国際医療福祉大学審査学位論文（博士）

大学院医療福祉学研究科博士課程

CLINICAL APPLICATION OF WEARABLE STRAIN SENSOR ON RESPIRATORY MEASUREMENT IN HEALTHY PARTICIPANTS AND INDIVIDUALS WITH BREATHING PROBLEMS

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保健医療学専攻・　理学療法学分野　・応用理学療法学領域

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健常者と呼吸困難者の呼吸測定における装着型変位センサの臨床応用

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要約：

装着型変位センサ（以下 WSS）は、呼吸運動の新しい測定ツールである。WSS の長所は、高感度、耐久性の安定、低コスト、最大 5 倍のストレッチ、姿勢や環境の制約なしに使用可能である。本研究の目的は、健常者および呼吸困難者での呼吸測定における WSS の臨床応用を検証することである。

本研究は、合計 175 人の対象者で行われた。研究 1 では、臨床での評価のために新たに開発された WSS を用いて、呼吸運動測定の信頼性と妥当性の確認を行った。研究 2 では、WSS で得られた呼吸運動データより身体機能を検出するための最適な身体部位を見つけることである。研究 3 では、加齢による呼吸パターンの変化を検討することである。研究 4 では、WSS を用いた頸椎脊髄損傷（以下 CSCI）患者の胸部 – 腹壁の変化の測定を決定することである。

研究 1、2 の結果より呼吸測定時に WSS の高い信頼性と妥当性が確認された。また、第 10 肋骨は、WSS での胸部–腹部の伸長データと肺活量と有意な相関がみられた。研究 3 の結果は、WSS により加齢により呼吸パターンが、徐々に変化していることを示した。研究 4 の結果は、WSS の測定により CSCI 患者への呼吸練習後に胸壁拡張性が改善傾向を示した。

本研究により WSS は、臨床現場での呼吸運動の客観的測定として身体機能の検診および触診に代わる新しい測定ツールと考えられた。

キーワード：装着型変位センサ、呼吸測定、臨床応用

Clinical application of wearable strain sensor on respiratory measurement in healthy participants and individuals with breathing problems

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Abstract

A wearable strain sensor (WSS) is a new measuring tool of respiratory movement, the merits of WSS include high sensitivity, durable stability, low cost, a maximal stretch up to 5 times, and easy to use without limitations of posture or environment. The aim of this research was to verify clinical application of WSS on respiratory measurement in healthy participants and individuals with breathing problems.

Four linked studies were conducted with total 175 participants. *The first study* was to confirm the reliability and validity of measuring respiration movement using WSS which has been developed newly for clinical objective assessment. *The second study* was to find the best body spot to detect the vital capacity from the respiratory movement data obtained by WSS. *The third study* was to explore change of breathing pattern by aging. *The fourth study* was to determine measuring changes of chest-abdomen wall in individuals with cervical spinal cord injury (CSCI) using WSS.

A high degree of reliability and validity for WSS was interpreted during respiratory measurement. The 10^{th} rib is the best body spot to detect the positive significant correlation between the expansion data of the chest-abdomen obtained by the WSS and the vital capacity data obtained by the spirometer. The results of third study indicated that the different people's breathing pattern in the progress of getting older are slowly changing with advanced age. And last results of fourth study revealed that trends for improvement on chest wall expansion following respiratory exercise were measured in individuals with CSCI by WSS.

A summary of all studies had been done, it is considered that WSS will replace inspection and palpation in physical examination as an objective measurement for respiratory movement in clinical practice.

Key words: Wearable strain sensor, Respiratory measurement, Clinical application

TABLE OF CONTENTS

Chapter 1 INTRODUCTION

1.1 Background

On the basis of report from the official statistics of the National Health Commission of China in 2015, the morbidity of respiratory disorders amounted to 6.94%. 92 million patients suffer from various respiratory diseases every year in China. However, the diagnosis rate of less than 35 percent was due to the patients' reason [1)]. According to a report from the National Health Commission of China in 2016, the mortality of the chronic respiratory diseases was sixty-nine thousand that ranks the 4^{th} for chronic diseases in China[2)].

Among the all, the smoking and aging are two major contributors to respiratory diseases in China. By the end of 2025 there will be two million smokers, and the population of elderly people will be predicted to four million[3)]. Furthermore, the harm of smog to people's respiratory system in recent years should not be ignored either. PM 2.5 of annual average value in 2016 reached to 83.2μ/m^3 in Beijing[4)].

Another two diseases leading to high morbidity of respiratory disorders are cervical spinal cord injury (CSCI, 55%) and thoracic spinal cord injury (TSCI, 15%)[5,6)]. And the next two are brain stem hemorrhage (BTH) which accounts for 10% of the intracerebral hemorrhage (ICH) and severe traumatic brain injury (TBI), which accounts for 10-30% of the multiple injury[7,8)]. Although these diseases are relatively small in number, it is still the target patients of respiratory monitoring because of their high mortality and disability.

In fact, the early symptoms of respiratory diseases are not obvious and not easy to detect, so the biggest issues are missed diagnosis and misdiagnosis, therefore convenient and objective tools for accurate diagnosis are badly needed.

1.2 Previous studies

1.2.1 Existing instruments for pulmonary functional test in clinical application

Among all means, spirometer is the most frequently used means to measure and trace changes in pulmonary function and to measure the volumes and airflow of the vital capacity. Other techniques and sophisticated instruments such as inductive or opto-electronic plethysmography, computed tomography or video systems have also been used for these purposes[9,10)]. However, these instruments are seldom applied for general clinical practices due to their high cost, long waiting time and limitation to patients in moving conditions as well as patients with cognitive disorders.

1.2.2 Instruments with low cost to measure respiratory movement

Measuring the chest expansion is a simple and practical method for assessing people's respiratory function. Especially for patients with restrictive pulmonary disorders, which were characterized by a decrease in total lung capacity. It's a chest deformity or a variety of causes that reduce the elasticity of the lung, decrease chest wall compliance, restrict lung expansion[2)]. The restrictive pulmonary diseases include such as pulmonary fibrosis, atelectasis after chest trauma, pneumoconiosis, post-pneumonectomy, and so on[2)]. Shobo A, et al. found that there was a highly positive correlation between the chest expansion and changes of the chest volumes as indicated by the changes of the chest-abdomen wall[11,12)]. Following this finding, some new devices with low cost were developed, such as, respiratory movement measurement instrument (RMMI), breathing movement measuring device (BMMD) and 3D motion analysis system[13-15)], but the application of these instrument needs special experimental environment or complex settings. A scale can also be used to measure the breathing movements, but it relied on the experiences of human assessors, so its results are not quite reliable[16)].

A simple and practical method is using a measuring tape to assess the mobility of the chest-abdomen wall [13,17)], but its process is painstakingly long, which may increase the fatigue of both patients and medical workers.

1.2.3 Sensors based on five different principles available for the respiratory measurement

Nowadays, there are sensors based on five different principles available for the respiration measurement i.e. based on the principles of wave, optical, temperature, pressure, and resistance. However, the instruments based on these principles still have some limitations, such as, being unable to carry, no movement during the test, making patients feel suffocated and dizzy, requiring complex setting during the test, combining nostril breathing with mouth breathing of patients, being fragile, having uncomfortable to the body of patients, etc.

1.2.4 WSS use for respiratory measurement and its advantages

Wearable strain sensor (WSS) based on the principle of resistance strain was developed in 2016, which features high sensitivity, high stretch ability, low cost, a tolerable strain of more than 500%, easy to use and no limitations to postures and environment[18] in Fig. 1.

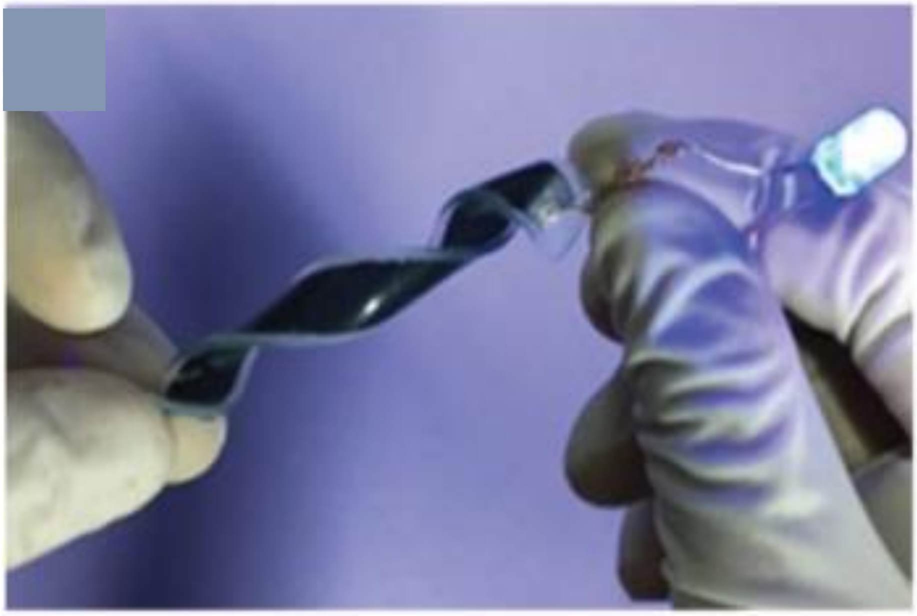

Fig. 1. The photographs of a strain sensor connected with a light

1.3 Rationality

1.3.1 WSS using carbonized silk fabric (CSF) exhibits fast response, low creep, and high durability. Relative resistance changes of the CSF strain sensor for cyclic loading in the strain ranging from 2 to 10% at the frequency of 1.25Hz can guarantee its immediate response[18)] in Fig. 2.

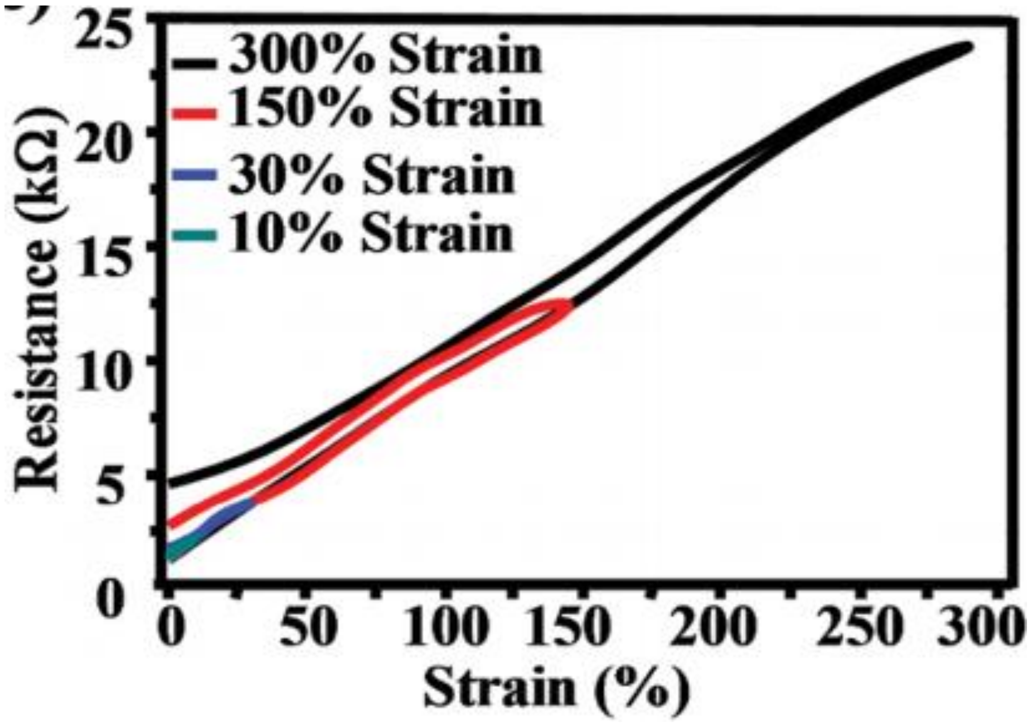

Fig. 2. Resistance performance for different strain of CSF

1.3.2 WSS using CSF is the optimal choice to detect respiratory movement compared with other sensors based on other strain principle.

