2020 IEEE International Conference on Robotics and Automation (ICRA)
31 May - 31 August, 2020. Paris, France

Wide-range Load Sensor Using Vacuum Sealed Quartz Crystal Resonator for Simultaneous Biosignals Measurement on Bed

Yuichi Murozaki, and Fumihito Arai, *Member, IEEE*

***Abstract*—Monitoring of biosignals on a daily basis plays important roles for the health management of elderly. The monitoring system for the daily life, the system should not require the subjects to take special effort like wearing a sensor. We propose biosignals measurement using wide-range load sensor on the bed. The sensing system can detect the body weight, heartbeat and respiration simultaneously by just lying on the bed. We have developed load sensor using quartz crystal resonator (QCR load sensor) as wide-range load sensor. However, the measurement range was not sufficient for the simultaneous measurement of biosgnals on bed. To realize such sensing system, we propose a QCR load sensor utilizing vacuum sealing technology for expanding the measurement range. We improved the oscillation characteristics of the QCR by the vacuum sealing to stabilize the sensor output. Accordingly, the resolution of the sensor was improved. Moreover, the load capacity of the sensor was increased by improving the bonding strength of sensor structure. The fabricated sensor had a measurement range of 0.27 mN - 1180 N (4.4 $\times$ 10^6). This wide enough compared with the conventional force sensor (10^3 - 10^4).**

Also, we developed mechanically robust jig of QCR load sensor for practical use of QCR load sensor. We succeed in simultaneous measurement of weight, heart rate, and respiration rate using fabricated QCR load sensing system. The accuracy of heart rate and respiration rate measurement are 0.4 bpm (0.6 %) and 1.1 brpm (6.1 %), respectively, in standard deviation of error compared with ECG signal.

I. INTRODUCTION

The importance of biosignal monitoring at home or care facilities is increasing with the aging society. Heart failure[1] and sleep apnea symptoms[2] is frequent in the elderly compared with young person. Moreover, elderly person easily become bedridden, since a decline in physical ability. Monitoring of biologicals in daily life on bed play important roles. For example, early detection of arrhythmia and apnea can be performed by monitoring heart rate and respiration. It is also valuable to record weight on a daily basis for the elderly. Appropriate dietary intake based on changes in body weight can help sustaining physical abilities. Therefore, a monitoring system which can measures heart rate, respiration, and body weight leads to health promotion of the elderly.

For the intelligent monitoring system of biosignals on a daily basis, the system should be in harmony with living environment such as bed without requiring to take special effort like wearing a sensor. As a sensing method which can realize such measurement, researches on ballistocardiograph(BCG) has been conducted. BCG can be obtained by measuring body movements which are minute vibrations caused by the heartbeat. Heart rate information and respiratory information can be measured by load sensors. Conventionally, heart rate and respiration measurements have been performed by measuring the load on the mattress of bed using a film piezoelectric sensor [3],[4] and a fiber optic strain sensor [5],[6]. In addition, load cells have been mounted in the post of bed to measure respiration for evaluation of sleep apnea [7] or to monitor 'wake' and 'sleep' stage[8]. Piezoelectric film sensors and FBG strain sensors are high-sensitive enough to measure heartbeat but it cannot measure body weight. On the other hand, general load cells which can measure a body weight are not able to obtain the heartbeat signal because of narrow measurement range.

Here, simultaneous measurement of body weight, heartbeat, and respiration can be realized if we have load sensors with a wide measurement range capable of measuring body weight and high-sensitive to measure heartbeat. In order to realize a wide measurement range, we have focused on the load sensor using quartz crystal resonator. QCRs can obtain an oscillation output signal with high time stability, and the oscillation frequency changes in proportion to the external force applied to the QCR in specific direction. The QCR has excellent characteristics as load sensor. On the other hand, QCRs are easily broken by bending or buckling because of the thin structure. A mechanism is required to hold the QCR unit stably and to transmit the load ([9], [10]). We proposed a sensor structure that stably holds the QCR and suppresses buckling, consequently a wide-range load sensor was realized and simultaneous measurement of weight and heart rate was achieved [10]. In the measurement of biological signals on the bed for elderly, it is necessary to measure the minute load fluctuation due to the BCG under the large load including the mass of body and bed. Moreover, the older persons usually gave BCG of smaller amplitude than young ones [11]. A sensor with a wider-range is desirable to achieve biosignal measurement on bed for elderly.

