Development of a Bolt Type Force Sensor using Strain Gauges for Sport Climbing

Akihiro Kawamura[1], Takato Nakashima[2], Masakado Danjo[2], and Ryo Kurazume[1]

***Abstract*— This paper proposes a novel bolt type force sensor that measures forces applied to an object fixed by the sensor. This sensor consists of a iron bolt and four strain gauges and can be made inexpensively compared to a 6-axis force sensor. Due to the feature of the bolt type sensor, it can measure the force applied to the object without dedicated holds, extra jigs, gaps between holds and walls. Therefore, the sensor can be applied to existing climbing holds without changes of difficulty of climbing problems. In this paper, the structure of the sensor is introduced and its calibration method is discussed. Finally, a force measurement experiments are conducted, and it was confirmed that the sensor is able to achieve highly accurate force estimation in practical situations.**

I. INTRODUCTION

Sport climbing is a sport in which athletes climb artificially constructed walls by grasping on the holds attached to the walls. In several studies, researchers have measured the force applied to the holds in order to measure and record the climbing movement of athletes[1] – [7]. In these studies, force is measured either by dedicated climbing holds with a built-in sensor or by inserting a sensor between the hold and the wall. However, the former restricts variations of climbing holds. Also, the latter changes and restricts the difficulty of climbing problems since the distance between the hold and the wall changes depending on the thickness of the force sensor.

This paper proposes a new type of force sensor which solves the problem of thickness of force sensors without any changes of holds and walls, extra jigs and gaps. The bolts used to attach the holds to the wall are converted into force sensors as shown in Figs.1 and 2. This bolt type force sensor has four strain gauges and can measure triaxial force. For highly accurate force estimation, calibration method is important. Various studies have been conducted on the method of calibration for force sensors[8] – [12]. For example, R.Tamura *et al*. proposed a calibration method for force sensor with strain gauges affixed to a flexure element with a Maltese cross structure [13]. In these researches, geometric features of sensors must be considered for calibrations. However, climbing holds have a variety of sizes and shapes. Therefore, a calibration method which does not need any information about holds is applied in this paper.

In the following sections, the design of the bolt type triaxial force sensor is introduced. Next, a calibration strategy

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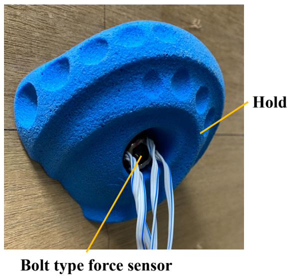

Fig. 1. Bolt type force sensor mounted on the wall

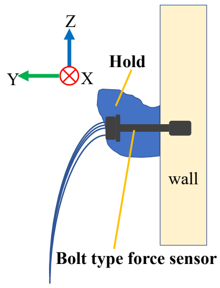

Fig. 2. Cross-sectional view of the installation of a hold using the bolt type force sensor

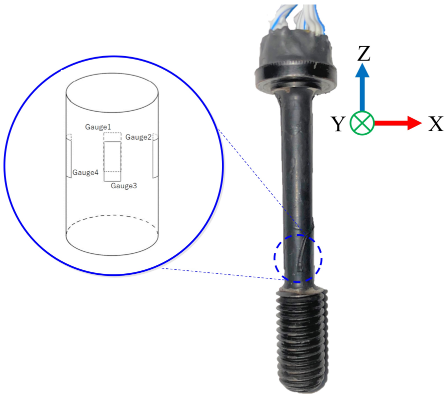

Fig. 3. Bolt type force sensor

for the sensor by using other triaxial force sensor is proposed. Finally, a force measurement experiments are conducted to show the performance of the proposed sensor.

II. Bolt Type Force Sensor

The bolt type force sensor consists of a metal bolt and four strain gauges (Tokyo Measuring Instruments Laboratory Co., Ltd., FLK-1-11) as shown in Fig. 3. The surface of the shaft is shaved by 1.8 mm and covered with an oxide film. Four strain gauges are arranged evenly around the shaft and affixed to the bolt. The cables coming out of the strain gauges pass through holes drilled in the bolt head. The four strain gauges detect the deformation of the bolt as force is applied to the affixed climbing hold. The bolt type sensor are tightened at a constant torque using a torque wrench. The sampling rates of this sensor is 1000 Hz due to the sampling rates of strain gauges. It is presumed that 100 [kg] is sufficient as the measuring range of this sensor on sport climbing due to body weight of climbers.

