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Technical note

Epidermal electronics for electromyography: An application to swallowing therapy☆

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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

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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.

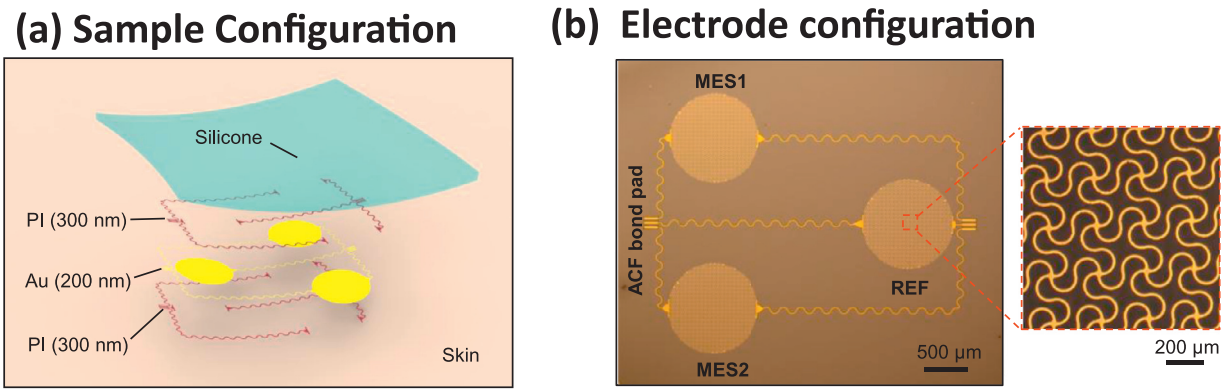

Fig. 1. (a) Layer-by-layer configuration of the epidermal sEMG electrode and (b) electrode configuration on the epidermal sEMG patch.

