Data-driven Modeling and Prediction of Obstructive Sleep Apnea based on Physics-guided Pathophysiological Understanding

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ABSTRACT

Obstructive sleep apnea (OSA) is the most common sleep orientated breathing disorder. OSA is characterized by upper airway obstruction, which is highly body position dependent. Specifically, head and head-neck position are critical in determining airway collapse, and adjusting head and head-neck positioning can be useful therapy for OSA. Thus, a real time monitoring and intervention of the head neck position and the corresponding airway collapsibility during sleep would allow an individualized adaptive positioning therapy. The main challenges of developing real-time OSA treatment systems include the unclear pathophysiological understanding of the collapse of pharyngeal walls and thus real-time cyber-physical system (CPS) based OSA therapy is underdeveloped. In this paper, we establish a data-driven method for modelling and predicting the occurrence of OSA in real time based on physics-guided pathophysiological understanding, which provides the basis for real-time CPS-based OSA therapy towards personalized and automated treatment.

KEYWORDS

Obstructive sleep apnea, pathophysiological understanding, data-driven modeling and prediction, cyber-physical system

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1 Introduction

Obstructive sleep apnea (OSA) is the most common sleep orientated breathing disorder affecting up to one billion people globally [1, 2]. Patients with OSA, if untreated, can develop adverse health outcomes and even mortality [3]. The pathophysiology of OSA is complex and encompasses both anatomical and functional factors, both of which are significantly influenced by body position. Indeed, in the majority of patients with OSA, the frequency and duration of sleep apnea are body position dependent [4, 5]. However, patients normally would not like to be forced at one position for sleeping. Real-time CPS-based OSA therapy is highly desired with which positions can be automatically adjusted when OSA occurs. Such systems should be able to achieve the optimal position immediately to avoid awakening patients. Due to complex fluid-structure interactions, however, accurate knowledge of the relationship between the airway morphological variation and its collapsibility is not yet available and thus achieving the optimal positions is often based on experimental trial and error. In this study, we develop a data-driven method for OSA modeling and prediction in real time based on physics-guided pathophysiological understanding. This method will be further used for CPS-based OSA therapy.

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2 Physics-based Pathophysiological Modeling

It is clinically believed that OSA occurs when the pharyngeal walls collapse and do not allow normal breathing. These affected structures include the back of the soft palate, the uvula, the tonsils, and the tongue, which form the airway of breathing.

To understand the pathophysiological causes of OSA occurrence, we developed an aerodynamics simulation model to understand the collapses of pharyngeal walls based on our previous study [6]. Vortex dynamics and pressure fluctuations in the pharyngeal airway and the force oscillations on the pharyngeal wall were analyzed. The aerodynamics reveals the physics inside the airway and the results indicate the influencing factors and the occurrence of the wall collapses. In position-based therapy, head and head-neck positions alone are significantly influencing the severity of OSA. The head bending angle is defined by the Harrison posterior tangent method as the angle difference between the second and the seventh cervical vertebrae. This study is based on the bending angle of 15°. It can be easily extended to other bending angles resulting from different OSA treatments.

In this computational study, the uvula motions are reconstructed from magnetic resonance imaging (MRI) and computed tomography (CT) scans of real humans. The pitching motions of the uvula are prescribed in the computational model using the same method described in the study conducted by [7], based on MRI data and high-speed photography of three subjects. The computation and simulation of the flow inside the airway are conducted in a direct numerical simulation solver based on the finite-difference method. The boundary conditions at the airway walls are defined using an immersed boundary method (IBM). In this solver, the 2D viscous Navier-Stokes equations as shown in (1) are solved, where u and v are x- and y-components of velocity, p is pressure, and Re is the Reynolds number. Simulations are run with several different Re values to study if air viscosity has any influence on our result. The Re values that we chose are 348, 700, and 1400, which align with the findings of [7].

$$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial y} = 0, \qquad (1)$$

$$\frac{\partial u}{\partial t} + \frac{\partial u \partial v}{\partial y} = -\frac{\partial p}{\partial x} + \frac{1}{Re}\frac{\partial^2 u}{\partial x \partial y},$$

$$\frac{\partial v}{\partial t} + \frac{\partial u \partial v}{\partial x} = -\frac{\partial p}{\partial y} + \frac{1}{Re}\frac{\partial^2 v}{\partial x \partial y}$$

Equation (1) is discretized in space using a collocated Cartesian grid and solved using a second-order central difference method. The boundary condition on the inner airway surface is imposed using the multi-dimensional ghost-cell method.