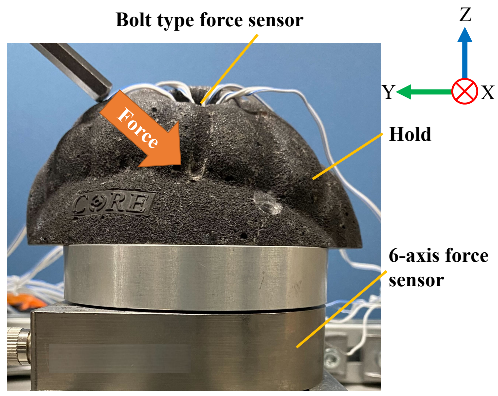

Fig. 4. Configuration of the device during calibration

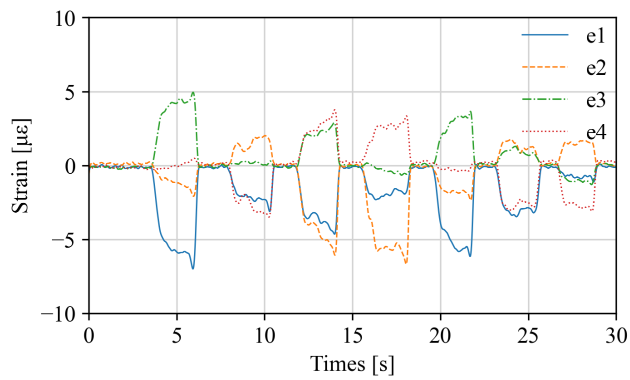

Fig. 5. Strain data

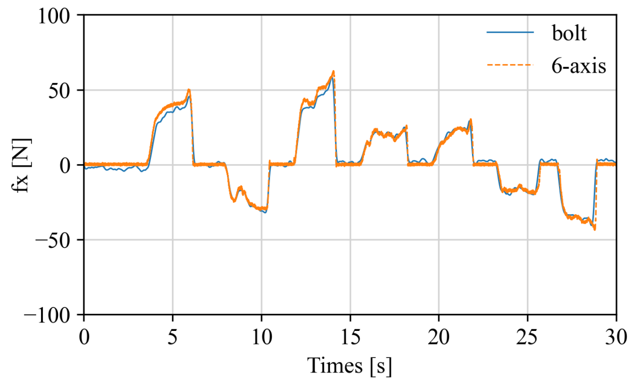

Fig. 6. Transient responses of fx

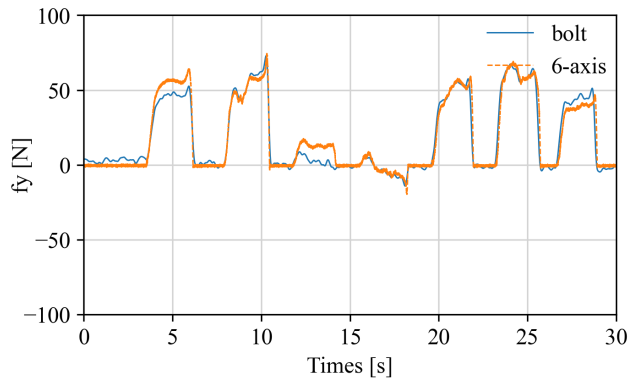

Fig. 7. Transient responses of fy

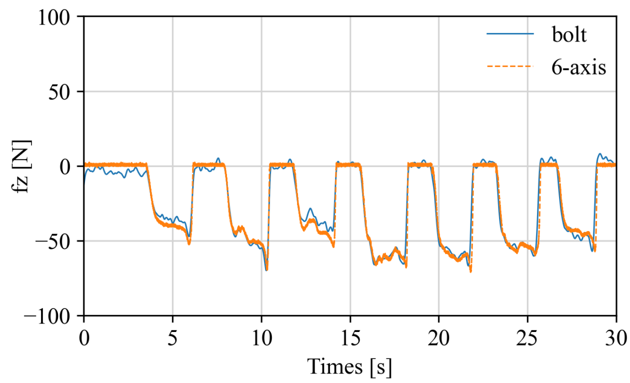

Fig. 8. Transient responses of fz

Next, a calibration method for the proposed sensor is described. The force measured by a 6-axis force sensor is utilized for the calibration as a true value. The 6-axis force sensor (Leptrino Co. Ltd.) is commercially available. Figure 4 shows the configuration of the calibration system which includes the bolt type sensor and the 6-axis force sensor. The calculation process of the conversion equation between strains on the gauges and forces on the 6-axis force sensor is shown below. The forces f_x, f_y and f_z acting on the center of the strain gauges are defined by using the coefficients C_{xx}, C_{xy}, C_{xz}, C_{yx}, C_{yy}, C_{yz}, C_{zx}, C_{zy} and C_{zz} as well as e_1, e_2, e_3 and e_4. The variables e_1, e_2, e_3 and e_4 denote the outputs of the four strain gauges on the bolt.

