Swallowing Detection for Game Control: Using Skin-Like Electronics to Support People with Dysphagia

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Abstract—In this paper, we explore the feasibility of developing a sensor-driven rehabilitation game for people suffering from dysphagia. This study utilizes the skin-like electronics for unobtrusive, comfortable, continuous recording of surface electromyograms (EMG) during swallowing and use them for driving game-based, user-controlled feedback. The experimental study includes the development and evaluation of a real-time swallow detection algorithm using skin-like sensors and a game-based human-computer interaction. The user evaluations support the ease of use of the skin-like electronics as a motivational tool for people with dysphagia.

Keywords— skin-like sensor, dysphagia, swallowing detection, biofeedback game

Dysphagia is a condition that affects the ability of a person to swallow. Managing this condition requires regular swallowing exercises that patients need to perform on a daily basis. As other cases of rehabilitation support have shown, wearable sensing technologies can play a significant role in monitoring the condition of a particular disease, and motivating patients to follow prescribed exercise regimes. However, when considering the case of dysphagia and odynophagia (painful swallowing) available wearable technologies either do not offer the right sensing modalities, or cannot be applied to the relevant parts of the body.

Novel sensing technologies that can easily be attached to any parts of the human body, can potentially detect the swallowing activities of patients suffering from dysphagia. Such technologies could in turn allow the development of biofeedback motivational tools as part of the daily rehabilitation routine of such patients. In this work we explore the feasibility of developing a sensor-driven training game for people suffering from dysphagia. In particular we use novel skin-like electromyography (EMG) sensors (Fig. 1) paired with a "swallow-drives" computer game to support the rehabilitation of such patients.

Wearable sensors as part of human-machine interaction system can allow the development of motivational tools to facilitate regular rehabilitation exercises. Accurate detection of the swallowing activities can be used as input to a computer game that would act as both a motivational tool, and as tracking instrument to record the performed swallowing exercises. In clinical settings, EMG sensing has been suggested as a means of supporting the screening of dysphagia and odynophagia [1], and for biofeedback therapy for dysphagia [2]. However, traditional approaches in detecting swallowing activity, involve the use of rigid body sensors applied temporarily to the face and neck using adhesive patches, and connected to physiological data collection devices. While existing clinical techniques are suitable for short-term assessment or therapy sessions, their bulky and obtrusive properties make them ill-suited to continuous, long term and mobile monitoring. In the context of rehabilitation support, there is a need for a light-weight, sensing solution that is easy to apply on the user's neck.

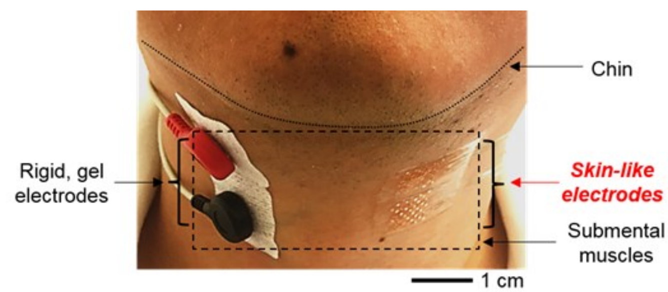

Fig. 1. Imperceptible skin-like electrodes compared to the rigid, gel electrodes: detected surface EMG signals during swallowing are used to drive a biofeedback game.

In this paper, we utilize a novel electronic system ('skin-like electronics') for recording electrophysiological signals (EMG) and driving interactive software. The skin-like electrodes are unobtrusive and comfortable to wear on the skin, while providing surface conformal contact for high quality signal recording without the use of conductive gels. EMG signals from the masseter and submental muscles are used to detect deglutition (swallowing). We use the deglutition (swallowing) behavior, measured by EMG signals, to demonstrate game-

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based biofeedback. Real-time analysis of the EMG signals captured by the skin-like sensors, allow the detection of swallowing activities with minimal delay, sufficient to enable the interaction with an arcade-type computer game. The motivation of this work is to support swallowing exercises that need to be performed regularly by users, over a relatively short session (approximately 15 mins). An arcade-type computer game that users can play with for short sessions using swallowing as input, was considered appropriate for this application.