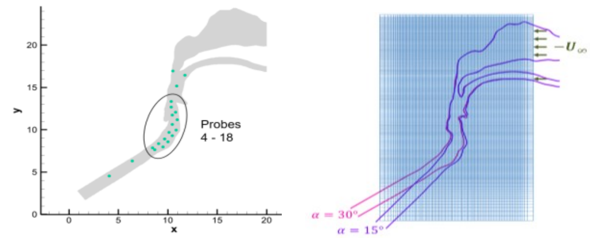

Fig. 1 Aerodynamics modeling for pathophysiological modeling.

3 Data-driven Modeling and Results

Most OSA monitoring devices can detect the OSA occurrence via symptom indicators in which the risk is already high. This study aims to predict the risk of OSA occurrence in real time before severe conditions happen based on the pathophysiological modeling as described in Section 2. In this physics-based analysis, we found that the airway surface pressure is the key to pharyngeal wall collapse, and such pressure results from uvula dynamics and aerodynamics in the airway. However, such simulation cannot be achieved in real time for CPS therapy. Thus, we utilize the results from the pathophysiological modeling to generate the data-driven model for predicting pharyngeal wall collapse. This model utilizes the probe data in the neck area as inputs and predicts the pressure oscillation in real time.

In the simulation, at each time step, the values of variables u_i and p are solved and stored at cell centers. At the airway inlet boundary, a condition of uniform x-directional velocity U_∞ is imposed. A total of 20 probes are placed, 15 of which densely populate the interior of the anatomical cervical region as shown in Fig. 1a, which is the area where in real-life applications pressure sensors will be placed on the exterior of the muscles.

In this study, we use different algorithms including support vector machines, extremely randomized trees, and gradient boosting, and the corresponding prediction results of time-varying pressure oscillation are shown in Fig. 2. Among them, the result from gradient boosting aligns with the measured pressure oscillation not only in steady harmonics but also in unsmooth oscillation conditions as shown in Fig. 2c. Thus, such model can be used in CPS-based therapy.

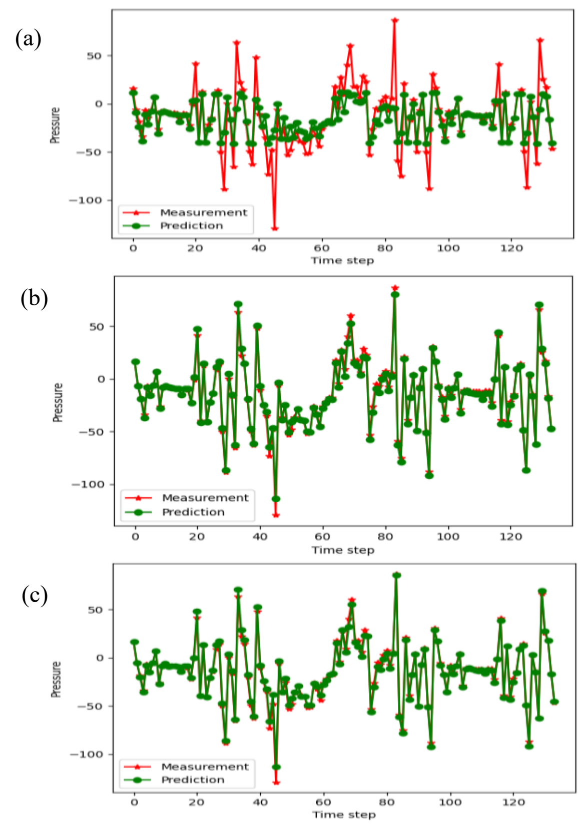

Fig. 2 Prediction results of pharyngeal wall collapsibility compared with probe measurements of pathophysiological models using (a) support vector machines; (b) extremely randomized trees; (c) gradient boosting.

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