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Dr. Xiaoyan Cao
Review Editor,
Journal of Visualized Experiments

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Dear Dr. Xiaoyan Cao:
Thank you very much for your E-mail of February 11, 2020, encouraging us to resubmit our manuscript. We are sending herewith a revised manuscript entitled "Measurement of spatial stability in precision grip", which we would like to resubmit for consideration of publication in *Journal of Visualized Experiments.*

In a separate transmittal letter, we summarized specific responses to all the queries. We hope that the paper has been improved and will now be considered suitable for publication in the *Journal of Visualized Experiments*.

We appreciate your prompt consideration of this manuscript.

Sincerely,

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TITLE:

Measurement of Spatial Stability in Precision Grip

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KEYWORDS:

kinetic analysis, precision grip, spatial stability, force direction, center of pressure, grip force

SUMMARY:

The goal of this protocol is to measure the center of pressure (COP) replacement using a high spatial resolution sensor sheet to reflect the spatial stability in a precision grip. The use of this protocol could contribute to greater understanding of the physiology and pathophysiology of grasping.

ABSTRACT:

The purpose of the protocol is to indirectly evaluate the direction of the finger force during manipulation of a handheld object based on the biomechanical relationships in which deviated force direction causes center of pressure (COP) replacement. To evaluate this, a thin, flexible, and high spatial resolution pressure sensor sheet is used. The system allows measurement of the COP trajectory in addition to the force amplitude and its temporal regulation. A series of experiments found that increased trajectory length reflected a sensorimotor deficit in stroke patients, and that decreased COP trajectory reflects a compensatory strategy to avoid an object slipping from the hand grip in the elderly. Moreover, the COP trajectory could also be decreased by dual task interference. This article describes the experimental procedure and discusses how finger COP contributes to an understanding of the physiology and pathophysiology of grasping.

INTRODUCTION:

Force control is the fundamental basis of precision grip. Compared with power grip, precision grip evaluates the minimal force output reflecting the ability to manipulate an object. Multiple sensorimotor systems contribute to precision grip. For example, during a grip and lift task, visual information enables the perception of the object's size and shape. After the fingertips touch the object, tactile signals are delivered to the somatosensory cortex to adjust the precision grip force. Grip force (GF) is generated when the fingertips make contact with the object, and it increases during the lifting phase[1]. When an object approaches the goal height in the air, healthy young adults produce the minimal GF to optimize cutaneous input from the finger pulps and conserve energy. On the other hand, older adults use a large grip force to avoid letting the object slip from their grip[2]. In stroke patients, onset of grip force is delayed and the ability to adjust the safety margin is impaired due to sensory and motor deficits. Exaggerated grip force is considered to be a strategic response to compensate for sensory and motor deficits[3].

The standard protocol to measure GF control in precision grip was suggested by Johansson and Westling in the 1980s[4]. They developed a device to monitor both load and grip forces simultaneously. Since then, GF amplitude and its temporal regulation have been used as typical kinetic parameters in numerous studies on precision grip. Another kinetic parameter is the force direction[5]. The force direction results from a combination of grip and lift forces. In order to maintain stable precision grip, properly directed grip and lift forces must be generated between the thumb and index finger, and the deviated force direction can cause spatial instability. Although various load cell-type force direction instruments are used in grasping studies, these instruments have a limitation in terms of monitoring the grip force control in manipulating objects of different sizes and shapes used in daily living. Thus, a flexible and attachable sensor is essential to investigate the relationships between grip force control and daily functions.

The purpose of this protocol is to indirectly evaluate the finger force direction during manipulation of an object based on the biomechanical relationship in which deviated force direction causes Center of Pressure (COP) replacement. The COP is the center of all the forces, and represents how the forces are balanced on the sensor sheet. The use of COP to evaluate grip force control was first suggested by Augurelle et al.[6]. They monitored COP displacement to investigate the role of cutaneous feedback and found that deviated COP occurred after digital anesthesia. However, COP displacement was monitored only vertically in their study; therefore, the COP displacement in a three-dimensional space has not been adequately evaluated. To solve this limitation a thin, flexible, and high spatial resolution pressure sensor sheet was used to measure COP. Relatively high spatial resolution sensors (~60–100 points per cm^2) to measure grip force control have been used[7,8], but recent advances in spatial resolution (248 points per cm^2) allow measurement of the COP trajectory as a parameter to quantify spatial stability. This paper describes the experimental procedure and discusses how finger COP contributes to the understanding of the physiology and pathophysiology of grasping.

