A Wearable Robot Mask to Support Rehabilitation of Facial Paralysis

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Abstract—In previous work, we introduced the Shape Memory Alloy actuator based Robot Mask that can be used to enhance the expressiveness of the face. The basic concept of that design was the pulling of the skin through wires attached to the face and we explained the human anatomy based criteria of selecting these pulling points and directions. In this paper, we describe a case study of using the Robot Mask to assist physiotherapy of a hemifacial paralyzed patient.

Earlier we reported the general design criteria of the Robot Mask. However, the significant difference in shape and size of human head among different individuals demands further customization of the Robot Mask. In this research a number of adjustment and customization stages were employed, from the design level to the implementation level and this paper briefly describes them. We also explain a depth image sensor data based analyzing method, which can record dynamics of facial expression in a continuous manner. We then evaluate the effectiveness of the Robot Mask by analyzing the range sensor data. We show that, while providing quick responses, the Robot Mask can also reduce the asymmetry of a smiling face.

Index Terms—Robot Mask, Facial Paralysis, SMA, Wearable interfaces, Biorobotic control

I. INTRODUCTION

We have been developing a wearable interface device called Robot Mask to support expressiveness for facial paralyzed patients [1]. In this paper, we discuss a case study of using the Robot Mask to assist the physiotherapy of a hemifacial paralyzed patient.

Due to various medical conditions such as Bell’s palsy, virus infections, stroke, trauma, tumor and neonatal conditions, the voluntary muscle activities of the face can sometimes degrade or disappear, resulting in facial paralysis. Facial paralysis can be congenital or acquired. The most common cause for the acquired facial paralysis is believed to be Bell’s palsy and it accounts for almost three quarters of all acute facial palsies. Overall it records 0.5 per year per 1000 persons with a recurrence rate of 7% and a life time prevalence of 0.64% to 2.0% [2], [3].

Although facial paralysis could occur on both sides of the face, its more common to find facial paralysis only on one side of the face. This single-side paralysis or the hemifacial paralysis can create appearance changes in the face. Due to the muscle tone of the unaffected or the contralateral side and its non-existence on the paralyzed or the ipsilateral side, forces become unbalanced and mouth and sometimes the nose deviates to the contralateral side distorting the symmetry of the face.

The effects of facial paralysis could be either temporary or permanent with the majority of around 80%-84% of patients recovering completely and the other 16%-20% retaining chronic facial paralysis [4]. In the case of temporary paralysis, the average time of recovery can vary from 15 days up to four years. The longer the recovery takes, the higher is the chances of sequelae such as synkinesis and contracture [5]. Although Bell’s palsy may develop at any age, it is more common among young or middle-aged adults between 31-60 years and pregnant women.

Regular physiotherapy is important for the recovery from facial paralysis. Patients with permanent facial paralysis undergo reconstructive surgeries such as cross-facial nerve grafting to obtain some functionality to the paralyzed muscles. However, the total change of motor controls associated with such surgeries mean they need proper neuromuscular retraining to learn how to make new motor actions. Bradbury et al., through a study with a group of 106 hemifacial paralyzed patients who has undergone reconstructive surgery and were 12 months post-surgery, have found out that: Of the total group, 35% were very satisfied with both process and outcome. 34% more were satisfied with outcome but had found the process difficult and were dissatisfied with aspects of the course of treatment. 15.1% were not entirely satisfied with neither process nor outcome but felt surgery to be worthwhile because there had been some improvement. The remaining 17.9% regretted having the surgery and were very dissatisfied [6]. Neuromuscular retraining with biofeedback might well be useful for such patients to learn new motor controls. Vaiman et. al [7] and Sugimoto et al. [8] have already reported that visual and electromyography (EMG) based biofeedback can be used to improve the effectiveness of neuromuscular retraining. In this research, we use EMG based biorobotic control as the basis for actuator control. We use the somatosensory feedback associated with the skin movement of the paralyzed side, which is due to the wearer’s self-initiated skin pulling to produce biofeedback.