The performance of different materials based on strain principle is represented by gauge factor (GF) and strain range (SR), Dan-Yang Wang et al. showed that an optimal value (OV) of strain sensor equal to the square root of GF multiplied by SR, (e.g. OV=$\sqrt{GF}$ X SR)[20]. The optimal values of different strain sensors demonstrate a good balance between the high sensitivity and the large strain. Although the laser-scribed graphene and nanomaterial-based sensor have a high optimal value in Table 1, the fabrication process is complicated with high cost and may generate environmentally hazardous.

Table 1: The comparison of strain sensors based on different materials

Different materials	GF	SR	Optimal Value
Carbonized silk fabric[18]	37.5	500%	**7031**
Electrospun carbon nanofibers[19]	72.0	300%	15552
Laser-scribed graphene[20]	402.4	7.5%	12150
Carbon nanotube thin film[21]	48.0	300%	6912
Graphene-elastomer[22]	82.5	100%	6806
Carbonized cotton fabric[23]	64.0	140%	5734
Three-D graphene foam[24]	98.7	30%	2922
Thin Elastomer film[25]	116.0	20%	2691

GF: Gauge factor.   SR: Strain range

1.4 Innovations

1.4.1 The development of an innovated WSS

In 2016, a WSS was developed to detect a group of heathy male participants' breathing movement in laboratory environment, which was monitored for both the quiet breathing cycles in relaxation and the quick breathing cycles after doing exercises[18)] in Fig. 3. However, it had not been clinically used. In view of that, WSS was further developed and adopted for clinical application in the objective respiratory measurement.

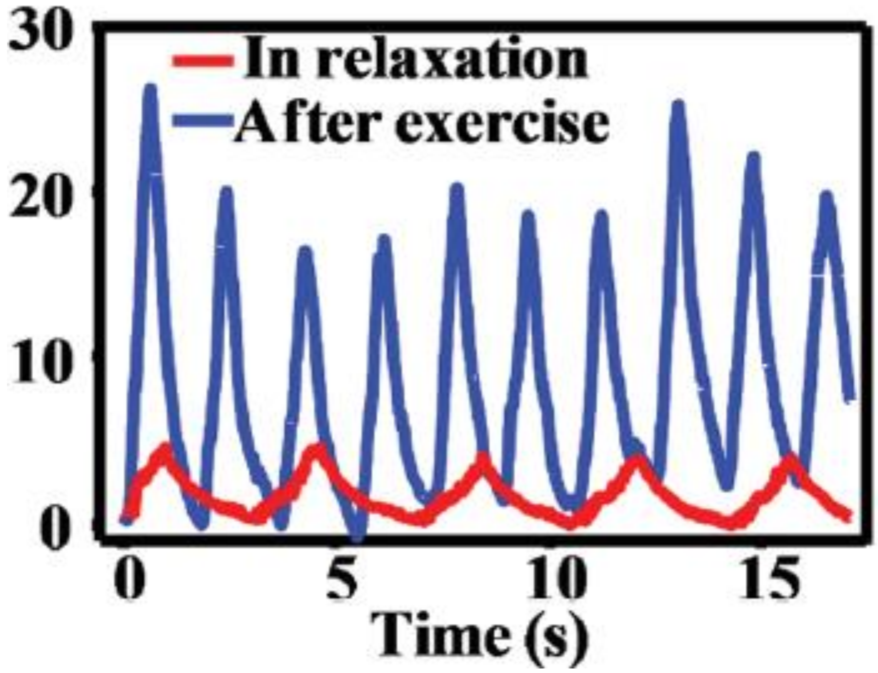

Fig. 3. Detecting the chest wall expansion for breathing movement using WSS

1.4.2 Innovation of medical service pattern

The way of application of the WSS for detecting respiratory movement is pattern-oriented. The first pattern is developed for hospital (medical service), and then the next patterns are for residential communities and families (self-assessment). This is also one of innovations in Star Medical Service Model (SMSM).

1.5 Hypotheses

1) The WSS is a reliable and valid measurement tool to detect the respiratory movement for healthy male participants.

2) The WSS can be applied to clinical practice as an objective quantitative measuring approach in participants with breathing disorders (e.g. the healthy senior people, individuals with cervical spinal cord injury)

1.6 Originality of the thesis

1) As an objective standardized tool, the WSS is experimented in the clinical settings for the first time in China.

2) Though the WSS for breathing movement had already been detected in the laboratory settings, it was yet to be improved and adapted to the clinical settings. In the preliminary measurement, the measuring length of WSS was suggested to be 5% of human axilla circumference (5%AC) after repeated tests. In view of that the WSS was developed not only for convenient application but also cost efficiency so as to be promoted to the market in the future, so the measuring length of each sensor was finally determined to be 3.5 CM.

3) The wireless connection to computer as a terminal for receiving sensor signals through Bluetooth, which is not quite convenient for family self-measurement, so it is considered to use smartphone instead of computer for the future.

1.7 Implication of the thesis

1) As a terminal of collecting sensor signals, the widely-used smartphone is much more convenient for people having breathing disorders in residential communities or families, and it collects data much faster. The data is to be stored real-time in the Cloud-based warehouse online and to be provided with basic support for the big data platform of breathing measurement.

2) The WSS to detect respiratory movement is just a starting point. Mobile Internet Device as a platform, combining breathing measurement with medical intervention, to achieve a real-time and full-time medical attention for patients in residential communities and families, thus forming a remote monitoring network.

3) The big data platform for breathing data obtained by the WSS is the basis of precision medicine evaluations.

1.8 Aim and objectives

1.8.1 Aim

To verify clinical application of wearable strain sensor on respiratory measurement in healthy participants and individuals with breathing problems

1.8.2 Objectives

1) To confirm the test-retest reliability coefficients and the validity of WSS on measuring respiration movement in healthy male participants

2) To compare the correlation between WSS and spirometer on measuring respiration movement in healthy male participants, then to find the best body spot (10^{th} rib) to detect the positive significant correlation on the chest -abdomen wall

3) To explore change of breathing pattern by aging using WSS among different age groups

4) To assess changes of chest-abdomen wall after respiratory exercise in individuals with CSCI using WSS

Outline map of research objectives

Study 1 WSS comparing with a traditional and accepted measuring tape on breathing measurement

→ To confirm the reliability and validity of WSS

Study 2 WSS comparing with spirometer which is an international standard tool for respiratory function assessment

→ To compare the correlation between WSS and spirometer, then to find the best body spot (10^{th} rib) for detecting the positive significant correlation

Study 3 Comparison among different age groups on breathing pattern

→ To explore change of breathing pattern by aging using WSS

Study 4 Measuring difference between before intervention and that of after using WSS

→ To assess changes of chest-abdomen wall after respiratory exercise in individuals with spinal cord injury (CSCI)

Summary

→ All hypothesizes were determined, WSS can be used to clinical application.

1.9 Ethical consideration

This study has been performed with the following consideration for medical ethics.

1) The purposes of this study are fully explained to all participants and their help-givers.

2) The written consent and verbal informed assent are taken.

3) All participants are free to accept or refuse take part in the study and have right to withdraw from the study at any time.

4) No charge from nor incentive to participants.

5) The results of this study are confidential and the findings are used only for the health care purpose and the relevant research

The certificate of Ethics was issued by the International University of Health and Welfare (IUHW), Ohtawara campus, Japan on 28th November 2016.

The ethical approval letter for this study was issued by the Ethics Review Committee (ERC) of IUHW on 24th March 2017 with the approval number 16-Io-176 and 16-Io-177 and on 14th April 2017 with the approval number 16-Io-237 and 16-Io-238.

The ethical approval letter for this study was issued by the Ethics Review Committees (ECR) of China Rehabilitation Research Center (CRRC) on 7th February 2017 with the approval number (CRRC-IEC-RF-SC-005-01).

1.9.1 The Sustaining Confidentiality

The examiner record forms of the WSS data includes name of participants. However, the name of participant belongs to privacy, so it is deleted and replaced by codes according to the procedure. All data from assessment sheets are to be transformed into electronic data, which includes video recording of participants, then the data are copied into a computer with password for assessment at the end of each day. The assessment sheets have been kept in a safe locker of the Department of Physiotherapy in the CRRC, Beijing China. All documents and electronic data shall be kept confidentially for three years before they are deleted.

The information about participants shall not be shared to anyone out of the research team. The information collected from this research project belongs to the privacy of participants. The information recorded is confidential, and no one else except the main researcher has access to it. Any information about any participant had a code on it instead of the participant’s names. Only the main researcher knows to whom the code belongs. The last but not the least, the information may not be shared with anyone.

Chapter 2 RELIABILITY AND VALIDITY OF MEASURING RESPIRATION MOVEMENT USING A WEARABLE STRAIN SENSOR IN HEALTHY PARTICIPANTS

2.1 Introduction and purpose

Respiration movement is an important component in the assessment of pulmonary function. In clinical practice, respiration movement is generally assessed by inspection and palpation in the physical examination, which not only provides real-time observation but does not require any other special measuring devices. Nevertheless, physical examinations are not quantitative, but qualitative analysis based on the experience of a particular examiner. Measurement devices include a magnetometers[26)], respiratory inductive plethysmography[27)], optoelectronic plethysmography[10,28-31)], and respiratory movement measured devices[32-33)], which can be applied for quantitative measurement. Because of the high cost and the complex settings of those devices, they are not suitable for clinical practice sometimes. A scale to assess breathing movements which was only depended on the experiences of the assessor, may not have sufficient reliability[16)].

Measurement of chest expansion is a simple and practical method for assessing participants' respiratory function. Shobo A et al. found that there was a highly positive correlation between chest expansion and changes in the chest volumes at all indicated locations[11-12)]. However, measuring devices of chest expansion were both 3-dimensional motion analyzer and a spherical reflective marker, which were required to conduct in a special experimental environment. It is inconvenient for patients in a clinical setting. The difference of chest expansion between the maximum exhalation and maximum inspiration measured chest circumferences at axilla, xiphoid process and 10th rib was correlated with respiratory function[34)]. The procedure of measurement would take a longer duration, which may increase the fatigue of patients. Therefore, a wearable strain sensor (WSS) was developed for easier to use and more objective measurement of chest expansion in a clinical setting. The purpose of this research is to verify the reliability and validity of measuring respiration movement using a wearable strain sensor (WSS) which has been developed newly for clinical objective assessment.

2.2 Participants and methods

The study was conducted at Shanghai Jiao Tong University. Twenty-one healthy male students were recruited from the university in this research, the characteristics of whom were shown in Table 2, and those with a history of respiratory, circulatory, or neurological disorders were excluded. The study was approved by the Ethics Committees of International University of Health and Welfare (No.16-Io-176 and 177) and China Rehabilitation Research Center (CRRC-IEC-RF-SC-005-01). All the participants signed their informed consent.