PROTOCOL:

The series of studies in the present paper were approved by Gunma University Ethical Review Board for Medical Research Involving Human Subjects.

NOTE: Inclusion criteria for participants were the ability to understand the use of minimal force and the ability to perform the task with the thumb and index finger. Exclusion criteria were selected based on the purpose of the experiments.

1. Equipment preparation

1.1. Connect two sensor connector cables to the USB ports of a computer. Pull up the lever attached to the sensor connector and insert the sensor's tab into the insertion slot. Return the attached lever to its original position.

1.2. Open the sensor software on a computer. Make sure that real-time pressure distribution maps appear automatically on the monitor when the sensor sheets are correctly connected.

1.3. Pressure adjustment

1.3.1. Insert the sensing area of the sensor sheet one by one into a compressor rig.

1.3.2. Turn on the air valve of the compressor's controller and start to apply pressure. Operate the regulator and adjust to the appropriate load value (i.e., 172 kPa) to check the indicator on the controller. Make sure that the whole area of the sensor sheet is equally pressurized on the monitor.

1.4. While applying pressure to the sensor sheets, perform equilibration and calibration.

NOTE: Equilibration is an operation to adjust the reactivity of the sensor cells equally. Calibration is an operation to convert the pressure on the sensor sheet (raw sum) into a unit of weight (grams or Newtons) and display it. Both must be done for the sensor sheet before starting data collection for each participant.

1.4.1. Select **Tool** | **Equilibration** on the software main window. Click **Equilibration1** | **Start** in the equilibration dialog box. Check the equilibration result in the dialog box and confirm the window of equilibration changes color to gray.

1.4.2. Save the equilibration settings by selecting **Tool** | **Saving Equilibration Settings** or click the **Save Settings** button in the equilibration dialog box when performing equilibration. Click **Save** in the save dialog box to specify the saving destination and file name.

1.4.3. Next, perform calibration by selecting **Tool** | **Calibration**. Click the **Add** button in the calibration dialog box. Enter the load value (**134.33 N**) in the **Calibration load** box in the point calibration dialog box.

1.4.4. Click the **Start** button in the dialog box. Check the calibration result in the calibration dialog box and confirm that the calibration was done correctly; the units of the real-time pressure distribution map are displayed as Newtons instead of Row Sum if the calibration is done correctly.

1.4.5. After that, save the calibration setting by clicking **Save Calibration Settings** in the dialog box. Click **Save** to specify the saving destination and file setting name. After equilibration and calibration, turn off the air valve on the controller and extract the sensor sheet from the compressor.

2. Measurement

2.1. Preparation

2.1.1. Connect each device and start up the software according to steps 1.1 and 1.2. Make sure that two real-time pressure distribution maps for each sensor sheet are displayed when the sensor sheets are connected via the cable at the same time.

NOTE: In this experiment, two sensor sheets are needed to measure the thumb and index finger, respectively. It is necessary to perform equilibration and calibration for each of them according to the procedures described in section 1.4.

2.1.2. Recall the equilibration and calibration files created in steps 1.4.2 and 1.4.5 from the real-time window. Make sure that the real-time pressure distribution map is displayed in Newtons.

2.1.3. Attach the pressure-sensitive parts of the two sensor sheets to both sides of the iron cube using double-sided tape. To prevent the sensor sheets from being damaged, cut 3−5 mm lengths of tape and place them on the four corners on the outside of the iron cube. Make sure that the surface of the sensor sheet is on the outside.

