# A New 3D Motion and Force Measurement System for Sport Climbing

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***Abstract*— Sport climbing is a form of rock climbing and has currently increased in popularity. This kind of climbing is played all over the world and becomes an Olympic sport. Motion measurement and analysis system have been required to improve the performance of climbers and instruct them properly. Several systems using motion capture have been proposed to analyze the movement of climbers so far. However, the conventional systems are not sufficient to describe climbing motions since the forces on holds have not been taken into account. This paper proposes a new 3D motion and force measurement system for sport climbing that can obtain the information on human motion and forces on holds simultaneously. The motion and force data are synchronized. Then, we can measure and analyze climbing motions geometrically and dynamically by using the proposed system. The performance of the proposed system is qualitatively verified by experiments.**

## I. INTRODUCTION

Sport climbing is one of the sports increasing attention all over the world. This sport has a short history as the first official competition on a world scale is the World Cup in 1980. However, the climber population and the number of athletic facilities have already increased enough to become an Olympic sport in 2020. Therefore, motion measurement and analysis system have been required to improve the performance of players and instruct them properly.

In sport climbing, players and competitors climb 3D shaped walls with various holds. The movement of sport climbing is quite complex compared to other sports due to multi-contact and to the diversity of the shapes of walls and holds. Several researches on motion analysis of climbing have been presented so far [1–6]. Sibella *et al.* analyzed the climbing motion for common patterns and differences in a group of recreational climbers [1]. The motion of climbers is recorded through motion capture based on passive markers. The movements of the subjects are evaluated by using some parameters derived from the center of mass (COM) trajectory. White *et al.* analyzed the time allocation of elite climbers in competitions [2]. In their research, time-motion analyses are performed by using video footages. Reveret *et al.* proposed a 3D motion analysis method for speed climbing [3]. They approximated the center of mass by a marker attached to subject's harness, close to the middle of the pelvic ilium bones. By recording this marker with two drone cameras, they analyzed the COM trajectory. Watts *et al.* measured a geometric entropy derived from the center of mass in lead and top rope rock climbing [4]. They manually digitized the back center of subject's waist harness from the video images and interpreted this position as the center of mass. Cha *et al.* measured the postures and movements in sport climbing using Microsoft Kinect, and calculated the limb velocity and joint angles during climbing [5]. They generated realistic 3D character animation by processing the motion capture data. Asakawa *et al.* analyzed the movement characteristics of experienced climbers in comparison with beginners [6]. They attached reflective markers to the body of subjects and recorded the motion using two digital cameras. They showed several characteristics using the data for joint angles and trajectories of the center of gravity.

Most of the previous researches on motion analysis of climbing have utilized the motion capturing method so far. The posture is certainly an important factor. However, the physical interaction between climbing walls and human bodies has not been taken into account. In order to analyze the body motion of climbers deeply, force information on multi-contact is indispensable since climbers always have multi-contact with walls and holds which have complex shapes. The force information shows the difference in the physical strength of climbers including core and grip strengths.

In terms of force sensing, several researches on force sensing on holds have been shown so far [7–9]. Fuss *et al.* and Lechner *et al.* developed force sensing systems of a hold. Fuss *et al.* measured and analyzed the mechanical parameters of climbing by instrumenting two 3D force transducers with a hold, and visualized the force vector diagrams [7]. In addition, they confirmed that experienced climbers have smaller contact force and shorter the contact time than beginners. Lechner *et al.* developed a three-dimensional force measurement system [8]. In their system, they measured the forces which the athletes exerted on the climbing hold by using three orthogonally mounted platform load cells and a wireless data acquisition system. On the other hand, Quaine *et al.* measured three-dimensional forces applied to holds by using four holds equipped with strain gages [9]. They analyzed the arrangement of forces on holds when subjects release their right foot from the hold. Most of the researches about force sensing on climbing holds have focused on only force information.

However, in order to more precisely analyze the physical strength of the entire body, we have to consider both motion and force information simultaneously. In addition, the force sensing systems referred above are not able to be applied

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for various shaped holds. Therefore, the main contributions of this paper are 1. Simultaneous measurement of motion and force information about sport climbing, 2. Adaptation capability for the diversity of the shapes of holds and 3. Modification of arrangement of markers on a model for motion capturing system.

