Wearable force sensor with parallel structure for measurement of ground-reaction force

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Abstract

This paper presents development of a wearable force sensor system for human dynamics analysis. Forces and moments are detected by combining responses from eight load cells fabricated on a parallel connection foundation. Finite element method was used for designing preliminary mechanical structures and simulating the mechanical stresses and strains in the load cells. Sensitivity of the load cells in the force sensor was increased by distributing strain gauges on the maximum strain positions. A smart electrical board consisting of signal conditioning circuits, A/D module and a micro-computer controller based communication module was built and integrated into the force sensor. The calibration experiments were performed using a force platform (EFP-S-2KNSA12) as a reference sensor, and in order to investigate interference errors of the sensor, preliminary characterization tests were implemented using a purposely developed characterization workstation. The sensor’s abilities to measure ground-reaction forces with high precision and low interference error were demonstrated. © 2006 Elsevier Ltd. All rights reserved.

Keywords: Wearable sensor; Load cell; Finite element method; Human dynamics

1. Introduction

1.1. Background

In many biomechanical applications, it is critical to detect loads and motions of certain segments of human body, such as hand-gesture analysis, gait analysis, and muscle tension analysis [1–3], which is the first step in implementation of biomechanical analysis system. Some sensory systems consisting of multi-camera motion capture system [4] and force platform have been successfully applied to tracking motions of human body segments and measuring ground-reaction forces and moments prepared for performing human dynamics analysis [5,6]. However, the camera system needs large-space and high-speed graphic signal processing devices, and the force platform cannot measure reaction force exceeding one step when performing human gait analysis. Moreover, cost of such system is high, and the system is not practical in industrial production.

Wearable force and motion sensory system with high reliability and high precision is a cost-saving multi-camera motion capture system [4] and force platform have been successfully applied to tracking motions of human body segments and measuring ground-reaction forces and moments prepared for performing human dynamics analysis [5,6]. However, the camera system needs large-space and high-speed graphic signal processing devices, and the force platform cannot measure reaction force exceeding one step when performing human gait analysis. Moreover, cost of such system is high, and the system is not practical in industrial production.

Wearable force and motion sensory system with high reliability and high precision is a cost-saving
solution, and has a great perspective for applications of biomechanical measurement. In daily life, human dynamics analysis has been becoming important [7], for example, gait analysis of pregnant women illustrates their different body dynamic conditions that ankle joint moment and hip joint moment are much larger than load burdens when being in non-pregnant situation. In order to address this problem about performing such biomechanical measurements, when some assistant and support devices will be invented for pregnant woman or patients, it is necessary to develop miniature wearable sensors appropriate to be worn on the human body without uncomfortableness.

Pressure sensors have been widely used to estimate the values and the distribution of normal ground-reaction forces and identify the loading pattern of the foot plantar soft tissue in the stance phase of a gait cycle [8–10], but these reported systems cannot address load evaluations of lower limb joint torques caused by the shear forces to which the support foot is subjected. Some silicon sensors recently were developed to measure normal and shear forces at the skin-object interface [11–13], and the force scale of these sensors are limited to the measurements of small forces (about 50 N). Two multi-dimensional sensors have been reported in [14,15] for applications of human biomechanical measurement, and their structures are designed to be serial. Whereas, they are bulky, because each serial load cell must be strong enough to stand loads from non-measurement directions. Moreover the serial structure sensors with large interference need complicated calibration. Liu and Tzo built a six-axial sensor with four six-axial load cells distributed on four support edges [16], but measurement ranges of the six-axial sensor are not satisfactory for measurement of human ground-reaction forces. A new force sensor with parallel support structure developed by Nishiwaki et al. [17] can be used to measure the reaction forces during human walking, and implement control algorithm of humanoid robots’ zero moment point (ZMP). However, the proposed sensor (weight about 700 g) manufactured with the hardened tool steel is a little heavy, which probably lead to uncomfortableness while worn under the human foot. Thus in the force sensor presented in this paper, we implement a more compact mechanical design to combine load cells, and the material of hard aluminum was used for fabricating load cells to decrease weight of sensor.

1.2. Force sensor with parallel-mechanism

Research attention has been paid in developing a wearable sensory system to perform measurements of human motions and forces [18,19]. In this paper we present the design and fabrication of the force sensor that we have developed to measure ground-reaction forces for human dynamics analysis. Many traditional and commercial sensors are generally fabricated with a serial structure, which leads to the fact that force and torque loads transmitted from normal axes may affect or break main axis load cell, and that all load cells in these sensors are designed to bear all-direction loads. However, in the case of measurement of ground-reaction forces during human walking, the gravity or normal direction forces may be over 1000 N, and the maximum shear forces are only about 50 N. Large landing impact load (about 120% body weight) and rotational moments are reported in the analysis of human walking, and this make it difficult to perform the measurement using traditional or commercial sensors.