In this study, we have improved the characteristics of the QCR load sensor using vacuum sealing technology, in order to realize the simultaneous measurement of body weight, heartbeat and respiration on the bed. To demonstrate the usefulness of the sensor, the sensor was installed in the bed and simultaneous measurement of body weight, heartbeat and respiration was conducted.

*Resrach supported by AMED under Grant Number JP19im0210811.
Y. Murozaki is with the Institutes of Innovation for Future Society, Nagoya, Japan (corresponding author to provide phone: 052-789-5220; fax: 052-789-5027; e-mail: murozaki@biorobotics.mech.nagoya-u.ac.jp).

F. Arai is with the Department of Micro-Nano Mechanical Science and Engineering, Nagoya University, Nagoya, Japan (e-mail: arai@mech.nagoya-u.ac.jp).

II. Concept of the Simultaneous Measurement of Biosignlas On Bed

Figure 1 shows the concept of simultaneous measurement of body weight, heartbeat and respiration using a wide-range load sensor on a bed. The load on the bed including the mass of bed can be measured by wide-range load sensors under the post of bed. We can get the weight of the subject taking the sum of the load values applied to the four sensors. Also, heartbeat information is obtained as minute load fluctuations caused by heart movement. Respiration information can be obtained from the changes of the center of body mass due to respiration. We can calculate the center of body mass from the applied load and position of four sensors. The center of the mass can be calculated from the balance of moments. The position of the center of the mass is expressed by the following equation using the outputs of the four sensors.

$$y_G = \frac{lS_1 + lS_2 - lS_3 - lS4}{S_1 + S_2 + S_3 + S_4} \qquad (1)$$

where S_1, S_2, S_3, and S_4 are the outputs of each sensor, and l is the distance from the zero point for each sensor in the y direction (Fig. 2).

III. Development of Wide-Range Load Sensor

We developed wide-range load sensor using vacuum sealed QCR to achieve simultaneous measurement of weight, heartbeat and respiration on bed for elderly. The principles of the sensor and method for measurement range expansion are described in the following sections.

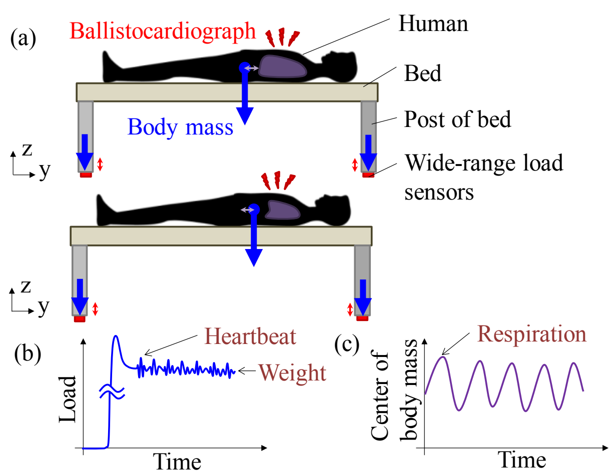

Figure 1. Concept of simultaneous measurement of weght, heartbeart and respiration using wide-range load sensors.

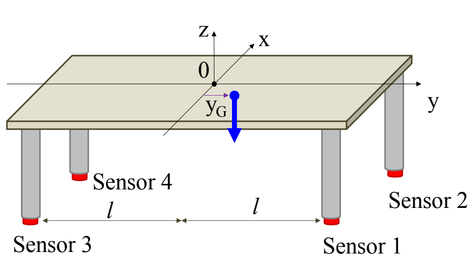

Figure 2. Dimentions of the bed for calculation of the center of the mass.

A. Load Sensor Using Quartz Crystal Resonator

QCR load sensor consists of a QCR layer and two cover layers bonded on both sides of the QCR layer. The cover layers prevent breakage of QCR layer by bending or buckling, and can provide a high load capacity. In order to expand the measurement range of QCR load sensor, it is required to improve the allowable stress of the sensor and to improve the stability of the sensor output. We propose a QCR load sensor utilizing vacuum sealing technology for expanding the measurement range. Improvement of the oscillation characteristics of the QCR is expected due to the vacuum sealing [12]. Atomic diffusion bonding with thin Au films have been used for the fabrication of the QCR load sensor [10]. The gap is required between the bonding plane and the electrodes, because the oscillation characteristic decay when the bonding plane and the electrodes are coupled. The vacuum sealing could not be utilized due to the gap.