This paper proposes a new motion and force measurement system for sport climbing. Both motion and force behaviors are measured simultaneously. Then, the system can provide more detailed information on the motion in sport climbing. For example, inner forces, contact point on holds and distribution of forces of multi-contact. The motion of climbing is measured by an optical tracking system using reflective markers. Joint angles and the center of mass are calculated accurately. In order to measure the force on the holds given by hands and feet, a new force measurement system is developed. This system consists of a 6-axis force sensor, several jigs, and a 3D printed protection cover. It is installed between each hold and walls. The motion and force information are synchronized accurately. In order to confirm the performance of the proposed system, several experiments are conducted in the climbing wall built in our laboratory and an actual climbing gym.

## II. MOTION AND FORCE MEASUREMENT SYSTEM

This section introduces the proposed system that measures motion and force during sport climbing. The motion information is observed by a motion tracking system using optical markers. The model for the motion capture is modified to apply for sport climbing since the occlusions due to holds, walls and human bodies are caused. The force information of multi-contact on holds are sensed by 6-axis force sensors. A force sensing system is proposed here that can measure the force and moment on holds and is applicable for various holds. The motion and force information is synchronized by time stamps.

### A. Three Dimensional Motion Capture System

A motion capture system using optical markers is utilized in this research. The cameras of the system are composed of six Vero v1.3 and one Bonita3 (Vicon). The software to analyze the data gathered by the cameras is Vicon Nexus 2.7.1. In this software, the detail of the motion such as joint angles and center of mass are automatically calculated by using a model named Plug-In-Gait. This model provides detailed whole body motion. However, in climbing situations, the occlusion due to holds, wall and human body occurs. Thereby, we modify the Plug-In-Gait model to apply for climbers.

The Plug-In-Gait model needs 39 reflective markers on the body of subjects. The arrangement of the markers is shown in Figure 1. Among them, the markers attached on the throat and the solar plexus are especially difficult to be detected by cameras. The recognition rates of the two markers are 15 [%] and 27 [%] respectively. Therefore, we made an extra attachment that has four markers to complement the missing markers. Figure 2 shows the attachment. After the completion using the attachment, the recognition ratios of markers are improved up to 78 [%] and 79 [%] respectively. In addition, two markers are added on the shoulders as shown in Figure 3 since the existing marker is also difficult to be detected when climbers raise their arms. The recognition ratios of the markers on the left and right shoulders are improved from 31 [%] and 35 [%] to 88 [%] and 94 [%].

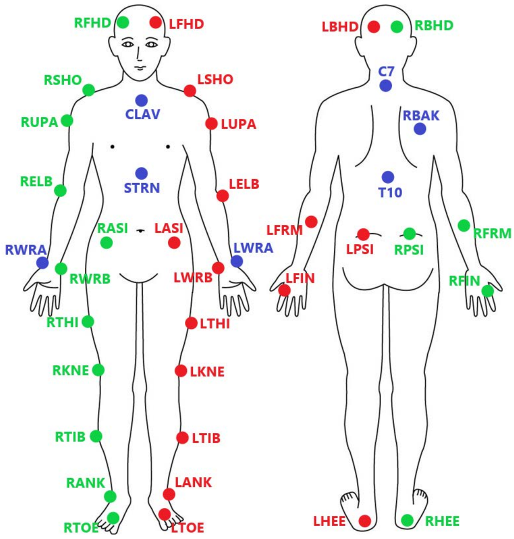


Fig. 1. Arrangement of the markers


Fig. 2. Attachment to complement the markers on front body


Fig. 3. Existing and added markers on shoulders

### B. Climbing Hold Force Measurement System

In sport climbing, climbers' movement is based on using their hands and feet. Then, they have four or three points of contact with holds. The force measurement of the forces applied for climbing holds is important to analyze the movement deeply. Additionally, the force and moment information from multiple force sensors are expected to estimate the inner forces and detailed contact points on holds. This system is

Manuscript 265 submitted to 2020 IEEE/SICE International Symposium
on System Integration (SII). Received August 30, 2019.