In this paper, after briefly introducing the Robot Mask, we will present the customization which were done to allow it to assist physiotherapy. We then describe the experimental set-up and the nature of the experiments. Afterwards, we introduce the depth image sensor based data recording system which was used to evaluate the effectiveness of the Robot Mask. From the results we show that while providing quick responses, the Robot Mask can also reduce the asymmetry of the smiling face.
II. EXPRESSION ASSISTANCE

A. Robot Mask

The Robot Mask is the wearable device which has been developed to support expressiveness of facial paralyzed patients. With the Robot Mask, physical support is provided by pulling the facial skin through flexible wires attached to the face. The Shape Memory Alloy (SMA) based linear actuators are used to pull the wires and a head supporter is used to mount them and other necessary peripherals. In the Robot Mask, pulling points and the pulling directions closely follow the human facial anatomy so that the displacement mechanism is similar to that of natural facial expressions. The device is mainly designed to assist hemifacial paralysis. By using biorobotic control, which is based on the bioelectrical signals of the healthy side of the face actuators are controlled according to the intention of the wearer.

In previous work, we reported the design criteria of the Robot mask and the detailed design of the SMA based unidirectional [9] and bidirectional [10] silent actuators (SIAC). We reported on the use of six actuators to support five facial muscles. Furthermore we proposed two different design methodologies for the actuators: single SMA unidirectional and segmented multiple SMA, bidirectional actuators. This study uses a simplified version of the latter, a single segment bidirectional actuator. In this study, we concentrated on the physiotherapy process and used three actuators to support zygomaticus major, zygomaticus minor and depressor anguli oris. The Robot Mask developed here is portable, can be worn unaided, light-weight and standalone with no necessity of additional peripherals. The fully assembled prototype rehabilitation version of the Robot Mask, which is made by a acrylic-based photo-polymer material weights 250 g.

Figure 1 shows an overview of the wearable Robot Mask. The back-pack which is on the back of the neck carries the actuators and the embedded feedback controller. The direction setting tubes, which are used to control the pulling direction and adjust the size of the Robot Mask to adjust to the wearer were designed to be easily replaceable.

1) Robot Mask supporter: For the subject who was paralyzed only on the left hand side of the face, the Robot Mask was designed to support only that side of the face. The truncated right hand side was used to clamp the Robot Mask on to the head. This approach was adopted to reduce both the obtrusiveness and the weight of the Robot Mask. Contrary to natural muscles, which are located underneath the skin, the pulling wires are attached to the skin externally. In order to improve the quality of the appearance, those externally running wires should stay as close as possible to the skin. To ensure both the wearer’s convenience and naturalness of pulling, the supporter needs to fit precisely onto the head. Therefore, we used a 3D model created from 3D images of the subject’s head and the supporter was designed to fit onto the head model. A 3D scanner (Danae 100SP, NEC Inc.) was used to prepare a 3D wire-frame head model and the supporter was designed on top of the head model.

2) Actuation unit: The actuation unit is made up of three bidirectional SIAC units in parallel, compacted to a 80 mm x 40 mm x 16 mm housing. Improvements were made to our previously proposed SIAC units of [9], [10]. The sliders were placed on a bronze guideway, which is connected to the electrical ground and copper brushes were used to transmit electricity from the guideway to sliders. This way, we managed to eliminate hanging power and signal wires inside the actuator and reduce friction in the guideway. Main components and the control algorithm are similar to [10], in which position control is achieved by switching between the segments of the forward and backward oriented SMA segments, except each forward and backward directions consist of one segment each.

3) Attaching the Robot Mask to the face: The Robot Mask is put on like a Behind-the-head headphone and the elastic straps are used to clamp it securely. Then the transparent pulling strips, which are connected to pulling wires through a tension adjusting mechanism were attached to the skin using 10 mm thick polyurethane film type tapers. The transparent strips of 5 mm width were used to reduce obtrusiveness and traces that can appear with thin wires due to sinking of the wires to the skin. The polyurethane tapes were about 15 mm x 20 mm rectangles in size with their corners rounded to reduce stress and facilitate easy removal by the wearer or the therapist. The transparent strips, cut-out from a transparent sheet, apart from increasing unobtrusiveness, provide a further stage of flexibility to adjust the size and shape of the Robot Mask. Although, only rectangular strips...
were used in this clinical trial, they can easily be cut into different shapes, quickly modify pulling position, attachment area and number of pulling points.