Fig. 3 shows the concept of a QCR load sensor which is vacuum sealed with a bonding resist. The cover layers are bonded to the QCR layer through the bonding resist. Since the bonding resist is resin material, which is an insulator, the cover layers can be bonded without coupling with the electrode. The cavity is sealed fully with bonding resist. Consequently, pressure of the cavity can be reduced. Moreover, the conventional sensor had holes for wiring to prevent coupling the bonding plane and the electrodes by wiring connection. However, the holes affect the allowable stress of the sensor due to stress concentration. The holes for wiring was omitted in proposed design. Stress concentration was investigated using finite element analysis with SolidWorks Simulation (SolidWorks Corp.). The analytical results are shown in Fig. 4. When load of 1 N is applied to the sensor, the maximum stress is 0.93 MPa and 0. 75 MPa for the conventional sensor and the proposed sensor, respectively. The maximum stress of

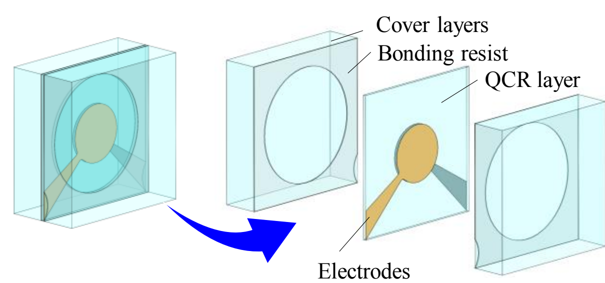

Figure 3. Schmetics of the QCR load sensor.

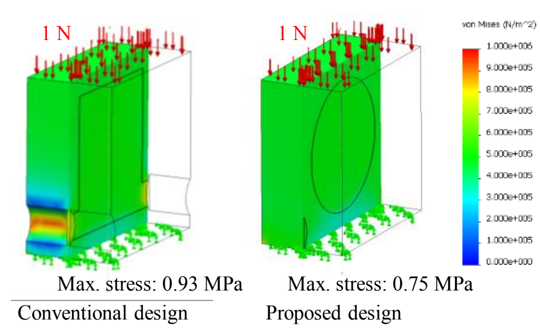

Figure 4. Result of FEM analysis.

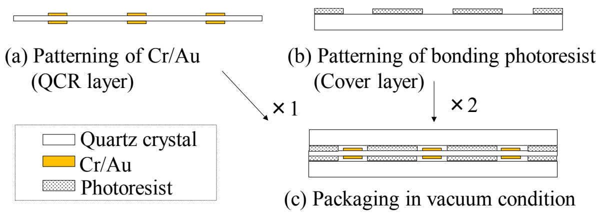

Figure 5. Process flow of the sensor fabrication.

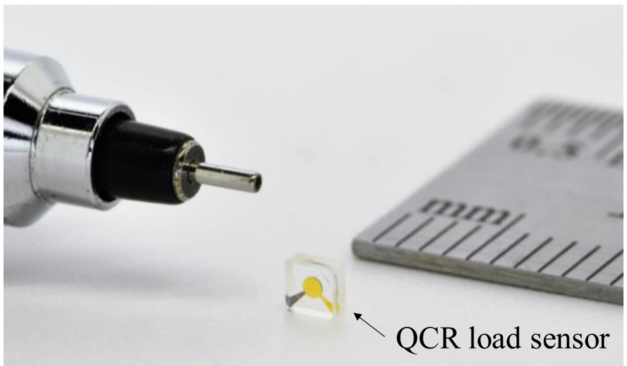

Figure 6. Photograph of the fabricated QCR load sensor.

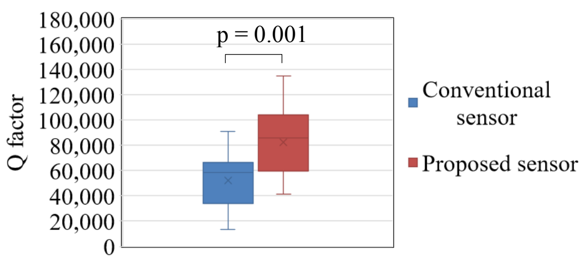

Figure 7. Comparison result of Q factor.

proposed sensor is reduced 19% compared with conventional design.

In addition, it was difficult to obtain sufficient bonding strength using atomic diffusion bonding since voids frequently occur around contamination like dust on the surface of the metal films. On the other hand, voids are unlikely to occur using bonding material, because bonding material has sufficiently low rigidity and be easily deformed. Improvement of bonding strength is expected. As a result, the allowable stress of the sensor can be expanded and the load capacity of the sensor can be improved.

