Simultaneous Measurements of Shifts of the Center of Gravity Caused by Ventilation and Cardiac Motions towards Three Body Axes

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A method is described for the simultaneous measurements of three dimensional shifts of the gravitational center of the body caused by ventilatory and cardiac motions. The measuring system consists fundamentally of three load cells which support an aluminum die-casting platform. Measurement of the shift towards the X axis (front-to-back) was achieved by double integration of the outputs of load cells in order to convert acceleration into a shift of gravity. The records of a volunteer subjects measured with ECG and ventilatory flow showed two cardinal oscillations; one coinciding with the heart rate and the other with the ventilatory frequency.

This became clear when recorded through either a low-pass or high-pass filter. Animals who breathed a SF6·O2 mixture into one side of the lungs or those with partial occlusion of a bronchus showed distinct changes in the pattern of the Y axis (right-to-left).

These preliminary experiments convinced us that the system can serve as a non-invasive monitoring system of cardiopulmonary functions.

(Key Words: Gravitational Center of the Body, Mass Movements by Ventilation and Cardiac Motion, Load Cell)

INTRODUCTION

Since the earlier work of Borellus in 1679 (Haycraft, 1930), many investigators have been interested in the location and movement of the center of gravity of the human body in connection with posture (5, 9, 10) and with body sways under both normal and pathological conditions (3, 6, 7, 8). In recent years, a platform type apparatus is commonly used for measurements of the gravitational center. Electrical signals are obtained through either a strain gauge (6, 9), potentiometer (2), electromagnetic plunger (1) or load cells (8, 10).

With such an apparatus, however, only two-dimensional approaches to the center of gravity have been performed, while Thomas and Whitney (1959) measured three dimensional reactionary forces at the feet, and Willems and Swalus (1967) measured the vertical projection of the center of gravity.

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in one plane. Also, little attention was paid to shifts of the center of gravity caused by ventilation and cardiac motion. Okabe (1975) referred to the effects of ventilation on body sways measured by a two-dimensional apparatus, but no significant change was found between those during breath-holding and those during spontaneous breathing. Concerning the data obtained by Thomas and Whitney (1959), it is not unfair to conjecture that the low frequency (0.12 to 0.39 c.p.s.) components of trunk displacement may in part be attributed to the movements caused by ventilatory and cardiac motions.

The purpose of the present study is to develop a new apparatus to measure simultaneously the shifts of the center of gravity towards the three body axes, and to observe the shifts caused by ventilation and cardiac motions.

METHODS

PRINCIPLE OF THE METHOD. A subject lies down on an aluminum die-casting board which is supported by three high-performance load cells as illustrated in Figs. 1 and 2. If we assume that the center of gravity of a body weighing P has unknown coordinates of z and y on the Y-Z body plane and that the weights measured at three points are P1, P2, and P3, respectively (Fig. 1), we get P·y = P2·m - P3·m from the moment around the Z axis, and P·z = P2·l + P1·l from the moment around the Y axis, where I and m stand for the coordinates of points P1 and P2, respectively. Thus we obtain the coordinates of the center of gravity as follows:

\[ y = \frac{(P2 - P1) \cdot m}{(P1 + P2 + P3)} = \frac{(P2 - P1) \cdot m}{P} \]
\[ z = \frac{(P2 + P1) \cdot l}{(P1 + P2 + P3)} = \frac{(P2 + P1) \cdot l}{P} \]

![Diagram](image-url)

Fig. 1 Measurement of the shift of the center of gravity on the Y-Z body plane. For details, see text.
Concerning the shift of the gravitational center towards the X body axis on the X-Z plane (Fig. 2), the weight towards the X axis is measured as the sum of static body weight \( P_0 \), and acceleration force \( \ddot{x} \), times \( P_0 \), i.e., \( P = P_0 + P_0 \cdot \ddot{x} \). Since the vertical displacement of the center towards the X axis can be obtained by the double integral of acceleration force, the shifting of the center towards the X axis can be measured by the following equation:

\[
x = \int \int (P/P_0 - 1) \, dt^2 + C
\]

where \( C \) is a constant of integration. Actually, the static body weight \( P_0 \) can rarely be measured as long as the subject is alive. Since \( P_0 \cdot \ddot{x} \) is, however, much smaller than \( P_0 \), we can consider that the weight measured at rest is approximately equal to \( P_0 \).

