Robot Assisted Physiotherapy to Support Rehabilitation of Facial Paralysis

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Abstract—We have been developing the Robot Mask with shape memory alloy based actuators that follows an approach of manipulating the skin through a minimally obtrusive wires, transparent strips and tapes based pulling mechanism to enhance the expressiveness of the face. For achieving natural looking facial expressions by taking the advantage of specific characteristics of the skin, the Robot Mask follows a human anatomy based criteria in selecting these manipulation points and directions. In this paper, we describe a case study of using the Robot Mask to assist physiotherapy of a hemifacial paralyzed patient.

The significant differences in shape and size of the human head between different individuals demands proper customizations of the Robot Mask. This paper briefly describes the adjusting and customizing stages employed from the design level to the implementation level of the Robot Mask. We will also introduce a depth image sensor data based analysis, which can remotely evaluate dynamic characteristics of facial expressions in a continuous manner. We then investigate the effectiveness of the Robot Mask by analyzing the range sensor data. From the case study, we found that the Robot Mask could automate the physiotherapy tasks of rehabilitation of facial paralysis. We also verify that, while providing quick responses, the Robot Mask can reduce the asymmetry of a smiling face and manipulate the facial skin to formations similar to natural facial expressions.

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

1. INTRODUCTION

Facial expressions are produced by the actions of the facial muscles that are controlled by the electrical signals sent through the facial nerve, the seventh (VII) of twelve paired cranial nerves [1]. Due to various medical 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 considered to be Bell’s palsy and it accounts for almost three quarters of all acute facial paresis. It records 0.5 per year per 1000 persons with the acquired facial paralysis is considered to be Bell’s palsy [2, 3]. Other frequent causes for facial paralysis includes virus infections, trauma, tumor, strokes and neonatal conditions. Although facial paralysis could occur on both sides of the face (bilateral), it more common occurs only on one side of the face (unilateral/hemifacial). For instance, 96.7%-99.3% of the Bell’s palsy patients have hemifacial paralysis [4]. The effects of facial paralysis could be either temporary or permanent. Majority of around 80% - 84% of patients recover completely whereas the remaining 16% - 20% retain chronic facial paralysis [5]. In the case of temporary paralysis, the average time of recovery can vary from 15 days up to 4 years. The longer the recovery takes, the higher is the chances of sequelae such as synkinesis and contracture [6]. Facial paralysis may develop at any age, however, it is more common among young or middle-aged adults between 31 years to 60 years and pregnant women [3, 7].

Treatments for facial paralysis could be pharmaceuticals such as steroids and antivirals; surgeries such as nerve decompression, nerve repair and grafting, reanimation and physiotherapy. Physiotherapy is normally used throughout the course of the recovery. Types of physical therapy for facial paralysis include: facial exercises such as strengthening and stretching, endurance, therapeutic and facial mimic exercises or “mime therapy” (i.e. a combination of stimulation of facial expression, functional movements and relaxation techniques including breathing control [8]), electrotherapy, biofeedback, transcutaneous electrical nerve stimulation (TENS), electrical nerve/muscle stimulation (ENMS), thermal methods and massage [9]. Physiotherapy, in particular exercise based therapy is performed to rehabilitate and recover muscle movements as well as to maintain the health of the paralysed side muscles so that there will not be any side-effects once the patient is recovered.

