Efficacy of Involuntary Deep Breathing by Postural-Respiration Feedback Control System

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***Abstract*— This study was undertaken to quantify heart rate dynamics and interactions during sequential use of a postural-respiration feedback regulation control system. The bent shape of the human back makes it easier to exhale air from the lungs, but challenging to inhale. On the other hand, when a human being leans over backwards, it becomes difficult to exhale, but easier to inhale. This simple feature opens up the possibility of regulating human breathing involuntarily through posture control. We developed and tested a postural-respiration feedback regulation control system. The process of the posture control architecture depends on an air chamber placed under the subject's back. For this experiment, subjects had to lie on a bed, and the subjects' respiration cycle was synchronized with the inflation and deflation of the air chamber. We analyzed the beat-to-beat heart rate and the continuous breathing signal data gathered from ten male university students. We investigated the hypothesis that the use of a synchronously controlled postural-respiration feedback control system would yield positive psychophysiological benefits. The heart rate and respiratory dynamics from the deep breathing response and segmented breathing were similar. The results indicate that deep breathing was successfully induced when posture control was precisely synchronized with the subject's own respiration. The implications of these findings for both future research and practice are addressed in a comprehensive discussion.**

Keywords-breathing control; posture feedback; respiration.

I. Introduction

Breathing is ventilation involving two stages: inspiration and expiration. The physiological background of breathing is the intake of oxygen and removal of carbon dioxide by the lungs. Breathing is essential to support bodily functions of human life. Breathing control has been accepted in modern society around the globe due to its numerous benefits in our daily life. Breathing control methods have become increasingly popular due to the growing significance of a holistic approach to healthcare. In this study, we have developed a new architecture for a breathing control system and investigated the efficacy of the system, which is based on our previous study regarding involuntary deep breathing by posture respiration feedback control system, published at ambient computing applications services and technologies 2017 [1].

A. Psychophysiological Benefits

Breathing techniques are frequently used to change psychophysiological conditions and to improve organ function [2]. Voluntary breathing control improves task performance [3], alleviates anxiety [4]-[6], appropriately controls autonomous nervous system activities such as heart rate, blood pressure [7]-[10], and even immune system functions [11]-[13]. One study reported that the regular practice of slow breathing exercises for three months improves autonomic functions [14], and regular practice of breathing exercises have shown to decrease sympathetic activity and increase vagal tone [15] [16]. Additionally, breathing-related disorders may be dangerous to our daily life, e.g., obstructive sleep apnea is a prominent risk factor for cardiovascular disease [17].

B. Yoga Training and Meditation

There are a variety of methods that have been developed for breathing control such as yoga training and spiritual meditation. Yoga training that uses voluntary breathing control methods is called pranayama [18]. Pranayama involves inhalation, holding, and exhalation, which can be performed either quickly or slowly. Such breathing training can affect oxygen consumption and metabolism [19]. The benefits of pranayama include improving cardiovascular indicators and respiratory functions through increasing vagal tone, decreasing sympathetic discharges, and reducing stress [18] [20]. Additionally, spiritual meditation can be used for breathing control. A slow breathing method is used by Zen monks while performing Zazen meditation [21]. The voluntary breathing control methods used decrease awareness of breathing, create controlled and even breaths, increase mindfulness, and improve respiratory performance.

C. Benefits of Deep Breathing

Numerous studies have suggested that deep breathing exercises have beneficial psychological effects. These studies demonstrate how relaxed, slow, deep breathing significantly reduces negative emotions [22], and yogic deep breathing represses working memory [23]. Additionally, deep breathing techniques have been successfully implemented to enhance academic performance [24]. One study proposed that controlled deep breathing is beneficial for relieving withdrawal symptoms after giving up smoking [25]. Another study stated that the investigations recognized how deep breathing progressively improves ventilation efficiency for oxygen [26]. Deep breathing supports quietening of the mind and body, which can provide psychological and physical benefits.

D. Breathing Control in Clinical Setting

Breathing control has numerous applications in clinical settings. Buteykyo breathing can be one of the most helpful techniques for asthma patients [27]. Using radiotherapy along with deep inspiration with active breathing control may decrease standard tissue irradiation in Hodgkin's disease patients [28]. Training pregnant women in breathing methods is an effective technique for decreasing anxiety, which can influence the duration of the delivery during labor [29]. Another study suggested that the use of deep breathing exercises was helpful after cardiac surgery for first stage patients [30]. Deep breathing exercises and walking have an advantageous effect on the heart rate variability in patients hospitalized for chronic heart failure [31]. In addition to voluntary breathing control, passive ventilation equipment has been developed and has proven to be useful [32] [33].