![Diagram of center of gravity shift](image)

**Fig. 2** Shift of the center of gravity towards the X body axis. See text for details.

**DESCRIPTION OF THE APPARATUS.** The platform consists of an aluminum die-casting table measuring 180 cm by 70 cm which is supported by three load cells fixed on a triangular metal plate. The load cells used (Kyowa LC-F, Japan) consist of wire-strain gauges and have a maximum weighing capacity of 100 kg each. Both linearity and hysteresis of the cells are less than 0.1% of full scale.

A block diagram of the whole system is shown in Fig. 3. Amplified and/or integrated signals from the load cells are recorded either directly or through low or high pass filters, both having a cut-off frequency of 2 Hz.

We employed two different calibration methods for the horizontal (Y-Z) and vertical (X-Z) planes. In the former case, a calibration board of metal with nine holes in it was placed on the platform and the outputs of the load cells were recorded by the X-Y recorder when a known weight was put in each of the nine holes of the calibration board. From the above measurement and analysis of resonant frequency, we can obtain the static characteristics of the apparatus as well as calibration of the Y-Z plane. Calibration of the vertical plane was performed using a cylindrical weight rotating around an eccentric axis (Fig. 4). The center of gravity towards the X axis shifts in parallel with the shift of the rotating axis from the center of the cylinder, and the dynamic characteristics can be checked by changing the cycle of rotation of the cylinder.
Fig. 3 Block diagram of the system for measuring the shift of the gravitational center. X, Y and Z indicate the three body axes, and P1, P2, and P3 stand for the weights measured by three load cells.

Fig. 4 Method of calibrating the shift of the center of gravity towards the X axis. A cylindrical weight of 5kg with an eccentric rotating axis is rotated by an electrical motor, and the eccentric distance from the center of the cylinder and the speed of rotation are changed.
RESULTS AND DISCUSSION

CHARACTERISTICS OF THE MEASURING SYSTEM. The outputs of the three load cells used in the present study produced essentially straight lines in proportion to the amounts of applied loads up to 100 kg, and the linearity was less than ±0.1% of full scale. Fig. 5 indicates the performance of the apparatus in determining the static location of gravity. Intersections of each line indicate pre-determined positions of weight on the calibration board and circles at the intersections indicate actually measured positions using weights of 20, 40 and 60 kg, respectively. The error in determining the location of weight on the board was within ±1 mm. The resonant frequency of the apparatus was 16 Hz when 60 kg of weight was placed on the platform.

The outputs of the load cells against the movement of the center of gravity towards the X axis had a linear relation to the eccentric distance of the rotating axis from the center of the cylindrical weight, as shown in Fig. 4, and frequency characteristics were flat from 0.2 to 0.5 Hz.

![Fig. 5 Static characteristics of the systems to determine locations of the center of gravity on the calibration board. Nine intersections indicate the predetermined points of a known weight and the circles close to the intersections indicate the points actually measured using weights of 20, 40 and 60 kg, respectively.](image_url)

EXPERIMENTAL RESULTS. We have applied this system of measuring shifts of the center of gravity of the body to volunteer laboratory workers, patients and experimental animals. A typical record obtained on a healthy volunteer subject, who lay down on his back quietly on the platform, is shown in Fig. 6. There are two cardinal, regular waves of approximately 1.0 and 0.2 Hz on the Z axis. By comparing the records with an electrocardiogram (ECG) and expiratory flow measured simultaneously, it is
clear that the slower oscillation of approximately 0.2 Hz in Fig. 6 coincided with the cycle of ventilation and the waves of approximately 1.0 Hz with the heart rate. With the use of a low pass filter, we can obtain clearer records of shifts of the gravitational center caused by ventilatory and cardiac motion.

\[
\begin{array}{c}
\text{CHART SPEED 15 mm/sec} \\
X \text{ AXIS NO FILTER} \\
Y \text{ AXIS NO FILTER} \\
Z \text{ AXIS NO FILTER}
\end{array}
\]

![Graph](image)

**Fig. 6** Experimental records obtained on a healthy volunteer subject. Two cardinal oscillations of approximately 0.2 and 1.0 Hz, respectively, can be discriminated on the record towards the Z axis.

