A Smart Framework for Predicting the Onset of Nocturnal Enuresis (PrONE) in Children and Young People

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***Abstract*— Bed wetting during normal sleep in children and young people has a significant impact on the child and their parents. The condition is known as nocturnal enuresis and its underlying cause has been subject to different explanatory factors that include, neurological, urological, sleep, genetic and psychosocial influences. Several clinical and technological interventions for managing nocturnal enuresis exist that include the clinician's opinions, pharmacology interventions, and alarm systems. However, most have failed to produce any convincing results; clinical information is often subjective and often inaccurate, the use of desmopression and tricyclic antidepressants only report between 20% and 40% success, and alarms only a 50% success fate. This paper posits an alternative research idea concerned with the early detection of impending involuntary bladder release. The proposed framework is a measurement and prediction system that processes moisture and bladder volume data from sensors fitted into undergarments that are used by patients suffering with nocturnal enuresis. The proposed framework represents a level of sophistication and accuracy in nocturnal enuresis treatment not previously considered.**

***Index Terms*— Bedwetting, Artificial Neural Networks, Machine Learning, Mobile Computing, Wireless Sensors.**

I. Introduction

Although urination is a function performed effortlessly by healthy humans, it is an extremely complex process that involves the rapid and precise coordination of numerous muscles and nerves in the ureter, bladder, sphincter and urethra [1]. Nocturnal enuresis (incontinence or bedwetting) is an event that is commonly considered as a disruption to the normal process in achieving continence. Nocturnal enuresis occurs involuntary during sleep without any inherent suggestions of frequency or pathophysiology 1 and its etiology is complex. However, it is believed to be caused by three main non-exclusive pathogenic mechanisms: nocturnal polyuria (passing large amounts of urine at night and normal amounts during the day) [2], detrusor overactivity (involuntary contractions during the filling phase) [3], and increased arousal thresholds (a patient's inability to waken in response to signals from a full bladder) [4]. The underlying reason for these conditions has been subject to different explanatory factors that include, neurological, urological, sleep, genetic and psychosocial influences [5]–[8]. Furthermore, general parental knowledge of the causes and effective treatments for Nocturnal Enuresis (NE) is lacking. Only 55% reported they would seek medical care for their child with NE and only 28% reported awareness of effective treatments [9].

The condition is socially disruptive and stressful and is reported to affect 20-25% of five year olds, 5% at 10 years, and 1-2% at 15 years [10]. Data from UK Avon Longitudinal Study of Parents and Children (ALSPAC) put prevalence at 20% at 10 years, 9% at nine years and 1% at 15 years [11]. Nocturnal enuresis can have profound effects on a child, low self-esteem [12], social isolation [13], and child abuse triggered by bedwetting [14]. Although, primary and secondary care interventions help, it has a major impact on the quality of life and health resources. According to the British Association of Urological Surgeons (BAUS) between three and six million people in the UK suffer with urinary incontinence of which nocturnal enuresis is a subset of2. Urinary incontinence collectively has a significant cost implication, with conservative estimates suggesting that £424 million is spent annually on treatment in the UK [15]. Unfortunately, in addition to nocturnal enuresis, urinary incontinence is a clinically common problem with several peripheral and central nervous system pathologies, such as Parkinson's disease [16], multiple sclerosis [17], dementias [18], cancer [19], and many other lesion related and neurodegenerative diseases, as well as prescribed medications [20].

The structure, of the remainder, of this paper is as follows. Section 2 describes nocturnal enuresis and its diagnosis and treatment. Section 3 discusses the proposed solution posited in this paper and Section 4 provides a discussion on its impact within national healthcare services. Section 5 then concludes the paper and makes suggestions for future work.

II. Nocturnal Enuresis: Diagnosis and Treatment

A. *Diagnosis of Nocturnal Enuresis*

A child that is at least five years old and experiencing bed wetting episodes at least twice a week for a minimum of three months would be diagnosed as suffering with nocturnal enuresis [21]. Investigations are triggered by complaints from the parents or child following presentation to the General Practice (GP) or referral to specialist provider [22]. At the initial assessment, clinicians are mindful of the risk of parent