The aim of this study is to demonstrate the feasibility of using unobtrusive skin-like electronics as a physiological sensing platform for game interactions. The main contributions of this work are:

- Analysis of the EMG signals captured through flexible skin sensors during deglutition (swallowing).
- Development of a light-weight signal processing system that can accurately detect swallowing activities through the EMG signal.
- Demonstration of the use of swallowing activities as input to game applications

I. Related Work

The use of physiological sensing has been suggested as a means of enhancing interaction with technology [3]. A practical application of this idea is the use of physiological signals to enhance gameplay. Nacke et al. [4] examined a range of physiological signals to best determine their use for game interaction. They concluded that voluntary and involuntary physiological signals such as EMG, body temperature, galvanic skin response (GSR), or heart rate can be used for direct game manipulation (in the case of voluntary signal responses) or to indirectly adapt the game environment (through sensing of involuntary reactions). Chanel et al. [5] similarly studied the use of EEG to monitor pressure, pleasure, arousal, and motivation to estimate emotional states of boredom, engagement and anxiety. This could be used to adapt difficulty in order to maintain the ideal state of engagement.

Conventional physiological measurement on the skin involves sensors being affixed to the skin using adhesive tape [6]. This is an approach often taken in the assessment of swallowing functionality and diagnosis of swallowing disorder, through the use of electrodes affixed to the face and neck for Surface EMG. However, such sensor placement is often intrusive, indiscrete and unsuited for mobile or continuous monitoring. Amft and Troster [7] describe the use of body wearables to bypass these limitations during dietary monitoring, such as the use of a collars with mounted EMG electrodes or stretch sensors. In their investigation they reported that the stretch sensors demonstrated inconsistent results between participants, while the EMG based collar resulted in discomfort. Acoustical detection of swallowing behavior has also been described in a number of studies reporting accuracies of >80% [8][9][10]. Sazonov, in particular reports a particularly robust detection algorithm, making use of specialist throat microphones capable of accurately acquiring swallowing sounds [9]. Although it is suggested that such specialist microphones may

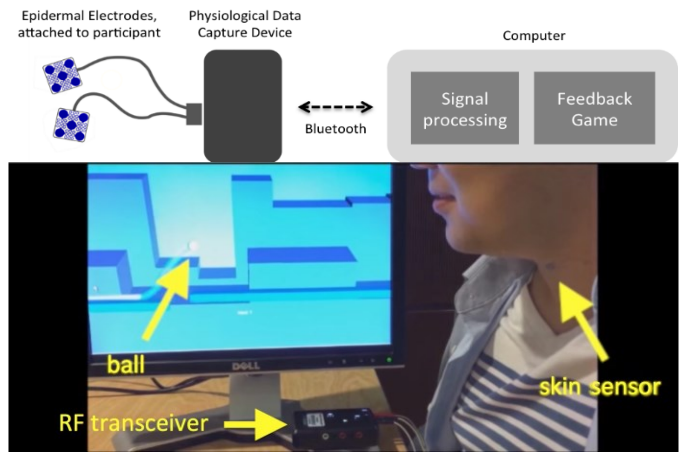

Fig. 2. System architecture showing the skin-like sensors transmitting EMG signals to the computer for a game control.

be considered non-intrusive when disguised as a neck worn pendant, they still demonstrate a significant and obtrusive presence to the user.

In recent years, researchers have focused on the development of novel bioelectronics that can be directly and conformably mounted on the skin [11]. Skin-like electronics (also known as "epidermal" electronics) are ultra-thin, ultra-light, and stretchable to minimize the thermal and mechanical loadings to the skin. The small form factor of the skin-like electronics have offered comfortable, intimate integration with the skin, without causing motion constraints. Our prior works demonstrated the use of such electronics for long-term (> 2 weeks) recording of EMG, ECG, and EEG signals [12], precise temperature mapping [13], thermal conductivity [14], hydration [15], and skin-like stimulation [16]. In this work, we explore the use of such sensors as inputs for gameplay interaction, in order to develop a rehabilitation support system for people suffering from dysphagia.