Table 2. The characteristics of all male participants in this study. (n=21)

	Mean±SD			
Age (yrs)	24.0±2.7			
Height (cm)	173.8±3.9			
Weight (kg)	67.6±7.5			
BMI (kg/m^2)	22.4±2.6			
IC (cm)	Axilla	Xiphoid process	10th rib	Umbilicus
	93.2±5.5	83.2±6.0	78.4±7.2	80.3±8.3

All values were shown as mean±SD (standard deviation).

BMI: body mass index.

IC: initial circumference (average of during ordinary respiration after measuring three times)

The initial circumferences of chest (axilla, xiphoid process and 10th rib)[34] and abdomen (umbilicus)[11] were measured by a measuring tape (length, 100cm. made in Guangzhou Fengren Ltd. China) during ordinary respiration. The axilla location was the biggest circumference in all the four locations. The 21 participants were advised to conduct a breathing movement with their shirt off and pants loosed in a standing position. Initial circumference was measured at each location as a starting point, and then from the maximal end of expiration to the maximal end of inspiration respectively, confirming the different degrees of chest expansion between the two. Every subject conducted the breathing movement for three times. There was a break between the first and second breathing movements, allowing each subject to feel fine before the second trial.

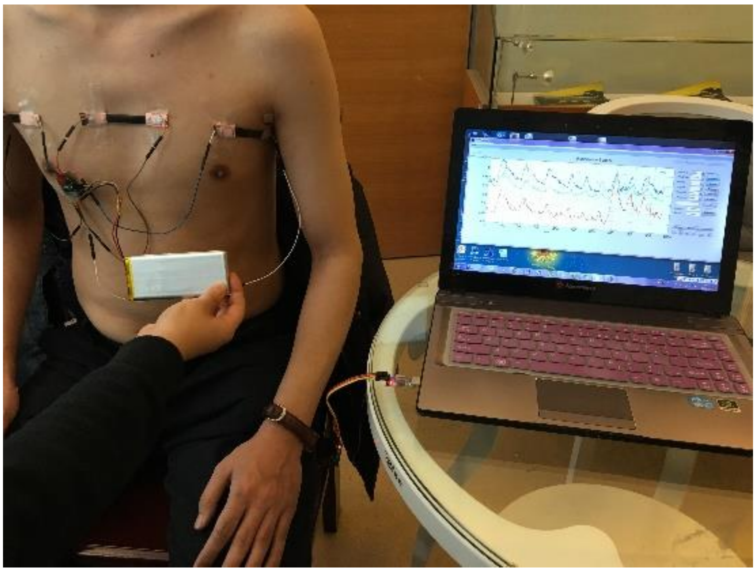

Fig. 4. Respiration measurement using WSS

The measurement with a wearable strain sensor comprises three sensors connected to each other in parallel. They were stuck to the chest and abdomen wall with medical adhesive tape to monitor the movement and the expansion of the thoracoabominal skin. The output of the sensors is connected to a self-designed circuit board, which is also stuck onto the chest or abdomen wall, as illustrated in Fig. 4. The circuit board received the sensor signals, and communicated wirelessly with a computer through Bluetooth[25]. The monitored data are processed using software (MATLAB Version 7.11.0.584 (R2010b), and the workable strain ranges of sensors were calculated using a spreadsheet software (Microsoft Excel, USA).

In the preliminary measurement, the stretched length of wearable strain sensor was selected using 5% of axilla circumference(5%AC), which was convenient and effective for measuring breathing movement. The measurement points were placed along the midline of chest and abdomen through horizontal midpoint of circumference at four locations such as the axilla, xiphoid process, 10^{th} rib and umbilicus. Besides, they were also placed along the second 5% AC bilaterally from the midaxillary line to midline of chest and abdomen at the axilla, xiphoid process, 10^{th} rib and umbilicus, respectively, to escape the cover for the limbs. There were three measurement points for each location, which were matched with the three strain sensors connected to each other in parallel. This means that the four locations had totally twelve points.

Every one of the 21 participants wearing three strain sensors at each measurement point was requested to start breathing while standing. The breathing was supposed to be a breathing as hard as possible which included from maximal end of expiration to maximal end of inspiration. The differences between the maximal end of expiration and the maximal end of inspiration were confirmed. While each subject was breathing for three times at each location, simultaneously the data from the three parallel sensors were collected. After the three different values were acquired from each sensor, the average value was calculated. There was a break between the first and second breathing movements, allowing each subject to feel fine before the second trial.

When one rater measured with the use of a measuring tape and WSS with the synchoronal instructional procedure of respiratory movement, the required criteria of the oral instruction in the two approaches was exactly same. The subject’s test was arranged in an hour after the meal in order to keep fasting state, the retest was conducted at the same time on the second day of test. There were no learning effects, furthermore every test was controlled in the same experimental condition.

The demographics of all participants were shown as mean±SD (standard deviation). The intra-rater ICC (1,1) with 95% confidence interval was used to assess for test-retest reliability and Pearson correlation analysis was performed to establish the related validity of respiratory measurement using the WSS. All data were calculated and analyzed using the IBM SPSS Statistics version 19.0 for Windows software as well as values of less than 0.05 were statistically significant level.

2.3 Results

The test-retest raw data of respiratory measurement using WSS were shown in Table 3, and the intra-rater ICC (1,1) values for test-retest reliability were presented in Table 4. All ICC values for intra-rater reliability were from 0.94 to 0.98 at all locations, there is a high correlation based on the standard of Landis et al.[35].

The raw data of the MT compared with WSS for measuring respiratory movement were indicated in Table 5 as well as to determine the validity of the WSS for measuring respiratory movement, Pearson correlation coefficient was calculated in Table 6. All the values for validity had significant positive correlations on respiratory movement between measuring tape and WSS at four locations ($p<0.01$).

Table 3. The test-retest raw data (Mean±SD) of respiratory measurement using WSS

	Left		Middle		Right	
	test(cm)	retest(cm)	test(cm)	retest(cm)	test(cm)	retest(cm)
Axilla	0.44±0.28	0.43±0.29	0.35±0.21	0.36±0.20	0.45±0.22	0.44±0.22
Xiphoid process	0.33±0.21	0.36±0.19	0.34±0.20	0.34±0.19	0.35±0.20	0.37±0.20
10^{th} rib	0.60±0.26	0.61±0.24	0.57±0.22	0.58±0.22	0.53±0.22	0.55±0.21
Umbilicus	0.45±0.17	0.44±0.16	0.46±0.24	0.47±0.25	0.45±0.24	0.45±0.25

WSS: wearable strain sensor   Mean±SD: mean ± standard deviation

Table 4. The test-retest reliability of respiratory measurement using WSS for ICC (1,1)

	Left	Middle	Right
Axilla	0.97**	0.97**	0.98**
Xiphoid process	0.94**	0.98**	0.95**
10^{th} rib	0.97**	0.98**	0.96**
umbilicus	0.96**	0.98**	0.98**

WSS: wearable strain sensor

**: p<0.01 was significant, 95% confidence interval. ICC: intraclass correlation coefficient.

Table 5. The raw data (Mean±SD) of the MT compared with WSS for measuring respiratory movement

	MT(cm)	Left WSS (cm)	Middle WSS (cm)	Right WSS (cm)
Axilla	5.43±1.56	0.35±0.31	0.36±0.29	0.36±0.27
Xiphoid process	5.19±1.92	0.41±0.21	0.42±0.20	0.42±0.20
10^{th} rib	6.71±1.86	0.56±0.22	0.60±0.19	0.56±0.21
Umbilicus	4.04±1.6	0.27±0.19	0.29±0.21	0.27±0.21

MT: measuring tape   WSS: wearable strain sensor   Mean±SD: mean ± standard deviation

Table 6. The validity of the WSS for measuring respiratory movement

	Left	Middle	Right
Axilla	0.72**	0.73**	0.73**
Xiphoid process	0.80**	0.82**	0.81**
10^{th} rib	0.83**	0.85**	0.82**
umbilicus	0.79**	0.82**	0.79**

WSS: wearable strain sensor

**: p<0.01 was significant correlation at 0.01 level (bilateral).

2.4 Discussion

This study confirmed the reliability and validity of the innovatively developed wearable strain sensor. The motivation of developing WSS was due to both the high subjectivity existing and complex limited setting during respiratory movement assessment in clinical practice at present. The reliability of WSS with a high correlation and validity of WSS with relatively high values, compared to the results of the measuring tape, were valuable. These findings indicate that the WSS is available as a convenient approach for objective measurement of respiratory movements on the chest and abdomen wall in clinical assessment.

In preliminary measurement, the stretching length of wearable strain sensor with 5% of axilla circumference (5%AC) was selected which is convenient and effective for measuring respiratory movement. This length was assumed based on the following reasons:1) Taking the same proportion of their individual AC for each subject, and performing the same measuring procedure, the results obtained from the test are comparable. 2) 5%AC was considered based on axilla circumference mean±SD of the subject's sample, which is the longest on the part of both length and coverage compared to 5%AC of the other three locations. Moreover, it's convenient for calculation and more effective for measuring expansion of chest and abdomen wall. 3) There was one developed size (3.5cm) based on initial axilla circumference (93.2±5.46) for the original length of strain sensor with the loading of strain in the range of 0%-250%[14]. Owing to the length with 3.5cm of three-channels, WSS was placed matching to 5% AC during ordinary breathing meanwhile the original length with 3.5cm was stretched to the individual 5% AC of each subject as a starting point to measure. Therefore, the original length of WSS with 3.5cm was applied in this study. In fact, the original length of WSS was not correlated with the percentage of circumference of chest and abdomen wall for measuring respiratory movement. The reliability and validity of WSS with 3.5cm were more essential in clinical evidence.

In this study, the reliability ICC (1,1) of WSS at each location performed high values. The values of both left and right of chest and abdomen wall, however were a little lower compared with middle place. The analyzed reason was the muscles strength with unbalance on the trunk bilateral or trunk with side-flexion in standing position during respiration movement. Although the same breathing was conducted, the measured stretching skin of bilateral trunk was diverse by WSS with high sensitivity and high stretchability based on stretching mechanism[14].

Regarding the validity, all the values of this study presented a significant correlation ($p<0.01$) between WSS and measuring tape. Therefore, we concluded that the validity of measuring respiration movement using WSS was satisfactory. The measuring tape was a reference variable in this study which was a circumference test of chest and abdomen wall that provided a difference between maximal end of expiration and, maximal end of inspiration. This test has limitations as follows: because there are four locations which were needed to measure on chest and abdomen wall, measuring respiratory movement for three times at each location, totally taking approximately 25 minutes, the whole measuring procedure for each subject may cause fatigue even for young people; the test may be not suitable for participants with both same circumference size on chest and abdomen wall and similar respiratory movement, because of the measured results among the participants without any distinction using measuring tape. The WSS with high sensitivity, however is more objective accuracy, which can capture signals with the tiny muscle movement caused by blinking[18)]; As noted above, the validity values of WSS were not significantly high from 0.72 to 0.85. The validity of axilla location were the lowest values compared with another three locations, the cause of which may be that the measuring tape was caught by both upper limbs in the armpit, resulting in reading errors. All correlation values of the left, right, and middle were satisfactory, however, the middle positions of chest-abdominal wall were more convenient to measure for clinical study; and the relationship between local measurement and integrated measurement need to be considered, it is vital to place wiring by the same proportion. The WSS with low cost compared with measuring tape really displayed a more precise advantage, and a decreased both participants' fatigue and medical worker's workload.

In clinical application, an objective measurement of respiratory movement may facilitate a more meaningful assessment of respiratory conditions which can be shared among professionals with existing respiratory problems. It is considered that WSS may replace the physical examination as an objective measurement for respiratory movement in clinical practice, because this study presented that WSS has been proved to have a high degree of reliability and validity, and without limitation of posture or environment during respiration measurement.