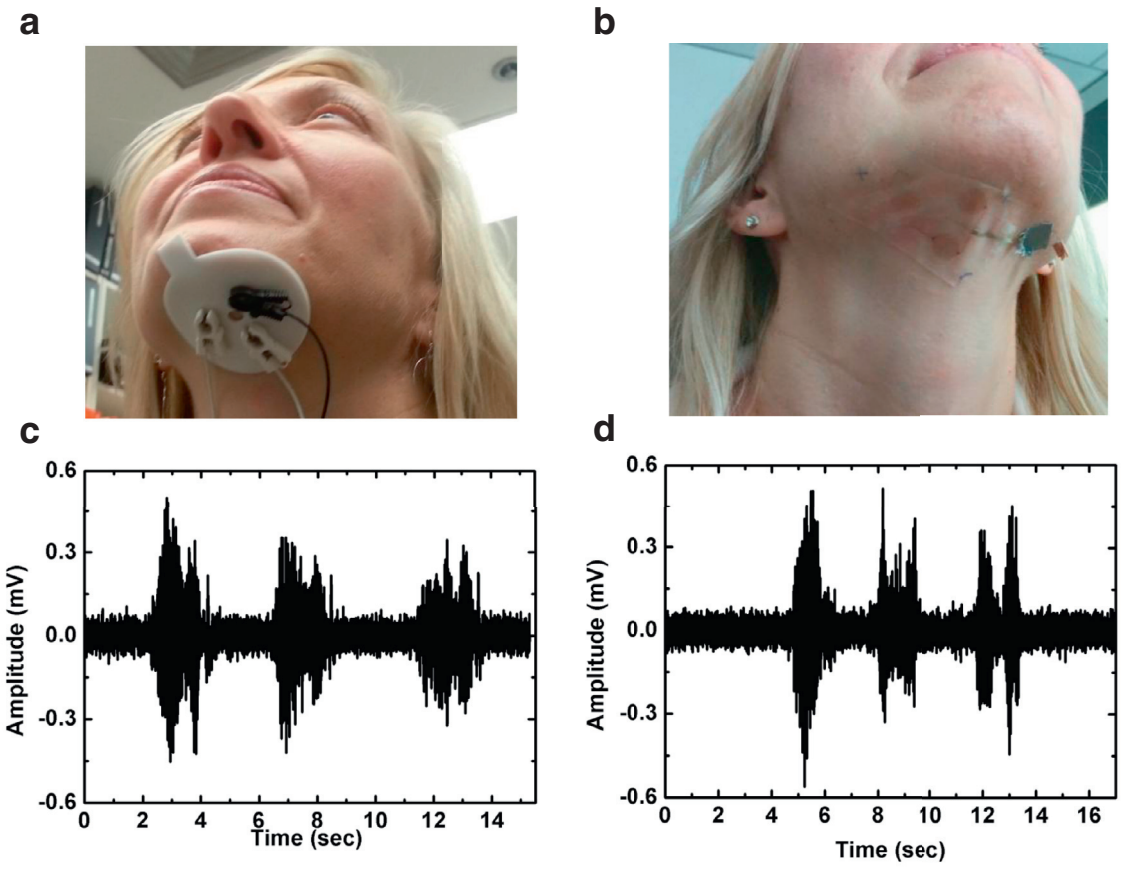

Fig. 2. Placement of the sEMG electrodes in the submental area: (a) conventional sEMG adhesive patch and (b) epidermal sEMG patch. (c) Sample signal collected during three saliva swallows using the conventional sEMG adhesive patch, with an integrated reference. (d) Sample signal collected during three saliva swallows by the epidermal sEMG patch, with an integrated reference.

d. Effortful saliva swallows (3 trials): The participant was asked to swallow her saliva with maximum effort.
e. Mendelsohn saliva swallows (3 trials): The participant was asked to swallow her saliva, and then contract her muscles at the height of the swallow, so as to "hold" the swallow. During this task, the larynx remained elevated for 3 to 5 seconds. The participant was familiar with this maneuver.
f. Tongue compressions (5 trials): The participant was asked to place her tongue tip to the alveolar ridge, behind the front incisors, and push up.
g. Jaw movement (5 trials): The participant was asked to open and close her mouth.
h. Head movements: The participant was asked to move her head up, down, left and right, while returning the head to the neutral position between each new direction.

2.6. Experimental protocol

Task *a* was used as a reference for the rest of the signal. Tasks *b* through *e* were included as potential Events targeted during swallowing therapy. Tasks *f* and *g* were included to note the activation of the same muscles during non-swallowing tasks. Task *h* was used to observe the robustness of the sEMG signal to extraneous movements that may result in a signal. The integrated reference

