Facial rehabilitative device based on Robogami (Robotic Origami) platform

Field of invention

The present invention relates to a device for facilitating the treatment of facial paralysis and its embedded components. Depending on the components embedded in the main frame of the device, it can be used in diverse therapies with different requirements.

Prior art

Facial paralysis is a disability that can be caused by infections, accidents, strokes or tumors. There is “an emerging rehabilitation science of neuromuscular reeducation” [1] to help the patients with facial paralysis restore their muscle activity. The therapy method for these patients is still very dependent on the therapist’s experience and even diagnosis remains to be subjective. Rehabilitative devices can enhance the therapy but due to the complexity of the face movements and the spatial limitations there are not many examples of such devices and the few available devices are very limited in number of degrees of freedom (DoF), functionality and adaptability for different therapy methods. The prior art patent documents listed in Table 1 are divided in to three categories: general arrays of stimulating and sensing electrodes that are applicable for different limbs, face specific application of such electrodes (stimulating and sensing), and resistive training masks.

The use of Electromyography (EMG) and elctro muscular stimulation (EMS) for rehabilitative devices is not new. Table 1 summarizes in the applications of these techniques pertaining to the face. ().

Passive masks for training facial muscles constitute another type of devices that are useful in the physical therapy for regaining the muscle strength, movement, and suppressing synkinesis of facial muscles The patent documents presented in Table 1, have rather limited design which makes them case dependent (based on the patients face geometry and the target muscle group).

Table 1. Related exsisting patent documents

Field of invention	Patent number	Description	Short comes
Flexible arrays	US2013041235 A1	Array of sensors, stimulators which are connected through flexible electronic components.	1- No physical activation 2- No means of morphological feedback
	US2011208029 A1	Microelectrode array for stimulating muscles.	1- No physical activation 2- No means of morphological feedback 3- No feedback from muscles movement
Facial application of flexible arrays	US2842136 A	Electrodes for stimulating muscles covered and secured by a mask with heating elements for increasing effectiveness of the therapy.	1- No means of morphological feedback 2- Personal design
	US3279468 A	Mask with embedded electrodes for stimulating muscles.	1- No means of morphological feedback 2- Personal design
	US3447537 A	Mask with embedded electrodes for stimulating muscles.	1- No means of morphological feedback 2- Personal design
	US3971387 A	Mask with embedded electrodes for stimulating muscles. The feature of this design is its adjustable parts that make it useful for different patients.	1- No means of morphological feedback
	WO9600108 A1	Mask with embedded electrodes for stimulating muscles.	1- No means of morphological feedback 2- personal design
	US2012022411 A1	A very general idea for a mask with heating, vibrating and electric stimulating elements.	1- No means of morphological feedback 2- Personal design
	US5192254 A	Using sensors for picking up the muscle activity. Couple of individual sensors attached to the frame.	1- difficult positioning 2- Personal design
Resistive training masks	US2009124462 A1	Elastic mask for resistive training for the facial muscles.	1- No means of morphological feedback 2- Personal design 3- For specific training
	US4666148 A	Resistive training mask with an air inflatable lining	1- No means of morphological feedback 2- Personal design
	US4189141 A	Training mask with embedded weights.	1- No means of morphological feedback 2- Personal design 3- For specific training

The prior art does not disclose facial prostheses with active components and with embedded sensing that can apply force to change the form of the device and to control the shape of the face. In academic literature there are only a few examples with very limited Degrees of Freedom (DoF) and hence functionality [2]. Using conventional methods and mechanisms of actuation to make a system with higher DoF to mimic the human face results in complex systems which are by nature not scalable (because of the actuation and sensing method they use) [3, 4]. There is, therefore, a need for a low-profile facial rehabilitative device with multi DoFs.

Description of the invention

The facial prosthesis according to the present invention is based on a Robogami platform. Robogamis are low-profile robots that are constructed from rigid tiles connected in the folding areas with actuators and sensors. According to the application, different functional components are present in the Robogami. Some non-limiting examples of the invention are provided below.

Brief description of the figures

Figure 1. Schematic of Robogami with different functional components.

Figure 2. Schematic of the facial rehabilitative device with different components. The embeded componenets aer: adaptive stiffness body (a), sensor for morphological feedback (b), sensors and adaptive stiffness body (c), and the actuators with embeded sensors and adaptive stiffness body.