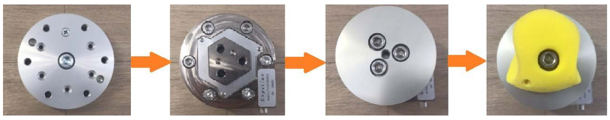

Fig. 4. Process of the assembly

Fig. 5. Protection cover

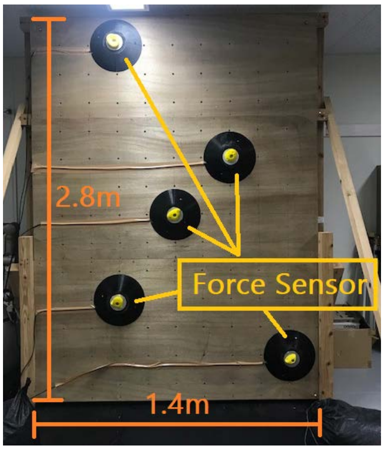


Fig. 6. Climbing wall

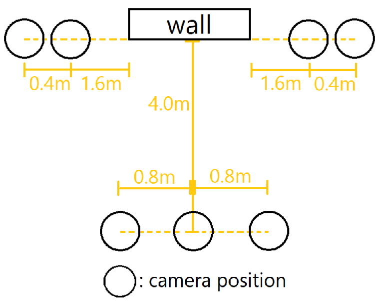


Fig. 7. Arrangement of cameras

designed to use various shaped holds and installed between holds and climbing walls. This system consists of a 6-axis force sensor(Leptrino Co. Ltd.), jigs and a 3D printed protection cover. Figure 4 shows the process of the assembly. Figure 5 shows a protection cover. This black cover is not mounted on the sensor and prevents the force sensor from grasping and being stepped on. The surface inclination of the cover is designed not to be grasped and stepped on. By using this system on multiple holds, all the force information for multi-contact is acquired.

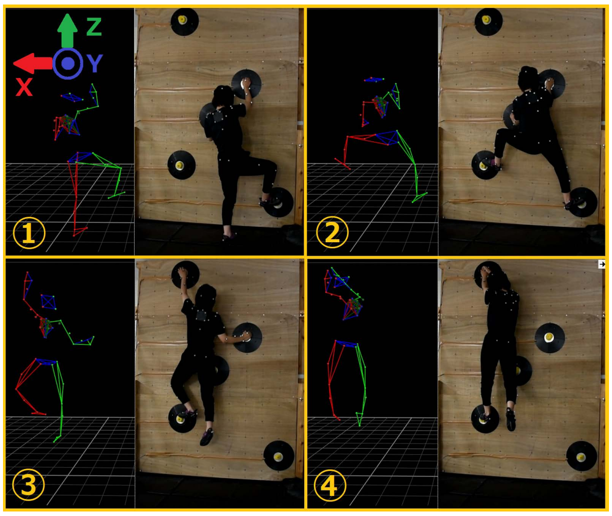


Fig. 8. Snapshots of the motion

## III. EXPERIMENTS

This section shows preliminary experiments using the wall built in our laboratory and experiments in an actual climbing gym. Firstly, it is qualitatively confirmed that the proposed system can measure the motion and force simultaneously in the preliminary experiments. Next, in an actual climbing gym, the experiments using beginners and experienced climbers in order to verify the performance of the proposed system and compare their performances.

### A. Preliminary Experiments in a Laboratory

This preliminary experiment is conducted to confirm the performance of the proposed system. The climbing vertical wall built in our laboratory is shown in Fig. 6. The height and width of the wall are 2.8 [m] and 1.4 [m] respectively. The number of the force sensing system installed into the wall is five. Seven cameras of the motion capture system are arranged around the wall as shown in Fig. 7. Figure 8 shows the snapshots of the climbing motion and stick pictures generated by the software Nexus provided by Vicon. From this figure, it is confirmed that the climbing motion of the entire body of the subject is measured properly by using the modified Plug-In-Gait model. The force and motion information are synchronized by using time-stamps. In order to confirm the synchronization between motion and force information, the sum of all forces applied to the subject's body using each information. The sum calculated using force information $\boldsymbol{F}_{force}$ is expressed as

$$\boldsymbol{F}_{force} = \sum_{i=1}^{5} \boldsymbol{F}_i, \tag{1}$$

where $\boldsymbol{F}_i$ is the force obtained from the $i$th sensing system. On the other hand, the sum of the forces calculated using motion information is given as

$$\boldsymbol{F}_{motion} = M\left(\boldsymbol{a} - \boldsymbol{g}\right), \tag{2}$$

Manuscript 265 submitted to 2020 IEEE/SICE International Symposium on System Integration (SII). Received August 30, 2019.