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[1] http://www.nice.org.uk/ [2] http://www.baus.org.uk/

intolerance towards their child's nocturnal enuresis since this can affect the treatments offered. During the initial assessment, a general history is completed to develop an understanding of the pattern of bedwetting over the previous few weeks. Further enquiry will include questions on urgency, frequency, and the type and amount of drinks consumed. Diaries are used as a self-reporting tool to record historical information [23]. A physical examination following an initial assessment is often required and laboratory tests requested to exclude other diseases, such as diabetes mellitus, urinary tract infection, and diabetes insipitus [24], [25]. Physical examinations include abdominal/flank examination for masses, bladder distension, and relevant surgical scars; examination of the perineum and external genitalia and neurological testing [26] is completed. Basic laboratory tests include urine analysis and urine culture and fasting blood sugar to rule out organic causes [27]. Other diagnostic measures include endoscopy, which provides direct visualization and access to the entire urinary tract [28]; ultrasound, which is a non-invasive method for imaging urological organs [29]. Radiograph is another technique, which is used to provide an abdominal X-ray called 'KUB' (kidneys, ureters and bladder) [30]. Computed tomography scans without contrast injection have also been useful to image the urinary tract [31]; and magnetic resonance imaging, for soft tissue investigations [32]. Parental decisions about the treatment of nocturnal enuresis are generally based on silent agreement with a physician's recommendation.

The conclusion from all the above is that diagnosis is based on subjective and often inaccurate information provided by the child and/or their parents. The process is further complicated by other key factors that include denial of the condition itself, a lack of awareness (only 28% reported awareness of effective treatments [9]), embarrassment and a parents intolerance of their child's condition. Faced with these difficulties, GP's and specialist providers find it challenging to provide a clear diagnosis and treatments often prove to be ineffective.

The personalized system presented in this paper has a real potential to mitigate many of these issues by providing an exploratory support tool, in the home, that allows a child and their parents, including medical practitioners, to carry out an initial diagnosis to help gain a better understanding of the condition and its severity. More importantly, it provides an idea of a standardized diagnostic support tool that helps to manage embarrassment and intolerance, collect data and reduce costs associated with physical examinations, laboratory testing or other expensive diagnostic measures, if they are not required.

B. *Treatment of Nocturnal Enuresis*

Lifestyle management is a first-line intervention that is useful during the exploratory stages of diagnosis, however, it is reported that only 20% of patients suffering with nocturnal enuresis respond successfully, while 80% will need additional treatment [33]. The use of retention control training in one study showed a success rate of 50% [34], however, in other studies it was reported that retention control training had negligible effect [35], [36]. NICE1 recommendations focus on patient centered care, listening to patient choice and clinical teams providing access to evidenced-based information and resources. Subsequent referral to a pediatrician or enuresis clinic is dependent upon local availability of Clinical Commissioning Groups (CCGs).

Alarms have been used with mixed results that range between 50% and 80% depending on the population (children and families need to be highly motivated) [37]. However, [38] founds no convincing evidence that any type of alarm leads to better results. In fact, alarm systems have never been standardized or packaged as a clinical procedure [39]. Nonetheless, [40] argues that the alarm system is far superior than other interventions. This is supported by [41] which claims a 50% overall success rate. While, [42] reports a 77.9% overall success rate (14 consecutive dry nights). With similar results [43], [44], [45] reported overall success rates between 65% and 75% with a 6 month relapse rate of 15%-30%.

Pharmacology interventions have also been routinely used in the treatment of nocturnal enuresis. The use of decompressing shows that one third of children remain dry, in one third it has a partial effect, and it has no effect at all in the remaining third of patients [46]. Whereas, the use of tricyclic antidepressants show success rates between 20% and 43% with high relapse rates and follow ups no better than placebo [47], [48]. Management of overactive bladder symptoms with the use of bladder training and also pharmacology intervention may be necessary, along with management of any underlying constipation [49].

The above issues are exacerbated by the fact that the entire procedure is heavily reliant upon the subjective expertise of trained clinicians and analysis techniques are not generalizable, as different clinicians use different assessment protocols. This is aggravated by the fact that children and parents will differ in the type and amount of information that they provide as it is evident in the literature. This variability in protocol, analysis and skill in fact means that it is impossible to compare studies across institutions (The UK National Health Service (NHS) providers designed to treat nocturnal enuresis), or even measure change in the same patient before and after treatment, a situation which is clearly unacceptable.

