Development of an AI-load-cell-based wireless ringer's solution monitoring and alarm system: insight into vibrational error correction

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Abstract

In this study, we developed an aluminum-load-cell-based wireless Ringer's solution monitoring and alarm (WRMA) system. The AI load cell was designed with a rectangular shape, and the load was concentrated in the lower beam part of the load cell because of the anisotropic thickness. From the static analysis, we identified the appropriate location for a Wheatstone bridge circuit consisting of four strain gauges. In addition, the modal and harmonic analyses showed that the vibrational frequencies of the hospital environment do not seriously interfere with the output voltage of the AI load cell. However, random vibrations generated by the movement of the WRMA system on various surfaces severely increase the standard deviation of the measured solution weight by ± 10 g or more. Such vibrational error is too large because the average weight of Ringer's solution is 30–40 g at the time of replacing Ringer's solution. Thus, this error could be confusing for nurses and result in mistakes in the timely replacement of the Ringer's solution. However, the standard deviation of the measured weight was dramatically reduced to ± 3 g or less by using the vibration correction algorithm developed in the present study.

Keywords Wireless Ringer's solution monitoring and alarm system · AI load cell · Wheatstone bridge · Static analysis · Modal analysis · Harmonic analysis · Vibrational error

1 Introduction

Medical staff must consider carefully the time for the replacement of intravenous infusion solutions to prevent blood backflow. This simple and repetitive task not only reduces the efficiency of the medical staff but also increases costs [1–4]. Therefore, the use of a wireless Ringer's solution monitoring and alarm (WRMA) system could improve the quality and efficiency of medical care [5, 6]. Thus, WRMA systems for use in hospitals have been developed to measure the infusion rate and the residual amount of Ringer's solution [7–9]. These systems have focused on the infusion rate rather than the fluid level because an excessive flow rate of Ringer's solution is a serious risk to patients [10,

11]. Therefore, most WRMA systems use ultrasound or a high-precision optical sensor to detect the dropping solution [12–16]. However, such droplet monitoring sensors are inefficient for detecting the solution level because of their high cost and large size [17]. In contrast, strain gauge load cells could be more efficient for monitoring the residual amount of the Ringer's solution because of their simple organization of circuits, low unit cost, and applicability to universal Ringer's solution container (e.g., polymer packs or glass bottles) [18, 19]. Knowledge of the amount of residual Ringer's solution could increase work efficiency by enabling nurses to finish their work before hand and prepare the Ringer's solution for replacement. In particular, a warning when the residual amount of the Ringer's solution is around 30 mL or less is required in a clinical setting. However, there is a severe problem in measuring the residual amount of Ringer's solution accurately when additional vibrational forces are applied to an intravenous infusion solution system, for example, during walking or patient transfer. Unfortunately, most WRMA systems released to the market do not consider vibrations originating from the irregular movements of patients [20, 21].

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In this study, we analyzed how horizontal and vertical vibrations affect the stress, strain, and displacement on the load cell using structural simulations. For this purpose, a structural interpretation was carried out using ANSYS (Ver.11), a structural interpretation tool using the finite element method (FEM). The special output characteristics were analyzed through the static analysis of the stress, the mechanical strain, and the displacement of load cell structure, and the interpretation of the special vibrational characteristics was carried out through dynamic analysis, including modal analysis and harmonic analysis. The optimizations of the load cell and the system were achieved by the development of an algorithm that can compensate for errors arising from vibrations by analyzing the special movement characteristics of the load cell. We believe that the present WRMA system could improve the quality of the medical service and the efficiency of on-site systems.

2 Materials and methods

2.1 Fabrication of AI-load-cell-based WRMA system

Fabrication of the WRMA system was supported by Daeyoung Inc. in Korea. Based on the results of ANSYS simulation, the load cell was fabricated in a rectangular shape with a length of 21 mm and a width of 57 mm and made of aluminum 2024 alloy (Al 2024), as shown in Fig. 1. The thickness of the lower part of the Al load cell was thinner by 2 mm than the upper part, which had a thickness of 5 mm, so that the applied load could be effectively concentrated on the lower part of the strain gauge rather than on the upper part. The Wheatstone bridge circuit was organized by arranging four strain gauges on the lower part of the Al load cell. The permeable output voltage of the resulting Al load cell was approximately 1–3 mV/V. The WRMA system was organized with the Al load cell as weight sensor, electric circuitry, and containment. The containment consists of the base and the base cover, the battery cover, a button, an organic

light emitting diode display (OLED, UG-2864ASYPG01, Wisechip Inc., Taiwan) window, a light emitting diode (LED, BL-B2141, Bright LED Elec. Inc., China) extension, and a power switch. The apparatus was made of acrylonitrile butadiene styrene (ABS) plastic except for the LCD window and the LED extension, which were made of polycarbonate (PC). The loop, where the Ringer's solutions with the different weights are attached, was directly connected to the Al load cell by stainless steel (SUS 630).