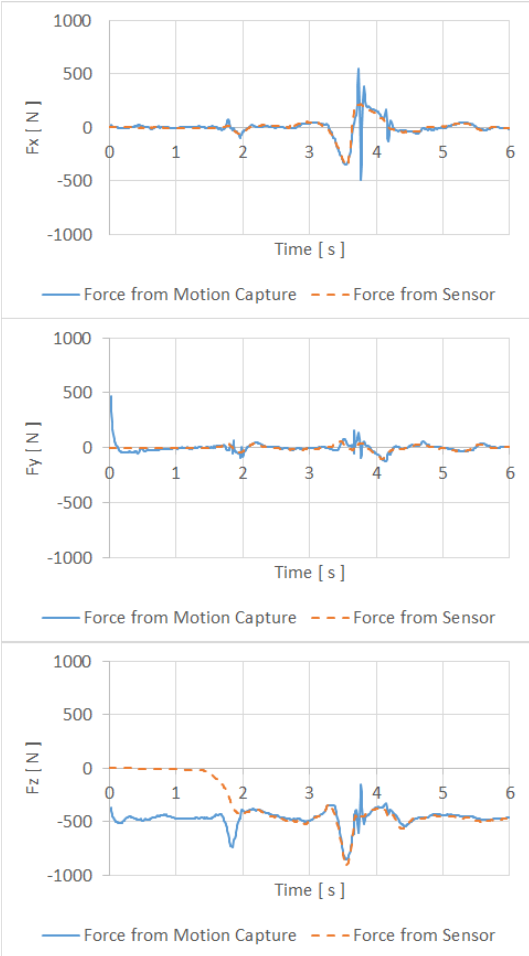


Fig. 9. Transient responses of force from motion capturing $\boldsymbol{F}_{motion}$ and force from force sensors $\boldsymbol{F}_{force}$

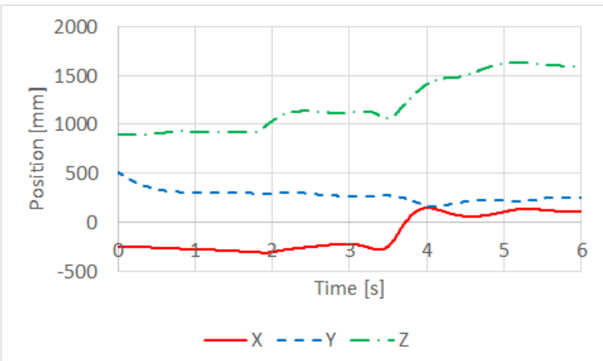


Fig. 10. Trajectories of COM

where $M$ is the weight of the subject, $\boldsymbol{a}$ is the acceleration vector of COM of the body calculated by the software Nexus and $\boldsymbol{g}$ represents the gravitational vector. These sum of forces are shown in Fig. 9. From these figures, it is shown that the synchronization technique using time stamps works appropriately. In addition, This result also shows the good performance of the force sensing system since $\boldsymbol{F}_{motion}$ and $\boldsymbol{F}_{force}$ are synchronized. The deviation between $\boldsymbol{F}_{motion}$ and $\boldsymbol{F}_{force}$ in z axis up to 2.0 [s] is caused by the contact of the left foot on the ground shown in Fig. 8.