II. Biofeedback System for Swallowing

In order to support the swallowing exercises for patients with dysphagia we developed a system that allows users to interact with an arcade game by detecting the muscle movements when they swallow (Fig.1). The detection of swallowing required the capture of electromyography (EMG) signals and the processing of such signals to identify swallowing patterns (Fig. 2).

To measure surface EMG during the swallowing process, we fabricated a set of skin-like electrodes by following the microfabrication process from our prior works [12]. We used two types of soft elastomeric membranes (transparent silicone) to integrate the gold nano-membrane electrode (Fig. 3). Without the use of conductive gels and adhesives, ultrathin elastomeric membranes provided sufficient adhesion force to mount electrodes on the skin purely via van der Waals interactions. The elastomer-silky fabric material allowed multiple cycles of cleaning and reuse to measure EMG on the skin, while transparent silicone (5 μm in thickness) offered long-term lamination on the skin. In combination this provided unobtrusive, comfortable, soft lamination of electrodes on the

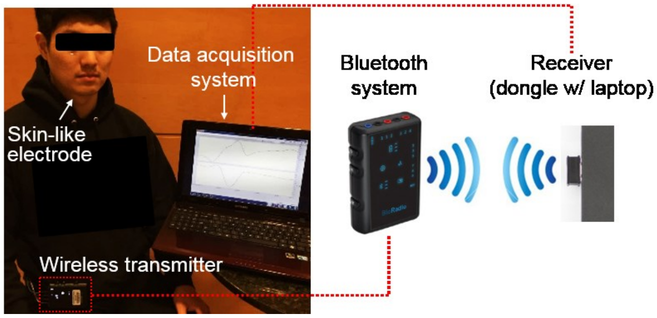

Fig. 3. Skin mounted electrode connected with a standard wireless communication unit for data acquisition.

skin. A flexible, ultrathin carbon cable connected the electrode to the wireless recording device. The recorded analogue EMG signals were converted and amplified in the device and wirelessly transmitted to the receiver via RF transmitter for continuous data recording (Fig. 3). In this work, the skin-like hardware only refers to the electrode themselves, with a standard wireless transmitter connected via micro-wires. The development of a full wireless circuit system made of stretchable interconnects and soft membrane is still under development.

A. Swallow detection

Six participants (three females and three males) between 21 and 40 years of age in good health (with no reported medical conditions) were recruited to take part in this research by following the approved protocol at Virginia Commonwealth University (approved number: HM20001454). Each participant underwent EMG data collection using skin-like sensors during a number of exercises intended to acquire information about deglutition (a total of 432 swallows were collected). EMG signals were recorded each session at a sample rate of 1 kHz. During the sessions, the participants were asked to perform a number of swallowing exercises, giving an indication of muscular activity during swallowing behaviors. The types of swallows that they asked to perform included:

- Dry swallow: 15 trials of voluntary dry swallows (saliva swallowing).
- Liquid swallow: 15 trials of voluntary swallowing of a small mouthful of water.
- Extended swallow (Mendelsohn Maneuver): An exercise performed to help improve swallowing, raising the larynx and opening the esophagus [17]. The participant performed a dry swallow and at the peak of the swallow the participants attempted to hold the swallow for 2 seconds, before releasing. This exercise was repeated 6 times.

During each data acquisition session, synchronized video footage was recorded. The recorded video clips provided manual extraction of the time and duration of each swallow event and also allowed the identification of corresponding EMG activity and the ground truth of these events.