2.1.4. Place the iron cube on top of a setting stand on a table before the measurement.

2.1.5. After arranging the measurement environment, fix the the recording settings for the total number of frames, frame interval, and number of frames per second. Select the **Setting | Recording Parameter** command. In the recording parameter dialog box, enter **36000** in the total number of frames box, **0.01** in the frame interval box, and **100** in the number of frames/second box. Click **OK** and close the dialog box.

2.2. Starting the measurement

NOTE: **Figure 1** demonstrates a grip and lift task.

2.2.1. Have the participant sit in front of a table and adjust the table height (participant's shoulder joint flexion 0° and elbow joint flexion 90° position). Set the iron cube and setting stand 30 cm from the participant in the midsagittal plane on the table. Wipe the participant's finger pulps with an alcohol swab or towelette.

2.2.2. Give the participant verbal instructions as follows: "Use minimal force with your thumb and index finger to grasp both sides of the iron cube to which the sensor sheets are attached. After that, lift it approximately 5 cm above the setting stand, hold it for 5−7 s, and then place it back on the setting stand."

2.2.3. If the participant is ready, give them a cue to start the task and start recording by clicking **Recording** on the toolbar. When the task is over, click **Stop** on the toolbar. After recording, save as movie data by selecting **File** | **Save as** and click **Save** to specify the saving destination and file name.

NOTE: The weight of the iron cube, number of lifts, and the interval between tasks should be considered according to the purpose of the experiment and task difficulty.

2.3. Change the measurement conditions according to the purpose of the experiment. For example, to investigate the effect of dual task interference in a grip and lift task, adjust the measurement conditions as follows depending on the type of interference.

2.3.1. For postural interference, have the participant stand in front of a table and adjust the table height. Give the participant verbal instructions as follows: "Stand on one leg, and use minimal force with your thumb and index finger to lift the iron cube approximately 5 cm above the setting stand. Hold it for 5−7 s and then place it back on the setting stand."

2.3.2. For visual interference, have the participant sit in front of a table and adjust the table height. Give the participant verbal instructions as follows: "Close your eyes. Use minimal force with your thumb and index finger with to lift the iron cube approximately 5 cm above the setting stand. Hold it for 5−7 s and place it back on the setting stand." Allow participants to touch the sensors without exceeding 0.5 N before closing their eyes.

2.3.3. For cognitive interference, have the participant sit in front of a table and adjust the table height. Give the participant verbal instructions as follows: "As a calculation task, continuously subtract 7 from 100 as accurately as possible. While performing the calculation, use minimal force with your thumb and index finger to lift the iron cube approximately 5 cm above the setting stand. Hold it for 5−7 s and place it back on the setting stand."

2.3.4. For contralateral hand movement interference (**Figure 2**), have the participant sit in front of a table and adjust the table height. Place the peg board 30 cm from the participant in the midsagittal plane next to the iron cube and consider the size and number of pegs to adjust the task difficulty. Give the participant verbal instructions as follows: "Manipulate the iron cube with minimal force using your thumb and index finger. Lift and hold the iron cube approximately 5 cm above the setting stand with one hand, and invert the peg using the other hand. Repeat using the opposite hand."

3. Data analysis

3.1. Analysis of grip force

3.1.1. Start the software on the computer. Click **File** | **Open**, select the movie file for analysis, and click **Open** in the open dialog box.

3.1.2. As the recorded pressure distribution map appears, click the **Display Multiple Windows** button on the map and open the graph window. Find the point in time when the load (grip force) starts to be applied in each lift, and note the time with reference to this graph.

3.1.3. After that, save the grip force data in ASCII format by selecting **File** | **Save as ASCII Data**. In the object-graph1 dialog box, select the **File Name** and click the **ASCII Saving** button. In the dialog box, select **Save load, Pressure and Area Values**. Make sure that the **Load Value** in the Y-axis box, **Time** in the X-axis box, and **Numerical Value** in the Y-axis mode box are specified in the dialog box.