Figure 3. Schematic of embedding additional functional layers on the main Robogami platfform. It can be an EMG sensor array, an electric stimulation array or a heater layer (a).The exploded view of the Robogami platform. Actuators are in layer (i), layers (ii) and (v) are adaptive stiffness body, layer (iv) is the heater and circuit layer and finally layer (iii) is the sensor leyer (b).

Figure 4. Conceptual design of the robogami facial prosthesis.

Figure 5. An example of the underactuatred transforming mechanism. two electric motor can selectively drive each of the four joints indipendantly or a combination of them based on the asigned temperature and stiffness. (a) actual device and (b) schematic of the system to illustrate how by enabeling a certain fold we can control its position.

Figure 6. 3D printed model for the concept of central actuation (electric motor via a tendon) with folds of controllable stiffness.

Figure 7. A module with antagonistic bending actuators (a). Side view of the tiles and actuators in unfolded (b), and folded states (c).

Figure 8. Mesh structure after it is cut by laser (a) and in deformed state (b)

Figure 9: Array of pressure sensors: before(a) and after (b) applying the conductive silicone layer. The perforated top electrode makes it possible for the conductive silicone to fill the gap between the two electrodes.

Figure 10 . Fabrication process of the curvature sensors. Kapton sheet (a), scortched surface (b), mask layer (c), applying the layer of carbon ink (d), adding the top protective layer and cutting the outline(e)

Figure 11. Stretch sensor design to detect the geometry and deformation. The stretchability of this sensor comes from the mesh structure. But the mesh structure on its own is not sensitive and the modulation of the path width presensted in (b) is what makes this sensors sensitive by changing the ratio of the part of material in tension and in compression.

Figure 12. Crawler robot: the model (a), the exploded view (actuators are in layer (i), layers (ii) and (v) are glass fiber layers, layer (iv) is the heater and circuit layer and finally layer (iii) is the sensor leyer) (b), and the fabricated robot (c).

Figure 13. Example of a Robogami platform of the facial prosthesis with bidirectional actuation on all folds.

Figure 1 presents a schematic of a general Robogami fold with different functional components it might contain (depending on application). Both the tiles and the folding area in Robogami can be made of materials with adaptive stiffness. The pressure sensors inside the tiles detect the contact force with the surroundings and the morphology sensors embedded in the tiles provide feedback from the length and shape change in the tiles. Other functional components can be embedded depending on the application (this is presented in the schematic with a special component sign). As shown below, the folding area is composed of bending angle sensor, adaptive stiffness material and actuators.

In general the embedded components in the system are selected according to the specific application and the type of the sensors, actuators and other functional layers are also determined by the application’s requirements like the activation frequency, blocked force and range of motion.

Compared to the devices disclosed in the patent documents of the first group in Table 1, the facial prosthesis of the present invention provides a morphological feedback in conjunction with the arrays.

In the most basic form the facial device is composed of just one or two components that are useful in specific therapy method. As an example a body that changes its stiffness in specific parts is useful in the resistive trainings for strengthening specific muscle groups. Figure 2 (a) presents a schematic of prosthesis with adaptive stiffness body (the linear springs represent the mechanical stiffness in the body). Compared to the previous designs this device can adjust its stiffness on demand and also it can stretch and change shape for fitting the face of different patients. The schematic of another device with only morphology sensing elements is presented in Figure 2 (b). This device is useful in quantifying the severity of the paralysis and the patient’s progress during the rehabilitation process. A device with both of these elements (Figure 2 (c)) makes an adaptable training prosthesis that can change stiffness based on the sensors feedback. Also comparing to a device with only sensors, it can change its shape to best fit the patient. Finally Figure 2 (d) shows the schematic of a device with adaptive stiffness, sensing and actuating components. It forms itself to the shape of the face and applies force in the required region to actively participate in the therapy process.

The features disclosed previously represent the minimum functionalities that are embeddable in the Robogami platform of the facial prosthesis. On top of this platform other functional layers such as electrical stimulator layer, EMG sensing array, or vibrating layer can be added (Figure 3 (a)).