Nevertheless, there are some limitations in this study: the communicated wireless computer through Bluetooth would be inconvenient compared with a smartphone; the measurement of ordinary respiration cycles would be needed in patients with respiratory problems; and the selected participants were only male in this study, so the findings based on the data of the male. Although the WSS may be useful as assisting assessment device for respiratory movement to augment objective measurement, further studies of respiratory measurement using WSS would be more valuable in patents with respiration problems.

Chapter 3 THE BEST BODY SPOT TO DETECT THE VITAL CAPACITY FROM THE RESPIRATORY MOVEMENT DATA OBTAINED BY THE WEARABLE STRAIN SENSOR

3.1 Introduction and purpose

Among all means to measure and follow changes in pulmonary function, the most frequently used means is to measure the volumes and airflow of the vital capacity by a spirometer. However, it is also important to measure the chest-abdomen expansion for exploring the rootcauses of the impaired pulmonary function, such as the dyspnea or rheumatic diseases, physical conditions after the thoracic and abdominal surgery, or decreased exercise tolerance [36-38], for which, various techniques can be used.

For example, such sophisticated instruments as inductive or opto-electronic plethysmography, computed tomography or video systems have been used in clinical practices [11,12]. However, these instruments are not suitable for general clinical practices due to their high cost. Therefore, some new devices with low cost have been developed, such as the respiratory movement instrument (RMMI), breathing movement measuring device (BMMD) and 3D motion analysis system etc. [12,13-15], but their application needs special experimental environment or to be installed in a complex setting.

A simple and practical method is using a measuring tape to assess the mobility of the chest-abdomen wall [13,17]. However, this method is unable to indicate the best body spot for detecting the correlation of the data obtained by the tape to that obtained by the spirometer.

In our previous studies, a newly developed wearable strain sensor (WSS) for respiratory measurement at different body spots from the chest to abdomen showed high reliability and validity compared that obtained by the measuring tape[39]. Nevertheless, we failed to find the better body spots than the spot at the chest midline where the most correlated data can be obtained to the vital capacity data obtained by the spirometer.

This study was conducted to explore the correlation of the data obtained by the WSS to the vital capacity data obtained by the spirometer. The purpose is to find the best body spots on the chest and abdomen wall to obtain the correlated indicators to the vital capacity.

3.2 Participants and methods

This research was carried out at Physical Therapy Department in China Rehabilitation Research Center. Thirty healthy male staff of the center served as the participants, whose characteristics were presented in Table 1. The physical criteria for the participants were without a history of respiratory, circulatory, or neurological disorders. All participants gave written informed consent before taking part in this study. The Ethic Committees of International University of Health and Welfare (NO.16-Io-238) and China Rehabilitation Research Center (CRRC-IEC-RF-SC-005-01) approved the study protocol.

The measurement of the vital capacity was performed from the maximal end of inspiration to the maximal end of expiration done by a spirometer (Pivot Flow 300, YiAn Technology Co. Ltd, China). A wearable strain sensor device (WSS) was used which comprises four sensors connected each other in parallel[8)], each with a length of 3.5 cm. The four sensors with medical adhesive tape were stuck to the chest-abdomen wall of each participant for monitoring its movement and expansion. The output of the sensors was connected to a circuit board, which was also stuck to the chest-abdomen wall. The circuit board received the sensor signals and transferred the signals to a computer through the bluetooth[25)]. The monitored data are processed by a software (MATLAB Version 7.11.0.584 (R2010b), and the workable strain ranges of sensors were calculated by a spreadsheet software (Microsoft Excel, USA)[39)].

Four strain sensors were stuck respectively to four body spots, i.e. the axilla, xiphoid process, 10th rib and umbilicus of each of the 30 participants. It was required to wrap up the mouthpiece of the spirometer while using the nose clip, and to perform the breathing movements with the shirts off and pants loosed in standing posture, the participants have been told not to move their trunk and shoulders during the measuring period, as illustrated in Fig. 5. The breathing range was supposed to be from the maximal end of inspiration to the maximal end of expiration. The differences between the two maximal ends were recorded by the WSS and spirometer respectively. While a participant was breathing each time, the respiratory movement data were collected by the four parallel sensors and the vital capacity data were recorded by the spirometer.

Fig. 5. Respiration measurement using WSS and spirometer

The demographic data of the participants were expressed as means±SD (standard deviation). The correlation analysis on the specific persons was conducted to find the correlation of the data obtained respectively by the WSS and spirometer during the breathing movements at the four body spots. All data were analyzed using the IBM SPSS statistics software version 24.0 for Windows, and the values of less than 0.05 were statistically significant level.

3.3 Results

All participants baseline characteristics of anthropometry and vital capacity were shown in Table 7. The raw data of the WSS compared by the spirometer for measuring breathing movement on axilla, xiphoid process, 10^{th} rib and umbilicus respectively were presented in Table 8. The correlation of the mobility data at the four body spots to the vital capacity data were calculated for each level by means of Pearson's correlation coefficient in Table 9, which showed that the values at each body spot were positive significant correlations and the highest value was at the 10^{th} rib.

Table 7. All male participants baseline characteristics (n=30)

	Mean±SD
Age (yrs)	30.1±5.3
Height (cm)	172.9 ±5.6
Weight (kg)	76.0 ±17.5
BMI (kg/m^2)	26.0±4.7

All values were shown as mean±SD (standard deviation).

Table 8. The raw data (Mean±SD) of the WSS compared by spirometer for measuring breathing movement at the four body spots

	Spirometer (l)	Axilla (cm)	Xiphoid process (cm)	10th rib (cm)	Umbilicus (cm)
Raw data	3.61±0.51	0.23±0.03	0.23±0.04	0.43±0.08	0.28±0.06

WSS: wearable strain sensor. All values were shown as mean±SD (standard deviation).

Table 9. The correlation of the WSS data at the four body spots to the vital capacity data were calculated for each level.

	Axilla	Xiphoid process	10th rib	Umbilicus
Correlation r-value	0.676**	0.631**	0.824**	0.715**

WSS: wearable strain sensor

**p<0.01 was significant correlation at 0.01 level (bilateral).

3.4 Discussion

The results from this study tell us that there was a positive significant correlation ($p<0.01$) between the mobility of the chest and abdomen and vital capacity at the four body spots. Furthermore, the 10th rib with a highest value is the best body spot to detect the correlation to the vital capacity. All of the results were satisfying.

Our previous study verified that the stretching length of each wearable strain sensor, i.e. 5% of axilla circumference (5%AC) was selected as the longest length for measuring breathing, and the original length of 3.5 cm can be used[8)]. In this research, if only 5% AC continues to be used, this is not obviously objective. Because 5%AC is not the longest circumference of the chest and abdomen for the four body spots in this sample size, most of the participants had longer abdomen circumferences than that of their chest. In order to collect more accurate results, 5% of each body spot circumference was used. Thus, all of the findings were convincing.

According to the Asian standards of the World Health Organization (WHO) regulations, if BMI is in the range from 25.0 kg/m^2 to 29.9 kg/m^2, then it is to be defined as being obese[40)]. The participants in this test with BMI mean (26.7±1.4 kg/m^2) belong obesity group, but their 10th rib with the highest correlation value (0.86) during respiratory movement were consistent with reports of both Cala et al. and Liu et al.[28,39)]. Meyer suggested that a correlation coefficient $r\geq0.8$ means a high correlation, r=0.6--0.8 means a good correlation, r=0.4--0.6 means a moderate correlation, and $r\leq0.4$ means a poor correlation[41)]. Therefore, the 10th rib is the most significant body spot to explore the correlation to the vital capacity. The correlation values of the chest were distinctly lower than that of the abdomen during the breathing movements. There are two reasons for that as follows: 1. To perform the breathing movement from the maximal end of inspiration to the maximal end of expiration in standing posture, the abdominal muscles press the abdominal content upwards to decrease the lung volume, the internal intercostals lower and decrease the rib cage[42-44)]. During the maximal expiration in this test, the vital capacity was collected by the spirometer without any interferences, but the mobility variation of the rib cage was measured by the WSS, which would be increased due to the shoulders adduction. In other words, the smaller the range of the rib cage is, the greater the differences between the two maximal ends of respirations on axilla and xiphoid process are. 2. There is another suspicion, that is, the higher the value of the vital capacity data obtained by the spirometer is, the lower the respiratory value data obtained by the WSS is. The explanation for this is that the existence of differences in individual physiological structures leads to a greater vital capacity, meanwhile the mobility of the chest is not monitored during the breathing movements. Or abdomen breathing is dominant as a factor among the male participants[42)]. Based on the above analysis, the 10th rib is the best measuring spot compared with the other three spots. Monika at al. found that the mobility of the rib cage is smaller at the lower thoracic level of the xiphoid process than that at the level above the 4th rib[45)]. This result would be explicating that the correlation at xiphoid process is lower than that at axilla in this test.

Several limitations in this study should be considered: firstly, the participants among the obesity group served as a disturbance factor that may increase errors; secondly, the measured data in standing posture may be unstable during the breathing movements, because of that the participants would move their shoulders, which would impact the chest movement, though they have been told not to move their trunk during the measuring period; thirdly, there was a random error when the strain sensors were placed at 5% of each body spot circumference, because some of the sensors were placed not so precisely; fourthly, the selected participants were only male in this study, so the findings based on the data of the male.

The awareness of the movement correlation between the chest and abdomen is very important in future research, because it can interpret the results of different treatment interventions or changes in range of motion. Although the spirometers used worldwide have such advantages as high reliability, validity and sensitivity, and easy to handle[46)], in many clinical tests when they are used to evaluate the effects of different breathing exercises of changes or to explore the improving dynamic ranges of the breathing movements at different body spots, the measuring outcome is not sufficient to make a conclusion. Therefore, the method is not satisfactory[47)]. In this study, the WSS with high sensitivity and accuracy, used to find the correlation to the data obtained by spirometer, presented certain advantages compared with the spirometer, such as low cost, easy to use without limitations of posture and environment, and specific body spot analysis. To detect voluntary mobility of the chest and abdomen during the breathing movements by the WSS seems to reflect better than the vital capacity. These findings could possibly be useful for evaluating the effects of breathing exercises at different body spots of a patient with a restricted lung capacity, such as the rheumatic patients, the senior people, and the postoperative patients. Therefore, in the future studies, the further research should pay more attention to participants with different disease in the chest and abdomen.

In summary, there was a correlation between the mobility data of the chest and abdomen obtained by the WSS and the vital capacity data obtained by the spirometer, for which, the 10^{th} rib is the best body spot to detect the positive significant correlation. Therefore, we can infer the pulmonary function according to the mobility of the chest and abdomen in the future.

Chapter 4 APPLICATION OF USING A WEARABLE STRAIN SENSOR ON RESPIRATORY EVALUATION IN PHYSIOTHERAPY---CHANGING WITH AGING IN BREATHING PATTERN

4.1 Introduction and purpose

The year 2000 witnessed a turning point when China's population started to be aging. In 2014 statistics showed that the elderly above 65 in China amounted to 138 million, that was 10% of the total population of the country. By 2020, the percentage would rise to 13%[48)]. In the near future, some of the appeared "disease" state of an aged person may be regarded as a "normal" physiological state in clinic. Therefore, to redefine a clear-cut line between the two states is vitally important. When people get old, their respiratory system would change accordingly. Such structural changes as the chest wall and thoracic spine deformities are most apparent and the variations in the physiological structural indexes are also obvious. That is why it is not easy to redefine the criteria to distinguish between the "disease" state and "normal" state[49)]. As the matter of fact, the respiratory muscle strength, chest expansion compliance, and lung functions of aged persons would all be degraded, thus their respiratory system functions would become weakening and their work of breathing rising, clearance of airway secretion narrowing and effective cough reducing. These changes can to some degree interpret some clinical manifestation and aberrant diagnostic cases of aged persons[50)].

