Wearable and Wireless Measurement System for Evaluating Penile Tumescence

Sungwoon Choi[1,2], Seijoon Kim[1], Jongmo Seo[1], Jae Young Park[3] and Sungroh Yoon[1,*]
[1]Department of Electrical and Computer Engineering, Seoul National University, Seoul 151-744, Korea
[2]Department of IT Convergence, Korea University, Seoul 156-731, Korea
[3]Department of Urology, Korea University College of Medicine, Seoul 156-731, Korea
*Correspondence: sryoon@snu.ac.kr

***Abstract*—The evolution of wearable smart devices coupled with advanced sensor technology has rejuvenated research in mobile healthcare. Despite the growing interest in the measurement of bio-signals, no studies have focused on mobile penile tumescence. Measuring penile tumescence daily is important not only for patients suffering from erectile dysfunction but also because it serves as a dependable barometer of men's health. Rigiscan has been the most reliable and widely used device employed to measure nocturnal penile tumescence, but it is heavy, bulky and has several limitations to being a wearable device. This paper introduces an innovative mobile penile tumescence measuring system connectable to any smartphone through wireless communication. It comprises of a progressive sensor that allows seamless everyday usage due to its small size, light weight and low power requirements. The sensor consists of inexpensive materials, so it can be replaced daily for hygiene reasons. We tested proposed system with 10 subjects in over 30 sessions for a total of more than 100 hours. To check the validity of PT-scan and its compatibility with Rigiscan, the two systems' measurement results were compared and a high correlation coefficient of 0.96 ($P < 0.001$) was obtained.**

I. Introduction

Healthcare technology continues to advance at a remarkable rate, allowing patients to monitor their conditions in real time and becoming part of people's everyday lives. In particular, with the emergence of wearable smart devices, mobile healthcare systems are generating considerable interest because they can reduce medical expenditure and improve treatment efficiency. Despite this growing interest in mobile healthcare and monitoring, no previous work has specifically focused on mobile monitoring of men's health [1]–[3], to the best of our knowledge.

Men's health is closely related to penile health, which can act as a barometer for evaluating overall wellness [4]. Typically, a man can experience several nocturnal erections during rapid eye movement (REM) sleep [5], and lack of erection may indicate erectile dysfunction (ED). ED is a common condition for elderly men, and approximately 13 to 86 percent of men between the ages of 40 and 80 suffer from ED [6]. ED is caused by either physical or psychological factors, and its diagnosis is critical for appropriate treatments.

Nocturnal penile tumescence (NPT) testing has been considered highly effective in determining the cause of the condition, and Rigiscan is one of the most reliable and commonly used devices for NPT testing [7]. However, the conventional Rigiscan system has obvious drawbacks and cannot be used as a wearable smart device. For instance, its large size and heavy weight significantly limit its mobility. Additionally, the loop component (a critical sensing mechanism in Rigiscan) is expensive to replace for everyday use.

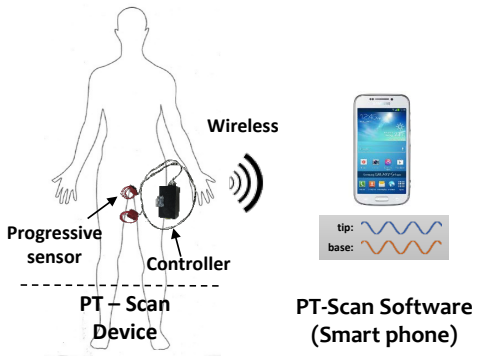

Fig. 1. Overview of Proposed PT-scan System

To address these limitations, we propose a wearable smart device system called PT-scan, which is incomparably suitable for the mobile healthcare. The device weighs only 60 grams and measures 35(w) by 65(h) by 35(d) millimeters, one-thirteenth the weight and one-fifteenth the size of a Rigiscan, which weighs approximately 800 grams and measures 125(w) by 210(h) by 45(d) millimeters. Our proposal includes the progressive sensor (P-sensor), which utilizes multiple wires of different length. The P-sensor reduces sleep disturbance and improves power efficiency, is cost effective, and can be replaced daily. Furthermore, the penile tumescence data can be transmitted to any smartphone using Bluetooth, allowing the patient to monitor his condition in real-time. Our test results show that PT-scan has high correlation with the conventional Rigiscan system (0.95 at the penile tip and 0.96 at the base in terms of correlation coefficients).