The components in the main platform are the actuators, heaters, circuit, sensors, and body (Figure 3 (b)). Low profile Shape Memory Alloy (SMA) actuators have large range of motion and torque to mass ratio which makes them one of the suitable options for the facial prosthesis platform. SMA actuators are heat activated and as an auxiliary component heaters are necessary for activating them. The design and the method of fabrication for a stretchable heater that focuses the heat flux on the active part of the actuator layer is embedded in the design of Robogami. The same design for a stretchable heater can also be used as an extra functional layer in the cases where mild heating can improve therapy. Also such heaters should be embedded in the variable stiffness elements for activating those. Embedded curvature sensors provide the necessary feedback for accurate control over the morphology of the Robogami. Sensors made from Piezo resistive materials are what is used for bending angle in the current design of the facial devices presented here. These are good choices for making sensors in the Robogami since they need very little supporting components and by nature are not restraining in shape and size. Carbon ink printed sensor is one option that is used here for measuring the curvature. It is fairly robust and sensitive and its fabrication process can be easily applied in large array of sensors. Robogami platform needs pressure sensor for detecting contact between its tiles and the surroundings. Pressure sensors based on conductive polymer are used in the current design. As was the case for the curvature sensors made from carbon ink, the best feature of this type of sensor is again the ease of fabrication in large arrays. We also need stretch sensors for detecting deformation in stretchable parts of the device (deformable tiles). Such stretch sensors can also be used for reconstructing the shape of the face by measuring the linear deformation between different anchoring points on the face. We have designed and developed a novel and accurate stretch sensor based on resistance change due to strain in metals for this and other similar application which can give better repeatability and robustness compared to carbon based piezo resistive stretch sensors.

Last important component in the Robogami platform is the body of the robot. In the most basic form, body only provides structural integrity. But in the facial device presented here the Robogami body is made from SMP and has adaptive stiffness. Such a structure can transform between rubbery (over the glass transition temperature) and hard states (under the glass transition temperature). This transformation is mainly useful in large shape changes necessary for fitting different patients. Also a method of actuation using an under actuated mechanism will be presented for the Robogami based on the stiffness controlled joints. On the Robogami platform other layers will be added for specific therapy methods (Figure 3(b)). It worth mentioning that the Robogami platform for facial prosthesis is a general concept and any of the components introduced here can be replaced for specific applications. Also as presented in Figure 2 not all of these components are necessary and in specific applications only some might be embedded in the device. Also the device can have different shapes according to the application. Figure 4 presents one design for the Robogami facial prosthesis that covers only a specific area. The final device has a modular design meaning that different modules can come together to change the shape of the device.

Examples of some of the components that can be embedded in the facial prosthesis are presented below.

Adaptive stiffness body

The adaptive stiffness body of the facial prosthesis has different functionalities. One is to selectively change the stiffness of folds for specific training methods. The other is the initial shape transformation in the device to make it fit different patients. In this device glass transition in polymers is used as the method of changing stiffness. Inventors have chosen a polymer with shape memory effect (SMP) to have a fixed shape above the transition temperature. This polymer is engineered in a way to have a memory shape that it retains over the transition temperature. The modulus of elasticity of SMP decreases two to three orders of magnitude as it passes glass transition temperature [5] which makes it a good choice for adaptive stiffness body of the Robogami platform.

Another useful application of adaptive stiffness body is in the under actuated Robogami mechanisms. Figure 5 shows a very simple example of this idea where only two actuator (electric motor) that can independently drive 4 folds. The folds in this mechanism are composed of two thin SMP layers instead of one bulk of SMP material (to increase activation speed). The novelty of this mechanism is using materials that can change stiffness for locking and unlocking each degree of freedom (this can also be used for changing stiffness in increments) to enable and disable different degrees of freedom. When the polymer layers of a joint are heated up and tendon is pulled the inner layer buckles under compression force while the outer polymer layer stretches. Each polymeric layer is about 0.5 mm in total thickness with an embedded heater layer. Using this technique the stiffness of the joint areas can be altered in a device so it can follow different folding motions using only one central actuator.

This actuation technique is embeddable as an optional functional layer in the rehabilitative Robogami prosthesis. Such a layer only has one motor that pulls a tendon that goes through all folding areas. According to the assigned exercise the stiffness of different folds are altered and pulling the string causes a certain folds to get activated. Figure 6 presents a 3D printed model of such a device to illustrate the idea. The electric motor can be the only source of actuation in the prosthesis or can work in conjunction with other actuation methods such as SMA actuators which will be introduced shortly.

Actuators

The facial prosthesis has to be thin and soft to have the least influence on the patient during the normal movement. It also should be able to apply enough force on demand during training. This means the actuators in the underlying Robogami platform should be soft, low profile, small (to increase the resolution and as the result softness) and yet powerful. More over these actuators need to have rather large range of motion. SMA bending actuator is a good choice that satisfies this long list of requirements. In the design presented here, two antagonistic actuators are used to make bidirectional folds in the Robogami (Figure 7).