One's breathing movement is concerned with the rib cage of the chest and the abdomen wall [49)]. The chest compliance depends on the elastic load when breathing in. When a person gets aged, his or her chest wall compliance would reduce and aging-related problems such as osteoporosis, stiff calcification of the rib cage, and kyphosis would occur[3)]. The most important respiratory muscle is diaphragm, which can drive the movement of the abdomen wall. The diaphragmatic muscle would atrophy, and all other muscle strength would reduce, thus causing lager residual volume, when people become old[51)]. Briefly speaking, how to measure and evaluate the breathing pattern changes with aging in timely and effective methods is crucial.

Though some sophisticated instruments such as inductive or opto-electronic plethysmography, computed tomography or video systems have been applied in clinical assessment for breathing movement[9,10)], these instruments are not available for general clinical studies because of their extremely-high cost. Therefore, some new devices with low cost have been developed, such as the respiratory movement instrument (RMMI), breathing movement measuring device (BMMD) and 3D motion analysis system etc. [12, 13-15)], but these devices need a special experimental environment or need to be installed in a complex setting. A simple and practical method with a measuring tape to assess the mobility of the chest-abdomen wall is developed [13,17], but this method is only suitable for the studies only with a limited sample size instead of those with a large sample size and those wanting repeated measurements, because in such a case, the measurement results would be affected due to the fatigue of those testers.

Therefore, the WSS has been newly developed to meet the special purpose of the study clarifying the changes of breathing pattern of aged people and ascertaining differences of the chest-abdomen movement of different age group, i.e. young people, middle-age people, and senior people. The study proves our hypothesis that human breathing pattern would change with aging.

4.2 Participants and methods

This study was conducted at Physical Therapy Department, China Rehabilitation Research Center. Twenty-three students from The Capital Medical University served as the youth group, thirty staff from the PT Department of the research center as the middle-aged group, and twenty-nine senior citizens from the nearby JiaoMen residential community as the aged group, altogether eighty-two participants, all being healthy male, had been recruited to take part in the study. The physical criteria for selecting the participants were that they should have no history of respiratory, circulatory or neurological disorders. All participants were informed to sign an agreement in their own will before taking part in the study. The Ethic Committees of International University of Health and Welfare (No.16-Io-177, and 238) and China Rehabilitation Research Center (CRRC-IEC-RF-SC-005-01) had jointly approved the study protocol.

For conducting this study, a wearable strain sensor device (WSS) was used to detect the chest-abdominal breathing pattern and movements. It consists of four 3.5-cm-long sensors, which are connected with each other in parallel. The four sensors were stuck to the chest-abdomen wall of a participant with medical adhesive. The output signals detected by the sensors were sent to a circuit board that is also stuck to the chest-abdomen wall, which then send the signals to a smartphone via the blue-tooth[25)]. The data thus produced were processed by an application software (MATLAB Version 7.11.0.584 (R2010b). The appropriate strain ranges of the sensors were thus calculated by a spreadsheet software (Microsoft Excel, USA)[39)].

All of the four sensors were stuck to four spots of the chest-abdomen wall, that is, the axilla, xiphoid process, the 10th rib and umbilicus of each of the participants in three groups, so as to monitor the chest-abdominal breathing pattern and its movements. During the process, the participants should be in standing position, with shirts off and pants loosen, and not move their torsos and shoulders as shown in Fig. 6. The participants should breathe in and out to the maximum. The WSS device would record the maximum movement range of the deep chest-abdominal breathing. The data of the breathing movement of each cycle were detected by the four sensors for five times and the average value of the five-time data of each sensor was calculated. It is required to have a break between the first and the second movement for all the participants in three groups to get a little rest, allowing each subject to feel fine and removing fatigue effects, to guarantee the quality of the second test.

The characteristics of all participants were described as means ± SD (standard deviation). The data to be studied include breathing movement values of the axilla, xiphoid process, the 10th rib and umbilicus on chest-abdomen wall, which were examined by the Two-way ANOVA so as to compare the four values detected by the WSS among different groups, the Bonferroni was done as a post-hoc test to ascertain significant differences. All data were analyzed using the IBM SPSS statistics software version 24.0 for Windows, and the values of less than 0.05 were statistically significant level.

Fig. 6. Respiration measurement by means of the WSS

4.3 Results

The baseline characteristics of anthropometry of all participants were shown in Table 10. The raw data detected at the axilla, xiphoid process, the 10^{th} rib and umbilicus respectively by the WSS were presented in Table 11 as the measurement of the breathing movement of the three groups. The result of the data analysis shows that all had significant differences at four spots between the senior group and the youth group ($p<0.05$); there are significant differences at the axilla, xiphoid process and the 10^{th} rib ($p<0.05$) except the umbilicus between senior group and the middle-aged group ($p>0.05$); there are significant differences at the axilla, xiphoid process, 10^{th} rib and the umbilicus between the middle-aged group and the youth group ($p<0.05$). As a whole, there is statistical difference as a main effect among the three groups, $F(2, 79) = 4.382$ ($p<0.05$). Next the Bonferroni test as a post hoc analysis showed that the expansion ranges at the axilla, xiphoid process, and the 10th rib of the senior group were obviously smaller than the youth group and the middle-aged group, but the expansion range at the umbilicus had no much difference from the middle-aged group.

Table 10. The characteristics of all male participants in this study. (Mean±SD)

	Youth group (n=23)	Middle-age group (n=30)	Senior group (n=29)
Age (yrs)	24.0±2.7	40.1± 4.3	75.5±8.2
Height (cm)	173.8±3.9	173.6±3.6	169.9±5.5
Weight (kg)	67.6±7.5	77.0±17.5	68.0±11.1
BMI (kg/m^2)	22.4±2.6	26.3±3.7	23.7±3.8

All values were shown as mean±SD (standard deviation).

BMI: body mass index.

Table 11. The raw data (Mean±SD) of the WSS among three groups for measuring breathing movement at the four torso spots

		Youth group	Middle-aged group	Senior group	p-value
Axilla	(cm)	0.33±0.20	0.31±0.04	0.23±0.02	*1, *2
Xiphoid process	(cm)	0.36±0.20	0.33±0.05	0.26±0.02	*1, *2
10th rib	(cm)	0.48±0.24	0.43±0.07	0.39±0.06	*1, *2
Umbilicus	(cm)	0.42±0.22	0.38±0.05	0.39±0.06	*1, 3

WSS: wearable strain sensor

*1. $p < 0.05$ Between youth group and senior group

*2. $p < 0.05$ Between middle-aged group and senior group

3. $p > 0.05$ Between middle-aged group and senior group

4.4 Discussion

The study finds that the respiratory function changes with aging remarkably. Aging would cause a decrease in the range of the chest and abdomen expansion, the scientific evidence of which is the difference of the breathing movement among youth, middle-aged, and senior group. Moreover, it is very essential that breathing pattern has been changed by aging.

This study also found that the maximum expansion range of the chest and abdomen in youth group is most noticeable among all three groups in terms of the chest-abdominal breathing pattern, and the expansion range of the chest wall is obviously smaller than the other two groups. For the in middle-aged and senior group, the expansion of the chest wall is smaller than that of the abdomen wall. This can be explained by the following two aspects: 1) due to the anatomical changes. There would be a reduction with aging in supporting tissue of the rib cage, which would result in premature closure of the small airway during normal breathing [52-54)]. or smaller chest wall expansion; 2) due to the morphological changes. The expansion of the chest wall would be affected by the capacity of thorax, which depends on the mobility of the skeletal muscles, the elasticity of surrounding soft tissues, and respiratory muscles intensity[55-57)]. Therefore, the chest wall expansion would diminish with aging. Owing to diaphragmatic strength decrease with aging [2,58-59)], the expansion ranges of the 10^{th} rib on the abdomen wall of the senior group would become smaller than that of the middle-aged group. Only thing on the contrary is that the expansion range at umbilicus of the middle-aged group would became smaller than that of the senior group. And there was another explanation, breathing expansion reduction on abdomen wall would have more irregular breathing rhythm in the elderly[60)], apart from external changes. In general, the five breathing movements from the maximal end of inspiration to the maximal end of expiration in this study were unable to be conducted at the same breathing rhythm.

In this study the WSS was used when measuring expansion of the chest wall and abdomen in clinical practice for detecting the changes in thoracoabdominal compliance. In fact, in the case of similar lung compliance, the chest wall expansion was lower for some of aged people[49)], so it is difficult to discriminate the differential diagnosis if only the routine spirometer or other similar instruments are used in clinical practice. Therefore, the WSS with high sensitivity and accuracy was developed for measuring the expansion of the chest and abdomen wall of the aged people, which does not need special environment nor to be installed in sophisticated settings[38)]. In addition, the WSS with lower cost is affordable for ordinary aged people, so WSS are used to monitor their respiratory conditions and expansion of chest-abdomen at home. The aged people usually have reduced respiratory space, weakened ventilatory tissue that causes hypoxia and hypercapnia. All these could induce ventilatory failure (i.g, heart failure, pneumonia, etc.)[49)]. So compared to young people, the aged people have lower respiratory capability and should be paid more attention to their respiratory function[49)]. Traditionally, breathing exercise in physical therapy was usually assessed only by observation or palpation of the experienced therapists during the physical examination, while now the WSS can replace the physical examination as an objective tool for measuring the respiratory movement in clinical practice[39], and trying to simplify the measuring approach on distinguishable breathing pattern using WSS. Moreover, the clinical measurement done by the WSS is an effective approach for monitoring lung function, thus being able to reduce the probability of delay in medical treatment. Compared with our previous versions, the data collection terminal of the WSS was replaced by a smartphone as a technological innovation. However, there are still some limitations in this study. First, the participants in the middle-aged group were on the younger side, which resulted in the similar respiratory conditions with the youth group; secondly, BMI indexes of the middle-aged group and the senior group were on the higher side and some people in the two groups had abdominal distension, which more or less interfered with their breathing movement; thirdly, when the respiratory signals were collected by a smartphone via blue-tooth, the data transmission would be disturbed or sometimes even be interrupted by some unidentified external factors; fourthly, if there exists some perspiration on the skin of the detected spot, the sensitivity of the strain sensors would be affected during the respiratory data detecting process; fifthly, the selected participants were only male in this study, so the findings based on the data of the male.

Chinese population are increasingly aging. Our further studies in the near future would include the evaluation of the age-related changes of the respiratory system and providing scientific and valuable evidence for the clinical medical practice. The expansion ranges of the respiratory movement at the axilla, xiphoid process, and the 10^{th} rib except the umbilicus detected by the WSS device were obviously weakened for the aged people. Thus, breathing pattern of the aged people would change. In conclusion, the results of this study also prove our initial hypothesis that people’s breathing pattern would gradually change with aging during their entire life span. Therefore, it is essential to call external medical attention and intervention.