B. *Sensor fabrication*

In the fabrication of the QCR load sensor, PermiNex 2010 (MicroChem Corp.) was used as the bonding resist. PermiNex is a photoresist which can be used as adhesive after patterning by photolithography. Bonding is possible by applying pressure and heat to the substrate. The sensor was fabricated with following procedure. Electrodes were patterned on the QCR layer (Fig. 5 (a)). Bonding resist was patterned on cover layers (Fig. 5 (b)). Cover layers were bonded to both sides of the QCR layer (Fig. 5 (c)). At the bonding procedure, the atmosphere was vacuumed to approximately 200 Pa. After the bonding procedure, the sensor was cut by dicing saw. An example of fabricated sensor is shown in Fig. 6.

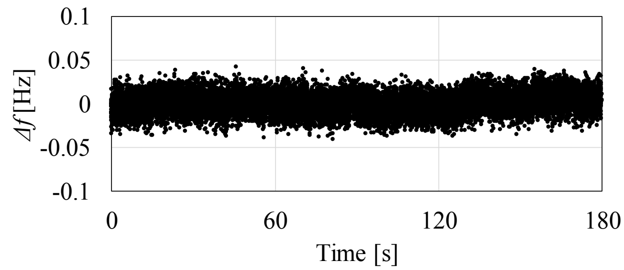

Figure 8. Sensor output for 3 minutes.

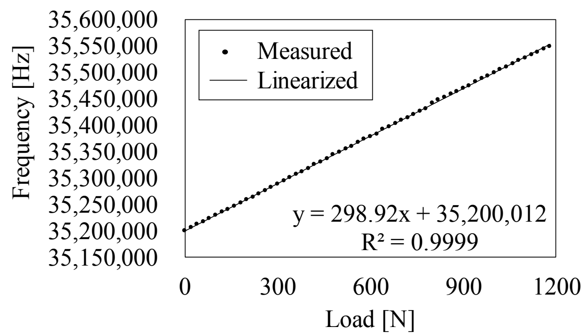

Figure 9. Result of loading test.

The Q factor of the fabricated sensor with bonding resist is compared with that of conventional sensor made by atomic diffusion bonding [10]. The comparison results obtained by measuring the Q factor of each 10 sensors are shown as box-and-whisker plot in Fig. 7. The Q factor of the proposed sensors are dominantly higher than that of conventional sensors due to the decompression of the cavity.

IV. EVALUATION OF FABRICATED SENSOR

The stability of the sensor output was measured under constant temperature environment. The output for 3 minutes under steady state is shown in Fig. 8. The sensor having Q factor of 1.0×10^5 was used for the measurement. The stability of sensor output was 0.08 Hz, which is the difference between the maximum value and the minimum value.

The loading characteristic of the fabricated sensor is shown in the Fig. 9. As a result, the slop of fitting line is 298.9 Hz/N which denotes sensitivity of the QCR load sensor. The practical resolution is calculated as 0.27 mN from the stability of sensor output and sensor sensitivity. The sensor output linearly changes up to 1180 N. Therefore, the fabricated load sensor had measurement range of 0.27 mN – 1180 N which is wider than conventional sensor [10].

V. BIOSIGNALS MEASUREMENT ON BED

A. *System setup*

As the QCR load sensors can measure only the force in the compression direction, it is necessary to prevent the force from unexpected direction. For the biosgnals measurement on bed, there is a high possibility that a large force is applied from unexpected direction due to the body motion like getting on the bed or turning over. We developed jigs with mechanism to apply the force in the compression direction to QCR load sensor (Fig. 10). The parallel spring and the steel ball reduce effect of unexpected load. Moreover, the parallel spring is easy to be deformed only in the compression direction, and the force in the compression direction is efficiently transmitted to the QCR load sensor. There is loss of force due to deformation of the parallel spring, and the force applied to the QCR load sensor is a force obtained by subtracting the loss of force by the parallel spring from the force applied to the load point.

When the ratio between the force applied to the load point and the force applied to the QCR load sensor is defined as the force transmission efficiency of the jig (η), the resolution and load capacity of the QCR load sensor with jig are Pres/η and Pmaxη, respectively. Where, P_{res} and P_{max} are resolution and load capacity of QCR load sensor alone. The jig of QCR load sensor was designed with η = 0.75 in this study.

Four QCR load sensors installed into jigs are fixed under the post of the bed. Experimental setup is shown in Fig. 11. Since the distance between bed legs is 1.74 m in the longitudinal direction, the value of l in Eq. (1) is 0.87 m. The oscillation frequencies of the four sensors are measured by a frequency counter and stored on a PC with a sampling frequency of 100 Hz. ECG signal and respiration signal were taken by finapres NOVA (Finapres Medical Systems B. V.) and recorded using data acquisition(DAQ) with sampling frequency of 100Hz.