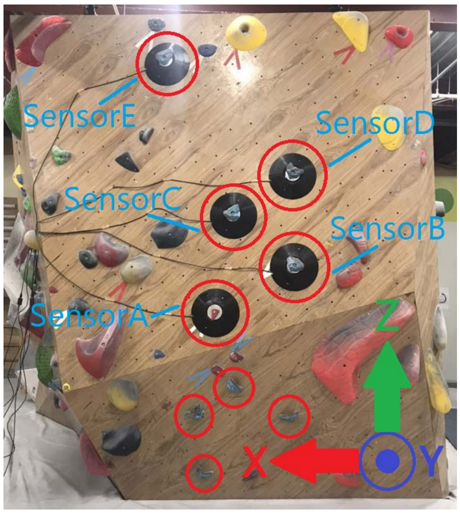


Fig. 11. Wall used in an experiment

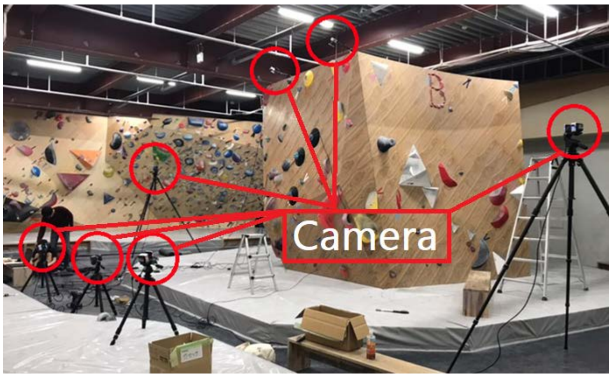


Fig. 12. Experimental environment

### B. Motion and Force Analysis of Beginners and Experienced Climbers

In this subsection, several experiments in an actual climbing gym are conducted. Figures 11 and 12 show the wall used in this experiment and the whole experimental environment. As shown in these figures, seven cameras for motion capturing and five force sensing systems are installed. The subjects of this experiment are a beginner who has experienced sport climbing several times and an experienced climber who represented a prefecture in Japan. They climbed the wall several times while changing the hold types. A part of the experiments is introduced in this paper. Figure 13 shows the snapshots of the motions of the subjects. This type of motion is high steps. In this motion, the subjects get their left foot up on to the hold mounted on sensorA and shift their COM above the hold. They can reach to the top hold then.

Figure 14 shows the trajectories of COM, and the position of the hold mounted on SensorA. As shown from the trajectory of COM in the horizontal x axis in Fig. 14, the experienced climber shifts his COM smoothly in a quick motion compared with the beginner. Additionally, the

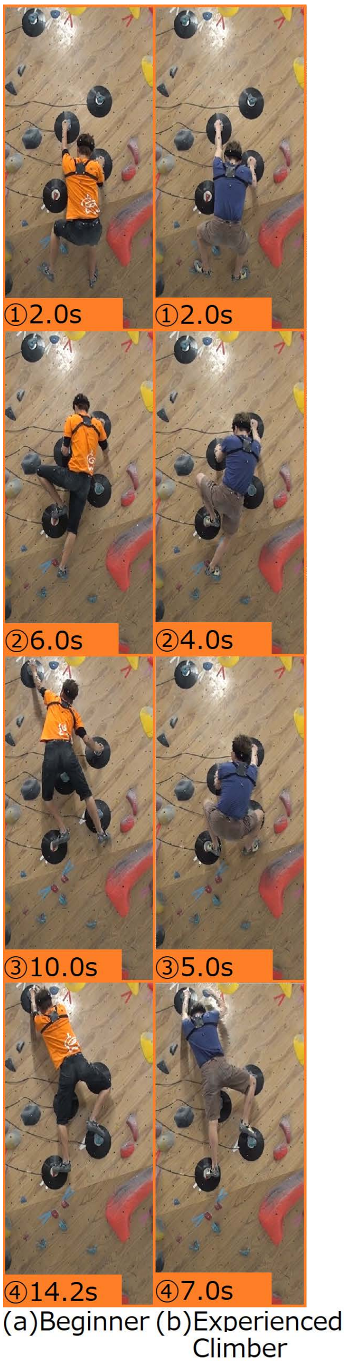


Fig. 13. Snapshots of movements

distance to the left of the experienced climber is bigger than the beginner. The final position of the COM is important to quantify their climbing skill since it is difficult for beginners to step onto such thin and tiny holds. Figure 15 shows the percentage of the force detected at the sensorA to subjects' weight. From the z values in Fig. 15, it is confirmed that the experienced climber shifts his weight onto the hold up to 93 [%]. In contrast, the beginner climber shifts his weight up to 73 [%]. This result supports the result from the trajectories of COM in Fig. 14. From these results, we finally confirmed that the proposed system performs well enough to measure the motion and force information and to quantify the climbing skills of subjects.