Regardless of the experience and specialty of the employed physicians, their training for nocturnal enuresis treatments is always demanding in terms of resources (equipment, time and staff). Another issue is that nocturnal enuresis research continually discovers new types of quantitative measures that may lead more precisely to an underlying cause of nocturnal enuresis. These features can be quite complex to measure manually. Lack of automation to track physiological occurrences makes comparison of these features fragile and hard.

The conclusion from all the above is that despite the various interventions, there are factors related principally to the collection and analysis of the data that prevent their correct clinical use. Regrettably, for the majority of the patients, the final decision to introduce a particular intervention is made based on a lack of understanding of the condition and its causes. Providing a personalized system delivers a standardized diagnostic support tool that helps that require no setting-up each night for use (which is a major issue with existing alarming systems); predicts when bed wetting is about to happen before the event happens (not possible with existing alarm solutions); and standardize diagnoses and treatments to enable them to be adopted widely into clinical practice (current solutions serve a very specific research purpose producing very specific measurements only).

C. State-of-the-art Technological Interventions for Managing Nocturnal Enuresis

There have been several technological interventions for managing nocturnal enuresis, that focus on detection and more recently on prediction, but which have largely produced disappointing results. The following paragraphs describe the reasons and discuss concisely previous works.

Arguably the earliest recorded attempt is the work of [50] who used a urine alarm system to alert the clinical staff at a hospital when bedwetting episodes by patients occurred (the problem is that the event has already happened and requires sheets and cloths to be washed and changed). Two components are used; a sensor that detects moisture, and an alarm that is activated when moisture is detected. However, the system was only effective if implemented consistently each night and only successful if treatment occurs between two and four months. Another type of alarm designed to detect urine was proposed by [51]. The system provides a moisture sensing mechanism fitted into diapers/undergarments that alert patients and careers when fixed levels of moisture are detected (again the event has already happened). Using the sensor, the patient can train to be aware of urine release. The system proposed in [52] utilises data to assess the natural bladder voiding pattern of individuals, to inform care plans and to personalise care (again the event has already happened). Using a wireless electronic monitoring device, moisture sensors are placed inside disposable pads. Alerts are sent, via a portable device, to care staff when moisture is detected. More recently, a wireless system was proposed in [53] that builds on many alarm-based monitoring systems to date, that monitors the occurrence of incontinence in a much more unobtrusive way.

The most relevant existing approach to our work, in terms of prediction, is proposed in [54]. The system uses ultrasound to estimate the volume contained within the bladder. The device is fitted to the person's abdomen. This can signal to the patient or a career when the bladder is empty, half-full, and full. A similar system was proposed in [55] where ultra wideband radar was used to estimate the volume of urine present in the bladder. An optical monitoring device, fitted to the abdomen, based on wireless near infrared spectroscopy is proposed in [56]. This system was also designed to estimate the volume of urine in the bladder. Our idea posited in this paper extends these relevant works with a feedback loop between sensed data and the setting of alarm thresholds using a moisture detector in the undergarment to personalise the system (during a training phase) to the specifics of an individual's nocturnal enuresis episodes.

III. Predicting the Onset of Nocturnal Enuresis (PrONE)

The idea in this paper proposes a theoretical framework to design, construct and implement a prototype measurement system. The framework will provide the capability to predict and calculate moisture and bladder volume data from wireless sensors fitted into undergarments. This will help to improve the diagnostic prediction of abnormal bladder movements, in patients, suffering with nocturnal enuresis, and thus provide a novel personalized management system to predict the onset of nocturnal enuresis (PrONE) not yet seen.

The PrONE framework:

- Identifies the system and analytic requirements for an extendable platform that predicts the onset of nocturnal enuresis.
- Provides custom electromagnetic wave sensor(s) and associated sensor platform for the detection of moisture and bladder volume during normal sleep.
- An intelligent system for data pre-processing, moisture detection, the classification of bladder capacity and to set alarm thresholds for early detection.
- Algorithms to unravel the complexity of the data captured and provide the necessary prediction meeting the clinical thresholds for nocturnal enuresis.
- A prototype implementation of the designed framework based on electromagnetic wave sensors, wireless communications, and a bespoke intelligent software for the prediction of nocturnal enuresis.

The proposed solution is novel and no other intervention for nocturnal enuresis provides the aforementioned functionality. Specifically:

- The proposed work goes far beyond previous attempts to predict the likely time a child will wet the bed.
- The nocturnal enuresis management system is personalised to the needs of individual children and their voiding patterns
- It offers the means for the automated extraction of bladder measurements, by using advanced computer algorithms never attempted before in the prediction of nocturnal enuresis events that occur prior to bed-wetting.