E. Contribution of the Automatic Nervous System

The autonomic nervous system influences breathing. In the background of the breathing pattern, the autonomic nervous system maintains control of the lungs through ventilation and the gas exchange method, which is the result of the electrical stimulation of nerves and correct physiological stimulus [34]. The autonomic nervous system controls the heart, smooth muscles, and endocrine/exocrine glands. It has both an afferent and an efferent segment [35]. The main branches of the autonomic nervous system are identified as sympathetic and parasympathetic. In sympathetic stimulation, the heart rate increases, whereas in parasympathetic stimulation, the heart rate decreases [36]. The primary characteristic of the autonomic nervous system is that it maintains balance in the body under varying conditions. The hypothalamus can control the body using three different methods. Apart from the ANS, the hypothalamus regulates the endocrine system and a neural system concerned with motivation [37]. It has three main branches: sympathetic, parasympathetic, and central. On a fundamental level, the whole autonomic framework is independent and distantly associated with the other parts of the sensory system.

F. Electrocardiography

Electrocardiogram (ECG) data is used commonly for monitoring the clinical diagnosis of cardiac function. The ECG signal measures the change in electrical potential over the time. Recently, researchers have been able to apply digital signal analysis to the ECG data [38]. Calculating and analyzing ECG signal and time interval of QRS complex existing with in the range between P-Q and Q-T corresponding to different part of the heart behaviors. R complex is the most important point of the QRS complex because several heart beats define R complex as the peek point. Further, beat to beat distance is measured by the milliseconds between each other R complexes as the RR interval. Numerical studies of the cardio system have been using ECG data for more complex diagnostic interpretations [39].

G. Background of Heart Rate Variability

Heart rate variability (HRV) is the measure of beat-to-beat differences in the heart rate influence based on the rate of release of the pacemaker, generally sinus-atrial node. HRV has been used to estimate and investigate cardiac autonomic behaviors in the several fields as clinical, physiological interpretation and process of ECG. HRV can be measured in a wide range of time intervals, such as for a short 2-minute interval or an extended period of 24 hours. HRV can be used to analyze Cardiac arrhythmia conditions by using the time domain, frequency domain, and nonlinear methods [40].

Time domain variable calculation involves the mean peak-to-peak interval (RR interval). The standard deviation of the RR intervals, or SDRR, is frequently used as an index of sympathetic nervous system activity.

The frequency-domain measure is obtained using the Fast-Fourier transform method. The power of the heart rate variation includes both high frequency (HF) and low frequency (LF) ranges. The HF commonly range from 0.15 to 0.40 Hz, while the LF commonly range from 0.05 to 0.15 Hz. The heart rate variation in the HF segment is considered to be an index of parasympathetic nervous system activity [41]. The LF segment reflects both sympathetic and parasympathetic nervous system activity, so the rate LF/HF is frequently introduced as an index of sympathetic–vagal balance [42].

H. Hypothesis and Objective of this Study

As stated earlier, breathing control can bring positive psychological and physiological effects. However, there are some limitations in both voluntary and passive breathing control methods. First of all, voluntary breathing control requires significant effort and concentration by the patient, and it is difficult to continue over a long period of time, especially for the elderly. Additionally, passive ventilation, such as continuous positive airway pressure (CPAP) [32] and adaptive servo-ventilation (ASV) [33] require patients to be fitted with a nasal cannula or respirator, so it is not suitable for daily use at home.

Therefore, in this study, we propose an alternative method for semi-passive breathing control via posture control. The idea is based on the bent shape of the human backbone making it easier to exhale but challenging to inhale. However, when a human being is leaning backwards, it becomes difficult to exhale, but easier to inhale. This simple feature opens the possibility to regulate human breathing involuntarily through posture control. Based on this simple idea, we developed a postural-respiration feedback regulation control system and tested the efficacy of the proposed architecture.

We developed an architecture that forces the user to change their posture synchronously with their own breathing cycle. In the next section, the architecture of the developed system and the procedure of the experiment to test the efficacy of the system are described. The following sections describe the results of the experiment, discussion, and conclusion.

