Science Advances
AAAS

advances.sciencemag.org/cgi/content/full/5/12/eaay3210/DC1

Supplementary Materials for

Flexible submental sensor patch with remote monitoring controls for management of oropharyngeal swallowing disorders

Min Ku Kim, Cagla Kantarcigil, Bongjoong Kim, Ratul Kumar Baruah, Shovan Maity, Yeonsoo Park, Kyunghun Kim, Seungjun Lee, Jaime Bauer Malandraki, Shitij Avlani, Anne Smith, Shreyas Sen, Muhammad A. Alam, Georgia Malandraki*, Chi Hwan Lee*

*Corresponding author. Email: malandraki@purdue.edu (G.M.); lee2270@purdue.edu (C.H.L.)

Published 13 December 2019, *Sci. Adv.* **5**, eaay3210 (2019)
DOI: 10.1126/sciadv.aay3210

The PDF file includes:

Other Supplementary Material for this manuscript includes the following:

(available at advances.sciencemag.org/cgi/content/full/5/12/eaay3210/DC1)

Movie S1 (.mp4 format). Pilot VFSS recording of a swallow.
Movie S2 (.mp4 format). sEMG, strain, and VFSS recordings of a swallowing treatment session.
Movie S3 (.mp4 format). sEMG, strain, and VFSS recordings of a swallowing treatment session.
Movie S4 (.mp4 format). sEMG, strain, and VFSS recordings of a swallowing treatment session.
Movie S5 (.mp4 format). sEMG, strain, and VFSS recordings of a swallowing treatment session.
Movie S6 (.mp4 format). sEMG, strain, and VFSS recordings of a swallowing treatment session.
Movie S7 (.mp4 format). sEMG, strain, and VFSS recordings of a swallowing treatment session.

Fig. S1. Sensor patch adhered to the human submental skin of different ages. Photos of the sensor patch placed on human subjects of different ages (26~64). The scale bar is 3.5 cm. Photo Credit: Min Ku Kim, Purdue University, West Lafayette.