Chapter 5 MEASURING THE CHANGES OF THE CHEST-ABDOMEN WALL IN INDIVIDUALS WITH CERVICAL SPINAL CORD INJURY USING THE WEARABLE STRAIN SENSOR

5.1 Introduction and purpose

Spinal cord injury (SCI) may cause an impairment of the respiratory function[61)]. In fact, respiratory insufficiency caused by SCI may lead to death[62-64)]. The number of traumatic SCI cases in the world ranges between 236 to 1298 in every one million persons[65,66)]. In the USA alone, there are about 300,000 patients with chronic SCI[67,68)], and 83% of which suffer serious respiratory complications[69,70)]. Among the 5.3 million SCI patients in the world, most spend the rest of their lives in the wheelchair and bed. Pulmonary disease is the No. 1 complication among the all[71)]. In general, majority number of traumatic SCI cases are male[72)]. Whether their SCI extend to the respiratory insufficiency or not, depends on the level of the injury as well as the completeness of the lesion[73)]. The risk of the pulmonary infections for the patients with complete lesions is 3.5 times higher than those of incomplete lesion[74)]. The mechanical properties of the lung and chest wall of patients with cervical level spinal cord injury tend to reduce the lung volumes, weaken the flexibility of the chest wall, impair the strength of the respiratory muscles and narrow the range of the breathing, thus causing a lager residual volume[75)]. Dysfunctional respiration cripples the cough and secretion clearance, impedes the airways and increase risks of the respiratory tract infections[76)]. Therefore, it is crucial to measure and evaluate the breathing movement of the cervical spinal cord injury (CSCI) cases timely.

Though some sophisticated instruments such as inductive or opto-electronic plethysmography, spirometer, etc. have been applied in clinical assessment for breathing movement of the CSCI cases [13,14)], they are not quite available in clinical study due to the extremely-high cost[77)]. So some new devices with low cost have been developed, such as respiratory movement instrument (RMMI), breathing movement measuring device (BMMD) and 3D motion analysis system etc. [12,13-15)], but these devices need a special experimental environment or need to be installed in a complex setting. For this reason, a simple and practical method with a measuring tape to assess the mobility of the chest-abdomen wall is developed [13,17)], but this method is not suitable for a large sample size and repeated measurements, because in such a case, the measurement results would be affected due to the fatigue of the participants with CSCI. In addition, to measure a peak cough flow by means of an “asthma” peak flow meter is not quite reliable, so it is not recommended to be applied in the CSCI cases of the daily clinical setting[78)].

In view of the above-said short comings and limitations of the existing instrument, this study proves that the wearable strain sensor (WSS) is an applicable and cost-efficient instrument that can meet the special purpose to measure the expansion change of the chest-abdomen wall of the CSCI cases after a breathing training.

5.2 Participants and methods

This study was conducted with a consecutive enrollment of participants from the Physical Therapy Department, China Rehabilitation Research Center between April 2017 and March 2018. Totally 93 male participants having C4-C8 cervical spinal cord injury (35 incomplete and 58 complete) had been recruited to the study, the characteristics of the participants is shown in Table 12. The criteria for selecting the participants were as follows: (1) post-injury more than 6 months, (2) no cardiopulmonary disease, (3) Mini-mental state examination-China version score was 24 or higher and fully understand and comply with therapists' instructions. But with the following exclusions: (1) with inherited and congenital neuromuscular disorder such as muscular dystrophies, congenital and acquired myopathies, spinal muscular atrophy, etc.; (2) without respiratory disorders caused by spinal injury, such as COPD, asthma, etc. All participants were informed to sign a consent in their own will before the start of the study. The Ethic Committees of International University of Health and Welfare (No.16-Io-237) and China Rehabilitation Research Center (CRRC-IEC-RF-SC-005-01) had jointly approved the study protocol. All CSCI participants were randomly assigned to one of the following two groups: experimental group (EG=56) and control group (CG=37). The intervention was conducted by Rancho Los Amigo Hospital[79] (RLAH) for the EG by the same skilled physiotherapist, the RLAH exercises method includes five exercises as follows: (1) Rib rotation; (2) Trunk rotation; (3) Trunk side-flexion; (4) Thoracic over-extension; (5) Sylvester. The "anatomic dead space" (Ttiri-ball breathing exercise, Type A Jinjie, China) for practicing taking deep breath in 150 ml was taken for the CG by participants to their own wills. Each exercise duration 15 minutes for each unit, five times for one week, total 4 weeks exercise.

Table 12. The characteristics of all male participants in this study. (n=93)

	Mean±SD
Age (yrs)	34.0±15.6
Height (cm)	172.8±5.7
Weight (kg)	70.6±7.3
BMI (kg/m^2)	26.4±3.5
MBI (scores)	10.0±5.0
Time post-injury (yrs)	3.0±2.2

All values were shown as mean±SD (standard deviation).

BMI: body mass index.

MBI: Modified Barthel Index, scores of 0~20 indicate complete dependence[80].

WSS is a strain sensor device containing four 3.5cm long sensors connected in parallel. The output of the sensors is connected to a circuit board, which then transfers the signals to a smartphone via bluetooth[25)]. Each participant had one strain sensor with a circuit board attached to his chest-abdominal wall by a medical adhesive tape to monitor the chest-abdominal wall expansion. The data was processed by a software (MATLAB Version 7.11.0.584 (R2010b). The workable strain ranges were calculation by a spreadsheet software (Microsoft Excel, USA)[39)].

Each of the 93 participants with CSCI had four units of strain sensor placed on the chest-abdominal wall at the following spots: the axilla, xiphoid process, the 10^{th} rib and umbilicus. Each participant was required to do the chest-abdominal breathing movement in the supine position on their knees on a pillow and with their shirts off and pants loosen[81)]. The participants were instructed to do the breathing in several cycles while not moving their trunks and shoulders during the measuring process. A complete breathing range from the maximal end of inspiration to the maximal end of expiration was measured. The differences between these two ends were recorded by the strain sensor. During each breathing cycle, the data of the breathing movements was collected by the four parallel sensors. A total of five cycles were collected, with a little break before each cycle. An average value of the data collected by each sensor was calculated. The chest-abdomen wall measurements for the participants in above-said two groups were arranged before and after each exercise with an interval of twenty minutes on the first day, and the same measurements were arranged after the exercises on the last day of one week and of one month.

The participants' characteristics were described in frequency tables, means, and standard deviations. Two-way ANOVA was used for analysis of the differences between the EG and CG, which were also calculated with the above-mentioned method. The Bonferroni as a post hoc test to ascertain significant differences. All data were analyzed by the IBM SPSS statistics software version 24.0 for Windows, a significant level of 0.05 was needed in all statistical analyses.

5.3 Results

The raw data of the participants both in the EG and CG collected from the breathing movement measurement for four times at the axilla, xiphoid process, the 10th rib and umbilicus respectively were shown in Table 13. The effects of the EG and CG on the chest-abdomen wall expansion at the axilla, xiphoid process, the 10th rib and umbilicus are obvious. The data showed significant differences in the expansion range of the chest wall (axilla, xiphoid process) after doing exercises for one month ($p < 0.05$). There is a significant difference in the expansion range at the xiphoid process after doing exercises for one week ($p < 0.05$), while no significant differences at four spots after doing exercises for the first day ($p > 0.05$) in EG. There were no significant differences at the 10th rib and umbilicus during the four measurements between the EG and CG ($p>0.05$). As a whole, there is statistical significance as a main effect between the EG and CG, $F (7, 364) = 11.957$ ($p<0.05$). The Bonferroni test as a post hoc analysis showed that the expansion of the chest wall (axilla, xiphoid process) after doing exercises for one month in the EG was more obvious than that for one week, while the abdomen wall expansion remained no change.

Table 13. The raw data (Mean±SD) of the strain sensor in EG and CG for measuring breathing movement at the four body spots

	The first day		The end of week	The end of month
	B-e	A-e	A-e	A-e
	(mm)	(mm)	(mm)	(mm)
Axilla				
EG	1.5±1.2	1.6±1.2	1.7±1.4	2.3±1.3*
CG	1.6±1.3	1.7±1.4	1.7±1.5	1.8±1.4
Xiphoid process				
EG	1.1±1.0	1.2±1.1	1.5±1.2*	1.9±1.2*
CG	1.1±1.1	1.2±1.1	1.3±1.1	1.4±1.1
10^{th} rib				
EG	0.7±0.3	0.7±0.5	0.8±0.4	0.9±0.5
CG	0.8±0.2	0.8±0.3	0.8±0.5	0.8±0.3
Umbilicus				
EG	0.6±0.3	0.6±0.3	0.7±0.3	0.7±0.4
CG	0.8±0.3	0.8±0.4	0.8±0.3	0.8±0.3

EG: Experimental group. CG: control group. B-e: Before-exercise; A-e: After-exercise.
All values were shown as mean±SD (standard deviation).
*: significance at $p < 0.05$ level.

5.4 Discussion

The above-mentioned study shows that the expansion of the chest wall (axilla, xiphoid process) is more helpful to improve the respiratory function of the participants having chronic cervical spinal cord injury after doing RLAH exercise for one week and for one month in the EG. The findings indicate that the WSS is a convenient approach in clinical assessment to objectively measure the respiratory movements on the patients' chest-abdomen wall.

Complete CSCI cases suffer from the absence of motor or sensory function below the injury area, so they have greater functional impairment than incomplete CSCI cases. The complete CSCI cases are often associated with respiratory muscle weakness, paresis, paralysis and spasticity, which restricted the movement range of the chest-abdomen wall and impair the lung elasticity[73, 82-84)]. All these factors bring about serious restrictive breathing changes. In this study, the data collected after doing exercise on the first day and after doing exercise for one week fully revealed that expansion changes of chest-abdomen wall were very little due to the restricted breathing movement. The analysis was assumed based on the following performances: (1) the respiratory muscles were not strong enough during the breathing movements; (2) the insufficient breathing movement were developed after post-injury; (3) the expansion of the chest-abdomen wall may lead to higher spasticity at the beginning of the exercises. Moreover, for the participants having sever lesion or those only relying on their mouth instead of nose to breath during three measurements after the exercises, and there were no differences in expansions at the 10^{th} rib and umbilicus. The chest wall expansion at the xiphoid process was dominant comparing with that at the axilla, because of that the participants' upper limbs were more involved in daily activities, thus making the xiphoid process a passive stretch[85)]. Therefore, increasing the upper limbs activities of the CSCI patients is good for improving their respiratory function. In fact, it took more than three weeks to do the respiratory exercises and to get good results. there was obvious expansion on the chest wall after exercise for one month. This finding suggested that extended respiratory exercises are needed for patients with CSCI. In this study, the expansion range of abdominal wall as a control variable to compare the expansion range of chest wall in individuals with CSCI, then the expansion range of chest wall has been significantly improved after breathing exercises.

To obtain objective results after respiratory exercises, it is essential to accurately measure the patients' breathing movement. The WSS with high sensitivity and accuracy can do the purpose. It has been applied for measuring the expansion of the chest and abdomen wall of the patients with CSCI, while it does not need special environment and sophisticated settings. In addition, the WSS device is affordable for patients with chronic CSCI, and therefore can be used not only to monitor the patients' expansion of chest-abdomen wall but also to achieve the patients' self-exercises and self-feedback at home, so as to provide a high-quality guarantee in activities of daily life. The above-mentioned advantages of WSS were irreplaceable to compare with that of other instruments. Traditionally, breathing exercise in physical therapy was usually assessed only through the observation or palpation of experienced therapists during the physical examination, while now as an objective tool, the WSS can replace the physical examination to measure the respiratory movement in clinical practice. Moreover, the WSS is an effective approach for monitoring lung function, so as to reduce the risk of delay in medical treatment. Although the WSS device has been modified based on previous study, there are still some limitations in this study. Firstly, there are many breathing exercises for the CSCI cases, the RLAH exercise is just one of them, different results were not anticipated when the exercises were applied without abdomen expansion of 10^{th} rib and umbilicus. Secondly, the chest-abdomen wall with medical adhesive tape may be loosened when a patient's spasticity occurs during the measuring process. Thirdly, when the respiratory signals were collected by a smartphone via blue-tooth, the data transmission may be possibly disturbed or sometimes even be interrupted by some unidentified external factors. Fourthly, the selected participants were only male in this study, so the findings based on the data of the male.

