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Noncontact Respiratory Measurement of Volume Change Using Depth Camera*

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Abstract — **In this study, a system is developed to measure human chest wall motion for respiratory volume estimation without any physical contact. Based on depth image sensing technique, respiratory volume is estimated by measuring morphological changes of the chest wall. We evaluated the system and compared with a standard reference device, and the results show strong agreement in respiratory volume measurement [correlation coefficient: *r*=0.966]. The isovolume test presents small variations of the total respiratory volume during the isovolume maneuver (standard deviation<107 *ml*). Then, a regional pulmonary measurement test is evaluated by a patient, and the results show visibly difference of pulmonary functional between the diseased and the contralateral sides of the thorax after the thoracotomy. This study has big potential for personal health care and preventive medicine as it provides a novel, low-cost, and convenient way to measure user's respiration volume.**

Index Terms—**Noncontact, depth camera, respiration volume, spirometer, isovolume maneuver**

I. INTRODUCTION

Breathing is an important physiological task in living organisms, and there are many respiratory diseases which require attentive care and respiratory training. Therefore, the measurement of the respiration and the evaluation of pulmonary functions are important. Currently, spirometer and pneumotachography are two of the most used methods to evaluate the pulmonary functions. However, these methods measure the full respiratory volume, but they cannot evaluate the pulmonary diseases with abnormalities in chest wall movement, such as pulmonary edema, regional thorax function, and thoracoabdominal asynchrony. In addition, it is inconvenient to hold the device or wear the respiratory masks. In decades, many respiratory measurement techniques are developed, such as respiratory inductance plethysmography (RIP) [1], thoracic impedance [2], impedance pneumography (IP) [3], photoplethysmography (PPG) [4], acoustic monitoring [5, 6], strain gauges [7], and magnetometers [8]. However, these techniques need to contact to the user while measuring, and it would have interference with the natural respiration of the user. Therefore, some noncontact respiratory measurements are developed, such as the methods of microwave-based [9, 10] and optical-based techniques. The optical-based technique includes thermal imaging [11], structured light plethysmography (SLP) [12, 13], and optoelectronic plethysmography (OEP) [14, 15]. These methods do not need to contact the user while measuring, but require specific measurement instrument and complicate set up procedure. In 2011, Poh, et al. [16] proposed a low-cost respiratory measurement using a web camera. It uses the technique of independent component analysis (ICA) and heartbeat rate variety (HRV) to estimate the respiratory rate through the face color.

In this study, a noncontact respiratory measurement technique is developed to measure the respiratory volume from the morphological changes of chest wall region in real-time using a commercial depth camera. In addition, the proposed optical-based method is capable of regional pulmonary function assessment in different chest wall behaviors. Therefore, we can estimate the respiratory volume of left thorax, right thorax, and abdominal regions, separately. Finally, we can evaluate the respiratory methods and respiratory problems of the user. The respiratory volume estimation using this method was validated by comparing the measured results from spirometer performed at the same time during shallow, middle, and deep breathing by the participants. Then, an isovolume test [17] was carried out to show the measurement variance of the system. Finally, a thoracotomy patient was asked to evaluate the regional pulmonary function.

II. METHODS

A depth camera, Kinect [18], is used in this study to measure the respiration volume of the user. Kinect consists of an infrared laser emitter combined with a monochrome sensor which captures color images and an IR receiver which captures depth images at the resolution of 640 x 480 pixels at 30 fps. In our system, the user needs to sit in a chair and put the depth camera in front of him, as seen in Figure 1. The procedure of respiratory measurement in this system includes the processing of depth camera calibration, region of interest positioning, and respiratory volume estimation.

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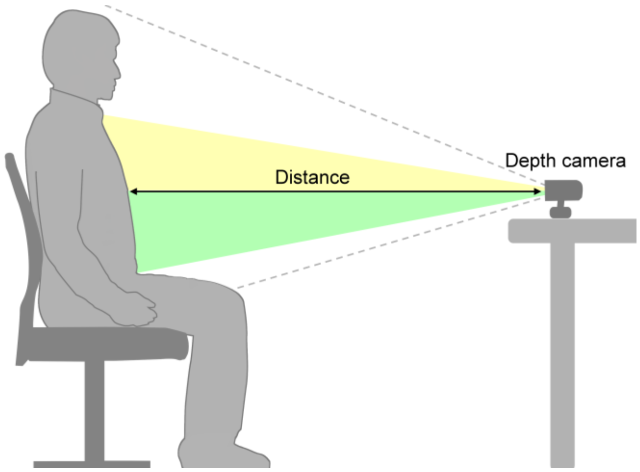