Fig. 7 shows an example of the record of a healthy volunteer subject which was measured simultaneously with ECG and ventilatory flow through a hot-wire spirometer. Ventilatory and cardiac movements of the gravitational center of the body are clearly shown in the low-pass filtered records of the Y and Z axes. Okabe (8) did not observe any significant effect of ventilation on the shift of the gravitational center of a standing subject, but this might be due to his method of measuring only two-dimensional shifts. When a system for measuring three-dimensional shifts is employed as in the present study, selection of filters with a proper cut-off frequency and attenuation constant make it possible to detect more clearly shifts of the gravitational center caused by cardiac motion and ventilatory movement.

Fig. 8 shows a record of a one month old baby during sleep. In this case the wave through a low-pass filter showed good agreement with the respiratory cycle. The waves recorded either directly or through a high-pass filter, however, showed quite irregular patterns which reflected involuntary movements such as yawns and crying. Any irregular movement of a subject on the measuring platform yields various degrees of noise, and this is the most serious drawback of the system employed. An attempt to reduce the noise electrically results in lowering the sensitivity of the system itself. One possibility is to analyze periodic phenomena of the waves to separate rough, ir-
regular movements.

Fig. 7 Experimental records of a healthy volunteer measured with ECG and ventilatory flow. The records through a low-pass filter towards the Y and Z axes represent waves coinciding with the ECG and ventilation.

Fig. 8 Shifts of the gravitational center towards the Z body axis of a one month old baby. High frequency irregular waves were caused by yawns and crying.
Ventilation and cardiac motion accompany movements of mass inside the body, and therefore, cause shifts of the gravitational center. This opens up the possibility of applying the present system as a diagnostic means for cardiopulmonary diseases and/or as a system of monitoring cardiopulmonary functions. Moreover, the records of the present system are, in a sense, similar to the ballistocardiogram (BCG), since BCG records change with acceleration and since double differentiations of the output towards the X axis of the present system yield BCG. From this standpoint we attempted some preliminary experiments on anesthetized dogs. Figs. 9 and 10 show experimental

![Graphical representation of experimental records](image_url)

**Fig. 9** Experimental records of an anesthetized dog, whose right bronchus was partially occluded by a balloon catheter. The records from the bottom indicate ECG and esophageal pressure, respectively. See text for details.
Observations on dogs in which ventilatory conditions of the right lung were changed artificially either by partial blockage of a right bronchus by a balloon or by letting the right lung breathe a heavier gas mixture (SF6-O2) through a Carlens double lumen catheter. As might be expected from the experimental maneuvers, changes in patterns of the records towards the Y axis were clearly observed in both filtered and non-filtered records. The records for the Y axis in Fig. 10 show that large spikes coincided with ventilation; a phenomenon that was not seen clearly in the control records.

Fig. 10 Experimental records obtained from an anesthetized dog whose right lung inspired SF6-O2 while the left lung inhaled air. Changes in ventilation from side to side induced by bronchial occlusion or by unilateral SF6 breathing yielded some changes in records towards the Y axis.
The forced and stepwise inspiratory movement of the thorax which was observed when a right bronchus was partially occluded is shown in the records towards the Y axis (Fig. 9). Heavier inspiration to the right lung also produced some changes in the patterns of the Y axis as seen in Fig. 10, whereas those of the X and Z axes remained unchanged.

Another interesting observation, which is not presented in this paper, is the ventricular extrasystole effect on the record of the X axis. By the use of the present system, irregular beats of the heart as well as irregular ventilation can easily be monitored. Although detailed analysis of the records has not yet been performed and might be very difficult, application of the present system of monitoring ventilatory and circulatory movements of patients non-invasively seems quite promising, and it may be possible to obtain some information for the diagnosis of certain cardiopulmonary diseases.

REFERENCES