4) **Tension adjusting mechanism**: When putting the Robot Mask on and attaching the flexible pulling strips to the skin, it is important to attach them tightly to the skin. However, it was usual to see a sag in the pulling wires. Therefore we incorporated an easily adjustable miniature tensioning mechanism between the pulling cables and the pulling strips (Fig. 3-c). This linearly sliding ratchet type non-returning mechanism was made to have a minimum adjustable resolution of 1 mm. After attaching pulling strips to the face, this mechanism was used to add tension to the pulling wires and pull-up the neutral position of the paralyzed side of the face.

**B. The Control System**

Figure 4 shows a block diagram of the Robot Mask control system. It accepts two types of inputs: binary inputs from a switch based interface or bioelectrical signals from the subject’s healthy side of the face. In the latter case, by using a smile detecting algorithm, the bioelectrical signals were converted to a binary signal. Then the active control input was selected by a dip-switch based interface. In the position reference block, this binary status is converted to a position value as: ON representing maximum displacement and OFF representing zero displacement. This reference value is used to control the sliders. Each actuator is equipped with its own feedback control system while all three actuators share the position reference. In the diagram \( \hat{y} \) is the slider position, which is the feedback controlled value and \( y \) is the actual skin displacement on the face. \( K_f \) is the feedback gain. Gain parameters, \( K_p, K_d \) and \( K_i \) of 0.85, 0.5 and 0.75 were used in the PID controller. Please refer to [1] for a detail description of the control system.

**C. Switch-based controller**

In physiotherapy, it is common for the therapist to ask the patient to make a facial expression and then use the therapist’s fingers to manipulate the patient’s skin with appropriate timing and force. This switching unit of Fig. 3-d was designed to give actuation commands directly to the Robot Mask so that either the therapist or the patient can control the Robot Mask manually. Three switches were used to control the three artificial muscles, independently. Small indicator lamps were used to provide a visual feedback of switch status and dip-switches were used to switch the input between manual switches and the bioelectrical signals.

**III. EXPERIMENTAL SET-UP**

**A. Test Subject**

The subject was a 31 years old female with a complete acquired paralysis on the left hand side of the face. The experiments were conducted with the informed written consent of the subject. She had been receiving therapeutic treatment under the supervision of a speech therapist at the university hospital. During the therapy, the subject was asked to make the [I:] sound and the therapist tried to move her mouth corner of the paralyzed side with his fingers.

Several biweekly sessions were conducted within a period of four months. Each session lasted about one hour each. Before the start of each session, the subject had participated...
in a rehabilitation session with the speech therapist that lasted about 30 min each. First, the subject was seated comfortably with her speech therapist seated beside her, a configuration similar to her regular therapy session. A small mirror was placed in front of the subject so that she could have visual feedback of her face. Additionally, a range camera was placed right in front of her to capture event details. During the experiments, we asked the subject to both put the Robot Mask on and attach the pulling strips to the face by herself. When done by herself, total putting-on time was found to be about two minutes and the time taken to connect the Robot Mask to the face was found to be about 2 more minutes. Fig. 5 shows the complete experimental set-up.

B. Switch-based control

In the switch-based control, two control methodologies were investigated: controlling by the speech therapist and controlling by the subject herself. Controlling by the speech therapist is based on the normal physiotherapy where the therapist ask the subject to smile and then using his figures to move the skin of the subject’s paralyzed side. With controlling by herself, we wanted to evaluate the possibility of using Robot Mask at home.

C. Bioelectrical signal-based control

In the bioelectrical signal-based control, we placed a pair of 19 mm × 36 mm Ag/AgCl disposable type surface electrodes on her healthy side of the face to capture bioelectrical signals of the anguli oris elevator muscle group: zygomaticus major and minor and levator anguli oris. A third ground electrode was placed on her neck. The particular facial expression detection algorithm of [11] was used to process bioelectrical signals and the boolean result was used to control the Robot Mask. At the Robot Mask’s side, detection of an expression was used to pull the skin with maximum pulling force and stay pulled and the subsequent disappearance of the expression was used to return the actuators to neutral. For biorobotic control, four natural facial expression patterns were tested: (a) rapid expression up, maintain for two seconds and rapid relax (b) rapid expression up, maintain for two seconds and slow relax (c) slow expression up, maintain for two seconds and rapid relax (d) slow expression up, maintain for two seconds and slow relax.