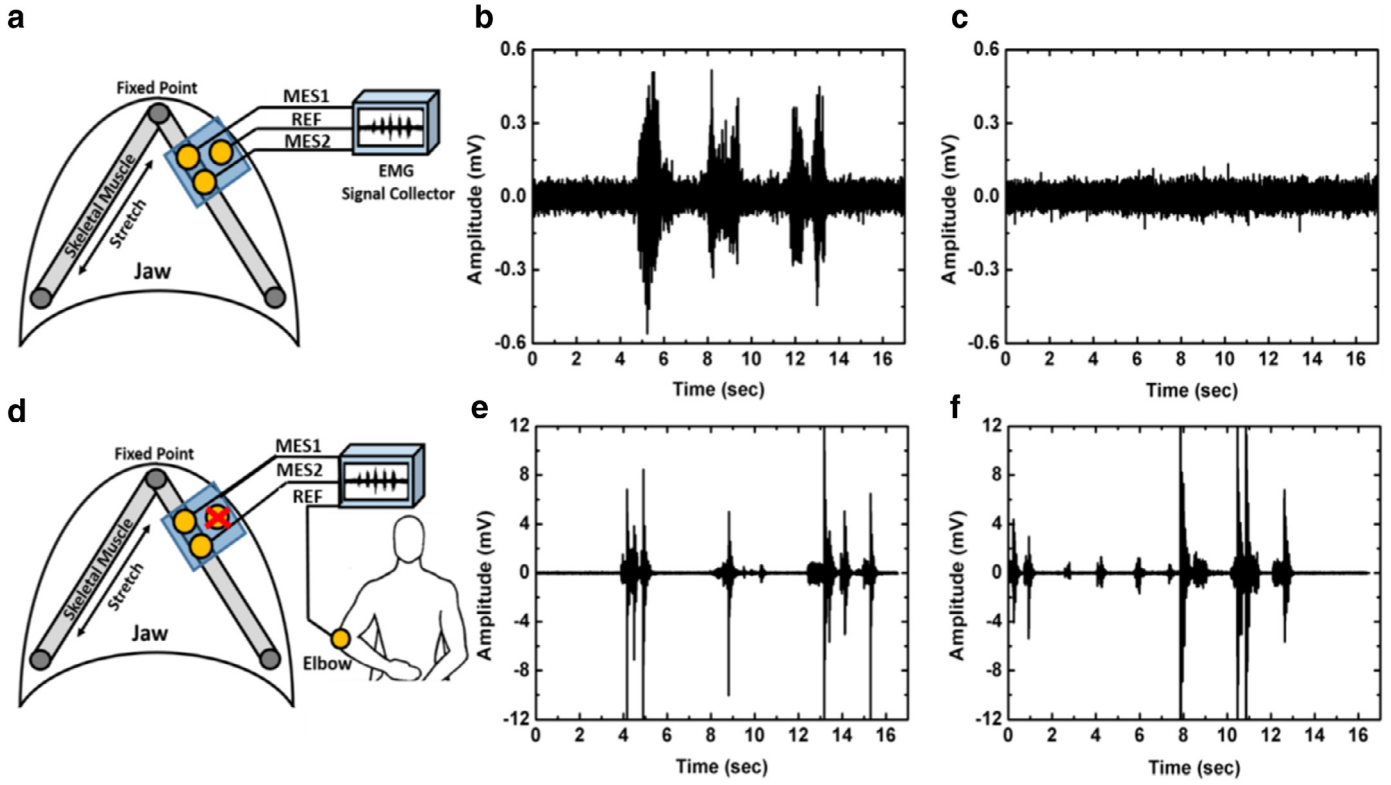

Fig. 3. (a) A schematic diagram of epidermal sEMG patch with an integrated reference. (b) Signal collected by epidermal sEMG patch with integrated ground from three saliva swallows. (c) Signal collected by epidermal sEMG patch with integrated ground from head movements. (d) A schematic diagram of epidermal sEMG patch with an external reference on the elbow. (e) Signal collected by epidermal sEMG patch with external ground from three saliva swallows. (f) Signal collected by epidermal sEMG patch with external ground during head movements.

electrode was placed on the body of the mandible, while the externally located reference was placed on the elbow. Signals were collected while the participant performed two tasks; saliva swallows and head movements. The effects of the reference electrode location on the collected signal also were studied. Both integrated (Fig. 3a) and externally located reference electrodes (Fig. 3d) were utilized; in both cases the reference electrode was positioned on a boney region, where little to no muscle activity is sensed.

2.7. Data analysis

The efficacy of epidermal electronics was evaluated using the following outcome measures: (i) the signal/noise ratio (R = average signal amplitude/noise amplitude) of collected signals; (ii) the amplitude of collected signals.

3. Results

3.1. Efficacy of epidermal electronics

This pilot study demonstrated that signals from the submental muscles can be successfully acquired using the new epidermal sEMG patch. First, the epidermal electrode was compared with the conventional sEMG adhesive pad during three saliva swallow trials with an integrated reference. The average amplitude of the epidermal electrodes was 0.433 ± 0.058 mV (Fig. 2d) with $R = 6.138$, and that of the conventional electrode patch was 0.415 ± 0.111 mV with $R = 5.231$ (Fig. 2c). The average amplitude and R of the signal collected by the epidermal sEMG patch were approximately the same as those collected by the conventional patch.

3.2. Location of ground electrode

The average amplitude in the signal captured by epidermal electrodes with the integrated reference was 0.433 ± 0.058 mV with $R = 6.138$ as discussed; no visible peaks were recorded during head movements. Alternatively, when using an external reference, the average amplitude of the signal captured with the epidermal electrodes during swallows (Fig. 3e) was 8.467 ± 3.453 mV with $R = 57.596$. Although this electrode configuration yielded signal with a magnitude one order larger than that acquired with an integrated reference, a limitation was noted. Specifically, noticeable peaks were recorded during head movements when using an external reference (Fig. 3f), with an amplitude of 4.744 ± 4.547 mV with $R = 31.213$. On the other hand, the integrated reference appeared to result in signal that was considerably more robust to head movements. This advantage could be attributed to the reference electrode being securely attached to the neck.

3.3. Signal captured

The signal acquired using the epidermal sEMG patch is shown in Fig. 4. The swallow events can be detected visually with ease and the general shape of the signal is representative of the associated task. For example, the saliva swallows (Fig. 4a) resulted in short bursts of signal, while the Mendelsohn maneuver swallows (Fig. 4d) showed prolonged muscle activity.

4. Discussion

From a clinical perspective, the device resulted in good adhesion with high fidelity to the anatomy of the chin. The signal acquired was suitable for clinical use and the speech pathologists