Evaluation of therapy is considered to be difficult due to high rates of spontaneous and complete recovery [10], and as a result, very few scientific evidence is available on the success of physiotherapy for facial palsy. Beurskens and Heymans have shown significant improvements in facial symmetry, voluntary facial movements and synkinesis due to mime therapy [8]. Elliott has reported a case study of physiotherapy involving muscle-re-education exercises aimed at restoring normal movements of a 53-year-old Caucasian male diagnosed with Bell’s palsy. He showed improvements in self-reported facial disability and significant drop in functional impairments [11]. Studies by Beurskens [12] and Wang [13] have reported improvements from facial exercises. Wen [14] reported significantly less synkinesis with 20% in the...
control group oppose to just 4.7% in the exercise group. Teixeira et al. [10] in their review on physical therapy for Bell’s palsy noticed statistically significant improvements in facial muscle functions due to functional exercises. They also reported on significantly less facial motor synkinesis after exercises. Perry et al. have found that, with intensive facial exercise, muscle weakness resulting from facial nerve damage sustained during childhood can be improved even years after the injury [15]. Cronin and Steenerson [16] have reported on the effectiveness of neuromuscular facial retraining with EMG in facial paralysis rehabilitation. With facial retraining, they found marked improvements in facial function, symmetry, and decreased synkinesis. The overall EMG readings after treatment (treatment durations varying from 3.3 months to 15 months) showed symmetric or within 2 µV/s to 5 µV/s of the normal side.

Although, the exact recovery mechanism or the effectiveness is not clear, physiotherapy is consistently practised in the treatment of facial paralysis. However, limitations in the availability of resources, both in terms of tools as well as therapists makes it difficult to undergo physiotherapy as often as possible. As a result, this study was carried out to develop robotic technology to assist rehabilitation physiotherapy on the face. We have developed the anatomically designed, EMG driven wearable Robot Mask to assist facial expressiveness through external manipulations of the facial skin [17]. This paper briefly introduces the improvements done to the Robot Mask and how we used it to assist physiotherapy of a hemifacial paralyzed patient.

II. ROBOTIC TECHNOLOGY FOR EXPRESSION ASSISTANCE

Assisting facial expressions with robotic technology is a unique problem that require designing of a novel solution. Its unique because assisting facial expressions require either assisting skin movements or muscle actions, which is different from assisting limbs or joints. Forces and the displacements required to provide the assistance are smaller. However, the skin is delicate so they need to be soft and carefully controlled. As the device supports facial expressions, which are naturally silent, and it is head mounted, the operation need to be silent. Furthermore, method of connecting the assisting system to the facial skin, in particular making it non-invasive and unobtrusive, itself is a novel problem. Unlike skeletal muscles, which often have pairs to produce opposite action, muscles of facial expressions are often unpaired, and facial tissue and the muscle tension in the contralateral face control the return to a resting state. Hence, following the facial anatomy in the artificial manipulating system could take the advantage of these skin characteristics. As the assistance is provided to make facial expressions, they need to be silent. Furthermore, like most other systems that deals with human-machine interaction, the actuators need to be compliant. Hence, in many ways, traditional motors are not very suitable for the actuators in this application and shape memory alloy (SMA) elements have been employed, instead.

A. Rehabilitation Robotics

The purpose of rehabilitation robotics is not replacing the human therapist, but providing a tool to increase their productivity [18]. Use of robots or robotic technology increases the movement repeatability and also provides additional tools to assess the progress and effectiveness of rehabilitation process [19]. Various sensors employed in robotics systems provide qualitative means to evaluate the rehabilitation progress. Neurorehabilitation is performed based on two basic assumptions: motor learning principles apply to motor recovery and that patients can learn [19]. A wide range of sensory and motor experiences can produce long-lasting plastic changes in the brain. Due to the plasticity of the brain, repetitive actions could help the brain, the spinal cord and the nervous system work together to re-route the signals that were interrupted by strokes, injuries and other illnesses [20]. Although, technology can be often found in upper/lower limb rehabilitation [21], [22], [23], it is not so true for the face. This is understandable given the vast majority of physical impairments are related to upper and lower limbs. People also tend to notice the disabilities due to upper and lower limb impairments. Nevertheless, with 25-65 per 100000 of the population experiencing facial paralysis annually, the number of people affected with facial paralysis is certainly not insignificant [2], [24], [25], [26], [27].