II. Method

This study aimed to develop an involuntary postural-respiration feedback regulation control system. We concentrated on the fact, that changing posture affects respiration. This physical condition of the bent shape of the human back makes it easier to exhale, but challenging to inhale. However, when a person is leaning backwards, it is difficult to exhale but easier to inhale. The idea of posture affecting respiration opens the possibility for breathing control by changing posture. To verify this idea, we developed a postural-respiration feedback regulation control system. Figure 1 shows the architecture of the system.

A. Materials

In this system a silicon air chamber is placed beneath the subject's back. The air chamber is synchronized to deflate/inflate according to the subject's own respiration cycle. For example, when a subject starts inhaling/exhaling, the air-chamber starts to inflate/deflate to assist the user in inhalation/exhalation of the air into/from the lungs.

The basic architecture of this system is shared with our previous studies [43]. A thermistor sensor detects the subject's respiration pattern in a time series. This analogue for respiration is amplified and digitized by analog-to-digital converter (NI USB-6008 DAQ, National Instruments Co., USA), and transmitted to the feedback regulator. The feedback regulator, developed with a visual programming language (LabVIEW, National Instruments Co., USA), controls the air flow to the chamber using a pair of air pumps (YP-20A, Yasunaga Air Pump Inc., Japan) and a switching circuit to regulate the volume of the air chamber.

With this adaptive architecture, we assume that such an adaptive intervention to the posture would make the subject's breathing deeper and longer, and the subject would be more relaxed in body and mind. To test our hypothesis, we conducted an experiment with three different respiratory intervention conditions: 1) the air-chamber inflates and deflates synchronously with subject's inhalation and exhalation (called "SNC" hereafter); 2) the air-chamber asynchronously inflates and deflates with breathing: inflating when the subject exhales and inflating when the subject inhales (called "ASN" hereafter); and 3) the air-chamber inflates and deflates with a constant rhythm (called "CST" hereafter). In SNC and ASN conditions, the inflation and deflation cycle of the air-chamber is precisely determined by the subject's respiration steps, whereas in the CST condition, the cycle of the air chamber is set to the same duration as each subject's mean deep breathing cycle, which has been determined in advance.

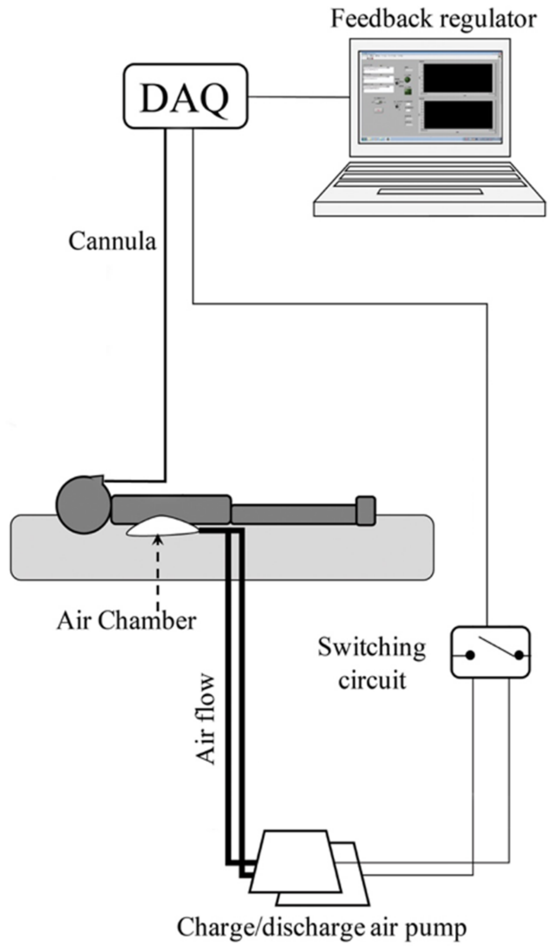

Figure 1. Schematic diagram of the posture-respiration feedback regulation control system.

Figure 2 shows an example of the respiration pattern and the movement of the air chamber regulated in the three different conditions. In the SNC condition, when the subject inhales, the air chamber continues to inflate and when the subject exhales the air chamber continues to deflate. Accordingly, the air chamber inflates and deflates synchronously with the subject's respiration pattern.

