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Meal-time and duration monitoring using wearable sensors

Bo Dong*, Subir Biswas

Dept. of Electrical and Computer Engineering, 2120 Engineering Building, Michigan State University, East Lansing, MI, 48824 USA

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ABSTRACT

In many recent studies it has been shown that the frequency and duration of meals taken during a day can have significant impacts on human health. Poor meal habits such as skipping breakfast, nighttime eating, and too many eating episodes can increase the risk of obesity. Researchers have often used self-reported questionnaires for analyzing such meal-time and dietary behaviors. Questionnaire-based data collection, however, often suffers from high errors due to reporting subjectivity.

This paper presents a wearable sensor system that can monitor breathing and hand movement for estimating the time and duration of a meal. The system combines swallowing signatures from breathing signal with hand movement signatures from hand acceleration to train a hierarchical Support Vector Machine (SVM) classifier and a Hidden Markov Model (HMM) for mealtime and duration estimation. Algorithms are developed for detecting various types of swallowing events including for solid and liquid in the presence of artifacts such as spontaneous swallows, laughing, coughing, and throat clearance.

The experiments were carried out on 14 healthy subjects wearing the proposed system. In each experiment session, the subjects were asked to have lunch, drink water, rest and talk. The subjects were asked to press a button for each swallow, and the whole experiment process was video recorded. The push button and video information were used as a ground truth for verification purposes. Through extensive experimentation in a semi-controlled setting, it was shown that the system is able to detect mealtime with high accuracy.

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1. Introduction

Results from the 2007–2008 National Health and Nutrition Examination Survey (NHANES) show that around 34.2% of US adults aged 20 years and over are overweight, 33.8% are obese, and 5.7% are extremely obese [1]. It has been shown that obesity can cause various health problems, both physical and mental. Mutsert [2] mentioned that obesity can increase the chance of cardiovascular disease, type-2 diabetes mellitus, cancer, osteoarthritis, work disability, sleep apnea, and it can have pronounced impacts on morbidity.

1.1. Impacts of mealtime and duration

Time and duration of meals were shown to be highly correlated with obesity. Ma et al. [3] analyzed the mealtime of 499 people for 1 year and concluded that a greater number of eating episodes each day was associated with lower risk of obesity, whereas practices such as skipping breakfast was linked with higher obesity risks. Gluck et al. [4] conducted experiments on 55 subjects and demonstrated that nighttime eaters, who consume considerable amount of food at night frequently tend to gain weight faster than non-nighttime eaters. Cleator [5] also showed that 52% of obese nighttime eaters reported normal weight before the onset of their nighttime eating habits. Andersen et al. [6] carried out experiments lasting for 10 years, and reported that obese women with nighttime eating experienced a weight gain of 5.2 kg on an average over 6 years.

Improper mealtime can have other negative impacts. Rogers et al. [7] showed that subjects with night eating syndrome had less stage 2 and stage 3 sleep, which contributed to shorter total sleep time and lower sleep efficiency, and they are more likely to suffer from depression. Sassaroli et al. [8] also found that night eating syndrome is highly correlated with anxiety.

The current research on meal intake behavior relies mainly on questionnaires, which was shown to be subjective and not always reliable [9–11].

To address this shortcoming, an instrumented diet monitoring system is proposed in this paper, which can potentially detect the time and duration of each episode of meal intake. Together with high level self-reporting of diet composition, the estimated mealtime and duration information can provide useful insight to users

* Corresponding author.
E-mail addresses: dongbo@egr.msu.edu, bodongmsu@gmail.com (B. Dong), sbiswas@egr.msu.edu (S. Biswas).

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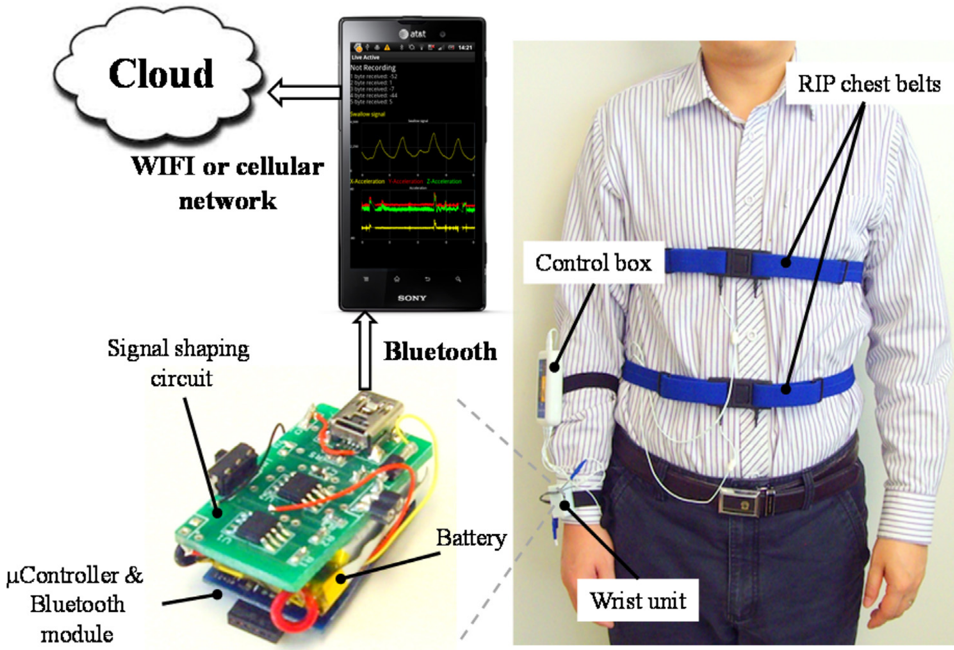