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In this study, we concentrated on the physiotherapy process and explored the possibility of realizing seamless control of the assisted expressions. In order to facilitate the needs in assisting rehabilitation, the fully assembled prototype rehabilitation version of the Robot Mask was designed to fit onto the head model. A 3D scanner (Danae 100SP, NEC Inc.) was used to prepare the 3D wire-frame model. The prototype model was created by an acrylic-based material.

![Fig. 3. Design of the head supporter by using a 3D mesh model of the head. The mesh model is prepared from 3D scans of the head.](image)

**B. The Robot Mask**

The Robot Mask is the non-invasive wearable device, which we have developed to realize expression assistance of facial paralyzed patients (Fig. 1). It is portable, can be worn unaided, lightweight and standalone with no necessity of additional peripherals. The Robot Mask mainly consists of a Head Supporter, a Silent Actuation Unit (SIAC), a skin pulling system and a command and control unit. It has been designed to achieve morphological changes, which are consistent with natural expressions, and as a result designing has been done to have strong similarities to the facial anatomy. The basic working principle of the device is mechanical manipulation of facial skin through wires that are pulled by SMA based actuators. As it can be seen from Fig. 2, the pulling points and the pulling directions closely follow the human facial anatomy, and therefore the skin displacement characteristics are very similar to that of natural facial expressions. The device mainly targets the assisting of hemifacial paralyzed patients.

By using biorobotic control, which is based on the bioelectrical signals of the healthy side of the face, actuators are controlled according to the intentions of the wearer, hence making it possible to realize seamless control of the assisted expressions. In this study, we concentrated on the physiotherapy process and used 3 actuators to support zygomaticus major, zygomaticus minor and depressor anguli oris. In this study, aside from enhancing the actuator design to make it more reliable, we followed a custom design approach for the head supporter and also introduced a new tension adjusting mechanism, which makes the fastening faster, and a switch based control system to facilitate the needs in assisting rehabilitation. The fully assembled prototype rehabilitation version of the Robot Mask weighs 250 g.

1) **The Head Supporter:** The Head Supporter provides the basic structure of the Robot Mask. It carries the SIAC units, controllers and the power supply units. The actuators are positioned at the backside of the Head Supporter. The displacement motion generated at the actuators is transmitted to the skin via pulling wires sent through the tubes. Further, the Head Supporter serves the purpose of setting pulling directions for the supported facial muscles and mounting electrodes for biorobotic control.

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. And 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. Furthermore, to ensure both the wearer’s convenience, which is important for the long-term continuous use of the Robot Mask, and naturalness of pulling, the supporter needs to fit precisely onto the head. Therefore, as illustrated in Fig. 3, 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 the 3D wire-frame head model and the supporter was designed on top of the head model. The prototype model was created by an acrylic-based photo-polymer material.

2) **Actuation System:** Fig. 4 shows the details of the actuation system. It consists of three bidirectional SIAC units, and to generate necessary pulling power, each SIAC unit consists of 3 SMA wires in parallel. Shape changes of SMA wires in the form of contractions due to Joule heating is used to move the sliders back-and-forth. And the pulling wires, which manipulate the facial skin, are connected to the sliders. In order to reduce friction, the sliders are placed on a bronze guideway that is connected to electrical ground. That eliminate the rubbing power and signal wires inside the actuator and copper brushes are used to transmit electricity from the guideway to sliders. An embedded controller mounted within the actuator housing performs feedback displacement control of the sliders. The modular configuration of the actuator makes it easily expandable from the current implementation of three to more.