Figure 3 shows how the posture of a subject changes with the inflation and deflation of the air chamber placed under the subject's back. It should be noted that the movement of the air chamber and following change in the posture in this image is exaggerated to illustrate how the system works. The actual movement of the air chamber and the change in the posture, was smaller than in this image in order to not place any burden on the subjects.

Compared with SNC, the ASN condition shows the opposite pattern as the air chamber asynchronously inflates and deflates with subject's inhalation and exhalation. In the CST condition, the air chamber inflates and deflates with a constant rhythm determined by each subject's mean deep breathing cycle.

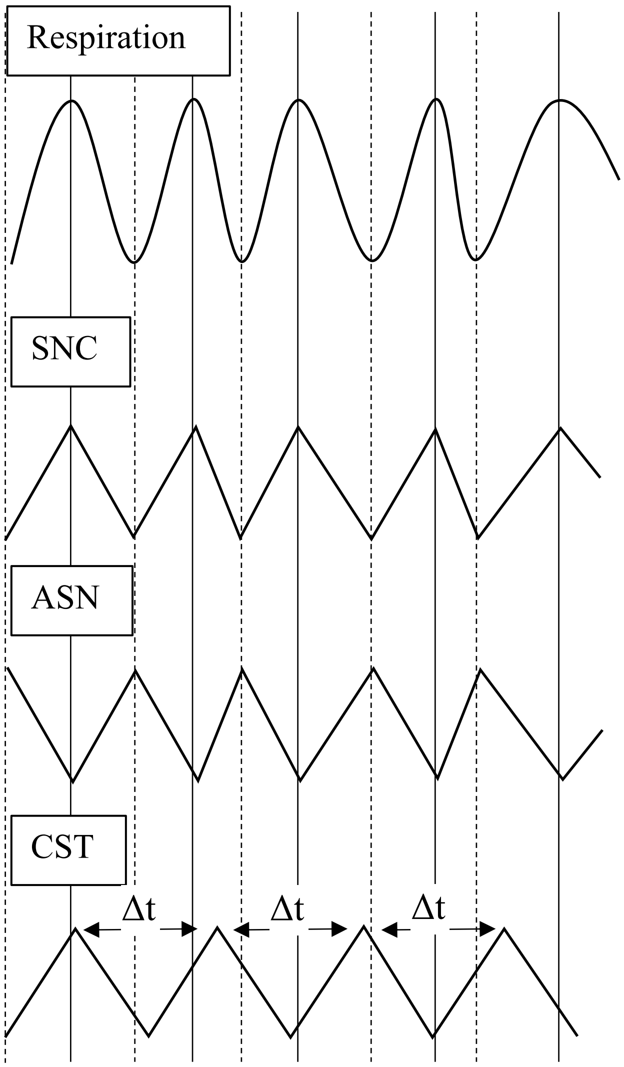

Figure 2 Patten of reparation and other conditions

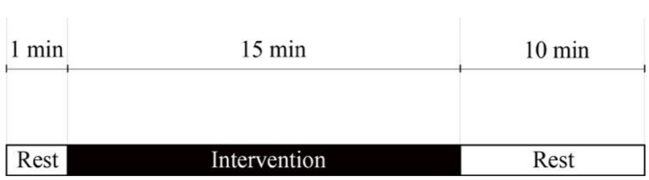

Figure 4. Experiment schedule

Figure 3. Postural-respiration feedback control system

B. *Experiment*

Subjects (n = 10) were male university students (age 22-24) and they voluntarily participated in this experiment. All subjects were rated for their health condition, and they had no heart or breathing related health problems. The study was conducted following ethical principles and informed consent was obtained from all subjects. The study was approved by the ethics committee of the Nagaoka University of Technology.

Figure 4 shows the experiment protocol. The experiment consisted of a 1-minute initial rest period, followed by 15 minutes of the intervention period, and another 10-minute rest period (recovery period). The total experiment time was 26 minutes. The postural-respiration feedback control system functioned only during the intervention period. A thermistor sensor measured respiration of the subjects. The heartbeat signal was measured by an electrocardiogram (ECG) with a bio-signal amplifier system (MP150, BIOPAC Systems, Inc., USA) to evaluate the cardio-physiological functioning by the postural-respiration intervention. The subject was instructed to lie on the bed with the rubber air chamber placed under the subject's back. In this experiment, the heart rate (HR) and the high frequency (HF) component of its variation were measured using the ECG data. The experiment was conducted in a within-subject design such that each participant went through all three conditions in one trial per day in a randomized order.