After completing data collection, the data was processed in order to analyze the swallowing EMG signals. In order to eliminate high frequency noise and movement artefacts, the data

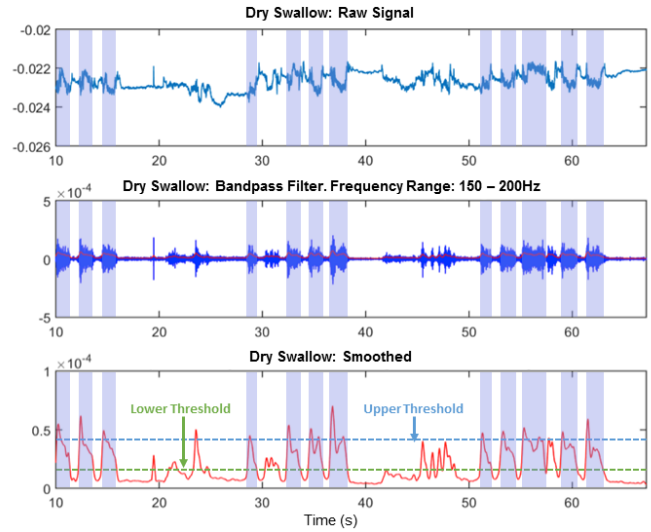

Fig. 4. Representative EMG data (submental muscles) collected using a set of skin-like sensors during swallowing with participant 1: raw EMG signals (top), filtered signals (middle), and smoothed RMS signals (bottom). Shows upper and lower thresholds used to segment the signal and identified swallowing (shaded) segments.

was filtered using a Finite Impulse Response band pass filter to extract the frequencies of interest from the signals. A band-pass frequency range of 20-500Hz is often suggested for SEMG of the face, in order to eliminate low frequency artefacts (<20Hz) and high frequency noise (>500Hz) [18][19]. However, with this experimental setup a band of 150-200Hz offered signal fidelity while helping to limit muscular cross talk and movement artefacts. A windowed root mean square and windowed average (window length: 0.2s) was applied across the data to provide smoothing and an informative interpretation of the muscle activity (Fig. 4). The data classification algorithm included magnitude and duration thresholds to detect segments of active signal that exceeded the signal baseline for a significant duration. Due to the variability of the recorded signals between participants, these threshold values were calibrated individually for each participant.

The primary magnitude threshold was used to check for instances of the signal magnitude exceeding the threshold, which could then be associated with swallowing periods; identifying start and end points. A secondary magnitude threshold and a duration threshold were then used to further eliminate unsuitable segments (as set during calibration). Ensuring that the signal remained above the primary threshold for a given duration, and that the magnitude exceeded the secondary magnitude threshold at some point within this period. Once the signal was considered to be demonstrating muscle activity, the same technique was used to determine the end of the signal segment, ensuring that the activity was only considered complete when the magnitude dropped back below the primary magnitude threshold and remained there for a number of samples indicated by the duration threshold. The precise detection of start point, end point and duration features ensured that the activity segments identified would consist of a signal above a certain level for at least a given duration and display a significant peak.

TABLE I. RESULTS OF THE SWALLOW DETECTION ALGORITHM

Per Participant	Ground Truth	Mean Detected±SD	Error±SD
Dry Swallow	15	14.80±1.92	-0.20±1.92
Liquid Swallow	15	15.50±0.55	0.50±0.55
Extended Swallow	6	6.83±1.83	0.83±0.98

We evaluated the thresholding technique for detecting swallowing by comparing the results with the manually annotated video feed. As shown in Table I although the study is relatively limited in scale, the results are very promising. Employing a simple thresholding technique to identify swallows, the algorithm maintains an average detection error of 1.3% for the dry swallow and 3.3% for the liquid swallow. The extended swallow appeared to be more challenging to detect with this technique, with an average error of 13.8%. Some participants reported difficulty with repetition of the task, likely due to a lack of practice performing such actions. We suggest that this may be the reason for the unexpectedly high error rate for this swallow type.

III. BIOFEEDBACK GAME

The processing technique used previously was adapted to analyze the EMG signals and identify active periods in real time using a custom-developed data processing application. It was then possible to investigate the use of this system as a means for driving user-friendly feedback software (feedback based game). Finally, we carried out a user evaluation to determine the user experience and opinion of the control method.