Figure 1. System configuration

A. Depth Image Calibration

Before the measurement processing, a view transformation procedure is needed to calibrate the camera view to ensure that the captured depth images are right ahead of the user, and each sensing pixel of the depth image is a uniform distribution. Then, the pixel-to-length transform function is needed to estimate the absolute height and width of user's chest wall. Therefore, a experiment was carried out to find the relationship between the sensing distance and the actual length of each pixel. Then, the transform table is estiblished, as shown in Figure 2, and a transform function is obtained by $C = 0.0002\times d^{0.9813}$. The parameter *C* indicates the length of each pixel (*cm/pixel*) could be obtained in the sensing distance *d*. After the calibration process, the actual length of the width and height of the chest wall can be estimated.

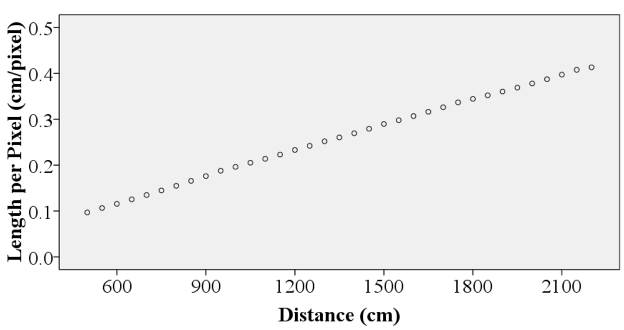

Figure 2. The relationship between the sensing distance and the actual length of each pixel of the depth camera, Kinect.

B. Region of Interest

In order to calculate regional pulmonary function with different respiratory volumes in left thorax, right thorax, and abdomen, we need to define the region of interest (ROI) of these specific regions. According to the structure of the human body, the region upper the thoracic diaphragm is defined as the thorax ROI and below it is defined as the abdominal ROI. Moreover, the thorax ROI could be divided into left thorax ROI and right thorax ROI. In this study, a predefined chest wall mask is used, and we need to adjust the position and size of it to fit user's chest wall. The point of user's processus xiphoideus is seen as a reference point to help us adjust the chest wall mask to the appropriate position, as seen in Figure 3a. After the adjustment, the system could measure the regional morphological changes in the chest wall from the depth image, as seen in Figure 3b.

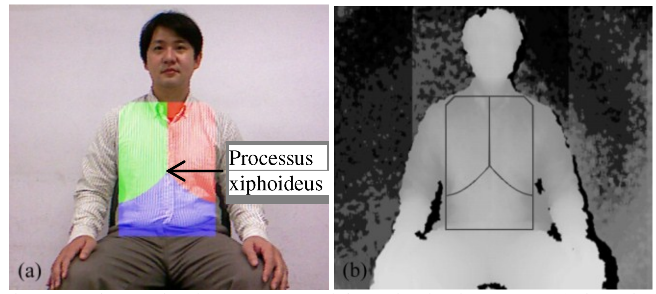

Figure 3. The sensing images captured from the depth camera. (a) the color image with chest wall mask (b) the depth image for respiratory measurement.

C. Chest Wall Volume Estimation

After the location and size of the chest wall mask is determined, the respiratory volume could be calculated from the ROI of the depth image. In the initial of the measurement, the average depth value of the ROI, *R*, is seen as the reference plane. Then, the average depth of the ROI, *L*, is seen as the current plane. Finally, a procedure to obtain the volume changes is implemented by calculating the difference of the current depth image and reference depth image. It is noted that the ROI could be calculated separately by left thorax ROI, right thorax ROI, and abdomen ROI. The difference of volumes *V* could be obtained by Eq. 1. In this equation, the size of the ROI is defined as an m (pixel)$\times$ n (pixel) matrix, and *C* indicates the parameter to translate the measurement unit from pixel number to actual length (*cm*), and then the respiratory volume (*ml*) could be obtained.

$$V = \sum_{i=0}^{i=m} \sum_{j=0}^{j=n} \left(L_{ij} - R_{ij}\right) \times C^2 \tag{1}$$

Finally, the respiratory volume in each breath cycle could be estimated by detecting the peak/valley points of the volume changes *V*. Moreover, the inhalation volumes, exhalation volumes, respiratory rate, and even the respiratory method, such as abdominal breathing, could be obtained.