$$B = \begin{bmatrix} C_{xx} & C_{xy} & C_{xz} \\ C_{yx} & C_{yy} & C_{yz} \\ C_{zx} & C_{zy} & C_{zz} \end{bmatrix} \tag{1}$$

The resulting conversion equations are expressed in (2), (3) and (4).

$$f_x = \frac{1}{|B|} \begin{vmatrix} \frac{e_2 - e_4}{2} & \frac{e_1 - e_3}{2} & \frac{e_1 + e_2 + e_3 + e_4}{4} \\ C_{yx} & C_{yy} & C_{yz} \\ C_{zx} & C_{zy} & C_{zz} \end{vmatrix} \tag{2}$$

$$f_y = \frac{1}{|B|} \begin{vmatrix} C_{xx} & C_{xy} & C_{xz} \\ \frac{e_2 - e_4}{2} & \frac{e_1 - e_3}{2} & \frac{e_1 + e_2 + e_3 + e_4}{4} \\ C_{zx} & C_{zy} & C_{zz} \end{vmatrix} \tag{3}$$

$$f_z = \frac{1}{|B|} \begin{vmatrix} C_{xx} & C_{xy} & C_{xz} \\ C_{yx} & C_{yy} & C_{yz} \\ \frac{e_2 - e_4}{2} & \frac{e_1 - e_3}{2} & \frac{e_1 + e_2 + e_3 + e_4}{4} \end{vmatrix} \tag{4}$$

In this calibration process, the hold and the bolt type sensor are regarded as a rigid body. Therefore, force data measured by the 6-axis force sensor is utilized as f_x, f_y and f_z. The coefficients C_{xx} to C_{zz} are determined by using three pairs of strain and force data at the same time.

III. EXPERIMENTS

In this section, two experiments using the proposed bolt type sensor are conducted. The first experiment is force estimation with point contact using a metal rod. The second experiment is that force estimation on sport climbing. A force applied to a climbing hold by a climber is estimated on a climbing wall. In this experiment, the climbing hold is grasped with multiple contacts by fingers and a palm.

A. FORCE ESTIMATION WITH POINT CONTACT

A force estimation experiment using the proposed bolt type sensor is conducted. The experimental setup is shown in Fig. 4. The target force is applied to the climbing hand hold by using a metal rod with point contact. The 6-axis force sensor is installed to calibrate the bolt type sensor and to get true force values for evaluation.

Figure 5 shows the output of the strain gauges. Figures 6 - 8 show the results from comparing the output of the 6-axis force sensor with the estimation results of the bolt-type force sensor. The results confirm that the force can be estimated with high accuracy in the case of point contact.

B. FORCE ESTIMATION ON SPORT CLIMBING

Force estimation experiment on sport climbing is conducted on the climbing wall in our laboratory shown in Fig. 9. In this experimental setup, the 6-axis force sensor is installed between the bolt type sensor and the wall shown in Fig. 10 for evaluation though the 6-axis force sensor is not necessary to measure the force by using the bolt type sensor except for calibration. The force is applied with bare hands as in a climbing movement shown in Fig. 11. It means that the force to the climbing hold is applied with multiple contacts.

Figure 12 shows the output of the strain gauges. Figures 13 - 15 show the results from comparing the output of the 6-axis force sensor with the estimation results of the bolt-type force sensor. The results show that even in sport climbing movements where the influence of moments is large, highly accurate force estimation can be achieved.

IV. CONCLUSIONS

In this study, a bolt-type force sensor using strain gauges was developed. This sensor overcomes the conventional problems in motion measurement of sport climbing due to the gap to install force sensors. Firstly, the structure of the sensor was presented and the calibration method was introduced. Secondly, two types of experiments were conducted. Then, the accuracy of the proposed bolt type sensor is confirmed from the two experimental results.

In future, the performance of the proposed sensor will be evaluated deeply. In addition, the wiring of the sensor will be redesigned not to interfere climbing movement.