The full system is described in Fig. 2. Skin sensors are used to capture EMG signals, which are then transmitted to a computer over Bluetooth. A swallow detection algorithm is then employed to detect swallow activities in real-time. Processing was performed every 0.125 seconds (125 samples) upon an overlapping signal segment 0.25 seconds (250 samples) long. Such events are used to drive an arcade computer game.

The processing application detected muscle activity in a binary manner. After the successful detection of the start of a period of muscle activity, the application would respond with a positive indicator for muscle activity until such time as an end of this period of activity was detected. This binary information could then be passed to the feedback-based game in order to drive its responses. Because of the individual variability in swallow magnitude and duration, as indicated by the first stage of the study, the threshold values were made fully adjustable using the software application, to allow the user (in this case the supervising researcher) to calibrate the values according to observed signal magnitudes and trends.

Biofeedback has been used in rehabilitation for a number of conditions, including the swallowing disorders our study focuses upon. Moreover, serious games have been demonstrated as useful in patient rehabilitation, for instance after suffering a stroke [18]. As such a simple game was considered as a viable format for the evaluation of feedback using this system, which could be applied in the context of rehabilitation therapy and other health related scenarios.

The simple game was designed to convey to the user when their muscles were considered active (a swallow was detected) in the EMG signal, and the duration they maintained this activity (Fig. 5). The game was based on a common game design, involving a ball that travels at a steady rate in a linear direction with user input controlling its progress 'jumping' along a series of platforms. Normally this would take the form of a button or similar methods of input. In the version developed for this study this is replaced by a value read from the input stream. A value positively indicating muscle activity results in the ball jumping. While the muscle activity is maintained (e.g. Mendelsohn Maneuver), the duration is shown in the game. While the value remains constantly active, the ball does not cease 'jumping'. However, as soon as the input (swallowing behavior) is no longer found, the 'jump' is released and the ball falls onto a platform.

IV. EVALUATION

A user evaluation was conducted to investigate the viability of the use of skin-like sensing as a technique for driving user-friendly feedback. In particular, we hoped to examine the proposed solution's capabilities in swallowing disorder

The same six participants were asked to take part in the evaluation. During the study the participants attempted to control the game by dry swallowing. They were given an unlimited time to attempt to guide the game ball through the game, traversing gaps by swallowing to trigger a 'jump'. They were instructed to continue for as long as they could manage, or until they could no longer comfortably dry swallow - at which point they should cease attempting to play and allow the game to end. Once the ball had fallen into a gap the game ended and the participants were provided with a drink of water and given up to two minutes to rest. At this point the participants were challenged to beat their previous score, the game restarted and the process repeated. The participants were given 5 attempts at the game. During each session, video footage of the participants and the game-play feedback was recorded, allowing information to be extracted regarding the game response and participant control.

At the end of evaluation sessions, each participant took part in an evaluation interview, to offer insight into the acceptability and appropriateness of the skin-like sensors for user interaction and monitoring. The questions were split into a number of topics, including sensor comfort and wearing the sensor itself, perceived potential comfort of using the sensor in public situations ('home/office') and any concerns, and the potential comfort levels which might be involved in prolonged use of the sensor. The final question concerned the control of the game based feedback and its ease of use. Each topic was answered on a 7-point Likert scale.

Fig. 5. Swallow driven game: swallowing EMG signals can make the ball jump between moving platforms. Coloured trail indicates signal activity and green tail shows the event of swallowing.