3) **Displacement Control for Robot Assisted Physiotherapy:** Fig. 5 shows a block diagram of the Robot Mask control system. It accepts two types of inputs: binary neutral/expressions 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 (Sec. II-B8), the bioelectrical signals are converted to a neutral/expressions status. When determining the position reference, this binary command is converted to position values as zero displacement or maximum displacement respectively. This reference value is used to control the sliders. Each actuator is equipped with its own feedback control system that can perform millimetre range continuous position control and all three actuators share the same position reference. As the Position ref. is calculated for the forward path, in the return path, Reference Estimation represents the displacement amount for return path SMAs,
which is equivalent to full stroke - Position ref. The forward and return paths, where only one of them is in operation during any actuation, are used to pull and release skin. A 10 ms sampling interval is used in the embedded controller (Microchip Inc.) and a PWM signal with varying duty-ratio is used to control the average load current. As the thermal inertia of SMA wires are large enough to produce smooth displacements, the SMA wires are driven directly from the 5 kHz PWM signal. A 150 lines/inch reflective linear encoder (Microchip Inc.) and a PWM signal with varying duty-ratio 10 ms sampling interval is used in the embedded controller (Microchip Inc.).

4) 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. As shown in Fig. 6(a), the transparent pulling strips, which are connected to pulling wires through a tension adjusting mechanism were attached to the skin using 10 µm thick polyurethane film type adhesive tapes. 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 × 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 modifying pulling position, attachment area and number of pulling points.

5) Tension Adjusting Mechanism: When putting the Robot Mask on and attaching the flexible pulling strips to the skin, in order to eliminate any play, 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. 6(b). This ratchet type non-returning mechanism with a linearly slider was designed 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 as well as to pull-up the neutral position of the paralyzed side of the face.

6) Switch-based Controller: In physiotherapy, it is common for the therapist to ask the patient to make certain facial expressions and then use the therapist’s fingers to manipulate the patient’s skin with appropriate timing and force. This switching unit of Fig. 6(c) 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. It minimizes external connections with the patient’s skin, providing better somatosensory feedback and unobscured visual feedback through the mirror. In this case-study, three switches were used to control the three artificial muscles independently. Small indicator lamps were used to provide a visual feedback of the switch status. Each of these direct control switches were coupled with enabling switches to select between direct and biorobotic control.

7) Biorobotic Controller: The biorobotic control uses the biorobotic signals of the healthy side of the face to realize intention based control. An instrumentation amplifier with gain
ANN training was done by using data of 16 s long voluntary
robot mask to assist rehabilitation of a hemifacial paralysed
patient and calculating the three parameters: facial symmetry,
final amplitude, even on the non-affected side of the hemifacial
mask 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.

Fig. 7 shows the bioelectrical readings of a healthy sub-
ject and the corresponding response of the Robot Mask for
the biorobotic control. EMG signals are the instrumentation
amplifier output, prior to digital filtering and the Robot Mask
response is the slider displacement taken from the feedback
sensor.

A) The Smile Detection Algorithm: As the bioelectrical sig-
nal amplitude, even on the non-affected side of the hemifacial
test subject was found to be very small\(^1\), it was difficult to use
a simple threshold based approach to detect onset and outset
of smile. As a result, we used a smile detection algorithm,
which is based on the work of Gruebler and Suzuki \([30]\). The
particular algorithm uses a pattern based approach to identify
different facial expressions. As the bioelectric signals captured
from the face is a mix of different facial muscle signals and other
artifacts, independent component analysis (ICA) was
performed in order to separate them after filtering the signals
with 5Hz-350Hz bandpass and 50Hz notch filters. The ICA
in this algorithm consisted of 4 independent components and
a Gaussian kernel with 2 DoF. Then, by using an artificial
neural network (ANN) with 4 sigmoid hidden neurons, the
ICA output was classified as \textit{smile}, \textit{neutral} or \textit{other}. The
ANN training was done by using data of 16 s long voluntary
expressions taken at the beginning of each session.

III. SYSTEM VALIDATION

Validation of the proposed approach was done by using the
Robot Mask to assist rehabilitation of a hemifacial paralyzed
patient and calculating the three parameters: facial symmetry,
latency of response and temporal characteristics.

\(^1\) Sassi et al. \([5]\) have reported similar observations where they have recorded
a 26\% reduction of muscle activity on the non-paralysed side during smiling
when compared to a control group.