III. RESULTS

The postural-respiration feedback regulation control system (Figures 2 and 3) produced results in the dynamic change in the beat-to-beat respiration interval (RI) and respiration amplitude (RA) of the respiration during the intervention period. Figures 5 through 8 show standardized values to compensate for the large variation among the individuals (Z-score). Figure 5 shows that RI response and the segment breathing induced significantly longer respiration (RI: $p < 0.01$) in the SNC condition. For the RA, Figure 6 shows a deeper response (RA: $p < 0.01$) in SNC condition. This means that in the intervention period the subject's respiration effectively synchronized with the air-chamber. Compared to the recovery period, the interval and amplitude were significantly changed during the intervention duration.

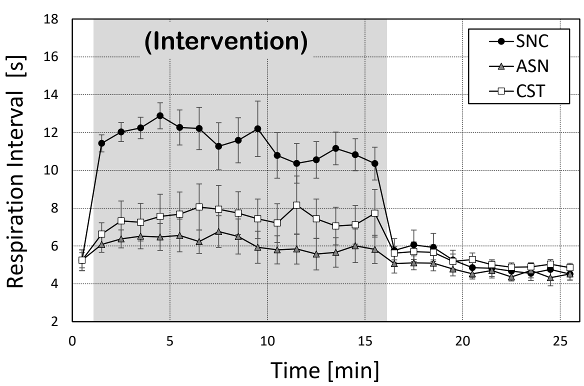

Figure 5. Change in the respiration interval (mean±S.E.M).

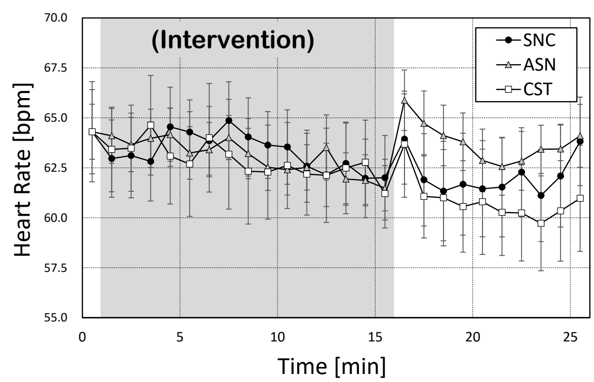

Figure 7. Change in the heart rate (mean±S.E.M).

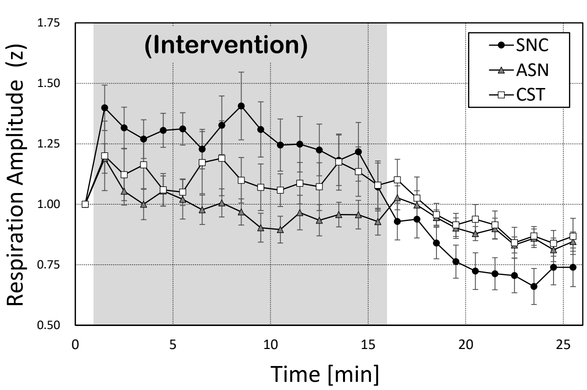

Figure 6. Change in the respiration amplitude (mean±S.E.M).

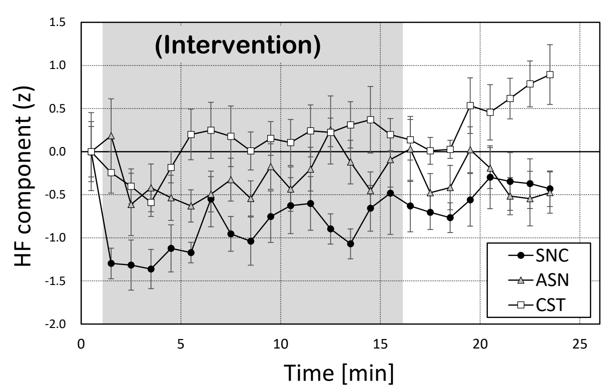

Figure 8. Change in the HF component (mean±S.E.M).