II. Related Work

A great deal of research has been done on NPT since the 1940s. Conducting an NPT test is the industry standard for determining whether the cause of ED is physical or psychological. In the 1970s, Karen and Fisher introduced the first NPT test [5] [8]. In this early stage, a mercury strain gauge was used to measure changes in penile circumference. Berry et al. furthered this concept, and proposed a simple and effective self-test called the NPT stamp test [9]. A strip of postal stamps was wrapped around the shaft of the penis;

978-1-4799-7234-0/15/$31.00 ©2015 IEEE

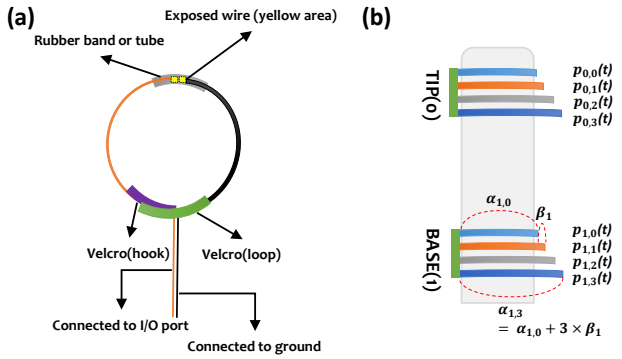

Fig. 2. Overview of P-sensor (a) Architecture (b) Attachment Area

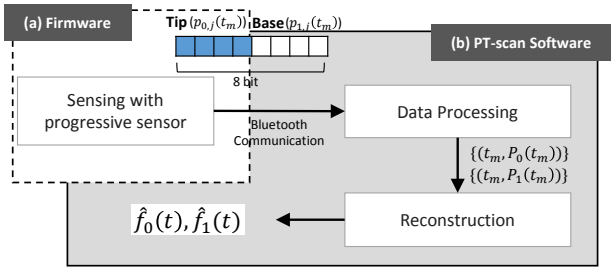

Fig. 3. Overview: (a) PT-scan Firmware (b) PT-scan Software

broken stamps indicated an erection during sleep. However, this test could not measure the duration and frequency of penile tumescence. To overcome the shortcomings of previous work, Bradley et al. developed an innovative device called Rigiscan [10]. Rigiscan is a computerized apparatus that allows continuous measurements of penile rigidity at the tip and base of the penis throughout the sleep cycle. To date, it is considered the most reliable and frequently used device for NPT testing. It is therefore important for a new device (such as PT-scan) to have a high correlation with the Rigiscan device.

III. Proposed Architecture and Design

Fig. 1 provides an overview of the proposed penile tumescence scan system (PT-scan). PT-scan consists of two parts: the PT-scan device (Fig. 2 and 3a) and PT-scan software (Fig. 3b). The PT-scan device comprises a P-sensor and controller, while the PT-scan software includes data processing and reconstruction software, and a mobile application. Detailed descriptions of these components are given below.

A. PT-scan Device

1) P-sensor: Fig. 2 provides an overview of the proposed P-sensor. Each P-sensor consists of multiple wires, a rubber band and Velcro. Multiple P-sensors can be placed at the penile tip and base to measure tumescence, similar to the Rigiscan. P-sensors have different lengths for measuring penile tumescence and satisfy the following equations:

$$\alpha_{i,j} < \alpha_{i,j+1} \tag{1a}$$

$$\beta_i = \alpha_{i,j+1} - \alpha_{i,j} \tag{1b}$$

where $i \in \{0, 1\}$ and $0 \leq j < n - 1$. $\alpha_{i,j}$ is the total length of a P-sensor where i is the location identifier (Base or Tip) and j is the order identifier (j^{th} P-sensor). Thus, in $\alpha_{i,0}$ is the length of the shortest P-sensor, while β_i is the difference in length between each P-sensor. The P-sensor output function denoted by $p_{i,j}(t_m)$ is defined as follows:

$$p_{i,j}(t_m) = \begin{cases} 0 & \text{if } f_i(t_m) < \alpha_{i,j} \\ 1 & \text{if } f_i(t_m) > \alpha_{i,j} \end{cases} \tag{2}$$

where $f_i(t_m)$ is actual penile tumescence at time t_m. In this experiment, $f_i(t_m)$ was substituted with the penile tumescence measurements obtained from Rigiscan. Note that $p_{i,j}(t_m)$ returns a value of 1 if $f_i(t_m)$ is greater than $\alpha_{i,j}$. In other words, the P-sensor output function returns a value of 1 when Rigiscan's penile tumescence exceeds the length of the P-sensor, otherwise it returns a value of 0.

