Medical Engineering and Physics 000 (2016) 1–6

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Technical note

Epidermal electronics for electromyography: An application to swallowing therapy[☆]

Gabriela Constantinescu[a,b,1], Jae-Woong Jeong[c,1], Xinda Li[d], Dylan K. Scott[b], Kyung-In Jang[e], Hyun-Joong Chung[d,*], John A. Rogers[e,**], Jana Rieger[a,b]

[a] Institute for Reconstructive Sciences in Medicine (iRSM), Misericordia Community Hospital, Edmonton, Alberta, Canada
[b] Department of Communication Sciences and Disorders, Faculty of Rehabilitation Medicine, University of Alberta, 8205 114 St 2-70 Corbett Hall, Edmonton, Alberta, Canada
[c] Department of Electrical, Computer, and Energy Engineering, University of Colorado, Boulder, CO 80309, USA
[d] Department of Chemical and Materials Engineering, Faculty of Engineering, University of Alberta, Edmonton, Alberta, Canada
[e] Department of Materials Science and Engineering, Beckman Institute for Advanced Science and Technology, and Frederick Seitz Materials Research Laboratory, University of Illinois, Urbana, IL 61801, USA

ARTICLE INFO

Article history:
Received 20 November 2015
Revised 4 April 2016
Accepted 24 April 2016
Available online xxx

Keywords:
Epidermal electronics
Surface electromyography
Swallowing therapy
Head and neck cancer

ABSTRACT

Head and neck cancer treatment alters the anatomy and physiology of patients. Resulting swallowing difficulties can lead to serious health concerns. Surface electromyography (sEMG) is used as an adjuvant to swallowing therapy exercises. sEMG signal collected from the area under the chin provides visual biofeedback from muscle contractions and is used to help patients perform exercises correctly. However, conventional sEMG adhesive pads are relatively thick and difficult to effectively adhere to a patient's altered chin anatomy, potentially leading to poor signal acquisition in this population. Here, the emerging technology of *epidermal electronics* is introduced, where ultra-thin geometry allows for close contouring of the chin. The two objectives of this study were to (1) assess the potential of epidermal electronics technology for use with swallowing therapy and (2) assess the significance of the reference electrode placement. This study showed comparative signals between the new epidermal sEMG patch and the conventional adhesive patches used by clinicians. Furthermore, an integrated reference yielded optimal signal for clinical use; this configuration was more robust to head movements than when an external reference was used. Improvements for future iterations of epidermal sEMG patches specific to day-to-day clinical use are suggested.

1. Introduction

Head and neck cancer is a devastating disease affecting more than 55,000 people in the United States in 2014 alone [1]. Treatment can involve surgical removal of the tumor, radiation therapy, and chemotherapy, leaving patients with facial disfigurement, as well as altered anatomy and physiology. Subsequently, approximately 70% of patients with head and neck cancer will experience impaired swallowing function [2]. Swallowing difficulties can lead to serious health concerns, such as malnutrition, dehydration, and aspiration pneumonia that results from food and saliva entering the airway.

Management of swallowing impairments can be achieved in a number of ways, including diet modifications, compensatory maneuvers, rehabilitative exercises, and even bypassing the system altogether through the use of a feeding tube. However, diet modifications and feeding tubes can negatively impact quality of life [3,4] and compensatory maneuvers have been suggested to be less effective than intensive rehabilitative exercises in managing the consequences of dysphagia [5]. One commonly used rehabilitative exercise is the Mendelsohn maneuver, an exercise that involves volitionally suspending or "holding" the larynx (voice box) at the height of the swallow [6].

Surface electromyography (sEMG) is typically used as a visual biofeedback adjuvant to swallowing therapy, guiding the patient in performing the exercises correctly [7,8]. sEMG in swallowing therapy involves adhesion of surface electrodes to an area under the chin (submental area); these electrodes monitor muscle

---

[☆] This material has never been published and is not currently under evaluation in any other peer-reviewed publication.

[*] Corresponding author. Tel: +1 7804924790; fax: +1 7804922881.

[**] Corresponding author. Tel.: +1 217 244 4979.

E-mail addresses: chung.hj13@ualberta.ca (H.-J. Chung), jrogers@illinois.edu (J.A. Rogers).

[1] G.C. and J-W.J. contributed equally to this work.

http://dx.doi.org/10.1016/j.medengphy.2016.04.023
1350-4533/

Please cite this article as: G. Constantinescu et al., Epidermal electronics for electromyography: An application to swallowing therapy, Medical Engineering and Physics (2016), http://dx.doi.org/10.1016/j.medengphy.2016.04.023

activity in the region of application during a prescribed exercise. Clinical experience has shown that surgery and radiation therapy can leave patients with chin disfigurement (e.g., bulky flaps, uneven contour of the submental area). The atypical submental area makes the adhesion of the conventional sEMG patch difficult, a clinical challenge that motivated the current pilot study. Owing to recent advances in new materials and mechanics design, the emerging field of epidermal electronics systems (EES) may offer a technological solution to this problem: ultra-thin sEMG electrodes that can comfortably attach and conform to the skin, similar to a temporary tattoo [9]. Epidermal sEMG patches may be superior to the existing adhesive patches if the epidermal technology results in a higher fidelity signal when applied to altered head and neck anatomy. Since its first introduction in 2009, the EES field has been rapidly burgeoning, leading to numerous meaningful applications, including human-machine interfaces for drone control [10], direct application on skin with spray-on bandage [11], human skin health monitoring [12], skin-adhesive rechargeable batteries [13], and RFID temperature sensors [14].