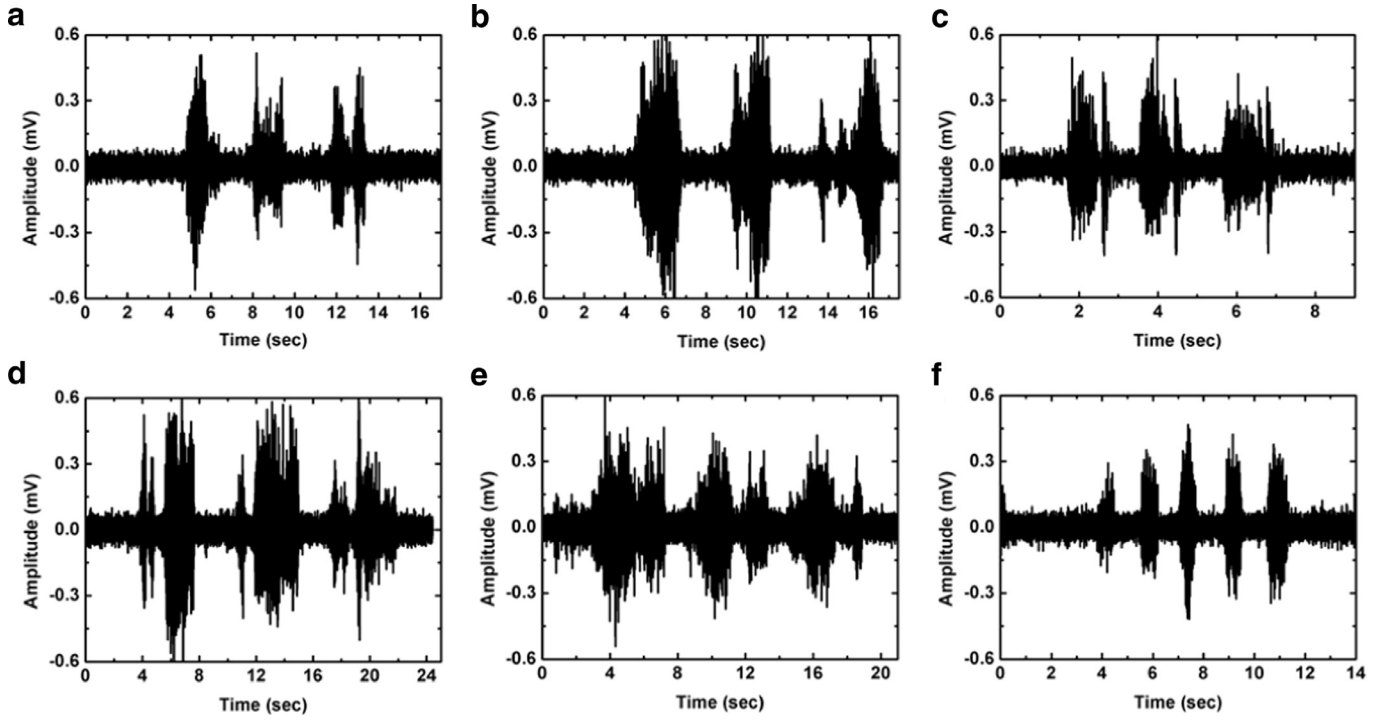

Fig. 4. Signal collected by epidermal sEMG patch with integrated ground of (a) saliva swallows, (b) water swallows, (c) effortful saliva swallows, (d) Mendelsohn maneuver saliva swallows, (e) tongue compressions and (f) jaw movement.

(GC, JR) could detect swallow events with ease. These two findings highlight the potential of epidermal sEMG technology in swallowing therapy. The primary function of visual biofeedback in swallowing therapy is to be able to detect true swallow events while the patient is comfortable and natural (i.e., not in ideal testing situations, where extraneous movements can be controlled).

The design of the current epidermal sEMG sensor would benefit from future improvements. The ultrathin ($<100\,\mu$m) electronics have the ability to create better contact to the chin contour. This is an important advantage of the epidermal sensor patch over the conventional alternative as it may be more comfortable for patients to wear. However, self-placement of the epidermal sEMG patch may be extremely difficult without a carefully designed, self-guiding scaffold, and a user-friendly application protocol for patients. When the authors trialed a thicker version of the sensor ($\sim300\,\mu$m), it was found that the electrode application was easier; however, the volunteer still required assistance to apply the sensor on herself correctly. One concern with increased thickness is that the conformal contact to the chin may be compromised especially for long-term applications. Future work on optimal thickness of the epidermal patch could explore a balance between prolonged wearability, signal quality, and ease of patch placement by a user. In addition, a smart scaffold design may be required to guide patients in self-application.

Additionally, the epidermal sEMG patch must contain components for wireless communication to gain true merit over a conventional patch. In this experiment, alligator clips were used to connect the sEMG pad to the data acquisition system. However, the weight of the alligator clips interfered with the attachment of the epidermal sEMG patch. Recent advances in RFID [14] and near-field communication [17] of epidermal electronics patches may offer a potential solution to this problem. Lastly, the device should be inexpensive or reusable, to match or surpass the cost-effectiveness of current technology. A recently developed "cut-and-paste" technology has the potential to significantly reduce the cost of manufacturing epidermal electronics; however, ultrathin patch thickness in this case may be difficult to achieve [18]. Future work should focus on the design and application of the epidermal patch, as well as incorporating wireless communication capabilities.