B. Experiment

The biosignals measurement was conducted to verify the simultaneous measurement of weight, pulse and respiration on the bed. In the experiment, the subject lay on the bed with the reference ECG electrode attached, then lay down on the bed and rested for about 3 minutes. An example of experimental result (subject: male, 65.8 kg in weight, 182 cm in height, 29 years old) of biosignals measurement is shown in Fig. 12. Figure 12(a) shows the summation load of the four sensors in the experiment. Fig. 12(b) shows enlarged data from 110 to 130 seconds. Figure 12(c) shows data from 110 to 130 seconds of the change in the center of weight calculated from Eq. (1).

We can see that the summation load has periodic peaks in the large load change due to body weight. The periodic peaks correspond to ballistocardiograph. Also, the center of body mass signal shows periodic peaks at the same period, because the ballistocardiograph appears in three dimensional direction [13]. The fluctuations with a longer period than ballistocardiograph are observed in the center of body mass signal, which are fluctuations due to respiration.

C. Signal processing

The signal processing was conducted using MATLAB R2018b (Mathworks inc.). Fast Fourier transform (FFT) analysis was conducted to confirm the frequency component of the measurement data. Figure 13 shows the spectrum of the subject is on the bed (Fig.12(a) 110 s – 130 s), and before the subject ride to the bed (Fig.12(a) 0 s – 20 s). The data of 1024 points (10.24 s) was used for the analysis. Before the subject ride to the bed, the large spectrum is seen at around 27 Hz. The large spectrum is considered to be noise due to mechanical vibration of the bed structure with the sensor is observed. On the other hand, when the subject on the bed, large spectrum is seen at less than 20 Hz, and it can be said that biological information including ballistocardiograph appears at less than 20 Hz.

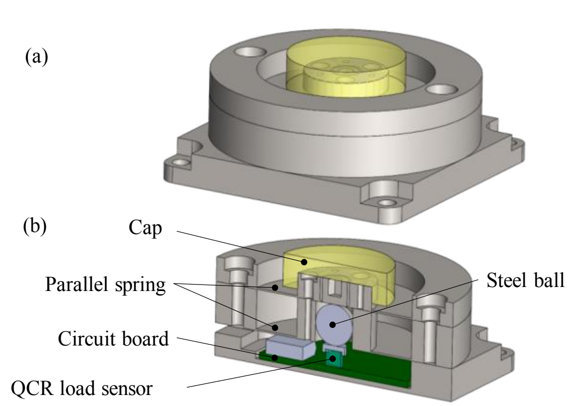

Figure 10. Schmetics of jig for QCR load sensor. (a) Overall, and (b)cross-sectional view.

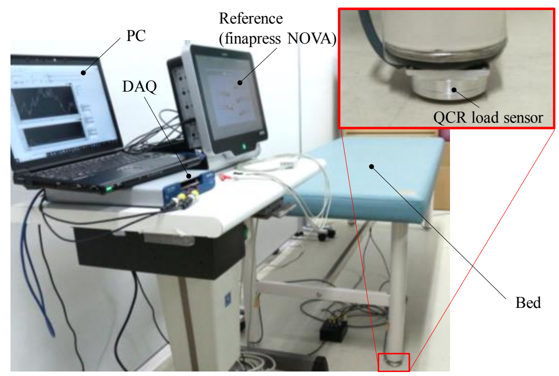

Figure 11. Experimenta setup for biosgnals measurement on bed.

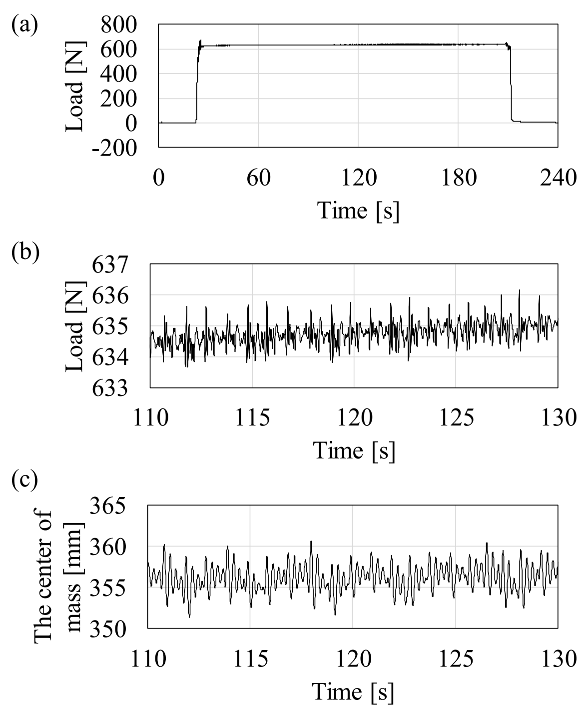

Figure 12. Experimental data for biosignals measurement. (a) Load signal, (b) enlarged load signal, (c) the center of mass signal.