3.1.4. If information on the contact areas between finger pulps and sensor sheets is needed, specify **Contact Area** in the Y-axis box and click the **OK** button. Click the **Save** button in the save dialog box to specify the saving destination and file name and close the software.

3.1.5. Next, open the movie file and confirm that the file opens in spreadsheet format and that the load value and time are indicated for each frame number on the spreadsheet. Find the frame number at which the load starts to be applied in each lift on the spreadsheet and note the frame number with reference to the time point that was noted in advance.

3.1.6. Calculate the total grip force used in a range, which is the sum of the load values in the range from that frame. Specify the range between the frames within the range to which the load is applied.

3.2. Analysis of center of pressure

3.2.1. Start the software. Click **File** | **Open**, select the movie file for analysis and click **Open**. Display the COP trajectory on the pressure distribution map.

3.2.2. With the recorded pressure distribution map active, click **COF** on the toolbar. Make sure that the COP trajectory appears on the pressure distribution map. Click **Play** on the toolbar to play the movie. Click **Next Frame** to advance frame by frame, find the frame when the COP starts to appear in each lift on the pressure distribution map and note its number.

3.2.3. After that, save the values of COP in ASCII format by selecting **File** | **Save as ASCII Data**. Make sure that **COF** in the type box and **All Frame** in the saving range box are specified in the dialog box and click the **OK** button. Click the **Save** button in the save dialog box and close the software once to specify the saving destination and file name.

3.2.4. Next, open the movie file. Confirm that the file opens in spreadsheet format and the position of the COP on X- and Y-axes coordinates is shown as a numerical value on the spreadsheet. Find the frame number when the COP starts to appear in each lift on the spreadsheet with reference to the frame number that was noted in advance.

3.2.5. Calculate the COP trajectory length between frames. Select ① a cell in the same row including the number of the frame when the COP starts to appear, and then ② previous cells for both the X- and Y-axes. Insert the following calculation formula: (=SQRT((Row①-Row②)^2+(Col①-Col②)^2) into a cell in the same row as the ① cells. The sum of the COP trajectory length between frames in a range is the total COP trajectory within that range.

NOTE: In the graph window, the vertical line shows the load value (N), and the horizontal line shows the time (s). This load value corresponds to the grip force. Data saved in ASCII format can be used in applications such as spreadsheets and text editors. In this experiment, the participants were instructed to hold the cube for 5−7 s in the task, so the grip force and COP trajectory were calculated and recorded for 4 s from their first appearance.

REPRESENTATIVE RESULTS:

Several studies have introduced experimental protocols and two kinetic parameters (the COP trajectory and the GF) to measure finger force during manipulation of an object. In previous studies, it was found that the COP trajectory increased in stroke patients[9]. In cervical myelopathy patients, the GF correlated with the cutaneous pressure threshold and upper extremity function[10]. In healthy young subjects, the GF increased with cognitive interference[11]. Similar exaggerated GF was found in contralateral hand movement interference. **Figure 3** shows the COP trajectories and the GF traces of the dominant index finger in single and dual tasks for representative young and elderly adults. The GF increased in the contralateral hand movement interference. In contrast, the COP trajectories tended to decrease (unpublished data).

Kurihara et al.[9] investigated the grip force coordination of grasping in stroke patients. They found that the COP trajectory increased in the paretic hand, although the GFs were not significantly different from the nonparetic hand. Hemorrhagic patients showed longer COP trajectories of the thumb and index finger compared to those in ischemic patients. They also found that the kinetic parameters were correlated with not only somatosensory function, but also cognitive function.

In cervical myelopathy patients, Noguchi et al.[10] evaluated the kinetic characteristics of individual finger grip force and investigated the relationship between the grip force and upper extremity function. They found that the GF was associated with the severity of hand dysfunction. Although there was no significant correlation in pinch power or grip power, there was a positive correlation between the GF and the cutaneous pressure threshold.

Lee et al.[11] investigated dual task interference in a grip and lift task. They reported that the GF increased in both hands mainly due the dual cognitive task. They also found a correlation between the perceived difficulty and maximum grip force in the dominant hand.