2) Controller: The hardware platform consists of ATmega128 (8-bit Atmel microcontroller) and a Bluetooth module. The P-sensor is connected to an eight bit I/O of ATmega128, and each I/O senses the on/off state of the P-sensor. Using Bluetooth, measured data can be transmitted to any smart device. The proposed PT-scan device is significantly smaller and lighter than Rigiscan because it does not require a high-capacity battery to run the sensor motor.

Fig. 3 shows an overview of PT-scan, with flow and non-shaded regions (Fig. 3a) describing the firmware of the controller. The firmware receives obtained data from the P-sensor and transmits eight bits of data, four bits each from the penile tip and base, to the mobile software using Bluetooth.

B. PT-scan Software

The shaded region in Fig. 3(b) illustrates an overview of PT-scan software. PT-scan software consists of two parts: data processing and reconstruction. In data processing, the penile tumescence is predicted based on sensed data received from the P-sensor. Accurate penile tumescence is predicted subsequently during the reconstruction process.

1) Data Processing: From the set of measured data, researchers created an actual penile tumescence function $P_i(t_m)$ which is defined as follows:

$$P_i(t_m) = \alpha_{i,0} + \beta_i \left(p_{i,0}(t_m) + \sum_{j=1}^{n-1} \left(\prod_{k=0}^{j-1} p_{i,k}(t_m) \right) p_{i,j}(t_m) \right) \tag{3}$$

There is a possibility that the P-sensors may not work properly in the order of size due to the patient's involuntary action during sleep. To resolve this issue, the function $P_i(t_m)$ considers output to be invalid if any of the preceding P-sensors are turned off. Fig. 4 confirms an error correction of the fourth P-sensor on the interval $[t_{M-2}, t_M]$. Another issue that needs to be considered is that actual penile tumescence may differ from $P_i(t_m)$ to the length of β_i. Attempts to achieve higher measurement resolution led us to introduce a penile tumescence reconstruction process.

2) Reconstruction: The main objective of the reconstruction process is to find $\hat{f}_i$ that minimizes the MSE. The function $\hat{f}_i(t)$ is the output of the reconstruction process where $t_0 < t < t_M$. The mean square error (MSE) between f_i and

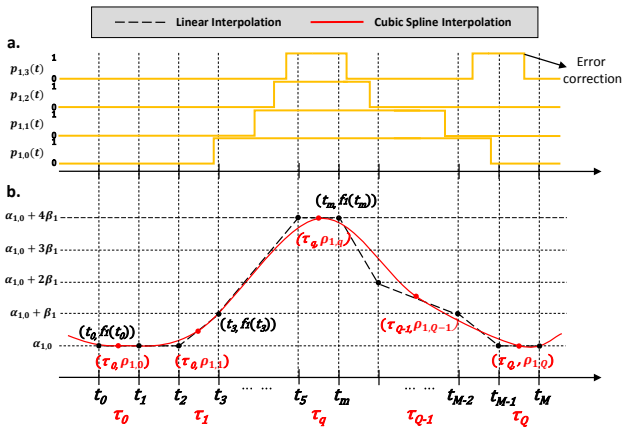

Fig. 4. Example of Cubic Spline Interpolation ($s = 2$, Base)

$\hat{f}_i$ is defined as follows:

$$MSE_i = \frac{1}{M}\sum_{m=1}^{M}\left(f_i(t_m) - \hat{f}_i(t_m)\right)^2 \tag{4}$$

In this paper, an interpolation method was applied to predict more accurate penile tumescence. However, the reconstruction process can be meaningless when an interpolation method is used because a generated function must go through all input data points. This led to the generation of new points $\tau_q, \rho_{i,q}$ which can be defined as follows:

$$\tau_q = \frac{\sum_{k=0}^{s-1} t_{q\times s+k}}{s} \tag{5a}$$

$$\rho_{i,q} = \frac{\sum_{k=0}^{s-1} P_i(t_{q\times s+k})}{s} \tag{5b}$$

where $0 \le q < \frac{M}{s}$.

