ARTICLE IN PRESS

Smart Health xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Smart Health

journal homepage: www.elsevier.com/locate/smhl

A smart medical system for dynamic closed-loop blood glucose-insulin control

Jialin Gao[a], Ping Yi[a,*], Zicheng Chi[b], Ting Zhu[b]

[a] School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China
[b] Department of Computer Science and Electrical Engineering, University of Maryland Baltimore County, Baltimore, MD, 21250, USA

ARTICLE INFO

Keywords:
Closed-loop control
Model prediction
Back end analysis
Medical cyber-physical system

ABSTRACT

Recent years have witnessed the rapid development of healthcare devices. The connections between patients and medical cyber-physical systems are becoming tighter and many patients have got enormous benefits from these convenient systems. Our research, mainly refer to blood glucose-insulin control system, is a hot topic in the field of connected health as the development of diabetes has attracted more and more attention during the past several decades. Mainstream methods for treating diabetes in hospitals is mainly confined to manually injecting insulin to patients, which is inconvenient and highly expensive. Meanwhile, they are not fine-grained for doctors to accurately control insulin levels, so we try to improve the whole system for blood glucose-insulin control. Medical cyber-physical system on blood glucose-insulin control consists of three parts; CGMS (Continuous Glucose Monitoring System), insulin pump and closed-loop control algorithm. CGSM and insulin pump have made great advances in recent years, but we are still trying to find a better method to decrease errors introduced by mechanical measurement. Closed-loop control algorithm is vitally important and complex to study in this system. We introduce a novel algorithm which can better control blood glucose and insulin levels. To optimize this algorithm and solve storage problem, we also add back end analysis to this system. Our simulations are based on real data from patients in Shanghai No.9 hospital. We have finally concluded that our system performs well.

1. Introduction

Medical cyber-physical systems have brought enormous benefits to human beings and promoted great development to the society. It is known to us that it can monitor some part of our body and support specific feedbacks. In other words, it aims to use real-time feedbacks to provide intelligent monitoring of patients. Wearable monitoring system assists in managing the treatment of chronic diseases such as heart diseases, asthma, and diabetes and the monitoring of vital signs such as heart rate, blood oxygen level, respiration, and body fat. They normally provide noninvasive sensing, local processing, user feedbacks, and communication capabilities (Fotiadis, Glaros & Likas, 2006). There are more and more products streaming into the market such as intelligent bracelets, heart beat detector, CGMS and so on. There are also some challenges during the research of medical cyber-physical systems, such as function, wearability, accuracy and security. The size and requirement of medical cyber-physical systems have defined these difficulties. In this paper, we will pay more attention to one kind of medical cyber-physical system which shows good performance on the blood glucose-insulin control.

For many decades, the control of diabetes has gone through many stages. However, external control cannot reach the perfect

* Corresponding author.
E-mail addresses: joshgoh@sjtu.edu.cn (J. Gao), yiping@sjtu.edu.cn (P. Yi), zicheng1@umbc.edu (Z. Chi), zt@umbc.edu (T. Zhu).

http://dx.doi.org/10.1016/j.smhl.2017.04.001
Received 25 February 2017; Accepted 2 April 2017

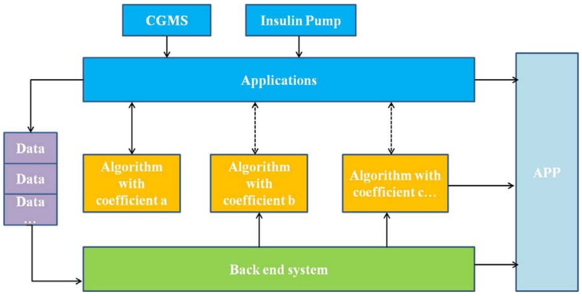

Fig. 1. The workflow of the whole system.

effect as the physiological insulin secretion pattern (Russell, El-Khatib, Nathan, Magyar, Jiang & Damiano, 2012). Human body system is complex, and it is difficult to construct a manual system to realize its function (Brown & Worthington, 2012). Especially for these patients who nearly cannot control the insulin by their own pancreas, the manual control can hardly give good performance as the blood glucose changes greatly. Artificial pancreas is a novel research direction in recent years, and it can imitate the pattern of pumping up of insulin by pancreas and inject insulin automatically (Phillip et al., 2013). Compared with the manual control, it is more reliable, more convenient and more flexible. Artificial pancreas in this paper consists of three parts, CGMS, insulin pump and closed-loop control algorithm. Medtronic is the biggest company which dedicated to research medical devices, and it has the best sale on CGMS and insulin pump. However, they have not given a complete system with closed-loop control algorithm.

(Except these, another question we have to consider is the communication or data exchange between CGMS and insulin pump. The communication between CGMS and closed-loop control can guarantee that the values of blood glucose can be transferred to the algorithm in time. The communication between insulin pump and closed-loop control can guarantee that the signal of insulin can be executed correctly. The closed-loop control algorithm can be embedded into insulin pump if the data processing is not too complex. However, if we want to make this algorithm accurate, we have to get enormous data, and we have to consider the storage of insulin pump algorithm memory and we call it back end system. In this paper, we introduce another part which is especially designed to process data and optimize the algorithm. Fig. 1 shows the whole workflow in the system. The first level is Applications, and it includes CGMS and insulin pump. Applications level mainly provides devices for users. The second level is Algorithms. For each patient, the original algorithm is same, we can call it algorithm with coefficient *a* and we embedded it in the insulin pump algorithm memory. After the system generate data with algorithm with coefficient *a*, it will transfer data to back end system. Next, back end system will analyze the control effectiveness. If necessary, it will generate a new algorithm which we think is better for the current patient, this is algorithm with coefficient *b*. Next is Algorithm with coefficient *c*, Algorithm with coefficient *d* and so on. Obviously, the third level is back end system. Finally, we make an app to integrate these components and provide a friendly interactive interface for patients and doctors. The essence of the whole system is dynamic iteration and optimization.

There are three innovative contributions in this paper and they can be summarized as follows:

- *Design of a system for blood glucose-insulin control:*We design the whole system for blood glucose-insulin control. This wearable medical system for blood glucose control consists of CGMS, insulin pump and closed-loop control algorithm. These three parts guarantee the automatic control.
- *The proposal of a complete control algorithm for blood glucose control:*To better control blood glucose and insulin, we put forward a kind of algorithm based on Model Predictive Control (MPC). We have done many kinds of experiments to validate the performance of this algorithm. Compared to other blood glucose control algorithms, the algorithm in this paper has excellent robustness and individuation.
- *The proposal of a kind of control mechanism in back end:*On one hand, we hope that the insulin carrier is portable, but it will influence the storage of data. Thus, we put forward one method which can solve the storage problem. Meanwhile, we introduce back end optimization which can dynamically optimize our closed-loop algorithm and make our algorithm adaptive to individuals.

This paper is organized as follows: First of all, we introduce the design of the system framework and the closed-loop control algorithm. Also, in this section, we will provide some optimization methods to algorithm including constraints. Next, we will introduce back end system which is designed to better store data and dynamically optimize control algorithm. Section 4 presents the simulation results of this system and introduce the application based on our design. Section 5 discusses some related work and describes future work. Finally, we give the conclusion of this paper.

In this part, we will introduce current research status and challenges of this system including CGMS, insulin pump and loop control algorithm.

1.1. *Current status*

1.1.1. *CGMS*

CGMS is a kind of wearable medical device (Mastrototaro, 1998) which can detect patients' blood glucose level. A sensor, which is