A complete set of EES is composed of ultrathin sensory electrodes and data processors that are placed directly on top of the epidermis (i.e., mechanically unnoticeable feeling to users when worn) and thus can act as the ‘second-skin’ transmitting electronic signals [9]. EES are ultra-thin (~5 μm), ultra-light (~1 mg/cm^2), and stretchable (30%), resulting in physical properties similar to the epidermis with respect to area mass, density, thickness and effective mechanical modulus. These features lead to conformal lamination of electronics directly on the curvilinear surface of the skin and allow the device to follow the skin deformation without structural damage or delamination. The objectives of this study were to (1) determine if an epidermal sEMG patch could yield signals comparable to conventional sEMG and (2) assess the significance of the reference electrode placement.

2. Methods

2.1. Conventional sEMG details

Commercially available sEMG sensor patches, where bulky and rigid Ag/AgCl electrodes are embedded in polymeric foams, were purchased and used as is (7179-0020-Demo/XP, Pentax Canada Inc., Mississauga, Ontario).

2.2. Epidermal sEMG details

Our epidermal sEMG patch consisted of narrow, thin interconnect wires, three gold electrodes (200 nm thickness) in the form of filamentary serpentine (FS) meshes for two sensing electrodes for differential measurement, and a reference electrode. The FS mesh electrodes were designed to have an optimized combination of width (20 μm) and radius of curvature (45 μm) to achieve over 30% elasticity with only 0.94% maximum principal strain in the metals (fracture strain of Au ≈ 1%) [10]. This layout ensured robust operation at strain levels well beyond those that can be tolerated by the skin (10–20%) [15] and was therefore ideal for sEMG measurement on the underside of the chin during swallowing therapy. On the other hand, the conventional sEMG adhesive patches were 57 mm in diameter with one reference electrode and two sensing electrodes in a bipolar configuration. All three electrodes were 7 mm in diameter with an inter-electrode distance of 7 mm.

2.3. Epidermal sEMG fabrication

Fabrication of epidermal sEMG patch (JWJ, KIJ, JAR) began with the preparation of a substrate to facilitate the delamination of electrode patterns by providing a low surface energy (Fig. 1a). This substrate was created by spin-coating polydimethylsiloxane (PDMS; 10 μm in thickness, Dow Corning, USA) on a glass slide. A polyimide layer (PI; 300 nm in thickness through dilution with pyrrolidinone, Sigma-Aldrich, USA) was cast on the substrate after making the PDMS surface hydrophilic by UV-ozone treatment for 3 minutes. The electrode and interconnect structure were created by deposition and photolithographic patterning of Cr/Au (5 nm/200 nm in thickness). These structures were encapsulated with a PI layer (300 nm in thickness), therefore placing the metal interconnect at the neutral mechanical plane and minimizing bend stress. The sEMG electrodes and pads for external connection were patterned and exposed using reactive ion etching of the corresponding regions on the top PI layer. This final layer completed the epidermal sEMG sensors, resulting in a total thickness of 800 nm in an open, serpentine mesh design. A water-soluble tape (3 M, USA) enabled pick-up of the device from the PDMS-coated glass substrate and its transfer to a thin silicone layer (5 μm in thickness) with a biocompatible adhesive (Silbione RT Gel 4717 A/B, Bluestar Silicones, USA) coated on a water-soluble paper (Aquasol, USA). Finally, the water-soluble tape was dissolved after transferring the device to a silicone layer.

2.4. Device application

For application of the EES to the skin, the device (Fig. 1b) was first placed on the right side of the chin (targeting the right anterior belly of the digastric muscle) so that the two measuring electrodes (MES1, MES2) were along the length of the muscle, while the reference electrode (REF) was placed away from the muscle. In this process, the water-soluble substrate acted as a temporary support for manual lamination of the device on the skin, and was subsequently removed using water from a spray bottle. This approach led to the conformal integration of the EES on the curvilinear surface of the skin, ensuring the device was well configured for sEMG measurement. The silicone substrate coated with an adhesive enabled excellent adhesion to the skin (~1.5 KPa) [16], thus allowing intimate application on the skin for long-term use.

2.5. Data acquisition

The participant (JR) was comfortably seated. The epidermal sEMG electrodes were prepped for placement by engineers (XL, DKS, HJC). The device was then gently applied to the submental area and water from a spray bottle was used to dissolve the backing. Conventional sEMG electrodes were placed as shown in Fig. 2a; epidermal sEMG electrodes were placed as shown in Fig. 2b. During the epidermal sEMG patch application, the lead wires were secured with tape to the chin or neck. This last step ensured that the weight of the connector (i.e., alligator clips) did not detach the epidermal sEMG patch. Signals were recorded at 1000 Hz with 16-bit resolution using National Instruments™ USB-6210 multifunction data acquisition unit (NI USB-6210, National Instruments Corporation, Austin, Texas). Data were visualized, pre-processed, and saved using National Instruments™ Biomedical Workbench software suite (Version 13.0.0, Edmonton, Alberta). Post-processing and analysis was carried out in MATLAB® (ver. R2014b, Edmonton, Alberta) using custom scripts. Once the equipment was set up, the speech-language pathologist walked the participant through a series of tasks:

a. Baseline: The participant was asked to remain still and breathe quietly for 5–10 s.
b. Saliva swallows (3 trials): The participant was asked to swallow her saliva.
c. Water swallows (3 trials): The participant was asked to swallow small sips of water. Any associated signal from arm and neck movement during the elevation of the cup also was captured.

Please cite this article as: G. Constantinescu et al., Epidermal electronics for electromyography: An application to swallowing therapy, Medical Engineering and Physics (2016), http://dx.doi.org/10.1016/j.medengphy.2016.04.023