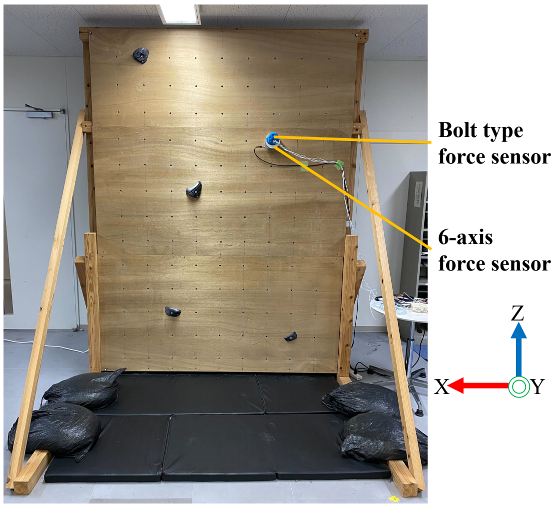

Fig. 9. Climbing wall

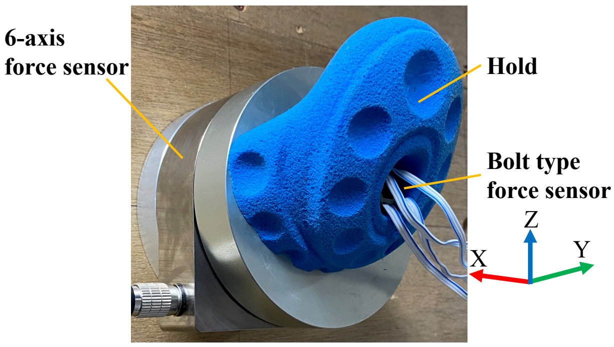

Fig. 10. Experimental setup on the wall

Fig. 11. Sport climbing movement performed in the experiment

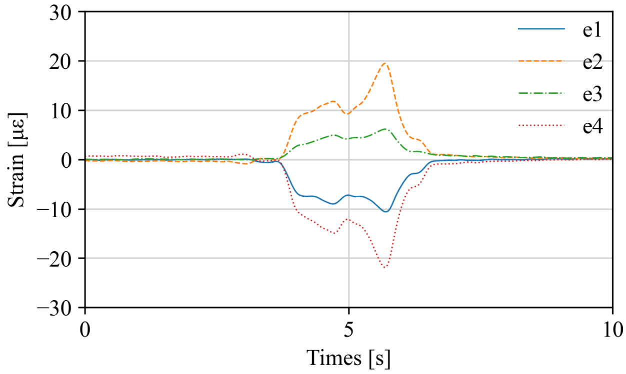

Fig. 12. Strain data for sport climbing movement

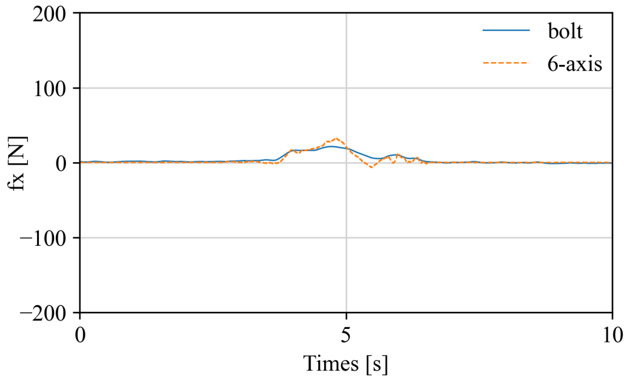

Fig. 13. Transient responses of fx for sport climbing movement

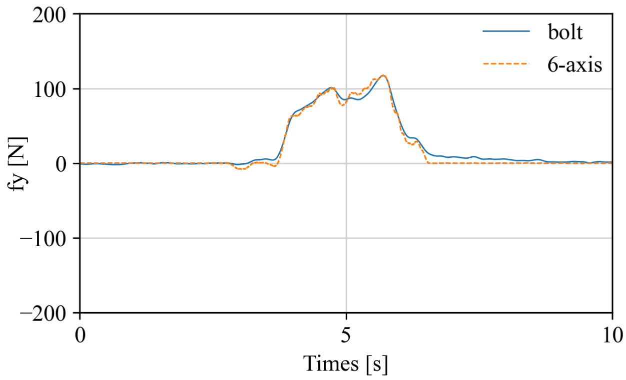

Fig. 14. Transient responses of fy for sport climbing movement

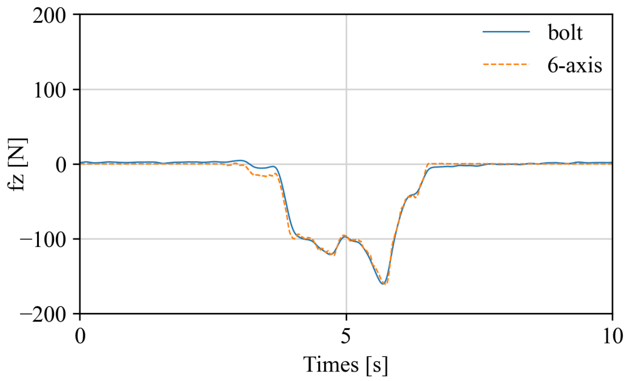

Fig. 15. Transient responses of fz for sport climbing movement

ACKNOWLEDGMENT

This work was partially supported by JSPS KAKENHI Grant Number JP21K11468. I would like to thank Mr. Sugioka from Tec Gihan Co.,Ltd. for supporting the development of the bolt-type force sensor.

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