IV. PERFORMANCE ANALYSIS

A marker-based motion capture system can accurately track movement of selected points and can be used effectively to evaluate the performance of the Robot Mask. Although, such data is highly precise, if used to evaluate physiotherapy it also puts extra burden on the subject. Therefore we decided to use a depth image sensor-based data recording system which not only can record data remotely but also can be used to analyze data at any point of its view field. Earlier we have introduced a depth image based system to analysis facial features and facial expressions [12]. The sensor we used is a 3D Time-of-Flight (TOF) depth mapping camera which can obtain depth images and infrared reflection intensities (SR4000, MESA Imaging AG). The camera was used to get 16 bit resolution distance data in a 176 px × 144 px view-field at 30 fps.

We used the data of this sensor system to analyze the response rate and displacement specifications of the Robot Mask assisted physiotherapy sessions. Figure 5 shows the arrangement of depth image sensor to capture physiotherapy sessions. We used facial symmetry to evaluate the Robot Mask. We also used this system to evaluate latency parameters of the Robot Mask.

A. Latency

The latency between the wearer’s intent and the actuator response of the Robot Mask was used to evaluate the response rate of the Robot Mask. The latency measure was defined as the time difference from the beginning of motion at the healthy side of the face to the beginning of motion at the paralyzed side of the face. In these experiments, mouth corner was taken as the tracking point. After determining motion beginning frames through manual inspection of the 30 fps reflection intensity images of the depth image sensor, we counted the number of frames between the motion beginning frames. The latency measures were obtained for both biorobotic control and switch-based control. The latency of switch-based control was analyzed from 3 different trials and the latency of the biorobotic control was analyzed from 10 different trials.

B. Facial symmetry

In this test, symmetry of the face, which attributes to the contribution of the Robot Mask to make the facial expression was quantified. We analyzed the quantized face shape data obtained from the TOF depth sensor. In order to analyze the facial symmetry, we used inter-frame gap at two time instances of the depth images of the same pixel point. This way, areas of the face that were displaced can be obtained as quantized data. The symmetry of the facial expression, how same the left and the right hand sides displacement are, can be analyzed by counting quantized data. We counted the
The number of pixels whose inter-frame gap is over a threshold level. We defined the number of pixels at time $t$ on the left-hand side of the face whose inter-frame gap is over the threshold, as $L(t)$. Similarly we defined $R(t)$ for the right-hand side of the face. Then we computed the percentage of symmetry $S(t)$ using the following equation:

$$S(t) = \begin{cases} \frac{L(t)}{R(t)} & \text{if } L(t) < R(t) \\ \frac{R(t)}{L(t)} & \text{otherwise} \end{cases}$$

In this experiment, $L(t)$ and $R(t)$ corresponds to paralyzed and healthy sides of the face, respectively.

Three different biorobotic control based trials were used for the facial symmetry analysis. By using a frame prior to the beginning of the Robot Mask, we analyzed the percentage of symmetry of the face which was not assisted by the Robot Mask. Similarly, by using frames after the engaging of the Robot Mask, we can analyze the facial symmetry which was assisted by the Robot Mask. Therefore, from each trial we obtained two values of percentage of symmetries: Unassisted and Assisted. We verified this methodology by applying it to 4 healthy subjects.

V. EXPERIMENTAL RESULTS

A. Latency results

Figure 6 shows the latency values of the Robot Mask for the two type of controls. The latency of the biorobotic control-based Robot Mask includes the latency of the bioelectrical signal processing system and the latency of the Robot Mask. While the average latency of the biorobotic control-based Robot Mask was around 1300 ms, the average latency of the manually controlled Robot Mask was -44 ms. is the standard deviation.

B. Symmetry property result

The left most figure of Fig. 7 shows an example of depth image data, colored according to depth values. Middle and right most figures of Fig. 7 shows the points where the inter-frame gap is over the threshold level, for unassisted and assisted facial expressions. As it can be seen from Fig. 8, the average percentage facial symmetry for healthy subjects was found to be 86.4%. The corresponding values for Unassisted and Assisted of this experiment was found to be 25.1% and 49.1%, respectively.