Fig. 4 demonstrates an example of the penile tumescence interpolation process where $f_i(t)$ is presented by black dots and $\hat{f}_i(t)$ by a red line. As $s = 2$, the new data points $(\tau_0, \rho_{1,0})$ are generated based on $(t_0, f_1(t_0))$ and $(t_1, f_1(t_1))$. Similarly, $(\tau_Q, \rho_{1,Q})$ are generated based on $(t_{M-1}, f_1(t_{M-1}))$ and $(t_M, f_1(t_M))$. The red line crosses through all points $(\tau_q, \rho_{i,q})$, causing differences in values at points such as t_2, t_5 and so on. There are various algorithms in cubic spline interpolation depending on its method. In the reconstruction process, the MONOH.FC [11] algorithm is applied.

IV. Experimental Results

A. Experiment Setup

The test on PT-scan was conducted simultaneously with a Rigiscan test to analyze and compare the characteristics of the proposed PT reconstruction model. For the proposed PT-scan, eight P-sensors, four each at the penile tip and base, were used in parallel with the traditional Rigiscan device. A patient is considered to have a full erection when a two-centimeter increase in tumescence at the tip and three-centimeter increase at the base occurs for more than ten minutes [7]. Thus, $\beta_0 = 0.5, \beta_1 = 0.75$ was initialized in all experiments.

Both nocturnal and diurnal penile tumescence were measured to compare PT-scan with the Rigiscan system. Diurnal penile tumescence was obtained from visual sexual stimuli. Complete tumescence records of the subject were required in calculating the deviation between the actual output and the estimate from the reconstructed PTR model. However, as the traditional Rigiscan device records actual data every 15 seconds, the same time interval was adopted for the experiment. The data was collected from 10 minutes to eight hours for each sample. The experiment relied on the Rigiscan and PT-scan outputs from 10 subjects with over 30 sessions, accumulating a total time of more than 100 hours.

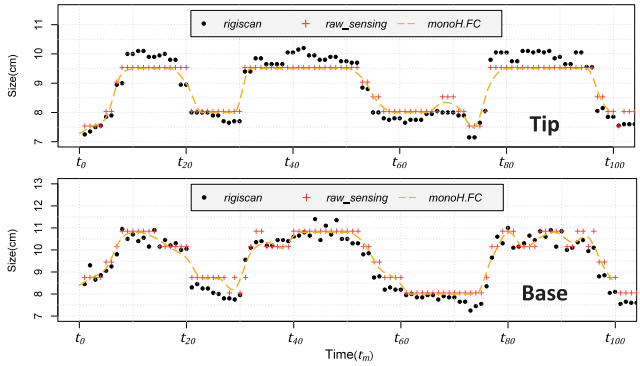

Fig. 5. Experiment Result for Tip and Base ($t_m, 0 \le m \le 100$)

B. Effects of reconstruction parameter s

In the reconstruction process, a new function $\hat{f}_i(t)$ is generated that minimizes reconstruction error to overcome low measurement resolution associated with a limited number of P-sensors. When $s = 2$, the MONOH.FC algorithm shows good performance. An increase in the value of s means a decrease in the number of data points used in interpolation, which led to performance degradation.

C. Reconstruction of Results

Fig. 5 compares the diurnal penile tumescence values from Rigiscan, the data collected from PT-scan before reconstruction, and the values from reconstruction. PT-scan value before reconstruction shows similar results when compared to Rigiscan, except where values fall outside the measurable range. However, PT-scan values before reconstruction show significant deviation when values are in the measurable range. For example, for the penile base (when $t_m = t_{29}$ with the Rigiscan value in the range of a PT-scan value of between 8 and 8.75 centimeters), the MONOH.FC algorithm correctly predicted the result, whereas using the raw sensing data was not successful. In other words, the raw sensing data value shows effective performance because the proper β_i value was set. In cases where β_i is not set properly, using the reconstruction method will give satisfactory results.

D. Correlation and MSE Results

Table I lists detailed correlation and MSE values when $s = 2$. Despite the high correlation coefficient and low MSE between raw_sensing and rigiscan data, we have obtained more accurate results using the cubic spline interpolation algorithm. These tests demonstrate that the accuracy of the NPT test has been improved through the proposed PT-scan reconstruction process.