As shown in Fig. 1, the old prototype of a six-axial force sensor has been built to validate the theory of the parallel-mechanism. The \( X \)-, \( Y \)-, and \( Z \)-directions indicate leftward, forward, and upward direction, respectively, while \( M_x \), \( M_y \), and \( M_z \) represent the moments around the \( X \)-, \( Y \)- and \( Z \)-axes. The mass of the sensor is about 300 g, and its dimensions are 170 mm \( \times \) 105 mm \( \times \) 26.5 mm. Based on the testing results obtained from the first sensor, in this paper we present a new sensor system consisting of mechanical structure, conditioning electronic
circuits and a micro-computer signal processor for performing human dynamics analysis.

2. Methods and materials

2.1. Parallel force sensor

As illustrated in Fig. 2, the sensor consists of the bottom plate, the load cells and four balls. The design choice of using parallel support structure is related to the facts that the foot interacting with ground is subjected to large impact moments which may break a generally designed multi-component sensors, and that a parallel structure distributing load to separated load cells is appropriate to perform measurements of the ground-reaction forces during walking. In order to transmit forces and moments exerted on the bottom plate to sensitive load cells, four support balls are mounted on the edges of the bottom plate. Ideally, the interface between support ball and load cell is a connection of point contacts, which exclusively transmit translational force to the corresponding load cell built using resistor strain gauge. The X-load cell measure force components of $F_{x1}$ and $F_{x2}$ induced along two parallel X-axis directions. Similarly, an external Y- and Z-direction forces applied to the sensor are transfer to Y- and Z-load cells, and are resolved into two components of $F_{y1}$ and $F_{y2}$, and four components of $F_{z1}$, $F_{z2}$, $F_{z3}$ and $F_{z4}$, respectively. Based on the sensed forces from the load cells, the forces and the moments applied on the bottom plane can be calculated as following equations.

\[
F_x = F_{x1} + F_{x2}
\]
\[
F_y = F_{y1} + F_{y2}
\]
\[
F_z = F_{z1} + F_{z4} + F_{z2} + F_{z3}
\]
\[
M_x = (F_{z2} + F_{z3} - F_{z1} - F_{z4})L/2
\]
\[
M_y = (F_{z3} + F_{z4} - F_{z1} - F_{z2})L/2
\]
\[
M_z = (F_{z2} + F_{z1} - F_{z2} - F_{z1})L/2
\]

2.2. Dimension optimization

The design detail of the shear force load cells (X- and Y-load cells) and normal force load cells (Z-load cell) is shown in Fig. 3. On each load cell, two strain gauges are attached to sense uniaxial force. In order to obtain maximum sensitivity, the strain gauges should be distributed on the points where maximum strains occur. ANSYS, FEA software, was used to perform the static analysis of the load cell. The mechanical structure of load cell
has been defined following an iterative process. A file batch has been generated in which the main dimensional parameters are defined. The mechanical dimensions of load cells were optimized by progressively varying the values of the dimensional parameters in file batch. Fig. 4 shows deformations of the load cells with the optimal dimensions from FEA.

3. Six-axial force sensor system design

In order to achieve high signal-to-noise ratio, signal conditioning circuits, A/D modules and a microcomputer system were integrated into mechanical packaging of the force sensor. The strain gauge with large resistance of 5000 Ω (Vishay Micro-measurements®) was selected for fabricating load cell in the sensor, so the sensor system can work in low power consumption and be powered using a 7 V battery. Fig. 5 shows the prototype of the integrated sensor system and the application program interface developed specially for monitoring data from the sensor.

The maximum forces that the sensor can bear are 50 kgf along the X- and Y-directions, and 1000 kgf along the Z-direction. The maximum moments are 100 N m around the three axes. The mass of the entire sensor system is about 0.5 kg, and the whole dimensions are 115 mm in length, 115 mm in width and 35 mm in height.

Fig. 4. Result graph of FEA. Finite element analysis has been performed to optimize the mechanism dimensions of load cell, and improve the sensitivity of force sensor. (a) Normal force load cell (Z-load cell). (b) Shear force load cell (X-load cell and Y-load cell).

Fig. 5. Sensor consisting of mechanical structure, electrical hardware and software interface. (a) Sensor hardware. The sensor system can be powered using a battery and lead data to personal computer through serial port of micro-computer. (b) A software interface for the operation of sensor and monitoring the data obtained from the sensor.
3.1. Mechanical design of the new sensor

Based on the FEA optimal design for obtaining the mechanical dimensions of the load cell (see Section 2), we built a 3D structure model of the sensor assembly. The load cells, support balls, and bottom plate are fabricated individually, and are assembled as illustrated in Fig. 6.