When SMA actuators are cold (in Martensite phase), changing their shape require small force and they show plastic behavior. When heated SMA actuators transform to Austenite phase and regain their memory shape and are able to apply large force if their path is blocked (the torque to mass ratio of these actuators is 100 times that of small electric motors [6]). Here memory shape of folded state is given to one actuator and unfolded state to the other one. Activating one actuator with folded / unfolded memory (by heating) while the other one is cold will cause the folding / unfolding motion.

One of the features of the SMA sheet actuators is the scalability of these actuators. This shows a possibility to scale down the same design for the actuators without losing functionality. This makes fabrication of Robogamis with many degrees of freedom and tiny actuators possible.

Heaters and circuit

Stiffness change of the polymeric body and activation of the SMA actuators are possible through manipulation of the temperature. For the body stretchable heaters are embedded in the polymeric layer.

For the actuators the easy method is to put the heaters inside the tile areas but the more power efficient method is to use heaters on the active part which requires stretchable heaters. Also deformation of the polymeric body requires stretchable heaters that can transform shape with the polymer in rubbery state (the same goes for the under actuated mechanism introduced before).

In the case of SMA actuators, the heating element is composed of a patterned Inconel sheet (a serpentine that makes the heater) and a layer of thermal pad with double sided adhesive to attach the heater to the actuator. To make the heater layer stretchable, a mesh structure is cut on the heater layer. The same mesh structure that was added to make the heater layer stretchable can also be applied for making the stretchable circuit for the folding areas in the Robogami and also heaters for the stretchable body of the Robogami. Figure 8 presents stretchability of the mesh structure while maintaining its functionality.

Sensors

Facial prosthesis is dependent on its array of sensors for carrying out its role. In each fold of the Robogami a curvature sensor and on each tile a pressure sensor are needed. It is not feasible to embed this many commercially available sensors; with fixed shape and size. So the sensor array for the Robogami is developed by the inventors. Different methods of fabrication for soft and flexible sensors have been suggested in the literature. Among these, sensors based on piezo resistive material cover a wide range of application. These sensors are composed of conductive particles in nonconductive filler. When strain is applied to these sensors the conduction paths break and the electrical resistance increases (with a right design, order of magnitude of the electrical resistance change can be achieved). These sensors are basically made of sensing material and no other supporting components are necessary. This makes these sensors highly scalable and customizable [13]. Also the fabrication process can be easily used to fabricate large arrays of these sensors at once. For pressure sensors, the inventors used conductive polymer sensors and carbon ink based sensors were used for measuring the bending angle. Finally for elongation (stretch) sensors, the inventors developed a new method of sensing which is more reliable and robust compared to rival piezo resistive technologies. In what follows the design and the fabrication process of the pressure, curvature and elongation sensors are presented.

Pressure sensors made of conductive silicone rubber are embedded in Robogami facial prosthesis to detect contact force between the patient’s face and the robot. Using this data, computer program can recognize the shape of the face and also detect if any of the tiles are about to come off. Figure 11 presents an array of four pressure sensors which were used in studying the performance and in optimizing the design of the sensors. As seen in figure 9 (a) the patterned conductive fabric and glass fiber layers provide the seat for the pressure sensors. To make this structure 3 layers of pre-impregnated glass fiber and 2 layers of conductive fabric where patterned, assembled, and cured in the heat press at 140 ^{o}C. Next, by laying a layer of conductive silicone all sensors are fabricated and automatically positioned. The top electrode was designed perforated (Figure 9 (a)) to let the conductive silicone fill the gap between this electrode and the one on the bottom.

Commercially available curvature sensors are based on carbon ink printed on polyimide sheets. Demanding requirements on overall size, minimum radius of curvature and ease of embedment in large arrays makes off-the-shelf sensors unsuitable for Robogami. So curvature sensors for this application were also developed by the inventors. Compared to commercial ones, their design for the sensors is different in couple of details. They have used a layer of polyurethane hotmelt adhesive as the top shielding material instead of Kapton to make the sensors thin and soft as possible. Also they have added scorch lines on the Kapton surface before printing the carbon ink (figure 10). Along these lines there will be stress concentration and crack induced resistance change will happen. Careful arrangement of these lines makes readings from different sensors more similar and the sensors more sensitive in specific directions (which can be helpful for example in reducing the effect of twist on resistance change). The fabrication process for these sensors starts with scorching the surface of Kapton with laser up to half its thickness (figure 10 (b)). Next the top layer is covered with masking tape. Using the Laser outline of the sensing part of the sensor is cut and the mask is removed from these areas (figure 10 (c)). Then, the surface is covered with a layer of carbon ink. It is necessary to have part of the Kapton layer uncovered so it would provide the anchoring point for the top protective layer that will be added next. If the sensor is completely covered with ink, the protective layer will delaminate easily. The mask provides us with these uncovered sections ((figure 10 (d))). Finally the top protective layer is added and the sensor outline is cut (figure 10 (e)).