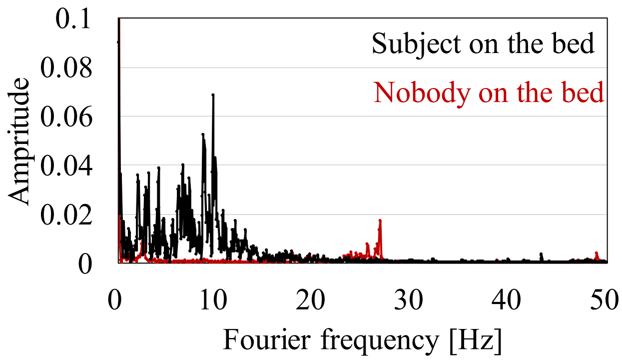

Figure 13. Result of FFT analysis of summation load signal

To extract the BCG signal, we applied bandpass filter within the frequency range of 0.8 - 20 Hz. The bandpass filter is the Butterworth filter with sixth order. The filtered signal and the ECG signal are shown in Fig. 14. The peaks of load fluctuation are seen in the same cycle as that of ECG.

We applied bandpass filter within frequency range of 0.1 - 0.5 Hz to extract the respiration signal from the center of body mass signal. The extracted signal was shown in Fig. 15(a). Figure 15(b) shows the reference signal of respiration taken by ECG electrodes. The center of mass changes the same cycle as the reference signal. In order to evaluate the accuracy of heart rate and respiration rate measurement, the error from the reference was evaluated. We evaluated the accuracy of heart rate measurement compared with reference signal. Figure 16(a) shows heart rate for each heartbeats. The average error at the stable condition was -0.006 bpm (-0.01 %) and the standard deviation was 0.4 bpm (0.6 %). Also, we compared peak to peak interval of the respiration rate with the reference signal. Figure 16(b) shows each peak to peak intervals. The average error at the stable condition was 0.03 brpm (-0.2 %) and the standard deviation was 1.1 brpm (6.1 %). From these results, we confirmed that the proposed QCR load sensing system is able to measure weight, heart rate, and respiration rate simultaneously.

In the future, it will be necessary to measure biological signals in the elderly. In long-term measurements, it is necessary to handle data that considers the effects of body movement such as turning over.

VI. Discussion: Evaluation of Weight

The load signal includes the fluctuation due to the ballistocardiograph. In order to determine the weight value, it is required to exclude the effects of ballistocardiograph. Since the ballistocardiograph is the vibration of the whole body caused by heartbeat, load signal measured on bed can be expressed by following equation.

$$u(t) = Mg + M\ddot{z} \tag{2}$$

where, M is the mass of the subject and z is vertical position of the center of subject's mass. As the heartbeat information is a periodic fluctuation, the following assumptions are made.

$$\ddot{z}(t) \approx \ddot{z}(t + T_h) \tag{3}$$

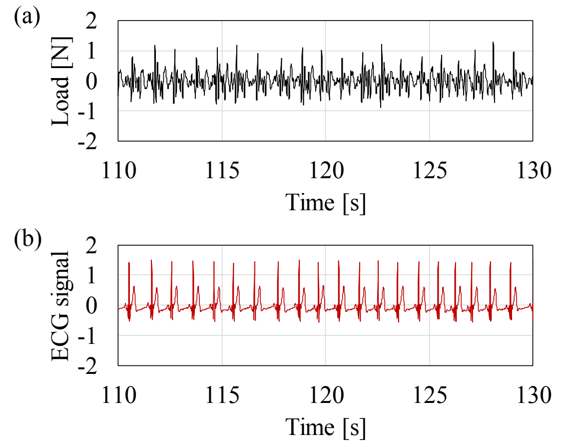

Figure 14. Comparison of heartbeat signals of (a) QCR load sensor and (b) ECG signal.