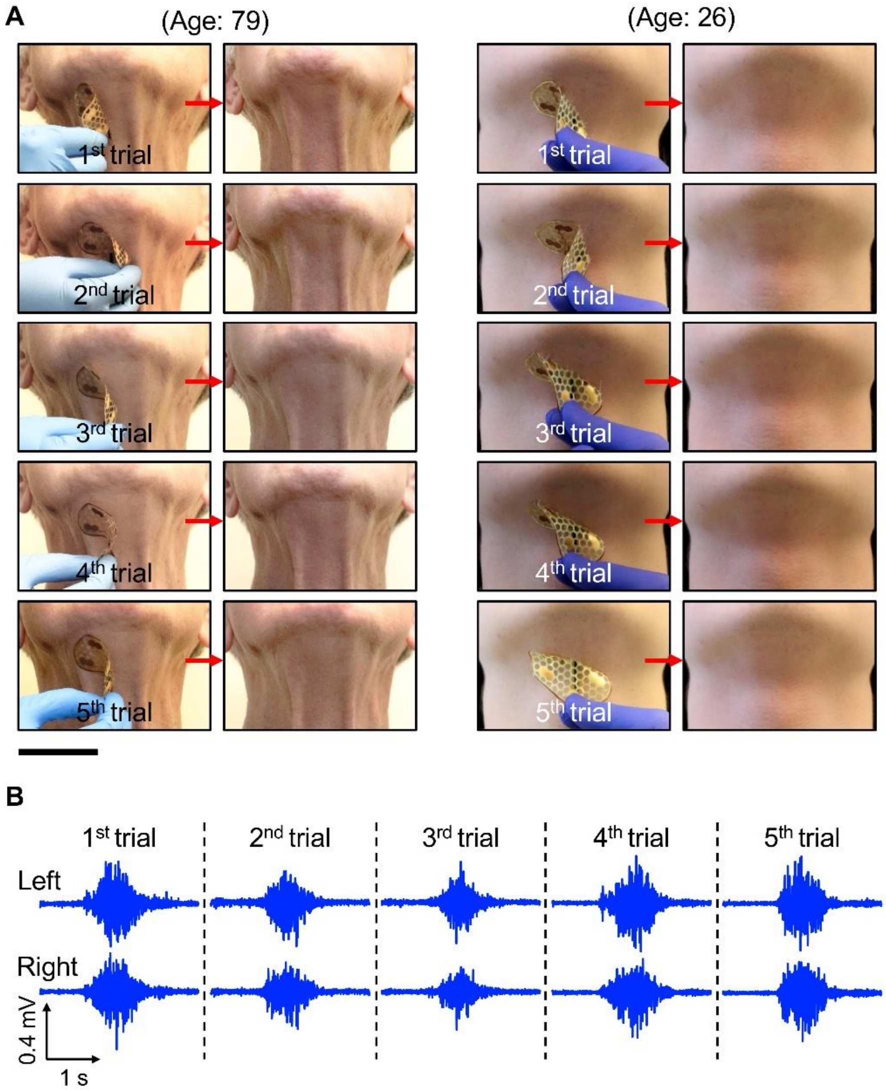

Fig. S2. Repeated use of the submental sensor patch. (**A**) Photos of the sensor patch repeatedly attached and detached to/from the submental skin of human subjects of different ages – 26 and 79 years. The scale bar is 5 cm. (**B**) The corresponding sEMG obtained from these multiple trials (subject age: 26). Photo Credit: Min Ku Kim, Purdue University, West Lafayette.

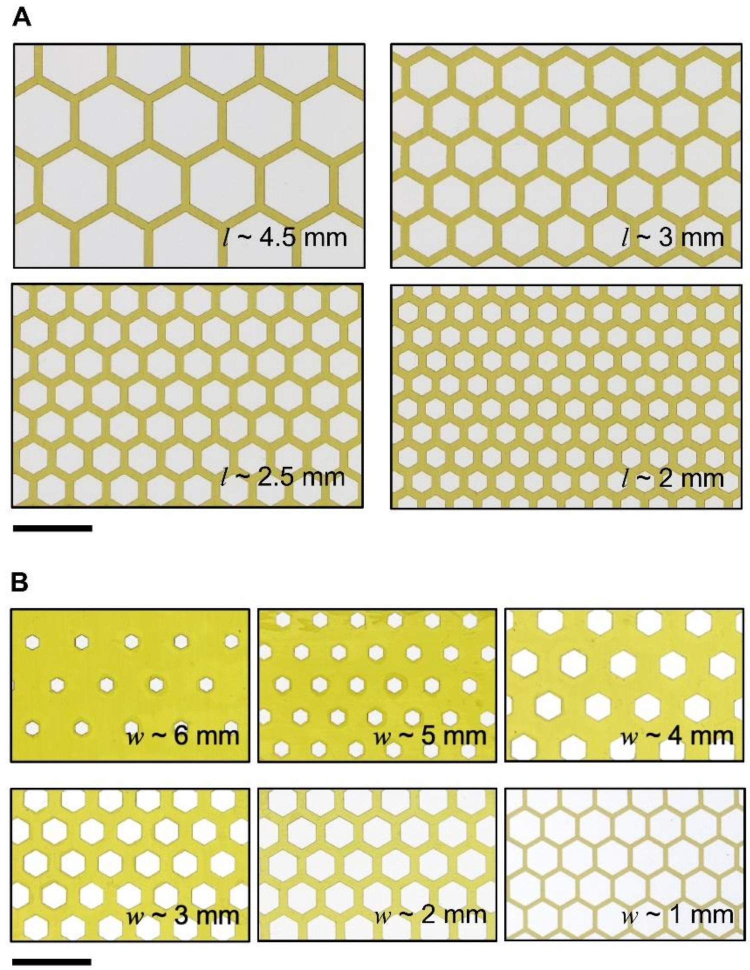

Fig. S3. Hexagonal test bed geometrical variation. Photos of several testbed structures with (**A**) varies l = 2-4.5 mm and (**B**) w = 1-6 mm. The scale bars are 8 mm and 16 mm, respectively.