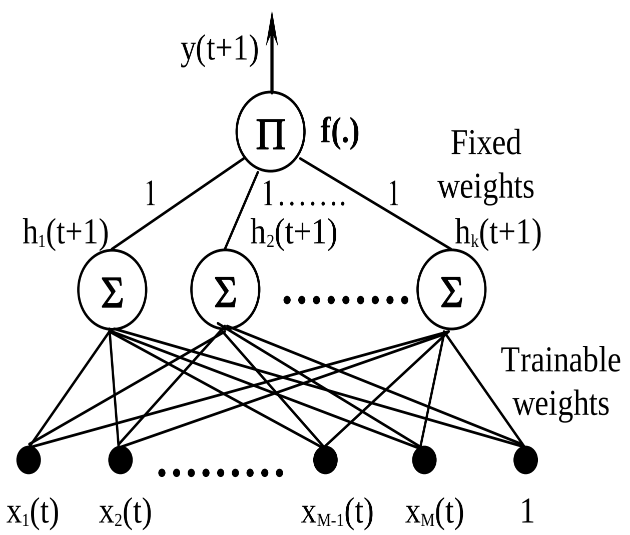
In the remainder of this section a full description of the proposed framework is discussed in more detail and a novel blueprint for the development of such a system is proposed.

A. Electromagnetic Wave Sensors

The communication platform is a Bluetooth low energy (BLE) network with supporting services for data processing, aggregation, storage and distribution. All sensors have a BLE interface connecting them to the network. Sensors transmit data using the Generic Attribute Profile (GATT) protocol in BLE [57] and all data is pre-processed using signal processing techniques. In the first instance, data is used to set the parameters of the algorithm and during runtime data is used for real-time prediction. The sensors are robust to variations in skin, fat, muscle thickness and bladder sizes. Electromagnetic waves are attenuated while passing through the bladder. Different attenuation is encountered at different frequencies. This is primarily because different body tissues, such as muscle, fat and skin own different relative permittivity. This means that electromagnetic waves undergo numerous reflections from the boundary between two tissues/organs that have different relative permittivity. This method is proposed to detect the presence of water because the value of the relative permittivity of the water (in this instance urine) is much larger than the values of the relative permittivity of the surrounding organs and tissues. A large reflection of the incident electromagnetic signal pulse occurs. The position, amount of water, and the water concentration in the reflecting organ, can be estimated since the electromagnetic signals own a fine range resolution and good penetration ability. The signals from transmitting and receiving antenna are processed using classification and prediction algorithms, which represent the relation between the signal frequencies and bladder volume. Bladder volume prediction is triggered during training by moisture sensors fitted into undergarments that consist of two electricity conductors separated by an insulated moisture absorbing material.

B. *Adaptive Neural Network Architecture*

A system to predict the occurrence of nocturnal enuresis before it occurs is provided by the proposed framework. The purpose of the system is to raise an alarm to the user using a mobile device based on the information collected from the developed sensor technology. Since the bladder volume varies from one person to the other, an adaptive system will be designed to personalise prediction and alarm thresholds. One possible solution is to use Spiking Neural Networks (SNNs) that have the ability to solve difficult problems in complex and informationally “messy” environments. Unlike the older class of neural network, “third generation” neural networks use spike times to encode data. It is argued that these new generation neural networks are potentially much more powerful at predicting non-stationary patterns, and are, in reality, a superset of the “traditional” or rate encoded neural networks. However, practical application of spiking neural networks requires long training times and complex structures which may make them unsuitable for mobile application. Another solution, would be to use the Adaptive Resonance Theory, or ART, which was introduced as a theory of human cognitive information processing by Stephen Grossberg in 1976 [58]. The theory has been used to develop a number of evolving neural network architectures for real-time applications using unsupervised-based category learning and pattern recognition due to its capabilities to learn in response to arbitrary input sequences. However, the application of the ART neural network in a real world has proved to be unstable with infinite streaming data [60]. To overcome this problem, we will introduce a pipelined structure similar to the adaptive fully recurrent pipelined neural network architecture proposed by Haykin and Li [59]. The main structure of the proposed network is the pi-sigma unit [60] as shown in Figure 1. The reason for introducing the pi-sigma units is due to their simplicity and the high learning capabilities of higher order neural networks which make them suitable for mobile device processing.