After measuring the weight of the Ringer's solution at the terminal of the WRMA system, the weight is represented on the graphical user interface (GUI) of the monitoring computer via wireless communication (IEEE 802.11 b/g/n, 2.4 GHz). Figure S1 in the Supplementary Information shows the hardware (H/W) configuration of the WRMA system, in which the built-in software was driven by a microcontroller unit (MCU, GS 2101, Gain Span, USA), where the core functions of the H/W module are responsible for signal control and wireless communication. A rechargeable lithium-ion battery (PSE H703562, Power Source Energy Inc., USA) with a direct current (DC) of 5 V was charged to an alternating current (AC) of 220 V to power the WRMA system. The weight information from the Al load cell was collected through an amplifier, a low pass filter, and an analog-to-digital converter (ADC, AD7780BRZ, Analog Devices Inc., USA), and the resulting information was transmitted to the MCU. The MCU displays the collected weight information and the operation status of the WRMA system through the LED interface, and then the collected data are transmitted wirelessly to the GUI of the monitoring computer using a 2.4-GHz wireless local area network (WLAN).

2.2 Software and algorithm driving the WRMA system

The MCU of the present WRMA system used a dual-core MCU. As shown in Fig. S2, one part is responsible for the operation of the MCU and the other part is responsible for the Wi-Fi communication network. The device module

Fig. 1 Photographs of WRMA system and Al load cell

initializes and drives each H/W block, and the scenario manager controls the entire operation including button input and other external events of the WRMA system. The host MCU processes the data input from the AI load cell, and a real-time OS (RTOS) was installed to process external input, output, and Wi-Fi communication in real time without delay. In addition, an algorithm for minimizing the vibrational errors of the WRMA system was programmed using the IAR Embedded Workbench® IDE compiler (Advanced RISC Machines Ltd.).

2.3 Static and dynamic simulation of the AI load cell

Structural interpretation of the AI load cell was carried out using ANSYS (Ver.11), which is a structural interpretation tool using FEM. ANSYS (Ver.11) has a pre-processor part for modeling the AI load cell, an interpretation part for interpretation of the applied weights, and a post-processor part for the representation of results. The material properties of AI 2024 used for structural interpretation are as the following: density = 2780 kg/m³, Young's modulus = 73 GPa, Poisson ratio = 0.33 [22]. The AI load cell was modeled for static analysis by using the node element type (SOLID 45 3-D 8 in ANSYS), and then the structural interpretation was carried out using three degrees of freedom for the AI load cell and an applied force of 3 kgf (29.4 N, 4160 kPa) at the end of a cradle. The modal and the harmonic analyses were carried out using the same conditions for the AI load cell and were used to find the resonance mode and the resonance frequency within the range of the frequencies of 0 Hz to 10 kHz.

2.4 Real-time vibration tests

The real-time variation of the output voltage was obtained by testing the WRMA system on various surfaces, for example, tiled floor, brick floor, and asphalt, as shown in Fig. 2. As mentioned above, Ringer's solution is usually

changed when the remaining solution is around 30 mL or less. Therefore, we tested the WRMA system after applying a weight of Ringer's solution of 30–40 g (excluding the bottle weight). The output voltages were monitored in real time while the Ringer's solution hanger was slowly reciprocated over various surfaces for a distance of 1 m. In addition, the flow rate of the Ringer's solution was 2–3 drops/s.

3 Results and discussion

3.1 Static simulation of AI load cell

As shown in Fig. 3, the results of the static simulations for the AI load cell with a loading weight force of 3 kgf (29.4 N, 4160 kPa) indicate that the stress, strain, and displacement are concentrated at positions denoted (1)–(4) in the lower beam of the AI load cell. In particular, we found that the tensile stress–strain was concentrated at points (1) and (4), but the compressive stress–strain was applied at positions (2) and (3) of the AI load cell. This indicates that suitable positions for the strain gauges in the present AI load cell are (1)–(4), as indicated by the red arrows (Fig. 3b) because the electrical resistance of the strain gauge is proportional to the strain.