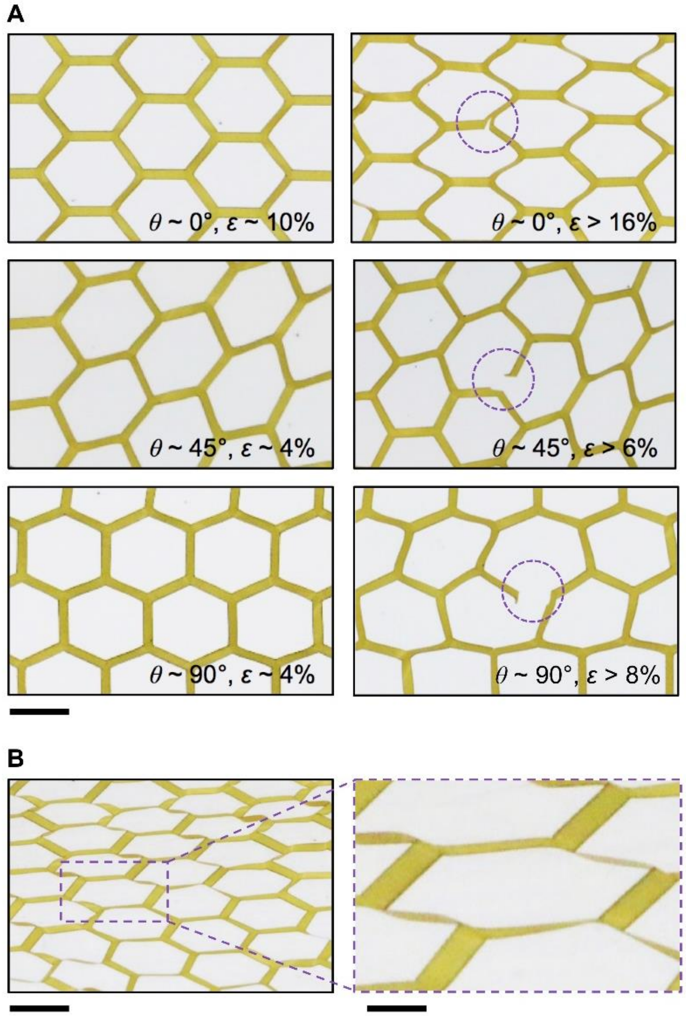

Fig. S4. Hexagonal test bed under mechanical loads. (**A**) Photos of the testbed structures under stretched up to the limits (left) and beyond (right) plastic deformation (left) at θ = 0°, 45°, and 90°. The scale bar is 6 mm. (**B**) Photos of the testbed structure under excessive load, stretched and twisted out-of-plane. The scale bars are 6.5 mm (left) and 2 mm (right), respectively.

