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Computer-assisted detection of swallowing difficulty

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ABSTRACT

To evaluate classification performance of a support vector machine (SVM) classifier for diagnosing swallowing difficulty based on the hyoid movement data attained from videofluoroscopic swallowing study, the hyoid kinematics during the swallowing of 2 mL of liquid barium solution were analyzed for 90 healthy volunteers and 116 dysphagic stroke patients. SVM was used to classify the kinematic results as normal or dysfunctional swallowing. Various kernel functions and kernel parameters were used for optimization. Features were selected to find an optimal feature subset and to minimize redundancy. Accuracy, sensitivity, specificity, and area under a receiving operating characteristic curve (AUC) were used to assess the discrimination performance. In 19 out of 26 features, mean comparison revealed a significant difference between healthy subjects and dysphagic patients. By reducing the number of features to 10, an AUC of 0.9269 could be reached. Common features showing the best classification in both kernel functions included forward maximum excursion time, upward maximum excursion time, maximum excursion length, upward maximum velocity time, upward maximum acceleration time, maximum acceleration, maximum acceleration time, and mean acceleration. SVM-based classification method with the use of kernel functions showed an outstanding (AUC of 0.9269) discrimination performance for either healthy or dysphagic hyoid movement during swallowing. We expect that this classification method will be useful as an adjunct diagnostic tool by providing automatic detection of swallowing dysfunction as well as a research tool providing deeper understanding of pathophysiology.

All authors have read and approved of the content of the manuscript as submitted.

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1. Introduction

A videofluoroscopic swallowing study (VFSS), the so-called modified barium swallow, offers a unique opportunity to observe the pharyngeal movement during swallowing [1]. The interpretation of a VFSS, however, is largely based on qualitative or semi-quantitative judgments [2]. Although overt abnormalities such as subglottic aspiration can hardly be missed with repeated observation of the recorded video clips, detecting minute differences or subtle abnormalities is a challenge even for an experienced professional. In addition, some items showed poor to fair agreement between raters [3]. One attempt to overcome this limitation of VFSS interpretation was a swallowing kinematic analysis [4]. This kinematic approach provides quantitative information on the distance and velocity of swallow-related structures such as the larynx and hyoid bone.

The hyoid bone plays a pivotal role in the closure of the airway and the opening of the upper esophageal sphincter during swallowing because the related muscles are attached to it [1]. The hyoid kinematics during swallowing has been analyzed by various researchers [5–8]. It has been shown that hyoid movement is different between healthy people and people with diseases [9], and between young and old participants [10,11]. Semi-automatic analysis for the hyoid movement has also been introduced [12]. Although there is clear difference in average maximal movement distance between groups, it is hard to tell if a certain hyoid movement is normal or abnormal. Unfortunately, quantitative kinematic analysis alone cannot discriminate the two with accuracy yet, which questions its clinical utility.

Computer-aided detection schemes have been introduced and applied to various radiologic studies such as mammography [13] or computed tomography [14]. It was developed to help radiologists detect subtle abnormalities suggesting cancers [15], but it is widening its application. Among the various classification algorithms that have been used in computer-aided detection, the support vector machine (SVM) is based on a statistical machine-learning technique. This method was introduced in 1990s and has spread rapidly to various biomedical applications such as analysis of gene expression profile [16]. Given a set of training data, the SVM finds a hyperplane or a set of hyperplanes in higher dimensional feature-space [17]. To date, however, whether a computational approach to kinematic analysis of swallowing can enhance accuracy in detecting abnormality is unknown.

The present study aimed to evaluate whether SVM-based approach can classify the hyoid bone movement in normal and dysfunctional swallowing. We also tried to optimize feature selection to reduce the computational cost and to improve the classification performance.

2. Methods

2.1. Subjects and videofluoroscopic swallowing study

The Institutional Review Board at Seoul National University Hospital approved this study. The sequential procedure of our method from data acquisition to classification performance evaluation is summarized in Fig. 1.

The data of all stroke patients with dysphagia were collected from the electronic medical records of Seoul National University Hospital from January 2005 to December 2008. We selected retrospectively all adult (age >18) stroke patients who were referred for the VFSS during the period. All patients were referred for the VFSS because (1) they failed the screening test (3 times of 5 mL water swallow test) or (2) had persistent symptoms (complaint about coughing or choking during eating; or difficulty clearing the throat of food residue) or signs (repeated history of aspiration pneumonitis; presence of vocal fold paralysis; or weaning failure of a nasogastric tube) suggesting dysphagia even after the acute phase. Only patients confirmed as having stroke by computed tomography or magnetic resonance imaging were selected. Among the stroke patients who underwent VFSS for the study period, patients with presence of other causes of dysphagia were excluded. The VFSS of 116 patients—67 men and 49 women with median age of 66.5 (range, 26–86)—with post-stroke dysphagia were included in this study. Demographics and characteristics of stroke and swallowing difficulty are summarized in Table 1. The severity of dysphagia was evaluated by the 14-item videofluoroscopic dysphagia scale [18], the total score of which can range from 0 (no abnormality) to 100 (extremely severe dysphagia). The mean VDS total score was 24.25 (interquartile range, 14.75–36.63), which implies that the majority of patients had mild to moderate dysphagia.

We used archived data of healthy volunteers, who had been recruited for other clinical studies of prospective designs (50 from the work of Kang et al. [11]; 40 from the work of Leigh et al. [7]). For Kang et al.'s archive videos, 19 out of 69 controls were excluded due to inadequate image quality of their archived video clips. As a result, the VFSS data of a total of 90 healthy subjects—32 men and 58 women with median age 57.0 (range, 23–78)—were used. Medical history had been taken from the volunteers using questionnaire prior to enrollment, and those without any symptoms of swallowing difficulty, or history of pulmonary/neurologic diseases, were included. Controls had the same protocol for liquid barium swallow, place of the examination, and equipment of VFSS with those for patients.

All participants sat lateral to the fluoroscopy instrument (Medix 3000, Hitachi, Japan). They were given 2 mL of diluted barium to drink twice. The liquid barium sulfate (Solotop Suspension® 140, Taejoon Inc, Seoul, Korea) was diluted with water to give 35% w/v. To patients with post-stroke dysphagia, test foods with various texture and viscosity were also presented afterward according to the severity of dysphagia. The entire fluoroscopic imaging was recorded and saved as movie clips. Among swallowing cycles recorded with various test materials presented to dysphagia patients as well as controls, only the one with 2 mL of diluted barium solution was used for kinematic analysis.

2.2. Kinematic analysis

For kinematic analysis of VFSS, we used the same methodology employed in the previous study [7]. The intra-/inter-rater reliability (intraclass correlation coefficient) of kinematic analysis for the maximal hyoid displacement and maximal vertical