VI. DISCUSSION

We have received positive feedback from the subject about the shape, size and weight of the Robot Mask. Furthermore she was comfortable with the attaching mechanism. Initially the subject wanted to have the position of the tension adjusting mechanism changed, so that it wont press against her face. Afterwards, she did not show any uneasiness. The tension adjustment mechanism, which was added the half way through, proved vary versatile as it helped to reduce set-up time, remove pulling wire slack as well as pull the base-line level of the paralyzed side.

During the experiments for biorobotic control, we noticed that her bioelectrical signals even on the healthy side of the face is significantly small compared to a healthy subject. This is similar to the observations of Sassi et al. [4] where they have observed a 26% reduction of muscle activity on the non-paralyzed side during smiling with respect to a control group. This reduction made it difficult to implement bioelectrical signal-based continuous position control of the actuators. Furthermore, reliable facial expression detection was possible only at a bioelectrical signal level corresponding to a fully completed expression status. Therefore, out of the

![Fig. 6. The latency of the Robot Mask for switch-based and biorobotic control.](image1)

![Fig. 7. Depth image data from the range sensor and the symmetry comparison of unassisted and assisted faces.](image2)

![Fig. 8. The average percentage of symmetry between healthy and paralyzed sides of the hemifacial paralyzed subject and the left and right hand sides of the face of healthy subjects](image3)
four expression-based actuation patterns we tried, the quick expression and quick relax approach provided best results and the results for biorobotic control in this paper are based on this method.

During switch-based control, when the controlling was done by herself, we saw that subject quickly adjusted to the delay of the Robot Mask and started to make a similar expression on her healthy side with a similar delay. This reaction due to somatosensory biofeedback and quick adaptation shown by the brain demonstrates the learning of the new assisted maneuver by the brain. As biorobotic control is based on self initiated motor commands, this provides positive signs for neuromuscular rehabilitation [13].

During biorobotic control, she felt the Robot Mask is slightly lagging behind, “one phase” according to her own words, however, with the switch-based system, she felt the response rate is totally adequate.

In our previous work, we found the latency of the Robot Mask actuators to be less than 500 ms [10]. Hence we can assume that the majority of the latency associated in this experiment is due to bioelectrical signal processing delay. Therefore by improving the bioelectrical signal processing system, we can reduce the latency of the Robot Mask with biorobotic control. The reason why the latency for the manually controlled Robot Mask was almost zero (-44 ms) is due to the fact that the subject quickly got used to the delay of the Robot Mask and therefore she intentionally delayed expressions of her healthy side to accommodate the delay of the Robot Mask. However, interestingly, this delay is not zero. Although, the average latency for this case was -44 ms, the maximum recorded during all the trials was -166 ms. Considering the fact that this latency is purely due to the intention/feeling of the subject, we think that a Robot Mask latency of similar proportions can be taken as the ultimate design target. The characteristic of the Robot Mask will be included in the further analysis.

As it can be seen from Fig. 8, the percentage of symmetry for the assisted side was almost twice as big as that for the unassisted side. This shows that the Robot Mask can contribute to increase the facial symmetry or in other words, the Robot Mask can assist making natural facial expressions.

VII. CONCLUSIONS AND FUTURE WORKS

In the previous work, we introduced the Shape Memory Alloy actuator based Robot Mask that can be used to enhance the expressiveness of the face. In this paper, we described a case study of using the Robot Mask to assist physiotherapy of a hemifacial paralyzed patient. As significant differences in shape and size of human head among different individuals demands further customization of the Robot Mask, in this paper we introduced number of such adjustment and customization stages employed during design and implementation levels. Furthermore, we provided two control strategies: bioelectrical signal-based and manual switch-based, to assist physiotherapy and rehabilitation.

We also employed a depth image sensor data based analyzing method to evaluate the effectiveness of the Robot Mask. By analyzing the range sensor data we showed that, while providing quick responses, the Robot Mask can also reduce the asymmetry of a smiling face.

Further work is required to improve the response rate of the Robot Mask, both in-terms of switch-based control and biorobotic control. In switch-based control, the delay is somewhat governed by inherent thermal characteristics of SMA, however improvements to biorobotic control can be done through targeted design of facial expression detection algorithms for the Robot Mask. Furthermore, we are currently working on designing a bioelectrical signal amplifier to suit the low facial bioelectrical signal levels of the subject and a threshold based algorithm aimed at targeted muscle rehabilitation.

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