5. Conclusion

Epidermal sEMG patches possess an advantage over conventional sEMG electrodes in their ability to conform to atypical chin anatomy, a benefit that could be particularly significant when working with patients following treatment for head and neck cancer. This study showed comparative signals between the new epidermal sEMG patch and the conventional adhesive patches used by clinicians for swallowing therapy. Furthermore, our findings indicated that an integrated reference yielded optimal signal for clinical use, as this configuration was more robust to head movements than when an external reference was used.

Conflict of interest

J.A.R. is involved as a founder and board member at MC10, a company that has commercial interests in skin-mounted electronics. All the other authors declare no conflict of interest.

Ethics approval

The University of Alberta Health Research Ethics Board confirmed that the formal approval was not necessary for this study; the only participant in this study was one of the co-authors.

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References

[1] Cancer.Net. Head and neck cancer: statistics. 2014.
[2] Langerman AME, Kasza K, Haraf DJ, Vokes EE, Stenson KM. Aspiration in chemoradiated patients with head and neck cancer. Arch Otolaryngol Head Neck Surg 2007;133:1289–95.
[3] Farri A, A A, Burdese C. Social importance of dysphagia: its impact on diagnosis and therapy. Acta Otorhinolaryngol Ital 2007;27:83–6.
[4] Paleri VP. J. Use of gastrostomy in head and neck cancer: a systematic review to identify areas for future research. Clin Otolaryngol 2010;35:177–89.
[5] Carnaby G, Hankey GJ, Pizzi J. Behavioural intervention for dysphagia in acute stroke: a randomised controlled trial. Lancet Neurol 2006;5:31–7.
[6] Arrese LC, Lazarus CL. Special groups: head and neck cancer. Otolaryngol Clin N Am 2013;46:1123–36.
[7] Crary MA, Carnaby Mann GD, Groher ME, Helseth E. Functional benefits of dysphagia therapy using adjunctive sEMG biofeedback. Dysphagia 2004;19:160–4.
[8] Ding R, Larson CR, Logemann JA, Rademaker AW. Surface electromyographic and electroglottographic studies in normal subjects under two swallow conditions: normal and during the mendelsohn manuever. Dysphagia 2014;17:1–12.
[9] Kim D-H, Lu N, Ma R, Kim Y-S, Kim R-H, Wang S, et al. Epidermal electronics. Science 2011;333:838–43.
[10] Jeong JW, Yeo WH, Akhtar A, Norton JJ, Kwack YJ, Li S, et al. Materials and optimized designs for human-machine interfaces via epidermal electronics. Adv Mater 2013;25:6839–46.
[11] Yeo WH, Kim YS, Lee J, Ameen A, Shi L, Li M, et al. Multifunctional epidermal electronics printed directly onto the skin. Adv Mater 2013;25:2773–8.
[12] Dagdeviren C, Shi Y, Joe P, Ghaffari R, Balooch G, Usgaonkar K, et al. Conformal piezoelectric systems for clinical and experimental characterization of soft tissue biomechanics. Nat Mater 2015;14:728–36.
[13] Berchmans S, Bandodkar AJ, Jia W, Ramírez J, Meng YS, Wang J. An epidermal alkaline rechargeable Ag–Zn printable tattoo battery for wearable electronics. J Mater Chem A 2014;2:15788–95.
[14] Milici S, Amendola S, Bianco A, Marrocco G. Epidermal RFID passive sensor for body temperature measurements. In: Proceedings of IEEE RFID technology and applications conference; 2014. p. 140–4.
[15] Arumugam V, Naresh MD, Sanjeevi R. Effect of strain rate on the fracture behaviour of skin. J Biosci 1994;19:307–13.
[16] Jang KI, Han SY, Xu S, Mathewson KE, Zhang Y, Jeong JW, et al. Rugged and breathable forms of stretchable electronics with adherent composite substrates for transcutaneous monitoring. Nat Commun 2014;5:4779.
[17] Kim J, Banks A, Cheng H, Xie Z, Xu S, Jang KI, et al. Epidermal electronics with advanced capabilities in near-field communication. Small 2015;11:906–12.
[18] Yang S, Chen YC, Nicolini L, Pasupathy P, Sacks J, Becky S, et al. "Cut-and–Paste" manufacture of multiparametric epidermal sensor systems. Adv Mater 2015;27:6423–30.