The Wheatstone bridge circuit consists of the two tensile strain gauges [(2) and (3)] and the two compressive strain gauges [(1) and (4)]. When the Ringer's solution is loaded on the AI load cell, the tensile strain gauges at (1) and (4) are stretched, increasing their resistance. Meanwhile, the resistance of the compressive strain gauges at (2) and (3) are reduced by contraction. Meanwhile, the upper part of the AI load cell exhibited the lowest displacement because the upper part was fixed to the main body of the WRMA system.

Fig. 2 Photographs of various surfaces for vibration effect testing of the WRMA system. The Ringer's solution hanger including the WRMA system was slowly reciprocated over various surfaces for a distance of 1 m

Fig. 3 Static simulation results for the **a** stress, **b** strain, and **c** displacement of the Al load cell induced by a loading weight force of 3 kgf (29.4 N, 4160 kPa)

3.2 Output voltage variation of Al load cell upon weight application

Based on the static simulations, we fabricated the WRMA system including the Al load cell equipped with the Wheatstone bridge circuit in the lower beam part. Figure 4 shows the weight variation obtained from the present WRMA system upon loading of a weight of 0–3.0 kg. Where the driving voltage of the Al load cell was DC 3 V, and the test was repeated five times for reproducibility verification. The weight measured from the WRMA system was linearly proportional to the applied weight, and the standard deviation was approximately $\pm 1 \text{ g}$. This indicates that the strain gauges were well placed on the Al load cell and worked well in the WRMA system.

3.3 Dynamic simulation of the Al load cell

Modal and harmonic analyses were performed to find how the vibrations generated from the external environment affect the Al load cell [23, 24]. The results of the modal analysis in Fig. 5 show the resonance modes of the Al load cell with a loading weight force of 3 kgf at an external frequency of 0–10,000 Hz. The modal analysis was carried out using three degrees of freedom by fixing the Al load cell as shown in Fig. 5a. The modal analysis revealed seven resonance frequencies that induce resonance modes of the Al load cell. At resonant frequencies of 2017 and 2242 Hz, the resonance mode of the Al load cell mainly occurred in the cradle part, as shown in Fig. 5b, c. However, there were no resonance modes in the strain gauge attachment of the Al load cell. In contrast, a resonance frequency greater

Fig. 4 Photographs of the WRMA system, and the variation in the output voltage of the Al load cell after loading with weights of 0–1.0 kg

Fig. 5 **a** Simulation of the Al load cell fixed to the ABS plastic cover. Modal analysis of the Al load cell subject to resonant frequencies of **b** 2017, **c** 2242, **d** 4651, **e** 5335, **f** 5361, **g** 6643, and **h** 9059 Hz

than 4651 Hz led to vibrations of the main body, including the strain gauges attached to the lower beam (Fig. 5d–h). Importantly, the vibrational frequencies generated in a hospital environment are normally less than 1000 Hz, which is lower than the first resonance frequency (2017 Hz) of the Al load cell [25]. Therefore, there is a low probability that the frequencies in the hospital environment will affect the resonance mode of the present Al load cell.

On the other hand, the harmonic analysis reveals the vibrational properties of a specific part of a mechanical structure because we can find the resonance frequency of a structure within a set frequency range. Figure 6 shows the results of the harmonic analysis for the Al load cell with a weight force of 3 kgf (29.4 N, 4160 kPa) along the *x*-, *y*-, and *z*-axes on the application of frequencies of 0–10 kHz and 0–1 kHz, respectively. The external force corresponding to a load force of 3 kgf was applied to the cradle part to induce vibrations at the end of the Al load cell. As shown in Fig. 6a, b, the main resonance peak of the Al load cell was observed around 4–5 kHz on the application of frequencies of 0–10 kHz along the *x*- and *y*-axes. For the harmonic analysis along the *z*-axis, the first resonance peak was observed at 2 kHz, as shown in Fig. 6c. These high frequencies above

1 kHz would not be generated in a typical hospital environment and, consequently, will not affect the output voltage of the Al load cell [26, 27]. Figure 6d–f show the results of the harmonic analysis along the *x*-, *y*-, and *z*-axes in the range of 0–1 kHz; there are no resonance peaks. The amplitude tended to increase with an increase in frequency but remained very low. However, the intensity of the resonance peak amplitude in the harmonic spectrum along the *y*-axis was approximately 10 to 100 times greater than those along the *y*- and the *z*-axes. Because the weight force (3 kgf) of the Ringer's solution was applied to the *y*-axis direction of the Al load cell.