TABLE I. CORRELATION AND MSE RESULTS ($s = 2$)

	TIP		BASE	
	Correlation	MSE	Correlation	MSE
raw_sensing	0.94723	0.12915	0.96093	0.16856
MONOH.FC	**0.95412**	**0.12332**	**0.96595**	**0.15700**

V. CONCLUSION

This paper presents an NPT measurement device that utilizes P-sensors, as well as a mobile healthcare system that enables real-time monitoring from smart gadgets. The device is easily wearable. In addition, sleep disturbance has been minimized by replacing sensing motors with P-sensors. Moreover, the device is simple enough to be used at home without the presence of a doctor, and the data can be saved and accessed in real time from afar, which allows remote healthcare services. Furthermore, the reconstruction of tumescence data obtained from PT-scan has helped to resolve the issue of a low measurement resolution, which stems from the limited number of P-sensors. The performance of the device was measured against existing devices in experiments, through which researchers found a high correlation coefficient of 0.96 at the penile tip and 0.95 at the base. The evidence from this study suggests that PT-scan is reliable and wearable daily. It would be possible to incorporate more advanced biological signal processing algorithms [12]–[14] to further optimize the data processing step. Based on the performance of the proposed PT-scan, we anticipate that it can be successfully applied to the field of mobile healthcare.

ACKNOWLEDGMENT

This work was supported in part by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science, ICT and Future Planning, MSIP) [No. 2011-0009963 and No. 2015M3A9A7029735], in part by the Brain Korea 21 Plus Project in 2015, and in part by Samsung Electronics Co., Ltd.

REFERENCES

[1] D. Sabo and D. F. Gordon, *Men's health and illness: Gender, power, and the body*. Sage Publications, 1995, vol. 8.

[2] C. Lee and R. G. Owens, *The psychology of men's health*. Open University Press, 2002.

[3] D. K. Yoon, J. Y. Park, S. Yoon, M. S. Park, D. G. Moon, J. G. Lee, and F. H. Schröder, "Can the prostate risk calculator based on western population be applied to asian population?" *The Prostate*, vol. 72, no. 7, pp. 721–729, 2012.

[4] G. Cirino, F. Fusco, C. Imbimbo, and V. Mirone, "Pharmacology of erectile dysfunction in man," *Pharmacology & therapeutics*, vol. 111, no. 2, pp. 400–423, 2006.

[5] I. Karacan, C. J. Hursch, and R. L. Williams, "Some characteristics of nocturnal penile tumescence in elderly males." *Journal of gerontology*, 1972.

[6] J. Prins, M. Blanker, A. Bohnen, S. Thomas, and J. Bosch, "Prevalence of erectile dysfunction: a systematic review of population-based studies." *International journal of impotence research*, vol. 14, no. 6, pp. 422–432, 2002.

[7] S. Elhanbly, A. Elkholy, Y. Elbayomy, M. Elsaid, and S. Abdel-gaber, "Nocturnal penile erections: the diagnostic value of tumescence and rigidity activity units," *International journal of impotence research*, vol. 21, no. 6, pp. 376–381, 2009.

[8] C. Fisher, R. C. Schiavi, A. Edwards, D. M. Davis, M. Reitman, and J. Fine, "Evaluation of nocturnal penile tumescence in the differential diagnosis of sexual impotence: A quantitative study," *Archives of General Psychiatry*, vol. 36, no. 4, pp. 431–437, 1979.

[9] J. M. Barry, B. Blank, and M. Boileau, "Nocturnal penile tumescence monitoring with stamps," *Urology*, vol. 15, no. 2, pp. 171–172, 1980.

[10] W. E. Bradley, G. W. Timm, J. M. Gallagher, and B. K. Johnson, "New method for continuous measurement of nocturnal penile tumescence and rigidity," *Urology*, vol. 26, no. 1, pp. 4–9, 1985.

[11] F. N. Fritsch and R. E. Carlson, "Monotone piecewise cubic interpolation," *SIAM Journal on Numerical Analysis*, vol. 17, no. 2, pp. 238–246, 1980.

[12] S. Yoon, L. Benini, and G. De Micheli, "Co-clustering: a versatile tool for data analysis in biomedical informatics," *IEEE Transactions on Information Technology in Biomedicine*, vol. 11, no. EPFL-ARTICLE-101484, pp. 493–494, 2007.

[13] B. Shim, H. Min, and S. Yoon, "Nonlinear preprocessing method for detecting peaks from gas chromatograms," *BMC bioinformatics*, vol. 10, no. 1, p. 378, 2009.

[14] J. Kim, S. Yu, B. Shim, H. Kim, H. Min, E.-Y. Chung, R. Das, and S. Yoon, "A robust peak detection method for rna structure inference by high-throughput contact mapping," *Bioinformatics*, vol. 25, no. 9, pp. 1137–1144, 2009.