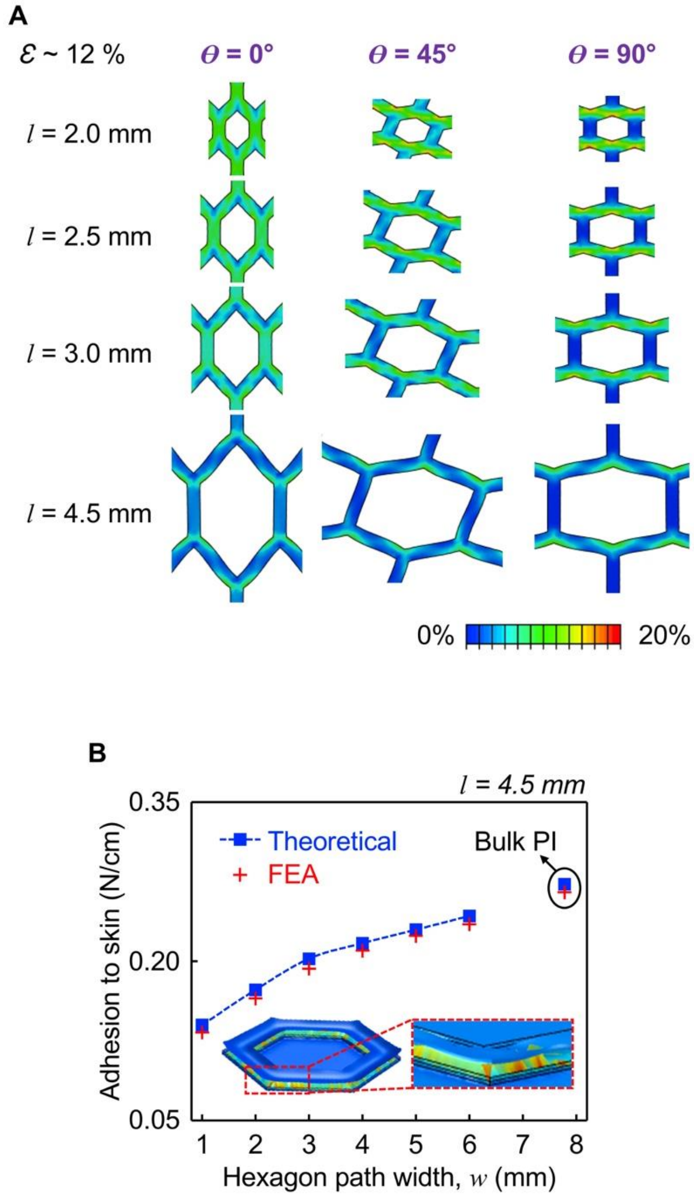

Fig. S5. Mechanical simulation of test bed structures under mechanical loads. (**A**)The corresponding FEA results of the testbed structure under stretched at 12% with varies l = 2.0, 2.5, 3.0 and 4.0 mm at θ = 0°, 45° and 90°. (**B**) Computational (FEA) and theoretical results of adhesive strength of the testbed structure to the skin with varied w = 1-6 mm.