Figure 7 shows the amplitude variation of the Al load cell upon increasing the weight force of the Ringer's solution from 1 to 3 kgf by applying a vibration frequency in the range of 0–1 kHz along the *y*-axis. There was little change in amplitude up to a vibration frequency of 100 Hz, but it was slightly increased in the range of 100 Hz to 1 kHz. Figure 7d shows that the intensity of amplitude at 100 Hz of the vibrational frequencies increased linearly with an increase in load weight of the Ringer's solution. However, such a small alternating current (AC) generated from the vibration frequency could be eliminated by using an LPF.

Fig. 6 Harmonic spectrum of the Al load cell by applying frequency of **a–c** 0–10 kHz and **d–f** 0–1 kHz along, **a, d** the *x*-, **b, e** the *y*-, and **c, f** the *z*-axes, where a load force of 3 kgf (29.4 N, 4160 kPa) of the Ringer's solution was applied to the cradle part of the Al load cell

Fig. 7 Harmonic spectrum of Al load cell for load-ing weight forces of **a** 1 kgf (9.8 N, 1387 kPa), **b** 2 kgf (19.6 N, 2773 kPa), and **c** 3 kgf (29.4 N, 4160 kPa) by applying frequency of 0–1 kHz along the *y*-axis. **d** Amplitude variation of Al load cell at 100 Hz vibrational frequency with an increase in Ringer's solution weight

From the modal and the harmonic analyses, we found that the vibrational frequencies in the hospital environment do not seriously interfere with the output voltage of the Al load cell. Nonetheless, if the cell was used in an environment (e.g., aircraft) where high-frequency vibrations above 2 kHz could occur, it would be necessary to consider errors arising from the frequency resonance generated in the Al load cell. However, this does not imply that random vibrations generated from patient movement do not affect the output voltage of the Al load cell.

3.4 Al load cell analysis upon horizontal vibration

When patients attached to the Ringer's holder are moved around, the output voltage (DC component) of the Al load cell could be mixed with the vibrational AC components, as mentioned the above. In particular, lateral vibrations could interfere with the output of the Al load cell to a greater extent than the vertical vibrations because the upper part of the Al load cell is fixed at the ABS plastic cover, as shown in Fig. 5a. Figure 8 shows the magnitude of the force applied to the Al load cell with swing angle along the x -axis when the loading cradle swings from right to left (horizontal vibration).

If the swing angle is 30° , the vector of the F_2 force is divided into F_2' and F_2'' , whose factors can be represented

as $F_2 \cdot \cos 30^\circ$ and $F_2 \cdot \sin 30^\circ$, respectively (Fig. 8a). Each force components of horizontal vibration can produce a deformation of the Al load cell, and, eventually, the output voltage of the Wheatstone bridge will be altered by the change in the resistance of the strain gauges as shown in Fig. 8b. The output voltage (V_{out}) of the Wheatstone bridge circuit is proportional to a change in the resistance (R) and the supply voltage (V_{in}), as shown in the following equation [28, 29].

$$V_{out} = \left[\frac{R_4}{R_2 + R_4} - \frac{R_3}{R_1 + R_3} \right] \times V_{in} = \left[\frac{R_1 R_4 - R_2 R_3}{(R_2 + R_4) \times (R_1 + R_3)} \right] \times V_{in} \quad (1)$$

Here R_1 – R_4 represent the resistances of the strain gauges, and their values are equal ($R_1 = R_2 = R_3 = R_4$). When the lateral vibration of the Al load cell occurs, a strain-induced resistance change (ΔR) is generated from the strain gauges. In the Eq. (1), R_x ($x = 1$ – 4) can be replaced by $R_x + \Delta R_x$, and as a result, the V_{out} depends on a variation of the ΔR_x . As shown in Fig. 8b, the F_2'' component of the x -axis force reduces ΔR_1 and ΔR_2 of the strain gauges (S_1 and S_2) located at positions (1) and (2) but increases ΔR_3 and ΔR_4 of the strain gauges (S_3 and S_4) located at positions (3) and (4). For the F_2'' force, ΔR_1 and ΔR_3 are equal to ΔR_2 and ΔR_4 , respectively. Thus, the F_2'' force balances the Wheatstone bridge circuit and no current flows ($V_{out} = 0$).