FIGURE LEGENDS:

Figure 1: Grip and lift task. Participants gripped the cube using the thumb and index finger, lifted it approximately 5 cm, and held it for 5−7 s.

Figure 2: Dual task interference with contralateral hand movement. Participants performed a grip and lift task with one hand and simultaneously conducted a peg test with the other.

Figure 3: COP trajectories and the GF traces of the dominant index finger in single and dual tasks for representative young and elderly adults.

DISCUSSION:

This experimental procedure provides evidence that a flexible pressure sensor sheet could be useful for evaluating spatial stability during precision grip. Altered grip force direction represents grasping spatial instability such as a finger slip. However, existing load cell-type force direction instruments have a limitation in terms of ensuring a natural reach-to-grip movement. To resolve this technical problem, the COP trajectory of the area between the finger pulps and contact surface based on a biomechanical relationship was monitored. The results suggest that the COP displacement is caused by divided force direction. Thus, the study found that the COP trajectory length is a useful kinetic parameter for evaluating the spatial stability in a precision grip.

A critical factor influencing the outcome of the experiment was each participant's understanding of the experimental protocol. If participants did not understand the aim of the experiment, they tended to use a relatively large GF in order to avoid spatial instability. Intentionally exaggerated GF interferes with the evaluation of precision grip. Another factor influencing the outcome can be the area between the fingertip and contact surface of the object. If the fingertip is not properly in contact with the surface of the object, the COP is not estimated appropriately. During practical trials, the examiner must adjust the location and orientation of the cube. When the cube is not placed properly, the fingertip protrudes from the edge of the cube, or participants tend to increase trunk and shoulder movements to compensate for hand orientation for grasping.

One limitation of the protocol is the unclear biomechanics of the COP. A slip, roll, or twist between the finger pulps and contact area can account for COP displacement, resulting in spatial instability. This is because the COP is calculated in the X- and Y- axes. Moreover, it is technically difficult to link the two COPs of the thumb and index fingers. Although there are limitations, it is clear that there are benefits to evaluating the spatial stability of grasping using the COP trajectory.

ACKNOWLEDGMENTS:
We thank Mr. T. Nishida (Technician, Dept of Sales, Division of Device Performance Materials, Nitta Co., Ltd, Osaka, Japan.) for technical support.

DISCLOSURES:
The authors declare that they have no competing financial interests.