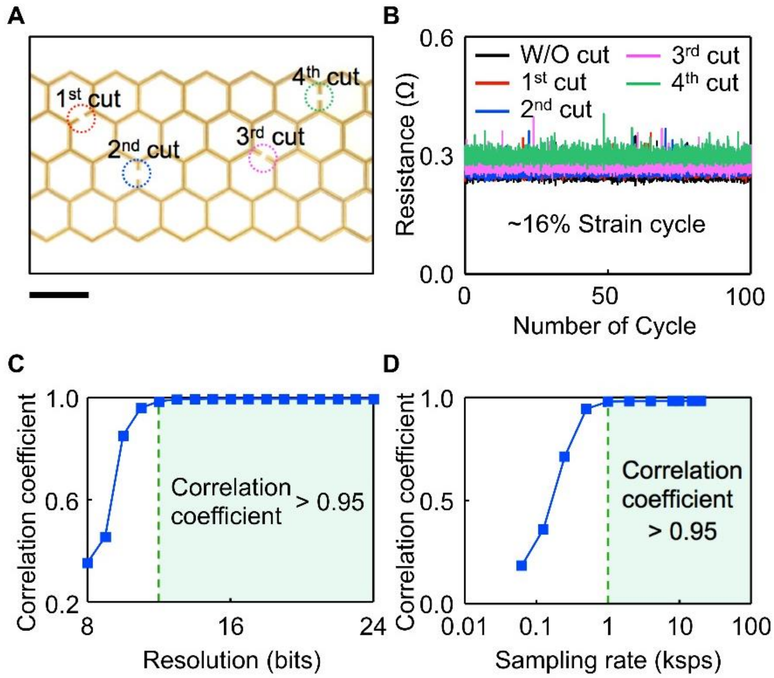

Fig. S6. Electrical reliability and performance comparison. (**A**) Photo of the testbed structure with intentional cuts. The scale bar is 1.2 cm. (**B**) Measured resistance of the testbed structure under 100 cycles of stretching at the maximum strain of ~16%. (**C, D**)The correlation of the sEMG signals obtained by using the portable unit and a commercial (control) wireless unit (BioRadio) with varies signal acquisition resolution (C) and sampling rate (D).

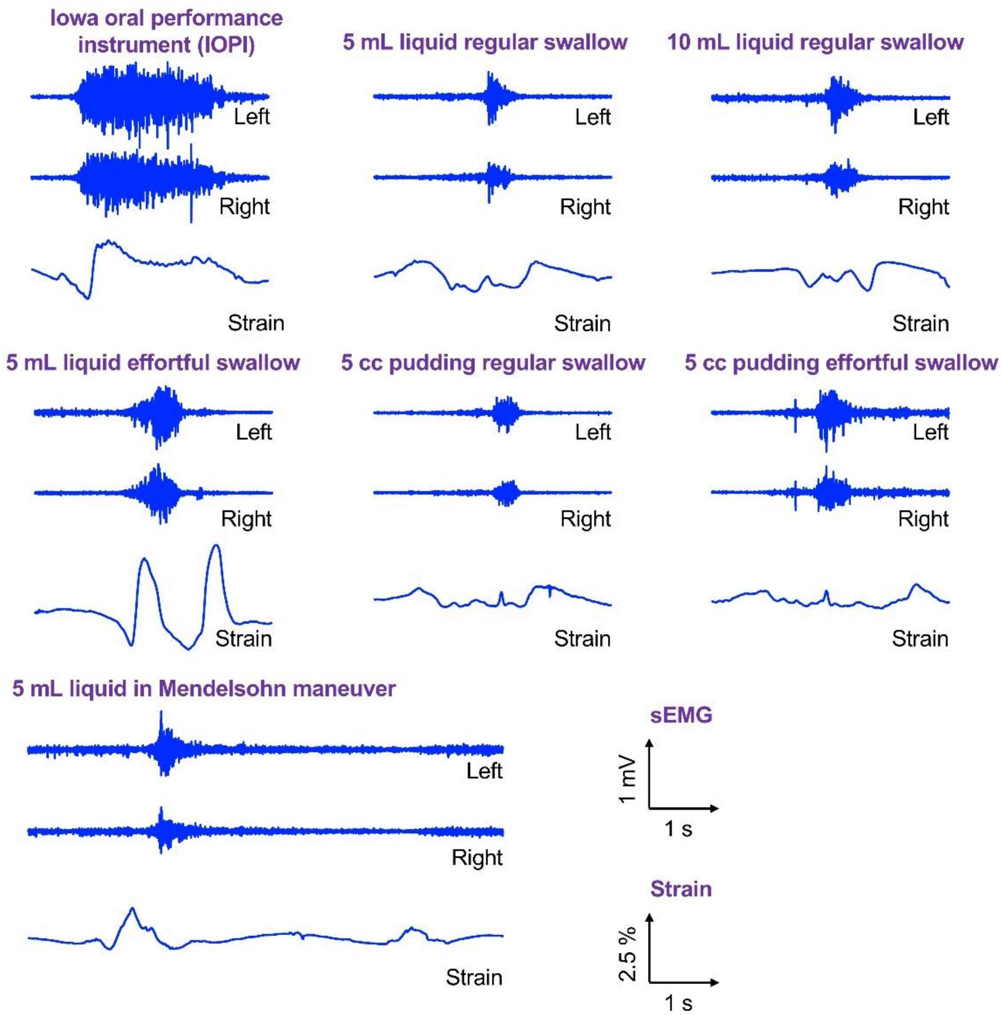

Fig. S7. Swallowing treatment session results. The raw data of the measured sEMG signals and strain waveforms, resulting in the summary depicted in Fig. 4.