Fig. 8 Schematic illustration of the **a** applied force analysis and **b** Wheatstone bridge when lateral vibrations are applied to the Al load cell. Here, S , R , and ΔR represents the strain gauge, resistance of the strain gauge, and resistance change arising from the strain, respectively

Meanwhile, the F_2' component of the y-axis force reduces ΔR_1 and the ΔR_4 of the strain gauges (S_1 and S_2) located at positions (1) and (4) but increases ΔR_2 and ΔR_3 of the strain gauges (S_3 and S_4) located at positions (2) and (3), in which ΔR_1 and the ΔR_2 are equal to the ΔR_4 and the ΔR_3 , respectively. The F_2' force corresponding to the y-axis component appears as an output of the Wheatstone bridge circuit when lateral vibrations occur, regardless of shaking angle ($V_{out} \neq 0$). That is, the output voltage of the AI load cell on loading with the Ringer's solution could suffer interference from the cosine component of the lateral vibration force when the Ringer's solution swings from left to right.

Figure S3 in the Supplementary Information shows the results of the strain simulations of the AI load cell, in which a weight force of 3 kgf was applied in the y-axis direction with a swing angle in the y-axis. When lateral vibrations are applied to the AI load cell, the strain is mainly induced from the force corresponding to the y-axis (cosine) component, and it will be proportional to $F \cos\theta$ (swing angle with respect to the y-axis), as mentioned above. Therefore, the strain change of the AI load cell decreases with an increase in swing angle from 0° to 60° , as shown in Fig. S3(d). However, it is difficult to obtain simulation results for the interference of the vertical vibration in the AI load cell; the results shown in Figs. 7 and 8 imply that vertical vibrations rather than lateral ones cause more interference in the output voltage of the AI load cell because the amplitude of the vibrational frequency linearly increases with an increase in load weight on the y-axis.

3.5 Programming algorithm for the correction of vibrational errors

If the strain change of the AI load cell via external vibrations is small enough, vibrational noise from the output voltage can be cut off by an LPF. However, if the vibration-induced displacement of the AI load cell increases beyond the permissible value of the LPF, the vibrational noise signal should be removed from the output of the AI load cell using the algorithm shown in Fig. S4. The output voltage of the AI load cell was sampled by an analog-to-digital converting (ADC) process of the MCU in 20 ms intervals. The ADC results were continually accumulated in the queue element, and the resulting queues were maintained as a window length of 500 ms using the circular queue method. That is, the oldest queue beyond the window size was removed from the entire queue when new sampling datum was input after 500 ms of data sampling. Every 500 ms, the queues corresponding to the output voltage out of the range of $0 \leq V_{out} \leq 250$ mV (5.5 kg) were eliminated from the accumulated queues. Because the typical Ringer's solution weight is approximately ≤ 3 kg without the weight of

the Ringer's solution bottles, we set the measurable weight of the WRMA system to 5.5 kg. Then the average value was calculated from the resulting 25 queue elements accumulated for 500 ms. Then, the queues with a deviation of 0.05 mV (corresponding to 1 g) or more from the average queue were replaced with the voltage average value to reduce the vibrational errors.

Figure S5 in the Supplementary Information shows why we set 0.05 mV as the out-of-range reference value. In the real-time tests of the effects of the vibration on the WRMA system on rough tiled floors, the raw data for the weight variation of the Ringer's solution weighing 45 g, which is the weight of the pure solution without the Ringer's bottle (246 g), showed a standard deviation (STD) of ± 11 g, but this was decreased to ± 6 g after setting the cut-off point of the STD to every 25 queue elements in the algorithm. In addition, the STD of the Ringer's solution weight was changed from ± 6 g to ± 4 g after setting the cut-off point to 0.50–0.05 mV. Interestingly, the STD of ± 4 g did not reduce further, even if the cut-off point was set to less than 0.20 mV. Possible, this is because the external vibration was very severe. However, we selected a cut-off point of 0.05 mV as the minimum value because the weight standard deviation of the WRMA system was ± 1 g.

3.6 Real-time test of vibration effect on WRMA system

For the smooth tiled floor, the loading weight displayed on the WRMA system was slowly decreased from 35 to 34 g after dropping the solution for 1 min. (60,000 ms), as shown in Fig. 9a. The standard deviation of the measured weight in the raw data was ± 3 g, but it was decreased to ± 1 g after correction with the vibration minimizing algorithm.