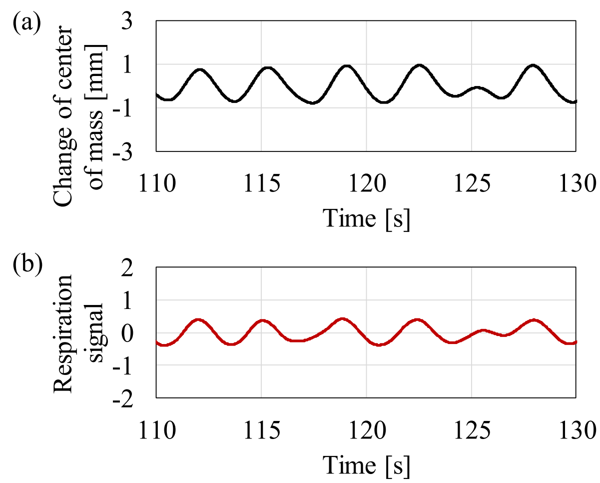

Figure 15. Comparison of respiration signals of (a) QCR load sensor and (b) taken by ECG electrodes.

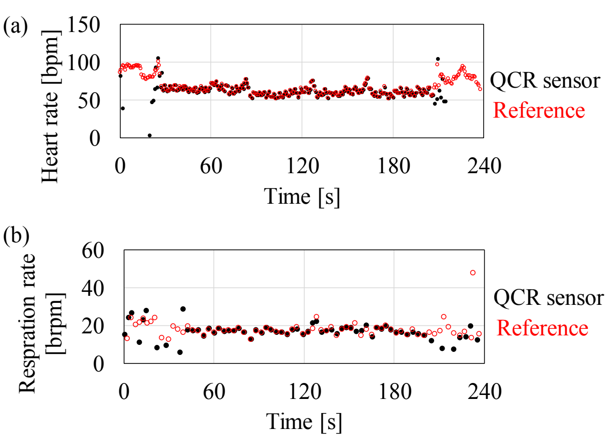

Figure 16. Comparison of peak to peak intervals with reference sensor. Black dots and red dots indicate the intervals of QCR load sensor, and reference sensor, respectively. (a) Heartbeat, and (b) respiration.

$$\dot{z}(t) \approx \dot{z}(t + T_h) \tag{4}$$

where the period of heartbeat is defined as Th. Here, the following equation is obtained by taking average load in the period of heartbeat.

$$\tilde{u}(t) = Mg + \frac{M}{T_w}\int_t^{t+T_h} \ddot{z}(\tau)\, d\tau \tag{5}$$

$$\frac{M}{T_w}\int_t^{t+T_h} \ddot{z}(\tau) d\tau = \frac{M}{T_h}(\dot{z}(t + T_h) - \dot{z}(t)) \tag{6}$$

From Eq. (4) and Eq. (6), the second term in Eq. (5) is much smaller than the first term. Therefore, equation (5) can be deformed as follows.

$$\tilde{u}(t) \approx Mg \tag{7}$$

Figure 17 (a) shows the result of moving average in the period of heartbeat with the signal before the averaging process. The period of heartbeat is determined by taking average of heart rate from 110 s to 130 s (T_h = 0.97 s). The load fluctuation due to the heartbeat becomes sufficiently small. On the other hand, fluctuations with the same period as the respiration remain, and it confirmed that the influence of respiration is included on load signal. The respiratory fluctuation was excluded by taking moving average in the cycle of the respiratory rate (T_r = 3.19 s). The results are shown in Figure 17 (b). As the result, the fluctuation caused by heartbeat and respiration could be eliminated. On the other hand, the load value has upward trend. This trend could be the influence of creep characteristics because the circuit board placed under the sensor and the adhesive used to assemble the sensor are resin. The effect of creep was observed during loading and unloading. For the accurate measurement of body weight, removal of the effect of creep is a future issue.

VII. Conclusion

The sensor fabricated by resist bonding had a measurement range of 0.27 mN - 1180 N (4.4 × 10^6), and the measurement range was improved compared with conventional sensor [1]. Proposed sensor has wider dynamic-range compared with commercial products. Eventually, simultaneous measurement of weight, heart rate and respiration rate is successfully achieved with proposed QCR load sensor.

Since, we developed a load sensor having wide measuring range of 10^6 order and a mechanically robust jig, the proposed load sensor has application not only to biosignal measurement but also the applications of robotics automation. The proposed load sensor is capable of fulfilling the role of force and tactile sensation, such as detecting the contact of a heavy object by installing the load sensor in robot hand.

