnar-radial deviation include the stretch areas for supination-pronation.

The second aspect to comment on is the direction of stretch. For this analysis, a 6x6 confusion matrix is built as shown in Fig. 8. There are two directions in each degree of freedom, thus we have six different motions to deal with. For this matrix, the number of total elements in a row, i.e. total inputs for each motion, is 66. Except for the deviation in the last row, the desired diagonality is observed. Thus, we can conclude that directions of the deformations are accurately determined. It is clear to see the same confusing effect of the intersection of stretch areas of supination-pronation set and ulnar-radial deviation set as mentioned above.

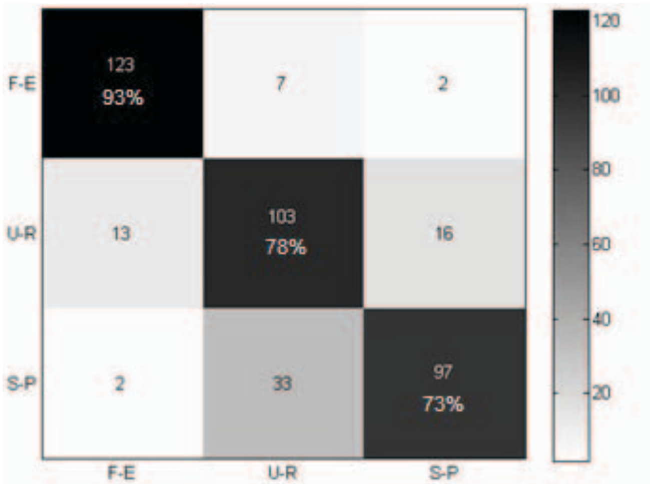


Fig. 7. 3x3 Confusion matrix – Testing the skin stretch regions.

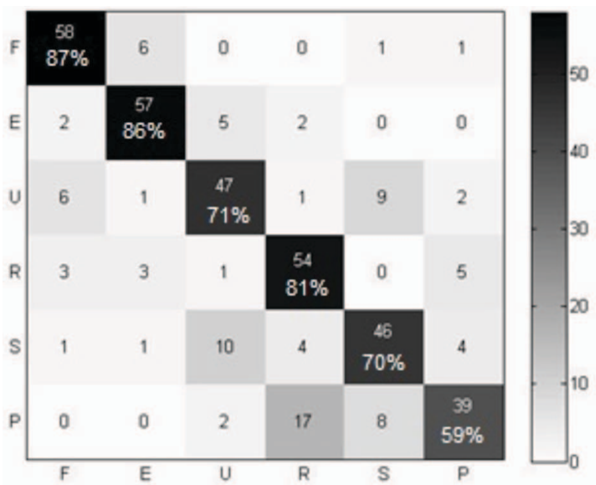


Fig. 8. 6x6 Confusion matrix – Testing the direction of skin stretch.

The final aspect to examine is the amount of deformation of the skin. As mentioned in II.B, the servomotors were set in two different angular positions for each motion. In order to evaluate this, a 12x12 matrix is utilized (see Fig. 9). Flexion-extension set clearly satisfied the expected diagonality. Therefore, feedback of this set is acceptable from every three aspects mentioned above. The subjects had problems in identifying the amount of deformation for ulnar-radial deviation. For supination-pronation set, the intersection phenomenon continues. The total of elements that break the diagonality in the last four rows, i.e. supination-pronation rows, is 68. 39 percent of them is due to the intersection phenomena. 30 percent of them is due to misidentifying the amount of deformation.

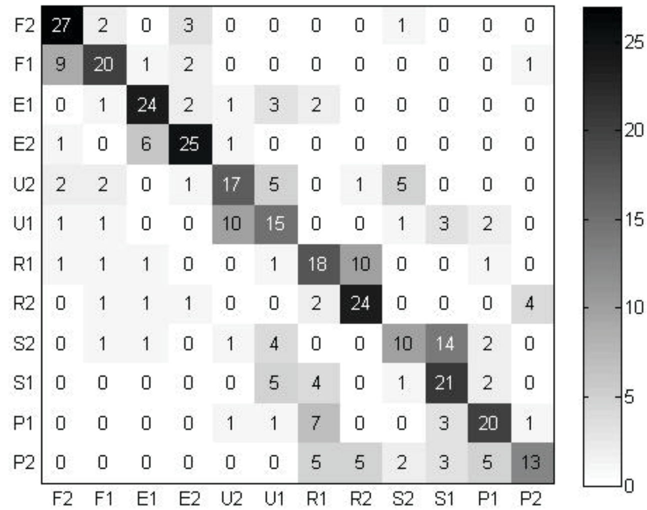


Fig. 9. 12x12 Confusion matrix – Testing the different stimulation levels.

When three aspects are considered, the experimental results are promising. The major obstacle is the overlap between feedback methods. In other words, the stretch area sets of supination-pronation and ulnar-radial deviation intersect with each other. This phenomenon is the main source of wrong identifications. The overall success rate of each input is given in Table 1. Subjects were more often confused when larger stimulation levels for supination-pronation feedback were provided.

According to the questionnaire at the end of the experiment, subjects rated the comfort and painlessness as 4.5 out of 5, where five indicates the highest comfort. Also, the rating of intuitiveness is 3.5, and rating of ease to learn is 4.4 out of 5.

Table 1. Overall Success Rates

F2	**F1**	**E1**	**E2**
82%	61%	73%	76%
U2	**U1**	**R1**	**R2**
52%	45%	55%	73%
S2	**S1**	**P1**	**P2**
30%	64%	61%	39%

IV. Conclusion

Providing proprioceptive feedback for robotic prosthetic hands is a topic of high interest in the literature. Ergonomics, efficacy and intuitiveness of the provided feedback are crucial concerning the freedom and the ease of usage of the system. Skin stretch has been proven to be a prominent method for proprioceptive feedback. In this study, a novel skin stretch tactor has been proposed for sensory substitution of wrist proprioception. By means of two bracelets and two actuators, six motions of the wrist can be provided via the tactor. A proof-of-concept prototype has been developed, and the proposed methodology was tested with a psychophysical study. Based on the participant responses, three confusion matrices were obtained. The results show promising data validating the feasibility of the proposed sensory feedback method. Thus, an intuitive skin stretch tactor design in three degrees of freedom with only two motors and two bracelets is completed. This is the important difference between this study and the early works.

There are still some ways to improve the proposed methodology. Due to the overlap between sensory feedback styles of supination-pronation and ulnar-radial deviation, participants were confused. Trying different stretch areas can reduce this overlap.

As a future work, we plan to focus on the implementation of the tactor on a prosthetic hand. Therefore, wearability of the device should be improved. According to the recent study of Pacchierotti et al. [21], four factors define the wearability of a haptic system: form factor, weight, impairment, and comfort. First of all, the main body of the test setup is bulky and cannot be used in a real prosthesis application. However, the prosthesis itself will replace this main part in the actual implementation. Second, weight of the device can be even lower by using miniature DC motors instead of the stepper motors used in the experimental setup. Third, the tactor should be able to naturally fit the arm without impairing it. Last but not least, adaptability of the tactor to different limb sizes should be guaranteed with the help of the adjustable velcros. Once the wearability of the tactor is achieved, the system will be tested with a target group, prosthetic hand users. Results of this future study will help us improve the tactor design and the sensory feedback method.

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