TABLE II. GAME RESPONSE: SUCESS AND FAILURE RATE, AND MEAN FALSE POSITIVES

#	1	2	3	4	5	6
Hits %	100.0	78.6	90.0	100.0	96.3	92.3
Miss %	0.0	21.4	10.0	0.0	3.7	7.7
FP	3.4	0.4	0.8	0.0	1.2	2.0

TABLE III. EVALUATION RATINGS OF INTERVIEW QUESTIONS (7-POINT SCALE)

	Sensor Comfort	**Different Environ.**	**Long-Term Use**	**Game Feedback**
Mean	6	5.83	4.5	5.16
SD	0.81	0.89	1.38	1.06

Data were manually extracted from the evaluation video trials to assess the performance of the game-based feedback and participant success rate. This included an estimated tally of successful responses (swallow followed by a successful game response), failed responses (swallow without any game response), and false positives (game response without any observable preceding swallow, or following a non-deglutition behavior). Response time (delay between swallow behavior and game response) was also recorded based on video footage, along with the total duration participants managed to maintain gameplay in each attempt.

The results demonstrated a high percentage of successful responses per gameplay as summarized in Table 4. The rate of failed game responses was not indicative of the performance of the system. Because of the nature of the feedback game, a failure to respond to a single swallow was likely to result in the participant 'losing' and the game resetting, leading to a low failed response rate. False positives on the other hand occur more frequently, with a mean of 1.3 per game. As shown in the results, distribution of false positives was mostly biased towards participant 1, participant 5, and participant 6; the other participants in comparison each demonstrated a mean number of false positives less than 1. This can be an indication that the use of a simple thresholding technique may not be very robust to minor fluctuations on the EMG signal.

In the interview results, the participants were generally very positive about the comfort of the sensor with an average mark of 6 out of 7. On the other hand, four comments were made by participants stating that they did not feel comfortable wearing them, suggesting that they were still 'aware' of the sensors, that the sensors felt like a 'Band-Aid'. The sensors were praised for their ease of application and use, however there was concern regarding restricted motion caused by the wires and the wireless device used with the sensor. These concerns may have been affected by the use of standard wiring and wireless transmission device in the setup; which might be eliminated in future work through the use of a transmitter using the skin-like format. One comment highlighted the requirement to shave as a significant inconvenience. Two participants raised concerns about using the sensors with the adhesive patches on exposed areas of the body such as the face and one participant stated that it would be socially awkward.

For the game-based feedback question, separate areas of focus were evident in the responses, including the game-based feedback 'fun', the 'ease of swallowing' and the 'responsiveness' of the game. Three participants reported that using the game was 'fun' and two indicated that it made repeated swallowing easier ('Ease of swallowing'), or improved their focus upon swallowing. However, three participants also highlighted the difficulty involved when required to swallow repeatedly.

Finally, three participants made comments praising the mobility of the system, and all but one participant stated that they thought that the sensors and wireless communication might allow for continuous and interesting monitoring.

V. DISCUSSION

This was a small scale study with a limited subject set. However, the study demonstrated promising results from the evaluation of the detection algorithm when used in a restricted scenario and positive feedback from the evaluation of the proposed game-based feedback. As the swallowing detection is calibrated individually for each participant, we also anticipate that the system will scale well with larger user sets.

It also highlighted other limitations and areas for further research. While the detection algorithm demonstrated relatively high successful detection rate, and low occurrences of false positives, the study protocol assumes a controlled scenario, asking participants to restrict non-swallowing behaviors during the sessions, and does not take into account the robustness of the detection algorithm in regards to false positives resulting from such actions.

Future work will concentrate on the development of a robust algorithm that can operate under real-world conditions, able to sustain any non-swallowing movements or other actions. We will also explore alternative detection models, particularly the use of trainable classifier models to provide validation of potential swallow segments, and the capability of such models to distinguish between particular types of swallowing behavior. Finally we will conduct more extensive user trials, with larger subject sets to evaluate the performance of the detection methods, and over repeated sessions to examine the effect of the feedback upon swallowing performance over time.

VI. CONCLUSIONS

In this study, we demonstrated the potential of the imperceptible, stretchable, skin-like electronics for high-fidelity EMG recording of swallowing behavior and the application for a game-control system. Our future work will focus on the further development of the swallow detection algorithm to improve its accuracy, expanding the functionality of the game to respond to different types of swallowing.

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