A. The Regular Physiotherapy Treatment Procedure

The subject participated in this study was a 31-year-old
female with a complete acquired paralysis on the left hand
side of the face. She has been receiving biweekly therapeutic
treatment at Tsukuba University Hospital. The treatment
course consisted of 15 minutes of facial massaging by her
speech therapist followed by attempts to make the [I:] sound
for another 15 minutes. During those attempts, her speech
therapist assisted her by moving her mouth corner of the
paralyzed side with his fingers. She was lying down on a bed
during the whole duration.

B. A Description of Robot Assisted Physiotherapy Sessions

By using the Robot Mask, biweekly sessions were con-
ducted for a period of four months, with each session spanning
approximately 1 h. She participated in these sessions directly
after attending the regular physiotherapy course.

During the Robot Mask sessions, the subject was first seated
comfortably with her speech therapist sitting beside her, a
configuration similar to her regular therapy sessions. 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 facial displacements
in 3D. In contrast to lying down on a bed, the Robot Mask
allowed her to sit on a chair while looking at the mirror
for the biofeedback. Afterwards we conducted robot assisted
physiotherapy in switch based (Sec. III-B1) and bioelectrical
signal based (Sec. III-B2) control modes. In the experiments,
we asked the subject to put the Robot Mask on and attach the
pulling strips to the face by herself. And when done by herself,
total putting-on time was found to be 1\textprime;47\textprime; and the time taken
to connect the Robot Mask to the face was found to be 2\textprime;00\textprime;.
Fig. 8 shows a picture of the subject wearing the Robot Mask
by herself. Fig. 9 shows the complete experimental set-up.

1) Switch-based Control : In the switch-based control, two
control methodologies were investigated: controlling by the
speech therapist and controlling by the subject herself. The
former was performed to replicate her regular physiotherapy
sessions with the speech therapist where the therapist asks the
subject to make an expression and then use his figures to move
the skin of the subject’s paralyzed side. This is important as
it involves instructions by the therapist on how to perform
expressions for physiotherapy. With controlling by herself, we
evaluated the usability of Robot Mask at home. With both

Fig. 7. Biorobotic controlling of the Robot Mask.

Fig. 8. Wearing the Robot Mask without the assistance of others
the methods we confirmed that both the speech therapist and the patient are comfortable of using the switch interface to manipulate skin.

2) 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. Although the smile detection algorithm (Sec. II-B8) has been developed to classify distal signals captured near the Temple area of the face (so the electrodes could be covered easily), in this experiment to assist rehabilitation, as the accuracy of classification was more important than the aesthetics, we placed the electrodes directly over the anguli oris elevator muscle group. A third ground electrode was placed on her neck.

We asked the subject to attempt the [I] expression at her own comfortable timing and observed the displacement characteristics of healthy and paralyzed sides of the face.

IV. PERFORMANCE ANALYSIS

Although, a marker-based motion capture system can accurately track movement of selected points, it is difficult to use such a system in physiotherapy because it also puts extra physiological and psychological strain on the subject. We therefore 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 analyze facial features and facial expressions [31]. The sensor we used is a 3D Time-of-Flight depth image camera, which can obtain depth images and infra-red 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. Fig. 9 shows the arrangement of depth image sensor to capture physiotherapy sessions. We used facial symmetry to evaluate the effects of Robot Mask. We also used this system to evaluate latency parameters of the Robot Mask.

A. 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. 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. We counted the number of pixels whose inter-frame gap is over a threshold level. By defining $L(t)$ as the number of pixels at time $t$ on the left-hand side of the face whose inter-frame gap is over the threshold and $R(t)$ as that for the right-hand side of the face, we computed the percentage of symmetry as $S(t) = L(t)/R(t)$. In this experiment, $L(t)$ and $R(t)$ corresponds to paralyzed and healthy sides of the face, respectively and $L(t) < R(t)$ is assumed due to the paralysis at the left hand side of the face. We verified this methodology analyzing facial symmetry by applying it to 4 healthy subjects [31].