Fig. 1. Components of the mealtime and duration monitoring system.

and healthcare providers regarding undesirable meal patterns and such.

Non-invasive swallow detection methods in the literature use sensors such as accelerometers, microphones, surface electromyography, and piezoelectric sensors to collect physiological signals related to swallowing. Compared to invasive methods which use X-ray or needle electrodes to monitor the movement of food or the activation of swallow related muscles, the non-invasive methods are safe, easy to use and suitable for long-term monitoring. Cichero et al. [12] observed that swallowing sounds were caused by a number of valves and pumps that produce vibrations and reverberations within the pharynx. Following this observation, the swallowing sound collected in the neck region became a popular modality for swallow detection. Hsu et al. [13] used microphone and SEMG sensor to discriminate severity of dysphagia when swallowing water. Lee et al. [14] used a dual–axis accelerometer attached to the neck to collect acceleration signals during swallowing, and found that accelerometry signals is correlated with the type of bolus. Nikjoo et al. [15] used the similar system to detect safe swallow versus unsafe swallows (swallows where bolus entered the airway). Jestrovic et al. [16] placed both accelerometer and microphone in the neck region to collect sound signal during swallowing liquid with different viscosity. It turned out that thicker fluid had higher acoustic regularity and predictability, and a lower frequency content. Walker et al. [17] used a microphone attached to the neck for collecting swallowing sounds. Amft et al. [18] presents an investigation to detect and classify normal swallowing during eating and drinking from surface electromyography (SEMG) and microphone sensors. The sensors were integrated into a collar-like fabric for continuous monitoring. Placing sensors in the neck region, however, brings user acceptability concerns for prolonged usage due to cosmetic and safety issues. Passler et al. [19,20] proposed a method of using an in-ear microphone and a reference microphone built within a hearing aid casing to detect chewing and swallowing sounds. By comparing the signal strength from the in-ear microphone and the reference microphone, chewing and swallowing can be detected. The reported experiments were done in a completely quiet room or in an office without any ambient background noise, thus limiting the ability to judge the applicability of the proposed mechanism in real life scenarios with background ambient noise. Amft et al. [21] proposed a food intake monitoring system based on detecting arm gestures. The reported experiments were fully controlled and only two subjects were included in the experiments. In another paper [22], Amft proposed a system using additional modalities, namely, monitoring arm movement using inertial sensors, detecting chewing sounds with an in-ear microphone, and sensing swallowing activity using SEMG from the neck region. It was demonstrated that the proposed system could achieve 80–90% for recall and 50–64% for precision in swallow detection. The low precision indicates large amount of false positives.

1.2. Proposed system concepts

The idea of swallow detection through breathing signal in this paper is based on an observation of swallow apnea [23,24]. The swallowing process can be divided into three phases [18]: (1) oral preparation phase: food is chewed into viscous bolus; (2) pharyngeal phase: the bolus travels through the pharynx and passes the upper esophageal sphincter. A set of muscles is activated to propel the bolus, before which the epiglottis closes down to cover the trachea; (3) esophageal phase: the bolus is pushed down to the stomach. As breathing is halted for a short time when the epiglottis moves down to cover the trachea, a swallow apnea can be observed in the breathing signal during the pharyngeal phase.

In this paper we present a wearable sensor system for estimating mealtime (i.e., time of the day for a meal) and meal duration based on those swallow-triggered apneas detected in breathing signals. Using two Respiratory Inductance Plethysmography (RIP) belts worn on the chest and abdomen, swallow-triggered apneas are detected. Since the RIP belts do not rely on pressure or skin-contact to pick up breathing signal, they can be suitable for prolonged usage without minimal cosmetic and comfort issues.

In addition to the wearable belt, an accelerometer on the wrist of the dexterous hand has also been used to improve the swallow detection performance. The hand movement helps improve detection accuracy by supplying side information, so that when there is confusion due to uncertainties in detection using breathing signal, the hand movement information helps. The accelerometer is