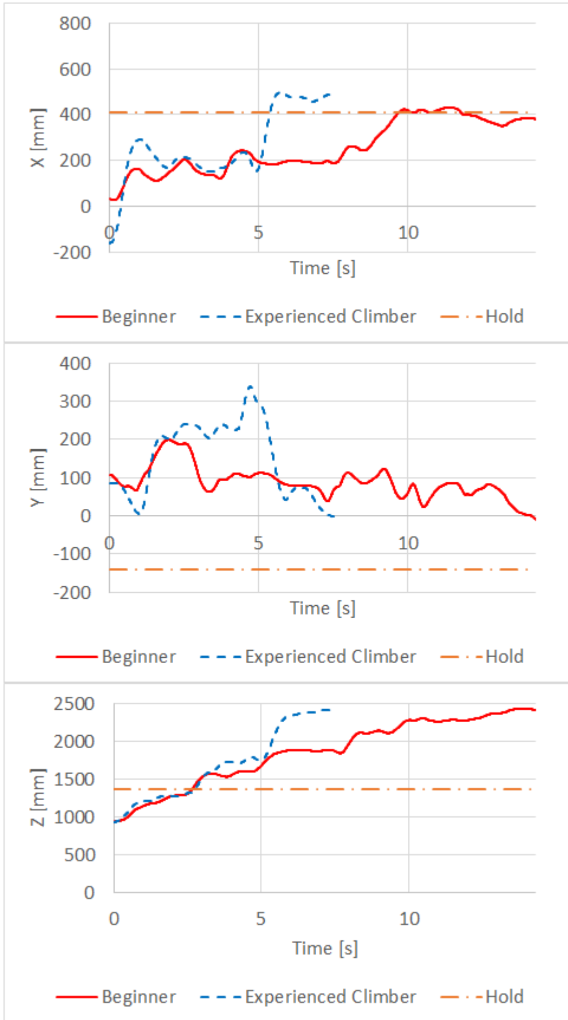


Fig. 14. Trajectories of COM

## IV. CONCLUSION

In this paper, we developed the new 3D motion and force measurement system for sport climbing. By using this system, the motion and force on the climbing holds during sport climbing are measured simultaneously. The arrangement of reflective markers on the model for motion capture was modified to apply for sport climbing. Moreover, the climbing hold force measurement system which applies to various shaped holds were proposed. The performance of the system and the synchronization between motion and force data were confirmed by several experiments: preliminary experiments in our laboratory and experiments in an actual climbing gym. The experimental results also showed that the climbing skills are quantified by using the proposed system.

In future works, it is necessary to increase the number of subjects and analyze their motion and force data. Then, we will suggest the characteristics of movements of experienced climber compared with beginners. Additionally, an intuitive interface system to provide feedback about climbers' movement to improve their performance and instruct them properly. Furthermore, the variety of the analysis object will

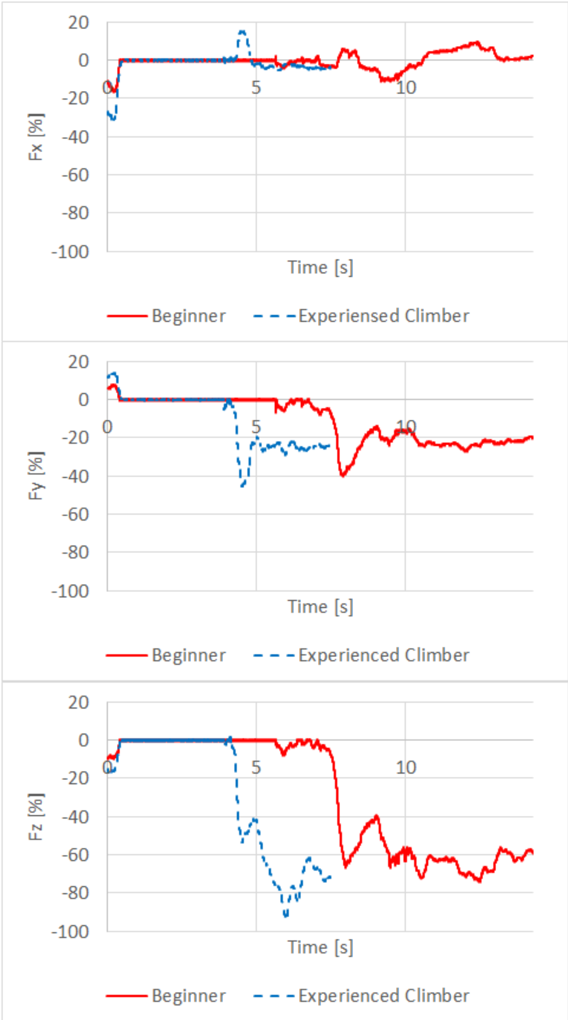


Fig. 15. Percentage of the force detected in sensorA to subject's weight.

be increased such as inner force generated between contacts, body strength, contact points on holds.

## ACKNOWLEDGEMENTS

This work was supported by JSPS KAKENHI Grant Number JP18K17824.

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