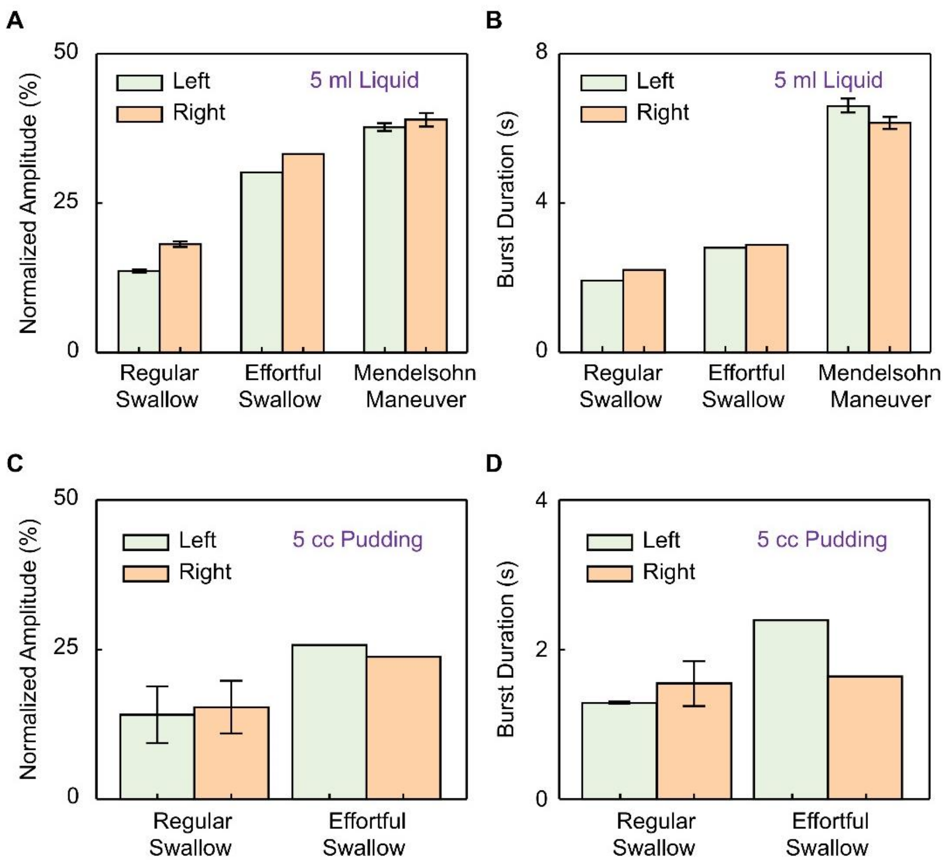

Fig. S8. Swallowing treatment session data analysis. Summary of quantitative analysis in bar graphs for Fig. 4. (**A**) Normalized amplitude and (**B**) burst duration of 5 ml barium liquid swallows. (**C**) Normalized amplitude and (**D**) burst duration of 5 cc barium pudding swallows.

Table S1. Initial needs assessment survey. Results of initial needs assessment interviews (N=30; % depicts frequency of response).