Results of 3 different sessions 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 has not been assisted by the Robot Mask. Similarly, by using frames after the engaging of the Robot Mask, we analyzed the facial symmetry, which has been assisted by the Robot Mask. Therefore, from each trial we obtained 2 values of percentage of symmetries: Unassisted and Assisted.

B. Latency of Response

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 measured the time between the motion beginning frames of each sides. The latency measures were obtained for both biorobotic control and switch-based control. The latency for the biorobotic control is caused by bioelectrical signal processing and the Robot Mask mechanical response. The latency of biorobotic control and switch-based control was analyzed from 3 different trials each.

C. Temporal Characteristics

Temporal characteristics were analyzed in order to evaluate the improvements in symmetry due to robot assisted facial expressions. The spatial symmetry which was discussed in the section IV-A is the final static symmetry. On the other hand, the temporal symmetry is the dynamic change of symmetry with time. The temporal symmetry is determined by the morphological change rates of the left and right hand sides of
the face. In order to analyze the temporal characteristics of the Robot Mask by using depth image sensor data, we analyzed the rate of change of facial morphological characteristics. We used the inter-frame gap at a selected pixel point at a given time $t$ compared to that at the beginning $t_0$ and counted the number of pixels whose inter-frame gap is over a pre-determined threshold level. The number of pixels at time $t$ on the paralyzed side of the face whose inter-frame gap is over the threshold is $P(t)$, and that of the healthy side of the face is $H(t)$. In this analysis, by using an area mask, we counted the number of pixels around the vicinity of the points pulled by the Robot Mask.

V. VALIDATION RESULTS

A. Facial Symmetry

Fig. 10 shows the neutral face, making an expression naturally and making an expression with the assistance of the Robot Mask. It qualitatively demonstrates the change of facial symmetry due to the Robot Mask. In the unassisted natural expression, although not used actively, the presence of the Robot Mask acts like a substitute for the unavailable muscle tone of the paralyzed side of the face and prevented that side from moving to the contralateral side of the face.

The left most figure of Fig. 11 shows an example of depth image data coloured according to depth values. Middle and right most figures of Fig. 11 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. 11, almost no skin movements were observed at the paralyzed side of the face for the unassisted case. However, for the assisted case, although less pronounce, the paralyzed side showed a similar distribution of skin displacements as the unaffected side of the face. As it can be seen from Fig. 12, the average percentage facial symmetry for healthy subjects was found to be 86.4% (S.D. = 3.0). The corresponding values for unassisted and assisted of this experiment was found to be 25.1% (S.D. = 5.5) and 49.1% (S.D. = 4.0), respectively.

B. Latency and Response

Figure 13 shows the latency values of the Robot Mask. The 3 latency values for EMG, Robot Mask and Manual were 1010 ms (S.D. = 510), 120 ms (S.D. = 50) and -44 ms (S.D. = 87) respectively. The time required for the EMG signal processing is based on threshold comparison and significantly affected by the expression rate at the healthy side of the face.

C. Temporal Characteristics

Fig. 14 shows the morphological change rates of the healthy ($H(t)$) and the paralyzed ($P(t)$) sides of the face of the test subject. The average time for the Robot Mask to pull the skin on the paralyzed side of the face to 63.2% of its asymptotic value since receiving of the EMG trigger signal was found to be 346 ms (8 trials, S.D. = 93). The curve profiles for both left and right hand sides of the face conforms to typical displacement characteristics of the face. Fig. 15 shows how the rate of change of morphological characteristics typically vary among healthy subjects. The graph was prepared by monitoring the trajectories of the mouth corner during natural voluntary smiles of five healthy subjects. A 3D motion capture system (Naturalpoint Inc.) was used to get the data and since the amount of maximum displacement was different among
the subjects, the displacements have been normalized for better visualization. The similar pattern of the natural smile profiles to the two curves of Fig. 15 validates the approach used to obtain temporal characteristics.