The load cell prototypes built using the ultra-hard duralumin is shown in Fig. 7. Four groups of the strain gauges were used to build the X- and Y-load cell, while another four groups were used to fabricate the Z-load cell. In order to make the sensor mechanism more compact, hybrid load cells were adopted to perform measurements of X- and Y-direction forces, which decrease the number of strain gauges and amplifier modules.

3.2. Electrical system design of the new sensor

As shown in Fig. 8, an integrated electrical system was developed and incorporated into the force sensor. Strains due to the forces applied to the load cell induce the resistance changes of strain gauge. The conditioning circuits have been designed in order to have an output voltage proportional to the fractional changes in the resistance. Since eight groups of the strain gauges were used (four groups for the X- and Y-direction shear forces and another four groups for the Z-direction normal forces), and there are eight channels of the voltage signals. The eight channels of amplified voltage signals of the load cells’ outputs $X_i$ are converted to digital signals that are fed directly into PC. The application program developed specially to sample the eight chan-
nels of the digital signals can perform real-time calculation of the forces and the moments according to Eqs. (1)–(6).

4. Experimental study

4.1. Calibration experiment

In order to calibrate the developed sensor, a six-axial force/moment KYOWA force platform (EFP-S-2KNSA12) was used as the reference sensor. These two sensor systems work in a synchronized mode. The experimental condition is shown in Fig. 9.

It is mentioned above that there are eight channels of the voltage signals \(X_i\) \((i = 1, \ldots, 8)\). Based on \(X_1, \ldots, X_8\), the forces and the moments can be calculated with the following equations.

\[
F_x = \sum_{i=1}^{8} A_iX_i
\]

(7)

\[
F_y = \sum_{i=5}^{6} A_iX_i
\]

(8)

\[
F_Z = \sum_{i=1}^{4} A_iX_i
\]

(9)

\[
M_x = \left(2 \sum_{i=2}^{3} A_iX_i - \sum_{i=1}^{4} A_iX_i\right)\frac{L}{2}
\]

(10)

\[
F_y = \left(\sum_{i=3}^{4} A_iX_i - \sum_{i=1}^{2} A_iX_i\right)\frac{L}{2}
\]

(11)

\[
M_y = \left(\sum_{i=3}^{4} A_iX_i - \sum_{i=1}^{2} A_iX_i\right)\frac{L}{2}
\]

where \(X_i\) is the load cells’ conditioning output, and \(A_i\) is the calibration coefficient for each load cell.
Table 1
Calibration coefficients of the sensor

<table>
<thead>
<tr>
<th>Load cell</th>
<th>Unstandardized coefficients</th>
<th>Standardized coefficients</th>
<th>$t$</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A_i$</td>
<td>Std. error</td>
<td>Beta</td>
<td></td>
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<tr>
<td>Z-load cell 1</td>
<td>22.38</td>
<td>10.683</td>
<td>0.253</td>
<td>23.454</td>
</tr>
<tr>
<td>Z-load cell 2</td>
<td>22.04</td>
<td>10.325</td>
<td>0.202</td>
<td>21.011</td>
</tr>
<tr>
<td>Z-load cell 3</td>
<td>15.13</td>
<td>7.519</td>
<td>0.224</td>
<td>33.114</td>
</tr>
<tr>
<td>Z-load cell 4</td>
<td>20.00</td>
<td>4.180</td>
<td>0.538</td>
<td>65.965</td>
</tr>
<tr>
<td>X-load cell 1</td>
<td>28.15</td>
<td>2.650</td>
<td>-0.718</td>
<td>-87.079</td>
</tr>
<tr>
<td>X-load cell 2</td>
<td>26.30</td>
<td>5.693</td>
<td>3.708</td>
<td>44.835</td>
</tr>
<tr>
<td>Y-load cell 1</td>
<td>28.94</td>
<td>17.945</td>
<td>0.274</td>
<td>22.157</td>
</tr>
<tr>
<td>Y-load cell 2</td>
<td>31.84</td>
<td>3.699</td>
<td>0.779</td>
<td>63.139</td>
</tr>
</tbody>
</table>

Fig. 10. Coupling effect tests. (a) Schematics of drag equipment for the calibration of $X$- and $Y$-axis load cells. We adopted the same drag mechanism to produce horizontal reference forces in the test of $X$- and $Y$-load cells. (b) Schematics of normal force calibration equipment. We directly put weights on the sensor as a reference force to calibrate $Z$-axis load cells which measure normal direction force. (c) Experimental equipments picture.
The multiple regression analysis was performed to calculate the calibration coefficients. In this study, the data was analyzed with a statistical software of SPSS 11.0J. The results of the multiple regression analysis are shown in Table 1, and the column $A_i$ of calibration coefficients was used for the experimental study of the developed sensor.