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Figure1

Click here to access/download;Figure;Figure 1.jpg

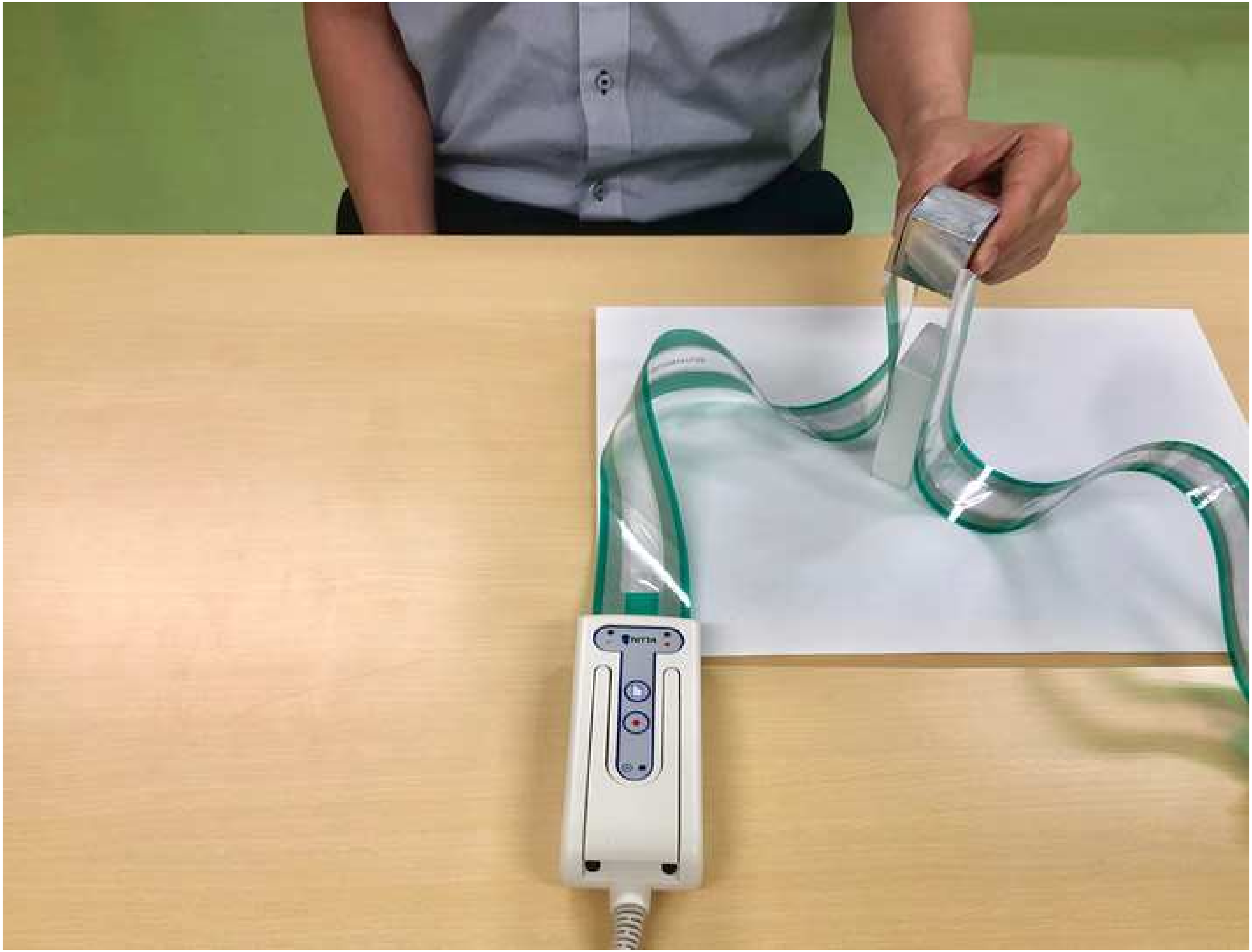


Figure2

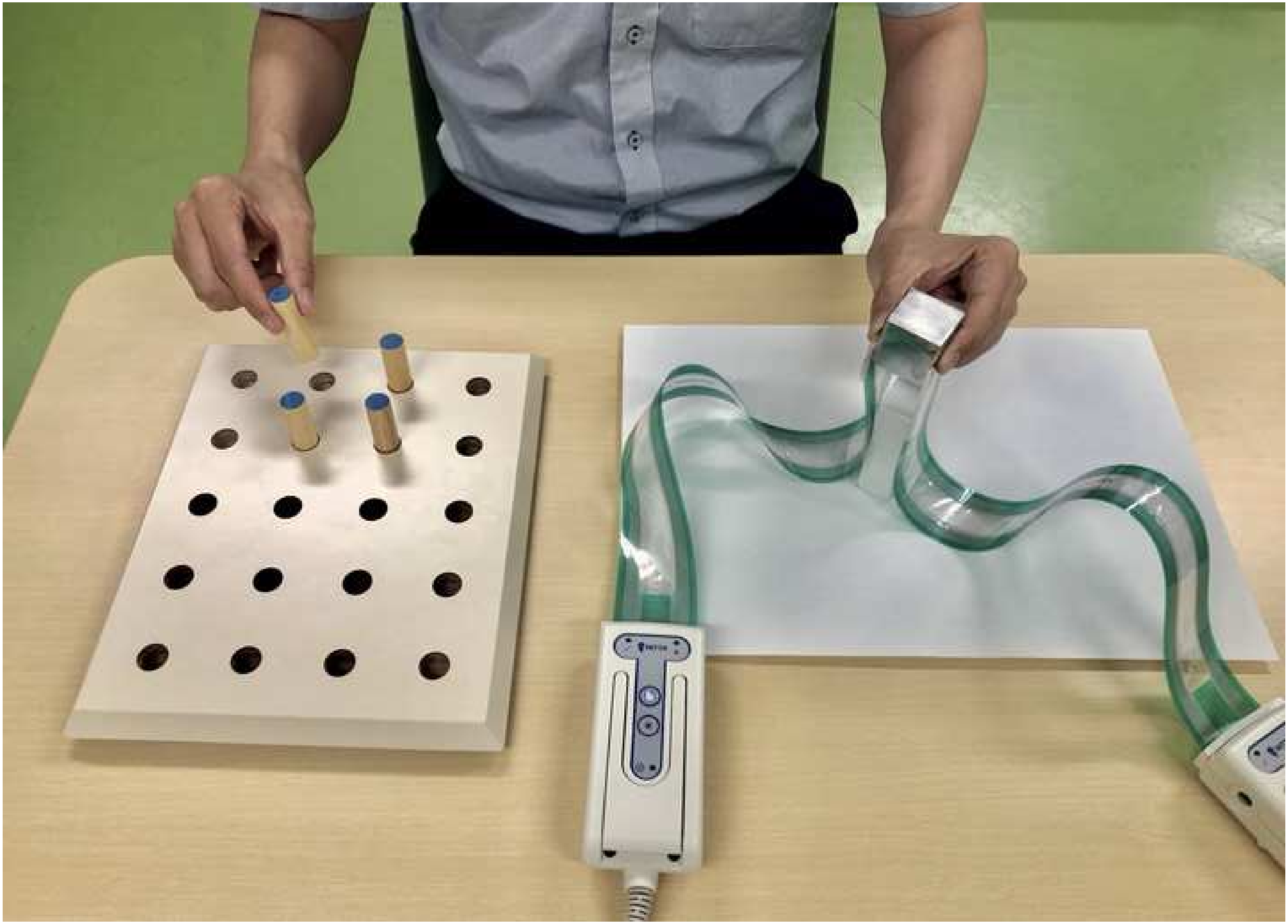
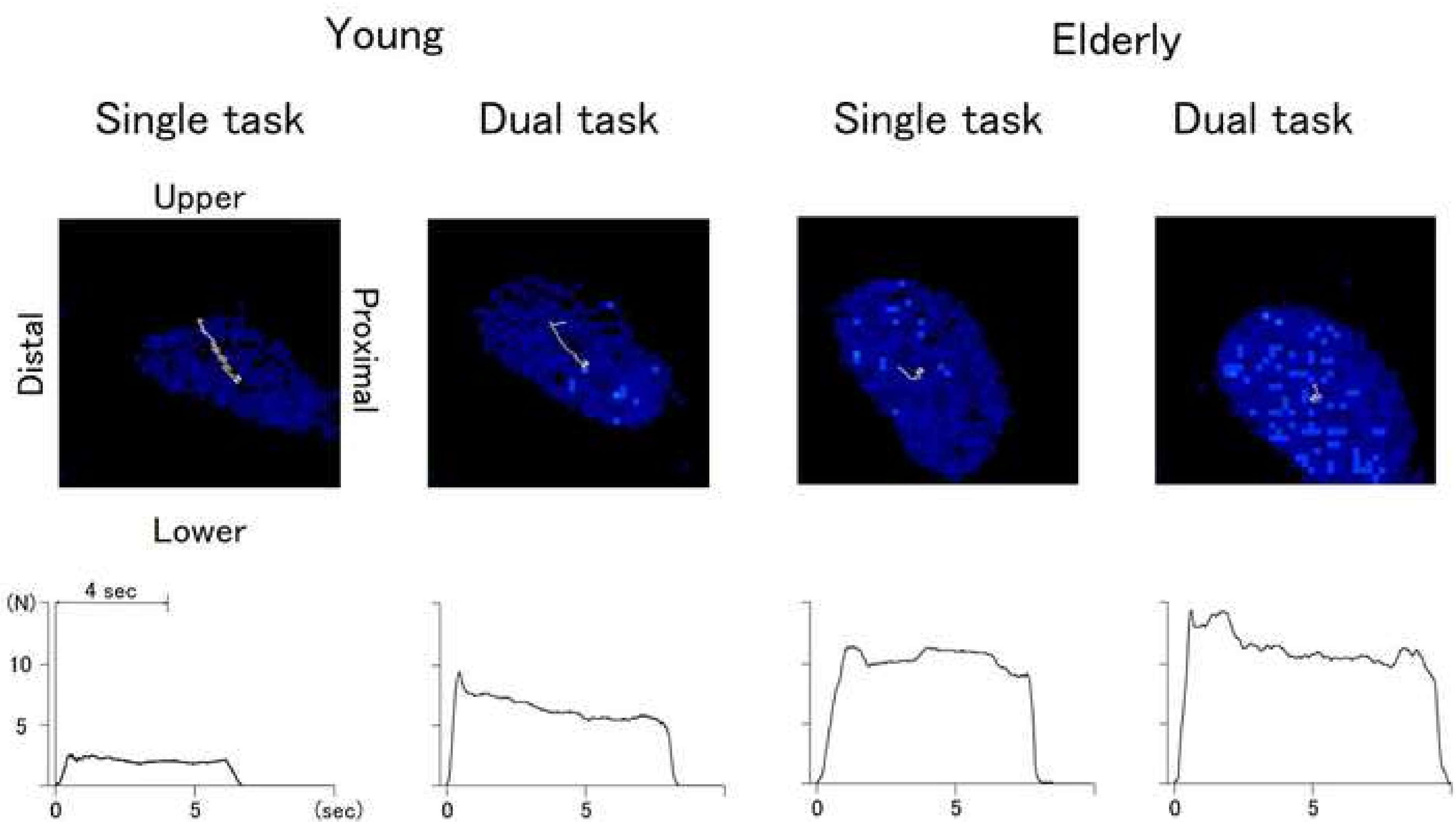