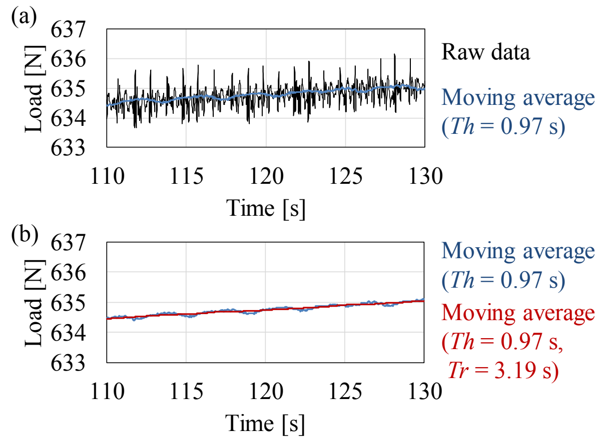

Figure 17. Result of moving averaging; (a) raw data and moving averaged data in the period of heartbeat(T_h = 0.97 s), (b) moving averaged data in the period of heartbeat(T_h = 0.97 s) and respiration(T_r =3.19 s).

References

[1] C. U. Chae, M. A. Pfeffer, R. J. Glynn, G. F. Mitchell, J. O. Taylor, and C. H. Hennekens, "Increased pulse pressure and risk of heart failure in the elderly," *J. Am. Med. Assoc.*, vol. 281, no. 7, pp. 634–639, 1999.

[2] D. Planchard, F. Moreau, J. Paquereau, J.-P. Neau, and J.-C. Meurice, "Sleep apnea syndrome in the elderly. [French]," *Rev. Mal. Respir.*, vol. 21, no. France OT-LE SYNDROME D'APNEES DU SOMMEIL DU SUJET AGE LG-French PT-Journal: Review EM-200504, p. 8S153-8S160, 2004.

[3] E. Pinheiro *et al.*, "Robust heartbeat detection from in-home ballistocardiogram signals of older adults using a bed sensor," *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBS*, vol. 2015–Novem, no. JANUARY, pp. 7175–7179, 2015.

[4] A. Vehkaoja, A. Kontunen, and J. Lekkala, "Effects of sensor type and sensor location on signal quality in bed mounted ballistocardiographic heart rate and respiration monitoring," *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBS*, vol. 2015–Novem, pp. 4383–4386, 2015.

[5] L. Dziuda, M. Krej, and F. W. Skibniewski, "Fiber bragg grating strain sensor incorporated to monitor patient vital signs during MRI," *IEEE Sens. J.*, vol. 13, no. 12, pp. 4986–4991, 2013.

[6] W. B. Spillman *et al.*, "A 'smart' bed for non-intrusive monitoring of patient physiological factors," *Meas. Sci. Technol.*, vol. 15, no. 8, pp. 1614–1620, 2004.

[7] Z. T. Beattie, T. L. Hayes, C. Guilleminault, and C. C. Hagen, "Accurate scoring of the apnea-hypopnea index using a simple non-contact breathing sensor," *J. Sleep Res.*, vol. 22, no. 3, pp. 356–362, 2013.

[8] B. H. Choi *et al.*, "Non-constraining sleep/wake monitoring system using bed actigraphy," *Med. Biol. Eng. Comput.*, vol. 45, no. 1, pp. 107–114, 2007.

[9] Z. Wang, H. Zhu, Y. Dong, and G. Feng, "A thickness-shear quartz resonator force sensor with dual-mode temperature compensation," *IEEE Sens. J.*, vol. 3, no. 4, pp. 490–496, 2003.

[10] Y. Murozaki, S. Sakuma, and F. Arai, "Improvement of the measurement range and temperature characteristics of a load sensor using a quartz crystal resonator with all crystal layer components," *Sensors (Switzerland)*, vol. 17, no. 5, 2017.

[11] I. STARR and E. A. HILDRETH, "The effect of aging and of the development of disease on the ballistocardiogram; a study of eighty subjects, originally healthy, followed from ten to fourteen years.," *Circulation*, vol. 5, no. 4, pp. 481–495, 1952.

[12] H. E. Bömmel, W. P. Mason, and a. W. Warner, "Dislocations, relaxations, and anelasticity of crystal quartz," *Phys. Rev.*, vol. 102, no. 1, pp. 64–71, 1956.

[13] J. A. Clin and P. Physiol, "Clinical Physics and Physiological Measurement Related content Three-dimensional ballistocardiographic responses to changes of posture Three-dimensional ballistocardiographic responses to changes of posture," 1982.