III. EXPERIMENTS

This study was approved by the Research Ethics Committee, National Taiwan University Hospital. To evaluate the established respiration measurement system, three tests were performed. First is a validation test to verify the measurement accuracy of respiratory volume in this system. Second is an isovolume test to evaluate the measurement variance of the system. Third is a regional measurement test to evaluate regional pulmonary functions. For the limitation of the sensing range and view angle, the distance between the user and the depth camera is defined as 1.4 m in these three tests. Following describe the experimental procedure and results.

A. Validation Test

For validation test, a spirometer was used to compare with our method. During the test, participants needed to exhale the air through a spirometer to record respiratory volume. In the meantime, the respiratory volume was measured by our system. In this experiment, twelve healthy participants of both genders (three females) were involved. The average age is 25.9 years old (*SD* = 3.1), height is 1.70 *m* (*SD* = 7.33), weight is 65.6 *kg* (*SD* = 11.5), and the body mass index (BMI) is 22.7 kg/m^2 (*SD* = 3.65). Every participant performed sixteen rounds of respiratory measurement which include shallow, middle, and deep breathing. In each round, participants need to inhale and hold the air, and then exhale the air to the spirometer. We recorded the respiratory volume from our method and spirometer, and evaluated the correlation coefficients between them. The experiment was conducted indoors and all participants were asked to sit at a distance of 1.4 m in front of the depth camera. During the experiment, participants were asked to keep still, breathe spontaneously, and face the depth camera.

Totally, we recorded 192 rounds of respiratory measurement from 12 participants. The level of agreement between the respiratory measurements measured by our method and spirometer was accessed using Pearson's correlation coefficients. The results achieved high correlations with $r = 0.966$ ($p<0.001$). The regression line and the scatter plot are shown in Figure 4. This test indicates that our method is valid for respiratory volume estimation, with values lower than those from spirometer.

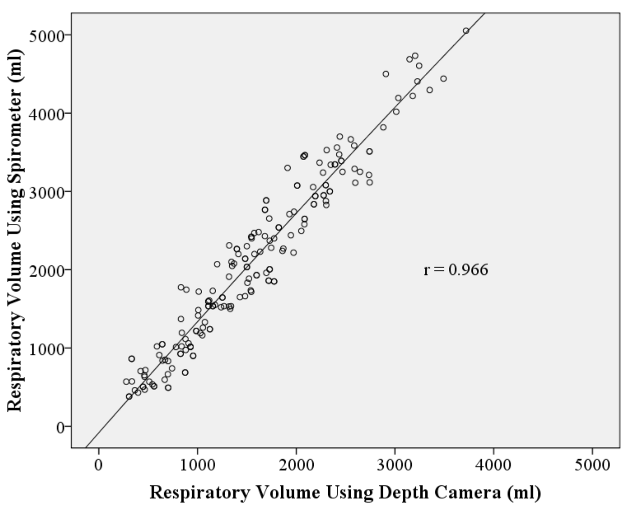

Figure 4. Comparison of the respiratory volume obtained by depth camera and spirometer.

B. *Isovolume Test*

In order to evaluate the measurement variance, an isovolume test was performed. During the isovolume test, the air changes in thoracic volume should be opposite and equal to the changes in abdominal volume, and the changes of total volume should approach to zero. The method of isovolume test is to hold the breath without any air flow through mouth and nose after a deep inhaling, and then move the air between thorax and abdomen. In this test, a healthy participant performed isovolume maneuver in the breath-holding period from 4.8 second to 15 second, the thorax, abdomen, and total respiratory volume are shown in Figure 5. Totally, the respiration volume is 3510 *ml*, and the standard deviation in the breath-holding period is 110 *ml*. The result shows that our method is reliable while the morphology of the chest wall changes. In addition, the correlation coefficient of the respiratory volume in the whole thorax and abdomen change with opposite phases in the breath-holding period is -0.94 ($p< 0.001$).

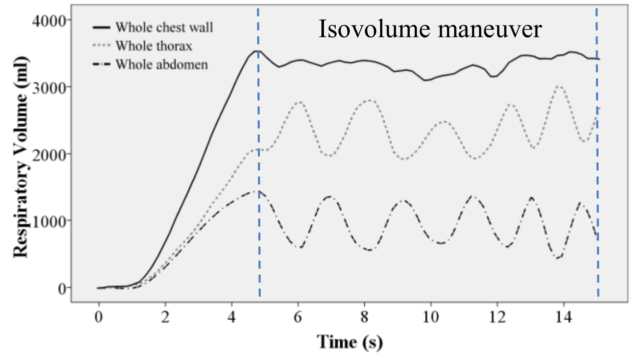

Figure 5. Waveforms of a healthy participant performing isovolume test from 4.8 second to 15 second.