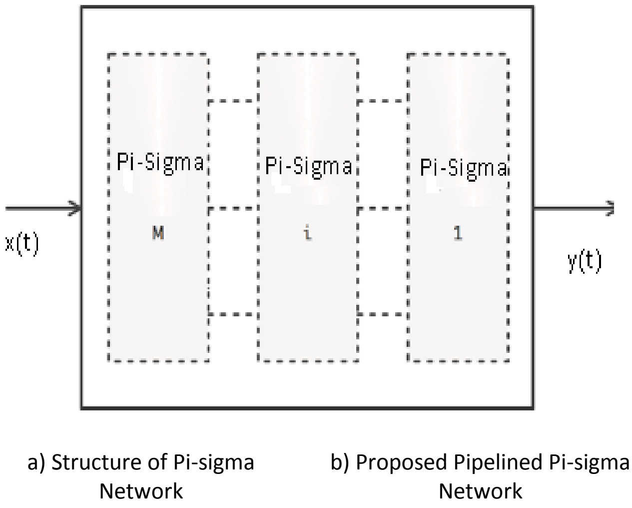


Figure 1: (a) The structure of the Pi-sigma network (b) The proposed pipelined Pi-sigma network

C. *Mobile Platform*

In the network configuration, a mobile device will form part of the mobile platform and will host the GATT server. A mobile application for the prediction of bedwetting using sensors, neural network architecture and algorithms mentioned in the previous sections will be implemented within this mobile platform. Specifically, the mobile platform will provide:

1. The GATT Server
2. House the signal processing, feature generation and feature selection and extraction algorithms
3. Implement the advanced artificial neural network algorithms
4. Mobile application for the bespoke intelligent software for personalisation and alarm threshold detection

IV. Discussion

The timeliness of this work can be realistically judged in the context of large number of patients and the demographics of the population. The overall worldwide prevalence of unary incontinence is said to be 200 million people. In the UK, the figure is between three and six million and in the US, it is said to be 25 million. The economic cost of treating adults over the age of 40 suffering with urinary incontinence annually was estimated to be £536 million in 1999/2000 prices. In addition, it is estimated to cost the individual £207 million for managing their symptoms (£29 million and £178 million for men and women, respectively). The conservative estimate for treating children and adolescents is £424 million annually in the UK. In 2005, the annual cost-of-illness estimates for urinary incontinence in Canada, Germany, Italy, Spain, Sweden, and the United Kingdom was 7 billion euros. A US cost-of-illness study reported a total cost of $66 billion in 2007. These figures are likely to rise significantly over the next 20 years as awareness of the condition and the mean age of the population increase [61].

There is no real “gold standard” for the diagnosis and treatment of nocturnal enuresis. Taking into account the important role of prediction in the clinical assessment of NHS patients, and the large volume of nocturnal enuresis research articles based on alarm systems, we believe that there will be significant interest in the framework posited in this paper as it represents a level of sophistication and accuracy in nocturnal enuresis treatment not previously considered.

V. Conclusions

This paper has proposed a novel, low cost measurement and prediction system that detects the onset of nocturnal enuresis episodes before they occur, which current technologies cannot do. Commercial scale ProNE has the capacity to revolutionise the treatment of nocturnal enuresis and other incontinence conditions, while offering an affordable personalized device that allows children and their parents to manage their condition in the home. In the UK alone, PrONE presents the NHS with a real opportunity to treat nocturnal enuresis under the recommendations set out by NICE, and will also help the NHS significantly reduce the costs associated with treating this condition.

The potential market for PrONE is vast, as personalized prediction systems can be used to offset the need for diagnostic and healthcare services. PrONE will improve the overall success rate of treatments (14 consecutive dry nights) while reducing relapses and help to gain a better and standardized understanding of the condition. It will reduce NHS costs and also costs incurred by parents (cleaning costs, mattress replacement, disposable products required). The anticipated efficiency of PrONE is such that it will standardize diagnosis and treatment compared with existing solutions and procedures as a result of its ease of use, data collection and communication capabilities between the child, parent and care practitioners.

There is no other product on the market that covers such technology that can help to treat and understand nocturnal enuresis personalized to an individual's condition and generalizable across all suffers of nocturnal enuresis.

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