This study concludes that trends of the improvement of the chest-abdomen wall expansion of the CSCI patients after doing respiratory exercise can be measured for the by means of the WSS. A lot of data have proven it. In clinical application, this objective measurement of respiratory movement can help more and more meaningful patients in different respiratory dysfunction cases. So this study can be shared by professionals who have met different respiratory disorders. Next, the future study of the WSS application shall focus a more valuable field, the apnea, i. e, the sleeping disordered breathing cases.

Chapter 6　FOREGROUND EXPECTION---THE WEARABLE STRAIN SENSOR IN CASE OF APPLICATION

6.1 Advantages of wearable strain sensor in case of application

For chronic COPD patients, regular measurement should be needed; and then self-feedback of monitoring breathing exercises using smartphone at home would be more convenient, to remind them deep breathing in to bulge out abdomen, slowly breathing out as long as possible during the exercise period. WSS is necessary and convenient, but spirometer with high cost in a special environment, inconvenient, without self-monitoring and self-measuring.

For patients after Thoracotomy, WSS can promote feedback of early physical exercises (such as upper limbs, expansion mobility of chest wall, maximal end of inspiration and expiration), whatever by medical workers or themselves. However, Spirometer, X-ray, CT, etc., these instruments are high cost and need a special environment, inconvenient, without self-monitoring and self-measuring.

Apnea Syndrome, WSS can monitor on loss or decrease in amplitude of monitored waveforms, but Spirometer cannot check apnea syndrome in patient without lung problems, so special monitor instruments are also high cost in a special environment, inconvenient, without self-monitoring and self-measuring.

Intensive care unit patients, WSS would be easy to measure local site differences, completed measurement at the patient's bedside, but the other instruments would be difficult to confirm the problems.

Neuromuscular Diseases, for example myasthenia gravis patients, observation for the long-term course would be needed, so comprehensive self-examinations should be included as follows: dyspnea, dysphagia, ptosis, masseter, neck muscles weakness, physically unable and so on, all of these problems would be measured by WSS with a wide use, but one of the other instruments would not measure all of the problems.

6.2 Discussion

WSS in case of application for the above-mentioned diseases should be expected, because WSS device is not only as a measuring tool but also as a breathing exercise of self-feedback to apply in clinical field.

The advantages of WSS device compared with other instruments really have very cheap, more precise, local self-measurement, self-feedback exercises, easy to use without limitations of posture and environment, and other wide range of uses.

Chapter 7 CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

This thesis had one general aim and four specific aims (objectives) which were described in the Chapter 1.

The aims were achieved through four linked studies.

The first study, both reliability and validity study of the WSS, recruited twenty-one healthy male students from Shanghai Jiao Tong University. The reliability of WSS for measuring breathing movement at four locations (axilla, xiphoid process, 10^{th} rib, and umbilicus) by using the test-retest, the intra-rater reliability test. all reliability coefficients of WSS at the four locations presented excellent agreement or consistency. For the validity of WSS on measuring respiration movement by using Pearson correlation coefficient test, all the values for validity had significant positive correlations on respiratory movement between measuring tape and WSS at four locations.

The second study, the best body spot (10^{th} rib) to detect the vital capacity from the respiratory movement data obtained by WSS, recruited thirty healthy male staff from physical therapy department in China Rehabilitation Research Center. The correlations of the mobility data at the four body spots by using Pearson's correlation coefficient test, showed that the values at each body spot were positive significant correlations, and the highest value was at the 10^{th} rib.

The third study, application of using WSS on respiratory evaluation in physiotherapy---changing with aging in breathing pattern, recruited total eighty-two healthy male participants: twenty-three students from The Capital Medical University served as the youth group, thirty staff from the PT Department of the research center as the middle-aged group, and twenty-nine senior citizens from the nearby JiaoMen residential community as the aged group. The result of the data analysis shows that all had significant differences at four spots between the senior group and the youth group, and that of between the middle-aged group and the youth group; there are significant differences at the axilla, xiphoid process and the 10^{th} rib except the umbilicus between senior group and the middle-aged group. The different people's breathing pattern in the progress of getting older are slowly changing with advanced age.

The fourth study, measuring changes of chest-abdomen wall in individuals with cervical spinal cord injury (CSCI) using WSS, recruited total ninety-three male participants with C4-C8 cervical spinal cord injury (35 incomplete and 58 complete), this consecutive enrollment of participants between April 2017 and March 2018 in Physical Therapy Department, China Rehabilitation Research Center. The result of the data analysis shows that that the expansion of the chest wall (axilla, xiphoid process) after exercises for the end of one month in EG was obviously more than that after the exercises for the end of one week, while the abdomen wall expansion maintained no differences.

In conclusion, the WSS will be able to available in clinical application on respiratory measurement in healthy participants and individuals with breathing problems. These investigations will be able to provide normative evidence for professionals with existing respiratory problems for future studies not only in China but also in other countries. And these investigations will be able to provide self-assessment on external medical attention and intervention in the overwhelming majority of inhabitant with acute and chronic respiratory problems.

7.2 Recommendations for service provision and future research

Firstly, the WSS has been confirmed a sufficient reliability and validity in the first study which matches the characteristics of WSS with high sensitivity and durable stability, so it is applicable for measuring respiratory movement in various types of target groups with breathing problems and WSS with low cost is advantageous to the family self-assessment.

Secondly, WSS is the objective quantitative measurement tool which would be applied to patients such as severe patients, patients with conscious disturbance, insubordinate child patients, and etc.. In fact, this kind of patients who could not take the initiative to cooperate with the respiration examinations, timely and accurate examinations make them receive efficacious interventions.

Thirdly, WSS is convenient, comfortable, noninvasive, and easy to use without limitations of posture or environment which may decrease the fatigue of patients and workload of medical workers.

Future trend of studies would be going on:

1) To evaluate expansion of back wall for severe patients in intensive care unit (ICU), then the patients will be provided more targeted interventions due to the accurate diagnosis.

2) To assess expansion of breathing movement for respiratory diseases such as sleep disordered breathing, sleep apnoea syndrome, COPD, and etc.;

3) To measure expansion of chest wall in patients after thoracotomy;

4) To measure flexibility and range of motion for limbs in patients;

5) To evaluate the subtle muscle movements on human face and neck induced by micro-expression such as winking, swallow, pursed lips, speech to recognize phonation, and so on.

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REFERENCES

1) The National Health Commission of China. 2015. Health care resources survey.

http://www.chiss.org.cn/hism/wcmpub/hism1029/inform.pdf 2015.12.9

2) Ma X, Yu X, Hou Y, et al. The mortality of the chronic respiratory diseases. China Health and Family Planning Statistics Yearbook in 2017. Bei Jing: Xin Huashu inn, 2017: 17-20

3) The National Health Commission of China. 2015. Epidemiological survey and analysis.

http://www.chiss.org.cn/hism/wcmpub/hism1029/inform.pdf 2015.9.16

4) The National Bureau of Statistics of China. 2016. Smog investigation report.

https://www.baidu.com/sf_edu_wenku/view. pdf.2016.2.3

5) Han X, An L. Rehabilitation care on respiratory function in patients with spinal cord injury. J. Practical Neuropathy 2011; 14: 30-33

6) Jiang J, Zhuo Y, Zhu Y. Prevention and care on lung infection in patients with spinal cord injury. Orthopedic Nursing Care 2013; 25:79-82

7) Zhang J, Zhang Z. The treatment for patients with acute brain stem hemorrhage. J. Current Medicine Reports 2016; 16: 209-212

8) Di R, Zeng J, Bu L, et al. Rehabilitation treatment of traumatic brain injury. General Practice Nursing 2012; 9: 92-94

9) Aliverti A, Dellaca R, Pelosi P, et al. Compartmental analysis of breathing in the supine and prone positions by optoelectronic plethysmography. Ann. Boimed. Eng. 2001; 186: 233-246

10) Romei M, Mauro A, Angelo M, et al. Effects of gender and posture on thoraco-abdominal kinematics during quiet breathing in healthy adults. Respir. Physiol. Neurobiol. 2010; 172: 184-191

11) Shobo A, Kakizaki K. Relationship between chest expansion and the change in chest volume. Rignku ryohougaku 2014; 29: 881-884

12) Shobo A, Kakizaki K. Effects of two sitting positions on chest volume. Rignku ryohougaku 2015; 30: 499-502

13) Fiamma, Samara Z, Baconnier P, et al. Respiratory inductive plethysmography to assess respiratory variability and complexity in humans. Respir. Physiol. Neurobiol. 2007; 156: 234-239

14) Ferringo G, Pedotti A. A dedicated hardware system for movement analysis via real-time TV signal processing. Biomed. Eng. 1985; 32: 943-950

15) Fagevik M, Romberg K. Reliability of the respiratory movement measuring instrument, RMMI. Clin. Physiol. Funct. Imag. 2010; 30: 349-353

16) Kaneko H. Assessing the reliability and validity of a newly developed breathing movement measuring device. J. Phys. Ther. Sci. 2013; 25: 425-429

17) Fregonezi G, Resqueti V, Guell R, et al. Effects of 8-week, interval-based inspiratory muscle training and breathing re-training in patients with generalized myasthenia gravis. Chest 2005; 128: 1524-1530

18) Wang C, Li X, Gao E, et al. Carbonized silk fabric for ultrastretchable, highly sensitive, and wearable strain sensors. Adv. Mater. 2016; 28: 6640-6648

19) Ding Y, Yang J, Charles R, et al. A highly stretchable strain sensor based on electrospun carbon nanofibers for human motion monitoring. RSC. Adv. 2016; 5: 9114-9120
20) Wang D, Tao L, Liu Y, et al. High performance flexible strain based on self-locked overlapping graphene sheets. Nanoscale 2016; 8: 90-95
21) Sun P, Joshua K, Michael C et al. Highly flexible wrinkled carbon nanotube thin film strain sensor to monitor human movement. Adv. Mater. Technol. 2016; 1: 53-60
22) Lin Y, Liu S, Chen S, et al. A highly stretchable and sensitive strain sensor based on graphene-elastomer composites with a novel double-interconnected network. J. Mater. Chem. 2016; 4: 6345-6352
23) Zhang M, Wang C, Wang H, et al. Carbonized cotton fabric for high-performance wearable strain sensor. Adv. Funct. Mater. 2016; 4795-4806
24) Li J, Zhao X, Zeng X, et al. Highly stretchable and sensitive strain sensor based on facilely prepared three-dimensional graphene foam composite. Appl. Mater. Interfaces 2016; 18: 954-961
25) Wei H, Chen S, Zhou B et al. Highly sensitive and transparent strain sensor based on thin elastomer film. Electron Device Letters 2016; 37: 667-669
26) Sharp J, Goldberg N, Druz W, et al. Relative contributions of rib cage and abdomen to breathing in normal subjects. J. Appl. Physiol. 1975; 39: 608-618
27) Gilbert R, Auchincloss J, Peppi D. Relationship of rib cage and abdomen motion to diaphragm function during quiet breathing. Chest 1981; 80: 607-612
28) Cala S, Kenyon C, Ferrigno G, et al. Chest wall and lung volume estimation by optical reflectance motion analysis. J. Appl. Physiol. 1996; 81: 2680-2689
29) Aliverti A, Dellaca R, Pelosi P, et al. Optoelectronic plethysmography in intensive care patients. J. Respir. Crit. Care Med. 2000; 161: 1546-1552
30) Aliverti A, Dellaca R, Pelosi P, et al. Compartmental analysis of breathing in the supine and prone positions by optoelectronic plethysmography. Ann. Boimed. Eng. 2001; 186: 233-246
31) Binazzi B, Lanini B, Bianchi R, et al. Breathing pattern and kinematics in normal subjects during speech, singing and loud whispering. Acta. Physiol (Oxf). 2006; 186: 233-246
32) Ragnarsdottir M, Kristinsdottir E. Breathing movements and breathing patterns among healthy men and women 20-69 years of age. Reference values. Respiration 2006; 73: 48-54
33) Kaneko H, Horie J. Breathing movements of the chest and abdominal wall in healthy subjects. Respir. Care 2012; 57: 1442-1451
34) Tahira K, Sukizaki T, Senjyu H et al. Investigation of correlation between standard values of chest expansion difference and pulmonary function in middle-aged and older adults. Rigaku ryohougaku 1993; 20: 84
35) Landis J, Koch G. The measurement of observer agreement for categorical data. Biometrics 1977; 33: 159-174
36) Moll J, Wright V. An objective clinical study of chest expansion. Ann. Rheum. Dis. 1972. 31:1-8
37) Finsback C, Mannerkorpi K. Spinal and thoracic mobility age-related reference values for healthy men and women. Nordisk. Fysioterapi. 2005; 9:1 36-43