	Common Themes	Frequency of specific responses
Rehabilitation Challenges	Poor Patient Compliance/Adherence	Expense of Equipment (50%), Availability of Equipment (30%), "Boring" Exercises (20%)*, Patient Travel (30%)
	Poor Patient Understanding	Lack of Evidence (30%), Complexity of Tools/Exercises (40%), Poor Feedback Quality (20%), Limited Time (20%)
Implications of Challenges	Poor Health Outcomes	Financial Costs (Patients/Clinics) (70%), Readmissions/Bounce Backs (40%)
	Psychological Outcomes	Frustration (Patient/Clinicians) (40%), Depression (20%)*, Social Isolation (20%)
Important Design Considerations	Ease-of-use (100%), Accuracy (80%), Frequency of use (50%), Ease of Attachment to the Body (40%), Quality of Feedback and Reward (40%), Time Efficiency (20%)	

**All respondents of this response were patients.*

Table S2. Cost estimation of the submental sensor patch system. Outline of the estimated cost associated with the electronic components, encapsulation and substrate materials and processing fees at a lab scale for the sensor patch system.

	Name	Cost per device
Electronic components	Pyralux (PI/Copper clad)	$0.50
	Piezoresistive (Velostat)	$0.01
	ACF cable	$0.71
Packaging materials	PDMS	$0.05
	Silbione	$0.05
Processing materials	Photoresist Film	$0.10
	Process chemicals	$2
	Conductive adhesive	$1
Labor	$60/hr	$10
Sensor patch unit		$13.92
Wireless modules	PCB	$10
	Bluetooth module	$10
	ADC	$22
	Additional components	$10
Remote control unit		$52

Captions for Movies

Movie S1. Pilot VFSS recording of a swallow. VFSS recording of a healthy young subject (subject age: 23) during a normal swallow of 5 mL barium liquid. The scale bar is 3 cm.

Movie S2. sEMG, strain, and VFSS recordings of a swallowing treatment session. Simultaneously recorded submental sEMG signals and strain waveforms and the corresponding VFSS recording obtained from a patient with dysphagia (subject age: 70) during a regular swallow of 5 mL barium liquid. The sampling rate for the monitoring of VFSS and sEMG is 30 frames per second and 1,000 Hz, respectively. The scale bar is 3 cm.

Movie S3. sEMG, strain, and VFSS recordings of a swallowing treatment session. Simultaneously recorded submental sEMG signals and strain waveforms and the corresponding VFSS recording obtained from a patient with dysphagia (subject age: 70) during a regular swallow of 10 mL barium liquid. The sampling rate for the monitoring of VFSS and sEMG is 30 frames per second and 1,000 Hz, respectively. The scale bar is 3 cm.

Movie S4. sEMG, strain, and VFSS recordings of a swallowing treatment session. Simultaneously recorded submental sEMG signals and strain waveforms and the corresponding VFSS recording obtained from a patient with dysphagia (subject age: 70) during a regular swallow of a 5 cc barium pudding. The sampling rate for the monitoring of VFSS and sEMG is 30 frames per second and 1,000 Hz, respectively. The scale bar is 3 cm.

Movie S5. sEMG, strain, and VFSS recordings of a swallowing treatment session. Simultaneously recorded submental sEMG signals and strain waveforms and the corresponding VFSS recording obtained from a patient with dysphagia (subject age: 70) during an effortful swallow of 5 mL barium liquid. The sampling rate for the monitoring VFSS and sEMG is 30 frames per second and 1,000 Hz, respectively. The scale bar is 3 cm.

Movie S6. sEMG, strain, and VFSS recordings of a swallowing treatment session. Simultaneously recorded submental sEMG signals and strain waveforms and the corresponding VFSS recording obtained from a patient with dysphagia (subject age: 70) during a swallow of 5 mL barium liquid using the Mendelsohn maneuver. The sampling rate for the monitoring of VFSS and sEMG is 30 frames per second and 1,000 Hz, respectively. The scale bar is 3 cm.

Movie S7. sEMG, strain, and VFSS recordings of a swallowing treatment session. Simultaneously recorded submental sEMG signals and strain waveforms and the corresponding VFSS recording obtained from a patient with dysphagia (subject age: 70) during an effortful swallow of a 5 cc barium pudding. The sampling rate for the monitoring of VFSS and sEMG is 30 frames per second and 1,000 Hz, respectively. The scale bar is 3 cm.