Figure3

Click here to access/download;Figure;Figure 3.jpg



Name of Material/ Equipment	Company	Catalog Number
Alcohol swab		
Compressor	Nitta Corporation	
Computer		
Controller of compressor	Nitta Corporation	
Double-sides tapes		
Iron cube		
Sensor connector		
Sensor sheet		
Setting stand		
Software; I-SCAN 5027, Ver. 7.51	Nitta Corporation	
Table		

Comments/Description

Wipe participant's finger pulps
Apply pressure to the sensor seats

Use to manupirate the compressor
Use to attach the sensorseats to the iron cube
150-250g, 30×30×30 mm
Connect the sensorseats to computer.
Pressure Mapping Sensor 5027, Tekscan, South Boston, MA, 50 USA
Set the iron cube on it during the measurement

Use for the measurement

Reply to the editor's suggestions and comments

Changes were highlighted with red color in the revised manuscript.

Editorial comments:

1. Please note that the editor has formatted the manuscript and adjusted the numbering of protocol steps according to JoVE guidelines. Please review for accuracy and retain the same style if possible. The updated manuscript is attached and please use this version to incorporate the changes that are requested.

Thank you for your kind support. We checked all changes by you and found nothing to add or delete.

2. Please revise lines 298-302 and 313-314 to avoid overlap with previously published text.

Thank you for your suggestion. As you pointed out, we revised paragraphs.

3. Please address specific comments marked in the attached manuscript.

Thank you for your suggestions. We responded to all your comments in the revised manuscript.

4. As we can only film 2.75 pages of the protocol, please review and shorten the highlighted portion to 2.75 pages. For example, some of the shorter protocol steps can be combined; however, please ensure that there are no more than 2-4 actions per step. Note that the highlighted content should contain essential steps of the protocol for the video, i.e., the steps that should be visualized to tell the most cohesive story of the Protocol. Please ensure that the highlighted steps form a cohesive narrative with a logical flow from one highlighted step to the next.

We shorten the highlighted portion within 2.75 pages.