4.2. Coupling effect tests

Coupling effect tests have been finished to evaluate the interference errors of the sensor with newly developed equipments. The test apparatus is shown in Fig. 10, and it consists of clamping device, loading device which uses a pulley mechanism and weights. Typical sensor load cells outputs, in terms of voltage change versus loading force, in responding to loading on the three-axial load cells ($F_x$, $F_y$ and $F_z$) are plotted in Fig. 11. The effect of loading in one axis on the other load cells was examined and minor fluctuations were observed. The interference errors of this sensor were evaluated based on the results of cross-sensitivity test. The cross-sensitivity can be expressed as the force measured on the load cells which are normal to the testing direction load cells [20]. When the sensor was tested in $X$-direction, the cross-sensitivity for $Y$- and $Z$-directions was calculated as 3.03% and 3.08%. While the test was being carried out on $Y$- and $Z$-directions, respectively, the cross-sensitivity was 9.01% and 6.15%, and 0.14% and 0.10% (Table 2).

4.3. Validation experiments of ground-reaction forces measurement

The KYOWA force platform was used as the reference sensor to validate the measurements of the

<table>
<thead>
<tr>
<th>Axes</th>
<th>Load (kgf)</th>
<th>Average interference errors (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_x$</td>
<td>0–10</td>
<td>3.03</td>
</tr>
<tr>
<td>$F_y$</td>
<td>0–10</td>
<td>9.01</td>
</tr>
<tr>
<td>$F_z$</td>
<td>0–39</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Table 2: Results of interference errors test

Fig. 11. Loading response of the three-axis load cells: (a) $X$-load cells, (b) $Y$-load cells, (c) $Z$-load cells.
developed sensor. The two sensor systems worked in a synchronized mode. As plotted in Fig. 12, data from the developed sensor and the force platform were sampled at the same frequency (100 Hz). The correlation coefficient was used as a measure of the association between the two sensor systems, and was defined as [21]:
\[
R = \frac{n \sum FF_i - \sum F \sum F_i}{\sqrt{n \sum F^2 - (\sum F)^2} \sqrt{n \sum F_i^2 - (\sum F_i)^2}} \tag{13}
\]

where \(F\) is the force measured with the developed sensor, \(F_i\) is the force measured with the reference sensor, and \(n\) is the number of the sample data.

Moreover, the root of the mean of the square differences (RMS) was used to compare the closeness in amplitude of the two sensor measurement results. The percent error (PE) was calculated as the ratio between the RMS errors and the average peak-to-peak amplitude of the force platform measurements.

\[
\text{RMS} = \sqrt{\frac{1}{n} \sum (F - F_i)^2} \tag{14}
\]

The correlation coefficients for the normal force and shear force are 0.91 and 0.89, respectively. The percent errors (PE) of the normal force and shear force measurements are 5.1% and 4.0%, respectively.

Fig. 12. Results of validation experiments. (a–c) show the comparisons between developed force sensor \(F\) and the KYOWA force platform \(f\) in the measurements of normal force and shear forces.
5. Conclusion

A wearable six-axial force sensor has been designed and fabricated to measure three-axial ground-reaction forces and moments for human dynamics analysis. A parallel support mechanism was proposed for the design of this new sensor’s mechanical design, in order to perform measurements of the impact forces and large rotational moments. Moreover, finite element method was adopted to optimize the mechanism dimensions, and improve the sensitivity of force sensor by distributing strain gages on the maximum strain positions. In order to achieve high signal-to-noise ratio, signal conditioning circuits, A/D modules and a micro-computer system were integrated into mechanical packaging of the force sensor. Coupling effect tests have been performed to evaluate the interference errors of the sensor using purposely developed equipments. When the sensor was tested in three directions, the cross-sensitivity for Y- and Z-directions was calculated as 3.03% and 3.08%. While the test were being carried out on Y- and Z-directions, respectively, the cross-sensitivity was calculated as 9.01% and 6.15%, and 0.14% and 0.10%. Preliminary validation experiments show the percent errors (PE) of 5.1% and 4.0% in the measurements of normal force and shear force. Future work will consist in the design of packaging shoes to embed the sensor, and implement complex ground reaction forces measurements with little constrain during human walking.

References