C. *Regional Pulmonary Measurement Test*

The proposed depth image-based method was applied to the analysis of regional pulmonary function for a female participant (age: 60 years old, height: 1.60 m, weight: 68 kg, BMI: 26.56 kg/m^2) with the thoracotomy for left upper lobectomy (LUL) lobectomy and mediastinal lymphnode dissection. We asked the participant to sit in a chair and breathe spontaneously for one minute. In addition, we also asked her to breathe as deep as possible for another one minute. The respiration volumes of left thorax and right thorax were recorded separately.

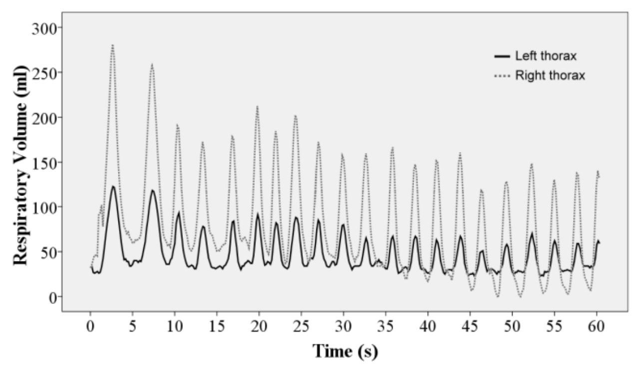

Figure 6. Waveforms of the patient with the left thorax (solid line) and right thorax (gray line) for a one-minute spontaneous breathing.

The waveforms of the right and left thorax respiratory volumes in spontaneous breathing test are shown in Figure 6. The result shows that the contribution of the left thorax to the whole thorax changes is 15.5%, and the average of respiratory volume in full thorax is 185.5 *ml* for spontaneous breath. In addition, the contribution of the left thorax to the whole thorax changes is 21.8% and the average of respiratory volume in full thorax is 341.8 *ml* for deep breathing. The results prove that the depth image-based method could estimate regional pulmonary functions.

IV. DISCUSSION

In this study, a depth image-based method was proposed. This method measures user's respiratory volume without any physical contact, and which could decrease the measuring interference. In addition, it has several advantages. First, the intensity of the ambient light would not affect the measurement accuracy because the depth image is captured from IR projector/receiver. Therefore, the system can still measure user's respiratory volume in a lightless environment or brilliant environment. Second, the depth image-based method is flexible to measure specific ROI of respiratory volume, such as right thorax, left thorax, and abdomen. Therefore, this system can also measure respiratory methods, such as abdominal breathing, inversed abdominal breathing, chest breathing, according to the relationship of the movement models.

In this study, three experiments were designed to evaluate the proposed method. The results of validation test show highly correlated with those from spirometer correlation coefficient. The isovolume test and the regional pulmonary measurement test also revealed significant and expected results. However, although the validation test show highly correlated, but the estimated respiratory volume of our system is less than those from spirometer. One possible reason is that only the morphological changes in the front part of the chest wall is measured, and the respiratory volume in side region and back region of the chest wall are not measured. Therefore, one possible solution is to find a measurement transform function to estimate the actual respiratory volume from the volume which we are measured.

According to our observation, some measurement limitations would be mentioned. First, the rigid forward movement of the user would affect the measurement accuracy. It is because that we cannot identify whether the movement is caused by breathing or other body movements. Therefore, a further study is needed to separate the respiratory movement from mixed body movements. Second, the system cannot detect well while the wearing is too thick or loose. If the respiratory movement could not be seen visibly, it is hard to measure the respiratory volume well.

V. CONCLUSION

This study proposed a noncontact respiratory measurement technique to measure the respiratory volume using a depth camera. The validation test demonstrated a strong correlation of respiratory volume measured by our method and spirometer. In addition, the small variations of total respiratory volume during isovolume maneuver, and visibly difference of the pulmonary function between the diseased and the contralateral sides of the thorax proved the regional respiratory measurement of the proposed method. In the future, we would like to integrate this technique with multimedia biofeedback to help patients learn appropriate breathing method and aware of their respiration conditions. In addition, the respiratory measurement while standing and walking needs a further study to separate the respiratory movement from mixed body movements. Finally, the system could be used to analyze and monitor the respiratory conditions for the patient in lateral decubitus or supine position, especially for the intensive care unit (ICU) patients.

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