As mentioned, stretch sensor is also a valuable component in gathering information regarding the shape of the Robogami platform and the object it envelopes. The inventors designed and introduced a new type of sensor based on change in the resistance of the metallic layer under strain (figure 11). This novel sensor is made by machining a mesh structure (using laser) on a metal layer and polyimide laminate to make a stretchable structure. But such a structure (which is similar to the heaters introduced in the previous section) is not sensitive on its own since the amount of metal in tension and compression is the same. To make such a structure sensitive to deformation, the inventors modulated the path that the current takes so the metal in compression or tension would have a bigger change of resistance. Based on this concept, sensors that increase or decrease resistance while being stretched were fabricated that can be used in any wearable device based on its low profile and low stiffness. Fabrication of stretchable heaters that can also give information on the amount of stretch is also possible by careful design of the conductive path.

Examples of Robogami structures

One of the advantages of the layer by layer fabrication method of Robogami is the possibility of developing these layers independently and later combining them together in the final device. Based on this, our case studies each focused on some of the layers in the final design.

To assess the performance of essential components of Robogami platform (actuators, sensors, and stretchable circuit) a robot consisting of four folds was designed and fabricated. Figure 12 presents the model of the robot and the exploded view; to better show all the functional layers; and the fabricated robot.

This simple four folds robot can be considered as a simple module of the facial prosthesis. This device confirmed that the proposed sensors and actuators can provide accurate bidirectional actuation.

A Robogami platform with bidirectional actuation on all folds was fabricated to study the effect of scaling down on performance of components and fabrication effectiveness. Figure 13 presents this platform in which all folds were successfully activated. Experiments on this platform confirmed that scaling the design has no effect on the performance of the components.

Based on the components, the facial device according to the invention can be used as a passive training device that can adjust its elasticity, a diagnosis device that can provide morphological feedback from the face, a rehabilitative device that uses EMG readings and electrical stimulation in therapy, an active prosthesis that can apply force during therapy or any combination of these.

References

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CLAIMS

1. Facial prosthesis based on a Robogami platform.

2. Facial prosthesis according to claim 1 comprising an adaptive stiffness body, sensing and actuating elements.

3. Facial prosthesis according to claim 1 or 2 made of several layers having each a specific functionality.

4. Facial prosthesis according to anyone of the previous claims comprising actuators, heaters, a circuit, sensors, and a body.

5. Facial prosthesis according to claim 4 wherein said sensors comprise pressure sensors.

6. Facial prosthesis according to claim 4 or 5 wherein said sensors comprise stretch sensors.

7. A wearable facial prosthesis according to anyone of the previous claims.

8. Use of the facial prosthesis as defined in anyone of the previous claims as a passive training device that can adjust its elasticity.

9. Use of the facial prosthesis as defined in anyone of the previous claims 1 to 6 as a diagnosis device that can provide morphological feedback from the face.

10. Use of the facial prosthesis as defined in anyone of the previous claims 1 to 6 as a rehabilitative device that uses EMG readings and electrical stimulation in therapy.

Abstract

The present invention relates to a facial rehabilitative device based on Robogami (Robotic Origami) platform. The device facilitates the process of the physical therapy for the therapist, to make this process more disciplined, and to enhance the result for the patient. Softness and low thickness are necessary in the facial prosthesis for safety and mechanical transparency; to patient's normal movements. Moreover the prosthesis may be adapted for different therapy methods, which means that different components are embeddable in the main platform of the prosthesis depending on the therapy requirements. Robogami platform is the main frame that embeds other functional components in the facial devices. Robogamis are low profile robots that can transform into different 3D shells. They provide softness through many Degrees of Freedom (DoF) that are driven by soft actuation (either soft materials or soft control). The layer by layer fabrication process of the Robogami is advantageous for the facial prosthesis since it allows embedment of different functional layers; such as electric stimulators, stiffness adaptive structures, and pressure sensitive layer; according to the requirements of the therapy method.