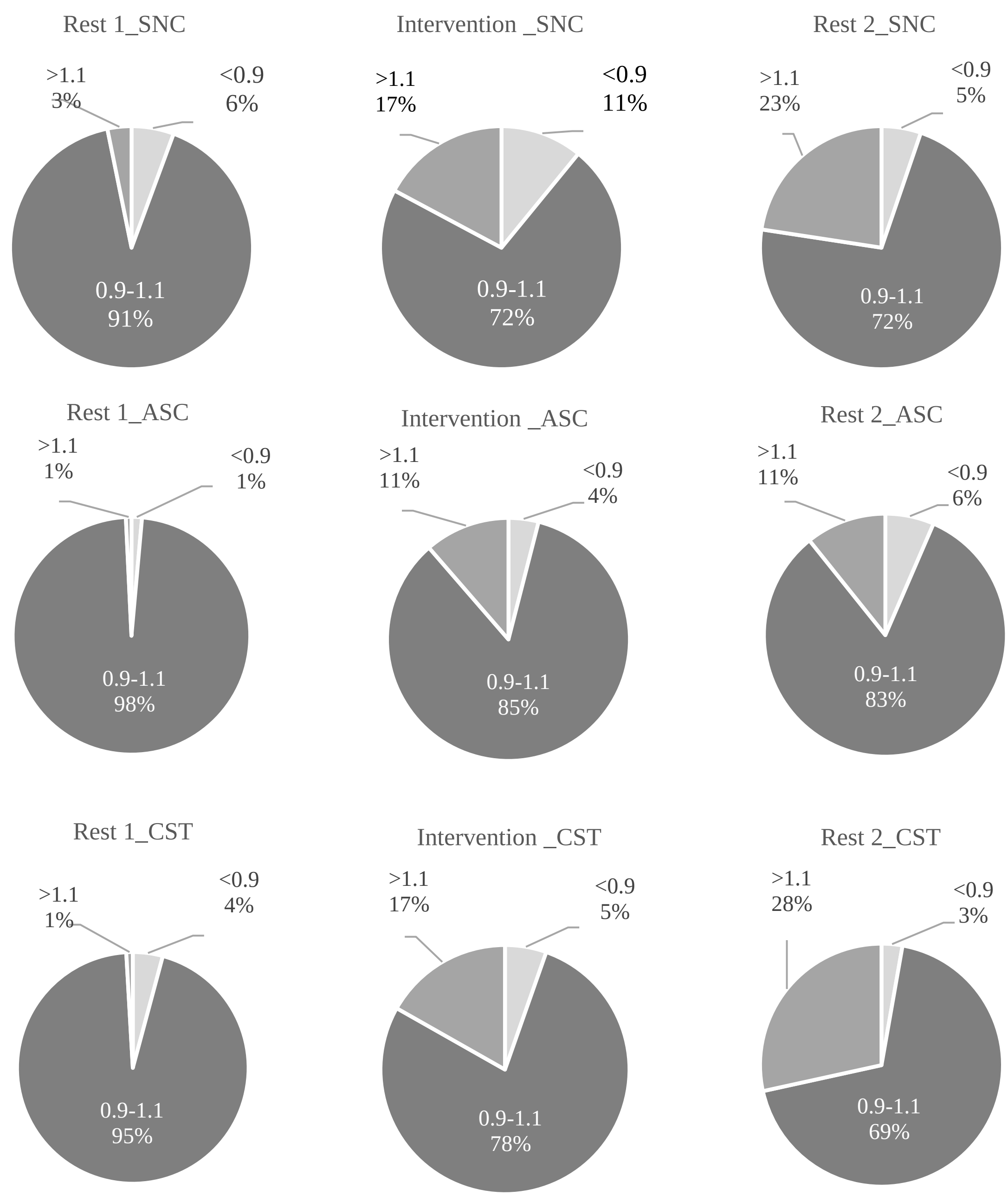

Figure 9. The ratio of RRI change.

As shown in Figures 5 and 6, in ASN condition the subject's breathing was remarkably restricted in intervention period. While, in CST condition, the change in respiration is in between SNC and ASN as shown in the graphs. The frequency analysis of the heart rate variability was used to evaluate the postural-respiration feedback system. Figures 7 and 8 show the results of the change in the heart rate (HR) and high frequency (HF: 0.15 - 0.40 Hz) component of the HRV. As seen in Figure 7, HR did not significantly change in any of the three conditions ($p > 0.05$) during the intervention period. However, HR in the recovery period in ASN was significantly higher than that of other conditions ($p < 0.01$), and it reached a higher value than the initial rest period (overshoot). With regard to the HF component in the SNC condition as shown in Figure 8, it was the lowest during the intervention period and recovery period ($p < 0.01$).