38) Malaguti C, Rondelli R, de Souza L, et al. Reliability of chest wall mobility and its correlation with the pulmonary function in patients with chronic obstructive pulmonary disease. Respiratory Care 2009; 24:1703-1711

39) Liu H, Guo S, Zheng K, et al. Reliability and validity of measuring respiration movement using a wearable strain sensor in healthy subjects. J. Phys. Ther. Sci. 2017; 29: 1543-1547

40) WHO. Obesity. preventing and managing the global epidemic. Report of a WHO Consultation. World health organization, 2000.

41) Meyer C. Measurement in physical education. New York: Ronald Press Co, 1979: 211-217

42) Lumb A. Nunn's applied respiratory physiology. Oxford: Butterworth-Heinemann, 2000: 427-435

43) Hlastala M, Berger A. Physiology of respiration. Oxford: Oxford University Press, 2001: 125-131

44) Olseni L, Wollmer P. Sjukgymnastik vid nedsatt lungfunk-tion. Lund: Studentlitteratur, 2003: 224-234

45)Monika F, Hilda L, Jenny L, et al. Measuring chest expansion: A study comparing two different instructions. Advances in Physiotherapy 2011; 13: 128-132

46) Quanjer P, Tammeling G, Cotes J, et al. Lung volumes and forced ventilatory flows. Eur. Respir. J. 1993; 6: 5-40

47) Pasquina P, Tramer M, Walder B. Prophylactic respiratory physiotherapy after cardiac surgery. BMJ. 2003; 327:1379

48) Xin Y. The research on the market depth of China's old-age industry and a report of its investment prospects. Nursing care 2010; 2259-2263

49) Gulshan S, James G. Effect of aging on respiratory system physiology and immunology. Clinical Interventions in Aging 2006; 3: 253-260

50) Mittman C, Edelman N, Norris A, et al. Relationship between chest wall and pulmonary compliance and age. J. Journal of Applied Physiology 1965; 20: 6-14

51) McClaran S, Babcock M, Pagelow D, et al. Longitudinal effects of aging on lung function at rest and exercise in healthy active fit elderly adults. J. Appl. Physiol. 1995; 78: 1957-1968

52) Gila B. Breathing pattern in humans: diversity and individuality. Respiration Physiology 2000; 122: 123-129

53) Gillooly M, Lamb D. Airspace size in lungs of lifelong non-smokers; effect of age and sex. Thorax 1993; 48: 39-43

54) Knudson R. How aging affects the normal lung. J. Respir. Dis. 1981; 2: 74-84

55) Janssens J, Pache J, Nicod L. Physiological changes in respiratory function associated with aging. Eur. Respir. J. 1999; 13: 197-205

56) Zeleznik J. Normative aging of the respiratory system. Clin. Geriatr. Med. 2003; 19: 1-18

57) Peterson D, Pack A, Silage D, et al. Effects of aging on ventilatory and occlusion pressure responses to hypoxia and hypercapnia. Rev. Respir. Dis. 1981; 124: 387-391

58) Tolep K, Higgins N, Muza S, et al. Comparison of diaphragm strength between healthy adult elderly and young men. Am. J. Respir. Crit. Care Med. 1995; 152: 677-682

59) Polkey M, Harris M, Hughes P et al. The contractile properties of the elderly human diaphragm. Am. J.

Respir. Crit. Care Med. 1997; 155: 1560-1564
60) Tobin M, Chadha T, Jenouri G, et al. Breathing patterns. 1 Normal subject. Chest 1983; 84: 202-205
61) Van M, Castellote J, De J, et al. Survival after spinal cord injury: a systematic review. J. Neurotrauma 2010; 27: 1517-1528
62) Zimmer M, Nantwi K, Goshgarian H. Effect of spinal cord injury on the respiratory system: basic research and current clinical treatment options. J. Spinal Cord Med. 2007; 30: 319-330
63) Waddimba A, Jain N, Stolzmann K, et al. Predictors of cardiopulmonary hospitalization in chronic spinal cord injury. Arch. Phys. Med. Rehabil. 2009; 90: 193-200
64) Winslow C, Bode R, Felton D, et al. Impact of respiratory complications on length of stay and hospital costs in acute cervical spine injury. Chest 2002; 121: 1548-1554
65)Lee B, Cripps R, Fitzharris M et al. The global map for traumatic spinal cord injury epidemiology: update 2011, global incidence rate. Spinal cord 2014; 52: 110-116
66) Furlan J, Sakakibara B, Miller W, et al. Global incidence and prevalence of traumatic spinal cord injury. Can J. Neurol. sci. 2013; 40:456-464
67) Van E, Castellote M, Mahillo I et al. Incidence of spinal cord injury worldwide: a systematic review. Neuroepidemiology 2010; 34: 184-192
68) James E. Spinal cord injury facts and figures at a glance. J. Spinal Cord Med. 2008; 31: 357-358
69) Berlly M, Shem K. Respiratory management during the first five days after spinal cord injury. J. Spinal Cord Med. 2007; 30: 309-318
70) Claxton A, Wong D, Chung F, et al. Predictors of hospital mortality and mechanical ventilation in patients with cervical spinal cord injury. Can J. Anaesth. 1998; 45: 144-149
71)The National Bureau of Statistics of China. 2014. The statistical report on spinal cord injury. https://www.baidu.com/sf_edu_wenku/view. pdf. 2014.3.23
72) Wyndaele M, Wyndaele J. Incidence, prevalence and epidemiology of spinal cord injury: what learns a worldwide literature survey. Spinal Cord 2006; 44: 523-529
73) Devivo J, Krause S, Lammertse P. Recent trends in mortality and causes of death among persons with spinal cord injury. Archives of Physical Medicine and Rehabilitation 1999; 80: 1411-1419
74) Haisma J, Van der woude L, Stam H, et al. Complications following spinal cord injury: occurrence and risk factors in a longitudinal study during and after inpatient rehabilitation. J. Rehabil. Med. 2007; 39: 393-398
75) Cardozo C. Respiratory complications of spinal cord injury. The Journal of Spinal Cord Medicine 2007; 30: 307-308
76) Brown R, DiMarco A, Hoit J, et al. Respiratory dysfunction and management in spinal cord injury. Respiratory Care 2006; 52: 853-868
77) David J, Berlowitz, Brooke W, et al. Respiratory problems and management in people with spinal cord injury. Breathe 2016; 12: 329-340
78) Stefan T, Victoria M, Surinder S, et al. Accuracy of portable devices in measuring peak cough flow. Physiol. Meas. 2015; 36: 243-257

79) Hosoda T, Yanagisawa K. Handbook of Physical Therapy. Tokyo: Kyodo-I sho Publ, 2011: 421
80) Mahoney F. Barthel D: Functional evaluation: The Barthel index. Md. Med. J. 1965
81) De T, Estenne M. Functional anatomy of the respiratory muscles. Clin. Chest Med. 1988; 9: 175-193
82) Jain N, Brown R, Tun C, et al. Determinants of forced expiratory volume in 1 second (FEV1), forced vital capacity (FVC), and FEV1/FVC in chronic spinal cord injury. Arch. Phys. Med. Rehabil. 2006; 87: 1327-1333
83) Stolzmann K, Gagnon D, Brown R, et al. Longitudinal change in FEV1 and FVC in chronic spinal cord injury. Am. J. Respir. Crit. Care Med. 2008; 177:781-786
84)Linder S. Functional electrical stimulation to enhance cough in quadriplegia. Chest 1993; 103: 166-169
85)Jain N, Sullivan M, Kazis L, et al. Factors associated with health-related quality of life in chronic spinal cord injury. Am. J. Phys. Med. Rehabil. 2007; 86: 387-396

REEARCH PERFORMANCE

List of Publications and Conference Presentations

Publications

1) Haijuan Liu, Shaopeng Guo, Kaipei Zheng, et al. Reliability and validity of measuring respiration movement using a wearable strain sensor in healthy participants. J. Phys. Ther. Sci. 2017; 29: 1543-1547
2) Haijuan Liu, Shaopeng Guo, Huilin Liu, et al. The best body spot to detect the vital capacity from the respiratory movement data obtained by the wearable strain sensor. J. Phys. Ther. Sci. 2018; 30: 586-589
3) Haijuan Liu, Shaopeng Guo, Sujie Chen, et al. Application of using a wearable strain sensor on respiratory evaluation in physiotherapy---changing with aging in breathing pattern. J. Nov. Physiother. 2018; 8: 396-399
4) Haijuan Liu, Shaopeng Guo, Sai Peng, et al. Measuring changes of chest-abdomen wall in individuals with cervical spinal cord injury (CSCI) using wearable strain sensor. It is being submitted.

Conference Presentations

1) Haijuan Liu, Hitoshi Maruyama: Reliability and validity of balance assessment tools on dual task in patients with chronic stroke. International Meeting of Physical Therapy Science, Silla University, Busan, Korea 2016/07/16
2) Haijuan Liu, Hitoshi Maruyama: Introduction of various sensors on monitoring of human motion. 第 86 回理学療法科学学会学術大会 IUHW, Odawara Campus, Japan 2017/01/22
3) Haijuan Liu, Hitoshi Maruyama: Reliability and validity of measuring respiration movement using a wearable strain sensor in healthy participants. Annual meeting of Orthopaedics of the Chinese Medical Association, Guangzhou, China 2017/5/17
4) Haijuan Liu, Hitoshi Maruyama: The best body spot to detect the vital capacity from the respiratory movement data obtained by the wearable strain sensor. International conference of China Association of Rehabilitation Medicine, Taian, China 2017/07/29
5) Haijuan Liu, Hitoshi Maruyama: Reliability and validity of measuring respiration movement using a wearable strain sensor in healthy participants. China Association for the Promotion of International exchanges of Health Care Rehabilitation Medicine Branch, Guizhou, China 2017/9/17
6) Haijuan Liu, Hitoshi Maruyama: Reliability and validity of measuring respiration movement using a wearable strain sensor in healthy participants. Huaxia Rehabilitation Medicine Nursing Forum, Anhui, China 2017/11/23
7) Haijuan Liu, Hitoshi Maruyama: The best body spot to detect the vital capacity from the respiratory movement data obtained by the wearable strain sensor. Early management of neurological severe disease, China Disabled Persons' Federation Rehabilitation association, Beijing, China 2018/10/28