For the rough tiled floor (Fig. 9b), the weight of the Ringer's solution was changed from 39 to 32 g after dropping the solution for 5 min (300,000 ms), and the standard deviations of the measured Ringer's solution weight before and after the correction were ± 11 g and ± 3 g, respectively. Sometimes, the weight of the Ringer's solution in the raw data was significantly increased by up to ± 60 g, which seemed to originate from the change in the direction of the Ringer holder on the rough tiled floor, which has substantial irregularities. These characteristics of the WRMA system on uneven surfaces were similarly generated from the brick floor and the asphalt surface, where the standard deviations of the Ringer's solution weight were ± 14 g and ± 9 g, respectively (Fig. 9c, d). That is, the vibrations transmitted to the AI load cell in the WRMA system increase and, subsequently, the standard deviation of the measured weight increased with an increase in floor unevenness. However, such large

Fig. 9 Weight variation of Ringer's solution monitored using the WRMA system using on surfaces consisting of **a** smooth tiles, **b** rough tiles, **c** bricks, and **d** asphalt. Here, Exp. and Corr. in the graph represent the raw and corrected data, respectively

Table 1 Summary of the variation in the weight of the Ringer's solution for the WRMA system used on different surfaces

	Smooth tiles	Rough tiles	Bricks	Asphalt
Measurement time (min)	1	5	5	5
Reduced weigh of solution over the measurement time	1 g (34 → 33 g)	7 g (39 g → 32 g)	15 g (40 g → 25 g)	22 g (45 g → 23 g)
Standard deviation of measured weight (before correction) (g)	± 3	± 11	± 14	± 9
Standard deviation of measured weight (after correction) (g)	± 1	± 3	± 4	± 3

vibrational errors were significantly reduced by the vibration minimizing algorithm, as summarized in Table 1.

Figure 10 shows the real-time monitoring result of the loading weight variation of the Ringer's solution connected

to the WRMA system when it was slowly reciprocated over an uneven surface made of tiles and bricks with a distance of 30 meters. As a result, the weight of the Ringer's solution changed from 38 to 19 g after dropping the solution for

Fig. 10 **a** Photographs of surfaces made of rough tiles and bricks for WRMA system testing. **b** Weight variation of Ringer's solution for WRMA system working on **a** smooth tiles, **b** rough tiles, **c** bricks,

and **d** asphalt. Exp. and Corr. in the graph represent the raw and data corrected using the algorithm developed in the present study, respectively

5 min. The recorded weight variation before and after the correction using the algorithm had standard deviations of ± 11 g and ± 2 g, respectively. From the tests of the WRMA system moving on various floors, we found that vibrations could lead to an increase in the standard deviation of the measured weight in the raw data of ± 10 g or more. This is a significant error considering that the average Ringer's solution weight is 30–40 g at the time that the Ringer's solution requires replacement. Such large vibrational errors can be confusing to medical staff, making mistakes in the replacement time of the Ringer's solution possible. However, vibrational errors in the WRMA system were dramatically reduced to ± 3 g or less by the present algorithm.

4 Conclusions

In conclusion, we have successfully developed an AI-load-cell-based wireless medical infusion monitoring and alarm (WRMA) system that minimizes the vibrational errors of the AI load cell through an LPF and algorithm. To find the appropriate position of the strain gauges in the AI load cell, we carried out static analysis and found that the stress, the strain, and the displacement were concentrated in the lower beam part of the AI load cell on loading. Consequently, the two tensile strain gauges and the two compressive strain gauges were attached to the lower beam sites with positive and negative strain, respectively. From the modal and the harmonic analyses, we found that the vibrational frequencies induced

by the hospital environment do not seriously interfere with the output voltage of the AI load cell. AI load cell analysis with lateral vibrations revealed that the output voltage of the AI load cell was affected by lateral vibrations corresponding to the y-axis component, regardless of swing angle. Therefore, the strain change in the AI load cell decreased with an increase in swing angle. This result suggested that vertical vibrations rather than lateral vibrations cause more interference with the output voltage of the AI load cell. From the real-time tests of the vibrational effects on the WRMA system, we found that the significant standard deviation in the vibration-induced raw data of the Ringer's solution weight could be remarkably reduced by an LPF and our vibration minimizing algorithm.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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