Cardiac vagal activity was measured by the ECG recording, and the HRV was calculated from this data. The

HF component of the HRV in SNC condition has an instantaneous R-R interval (RRI) result shown in Figure 9. The R-R interval data has been analyzed to identify vagal activation with inclusion of feedback SNC, non-feedback ASN, and control CST during the experiment period. The average values of the RRI data during the Rest 1, Intervention, and Rest 2 periods were calculated. The ratio of the x is obtained by dividing the value of RRI when the average value is 0. The RRI results are shown by pie charts in Figure 9, either $x < 0.9$, $0.9 \leq x \leq 1.1$, or $1.1 < x$ values. The results of the statistical test are show in Table I. Heart rate variability and Rest 2 periods tended to increase in all intervention conditions in the feedback period, and there was a significant difference between SNC and ASN ($0.9 \leq x \leq 1.1$) and between ASN and CST ($0.9 < x < 1.1$) in the Rest 2 period the results with a p value $p < 0.05$. These results show vagal activity of the HF component. The results from the rest periods without movement of the chamber also show cardiac vagal activation.

Table I. RRI RATIO AMONGST CONDITIONS

SNC vs ASN	SNC vs CST	ASN vs CST	RRI	*p* value
Intervention period				
0.061	0.114	0.362	$x < 0.9$	$p < 0.05$
0.013	0.428	0.243	$0.9 \leq x \leq 1.1$	
0.276	0.957	0.360	$x > 1.1$	
Rest 2 period				
0.507	0.224	0.020	$x < 0.9$	$p < 0.05$
0.221	0.683	0.113	$0.9 \leq x \leq 1.1$	
0.187	0.541	0.042	$x > 1.1$	

The result of paired t – test, RR interval vagal activation intervention period and rest 2 period.

IV. DISCUSSION

In this study, the impact of the postural-respiration feedback control system on respiration and autonomous cardiac system function was investigated. The hypothesis examined the efficacy of the proposed architecture accompanied by three different respiratory intervention conditions. Our results were as expected in SNC condition, meaning that the subject's respiration (inhalation/exhalation) synchronized with air chamber inflation/deflation successfully. The results of Figures 5 and 6 show (RI: $p < 0.01$) that respiration was made significantly longer, (RA: $p < 0.01$) and significantly deeper. This result implies that the developed posture control system can induce deep breathing unconsciously.

However, in ASN condition where the posture regulation was administered asynchronously with respiration (i.e., the phase delay is 180 degrees), there was no change in the respiration interval and amplitude. Among the components, moreover, in the recovery period (Rest 2), an overshooting of HR was observed in ASN condition. HR overshooting is frequently observed in the recovery period after mild exercise [44]. It occurs to meet the requirement of balancing the greater oxygen cost of fat catabolism during the early recovery period. It may be that if the HR overshoot seen in this study shares part of the same background with that of after exercise, it might reflect a lack of oxygen during the intervention period. Despite the large effort of doing respiration, whether it be intentional or unconscious, ASN condition made breathing difficult, and this phenomenon misled the body into believing that the concentration of air oxygen was "low", resulting in a higher requirement for oxygen after intervention (during "normal" circumstances).

In CST, the impact on respiration and cardiac autonomous system were marginal compared to SNC and ASN, and the breathing seemed to be gradually entrained with the constant rhythm. The cycle of the air chamber movement in CST was fixed at the same duration as each subject's mean deep breathing cycle, so subjects might modulate their breathing cycle voluntarily to their deep breathing. However, the interval and amplitude of the respiration in SNC reached far beyond CST. In this sense, our developed posture-respiration intervention architecture has demonstrated a prominent impact on the respiration.

However, HF in SNC was strongly suppressed as shown in Figure 8. The HF component of the heart rate variability has been frequently taken as an index of cardiac parasympathetic nervous system activation [45]. However, as demonstrated in Figure 9 and Table I, the change in RR-interval, i.e., the variation of the instant heart rate, was prominent in SNC. Therefore, it is unable to interpret the result of our study as the SNC condition suppressing parasympathetic nervous activity.