D. Qualitative Evaluation and Subject feedback

We have received positive feedbacks 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 will not press against her face. Afterwards, she did not show any uneasiness. The tension adjustment mechanism proved very 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 biorobotic control, she felt the Robot Mask is slightly lagging behind, however, with the switch-based system, she felt the response rate is totally adequate.

We continued the experiments for a period of 4 months and confirmed that Robot Mask could be used effectively to assist facial rehabilitation. However, we did not observed significant improvements on the patient’s condition.

VI. DISCUSSION

The Robot Mask is the device we developed to assist expression on the face. The design principal adopted with the Robot Mask enables a lot of flexibility to the device. The compact modular design principal of the actuators is such that the number of pulling wires could easily be changed by adding or removing SIAC units from the actuator. Also, the possibility of changing the shape of the pulling strips, makes the Robot Mask easily reconfigurable.

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 customizations 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 introduced a new methodology to evaluate the effectiveness of the physiotherapy by using a 3D range sensor. From a technical designing point of view, use of the range sensor makes it possible to track facial morphological changes remotely and continuously, without disturbing the subject. Furthermore, compared to traditional physiotherapy where only a mirror was available for the subject to get a visual feedback, this new evaluation methodology enables the quantitative evaluation of the physiotherapy and the rehabilitation process.

During the experiments for biorobotic control, we noticed that subject’s bioelectrical signals, even on the healthy side of the face, are significantly small compared to a healthy subject. This is similar to the observations of Sassi et al. [5] where they have observed a 26% reduction of muscle activity on the non-paralyzed side during smiling with respect to a control group. Typically, facial EMG signals are much smaller than skeletal muscle signals and this further decrease 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 and that made the bioelectrical signal processing susceptible to the expression rate. But it was possible for the subject to consciously adjust her own expressions on the healthy side of the face, as observed with the switch-based control. During switch-based control, when the controlling was done by herself, we saw that subject quickly adjusted to the response rate of the Robot Mask and started to make a similar expression on her healthy side. This reaction observed is considered to be a result of visual and somatosensory biofeedback and quick adaptation of humans. 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 response rate of the Robot Mask and therefore she intentionally delayed expressions of her healthy side to accommodate the response rate of the Robot Mask. 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 consider that a Robot Mask latency of similar proportions can be taken as the ultimate design target.

VII. CONCLUSIONS AND FUTURE WORK

We have developed the EMG driven Robot Mask to assist 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. Within the limited evaluation period of 4 months, we confirmed that our proposed method can automate and assist the tasks carried out during traditional physiotherapy. By using EMG of the wearer, we took a new level that enables completely voluntary participation of the patient in the physiotherapy.

We introduced number of adjustment and customization stages employed during design and implementation levels. Furthermore, we explained 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.

Facial neuromuscular re-education requires to isolate muscle contractions and reduce muscle activities of abnormal patterns of movements such as synkinesis. Furthermore, home facial movement exercise programs can provide additional practice components of motor learning necessary for neuromuscular re-education. However, it is important that the patient has the ability to perform these components accurately and we believe the Robot Mask can effectively assist these exercises. Repeated attempts to smile as much as possible, as a part of the rehabilitation program, can abnormally lengthen the partially or completely paralyzed ipsilateral side smiling muscles. By using the Robot Mask and assisting the ipsilateral side according to intention of the patient and at the exact timing, we are trying to develop new training programs for the rehabilitation of facial paralyzed patients.

Further work will include the improving of the response rate of the biorobotic control and the facial expression detection algorithms for the Robot Mask. We will also continue evaluating the effectiveness and the developing of protocols for robot assisted physiotherapy through long-term studies.

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REFERENCES

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