The physiological background of the above mentioned phenomenon is the relationship between deep breathing and cardiac behavior. The central school of thought in physiology discusses on how respiratory sinus arrhythmia (RSA) and cardiac vagal tone contribute to the heart rate. In the normal condition of RSA in the respiratory process, the HR increases during inspiration and decreases during expiration; this is called RSA. Sinus arrhythmia is a normal physiological phenomenon most typically seen in young, healthy people. RSA can be utilized as the key to understanding the cardiac vagal tone and contributes to heart rate variability [46]. RSA has been shown to significantly contribute to the rhythmic waxing and waning of cardiac vagal efferent effects upon the sinoatrial node and, therefore, the heart rate [47]. The respiratory rate and tidal volume produce independent and interactive effects [48]. This physiological background contributes to the understanding of the breathing process as a gas exchange mechanism. Numerous studies have documented how gas exchange productivity improves with deep breathing and increased mean heart rate, but in this process it is unconnected to the RSA contribution. Among the studies mentioned, HR was remarkably similar to RSA with slow and deep breaths [49].

The result of the posture control system we developed showed that deep breathing was successful at producing the desired effects. If the participant were to breathe in deeply, the heart rate would increase. That is because the heart is making the most of a fresh supply of oxygen to the lungs and sending a ration of blood through the lungs to receive the oxygen. When breathing out, it is more energy-efficient for the heart not to pump as fast, because there is less oxygen available in the lungs. This reaction, controlled by the brain, detects a slight change in the gas composition of the blood. This is detected and sent by the vagus nerve to the sinoatrial node. That node cell is at the top of the heart. The node works as a heart pacemaker meaning that the heart rate is changed by a deep breath. In this study, the heart rate condition did not significantly change during the conditions ($p > 0.05$) in the intervention period, but it seems that a deep breath with gas exchange changes the cardiac mechanism by means of RSA. From the above, it can be concluded that deep breathing gives rise to RSA that is more pronounced than standard RSA. In the HF analysis using the HRV method, the response is about 0.3 Hz (HF). Additionally, it seems that the HF component of the SNC condition has decreased. Frequency domain analysis is the most accurate method of discovering correlations between the HF and LF components and autonomic activation. HRV measures can be associated with several cardiac functions with the assumption of sympathetic or parasympathetic activation. Normally, the LF condition is associated with sympathetic activation. Generally, the HF component is associated with vagal modulation and respiration because HF is dependent on the respiration pattern.

In our study, the high-frequency component of the RR interval results indicated cardiac vagal activation in the HF component. These results are shown in Figure 9. The changes in RR intervals describe the cardiac vagal activation during the intervention period and the rest period. These results are a valuable part of this study because the vagal activation response contributes both physiological [50] and psychological benefits. The vagus nerves also control the central part of the parasympathetic nervous system. Their influence on breathing, digestive function, and heart rate has an impact on mental health conditions.

A. Limitation

This study was conducted in a within-subject manner with randomized order which can free from group effect. However, the small sample size ($n = 10$) with homogeneous population limits the generalization of the interpretation of the results. The strength of posture control, i.e., the air pressure in the air chamber, was not varied regardless of the attribute of each subjects, which can also form the limitation of this study

B. Implications and Future Research

Using this architecture, inspired by involuntary deep breathing, can create psychophysiological benefits. After the development and modification of a clinical instrument, this posture control system can be used for clinical treatment for patients with respiration problems. Further, in future investigations, psychological and physiological changes can be evaluated using the different types of parameters with a more significant number of subjects. In the future, it is expected that this posture control system can be developed and improved as a stress-reducing mechanism with an involuntary breathing control and as a health product for the global market. Future research using this architecture will improve psychophysiological benefits through an involuntary deep breathing and inspiration.

V. Conclusion

In summary, we tested the efficacy of our postural-control respiration intervention system in the manner of real-time feedback regulation. The results indicate that deep breathing is successfully induced when the posture control is precisely synchronized with the user's own respiration. Regarding the impact on cardiac function, HR overshoot was observed as the after effect of asynchronous regulation. We found this from the results of cardiac vagal activation. Further physiological study promises to reveal the background mechanism of the impact of our system.

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