Measurement of Brain Activity under Virtual Reality Skills Training Using Near-Infrared Spectroscopy*

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Abstract

In the present paper, we describe the measurement of brain activation response during lathe operation in a VR lathe environment and an actual lathe environment by near-infrared spectroscopy. In the frontal lobes and the motor cortex, oxyHb tended to increase during the operation in both the VR lathe environment and the actual lathe environment. The results show that the brain activation response during the performance of lathe operation in the VR lathe environment was very similar to that which occurs during lathe operation in the actual lathe environment.

Key words: Near-Infrared Spectroscopy, Brain Activity, Virtual Reality, Skills Training, Lathe

1. Introduction

Recently, with the aging of society (1), the future of the Japanese manufacturing industry is facing a crisis. As an example, a number of NC lathes and other systems have been developed for automated lathe operation. However, high-precision machining is often difficult to automate and requires manual lathe operation by highly skilled machinists. In lathe operation, highly skilled machinists can judge the state of the operation by sensing vibration, sound, and smell. With the aging of highly skilled machinists, this skill set could be lost (2). Therefore, it is important to pass skills on to the next generation and to train young workers. In the past, younger workers learned skills from master machinists, who guided younger workers in the actual use of lathes. Guidance was chiefly provided through physical experience. This is referred to as on-the-job training (OJT). Trainees can acquire the required implicit knowledge, awareness, and sensitivity to potential problems in lathe operation (3). However, this method has a number of limitations, such as time, money, and space limitations. On-the-job training is highly dependent on the capabilities of the trainer in nurturing the requisite skill.

We have proposed a training method that merges OJT with a virtual reality (VR) environment for physical experience (4)-(6). In the proposed method, trainees can be trained in a safe environment, and repeated lathe operation can be readily performed.

Near-infrared spectroscopy (NIRS) is a new technique for non-invasive monitoring of tissue oxygenated hemoglobin (oxyHb) and deoxygenated hemoglobin (deoxygenHb) (7). Near-infrared spectroscopy measurement has fewer restraint conditions and so is commonly used for measurement of movement (8)-(10). In this paper, we describe the measurement of brain activation responses during lathe operation in the VR lathe environment and in the...
actual lathe environment by NIRS.

2. Measurement of motor cortex response by NIRS

2.1 Optical brain imaging system

During neural activity in the brain, humans transmit and process information and decide actions or responses. When neural activity occurs, blood flow and blood quantity increase in the tissue near the active neurons, and the ratio between oxygenated and deoxygenated hemoglobin (oxyHb, deoxyHb) in the blood changes. Hemoglobin characteristically changes in near-infrared (700–900 nm) absorbance in accordance with its oxygen content. Therefore, it is possible to determine changes in the oxygen level in the hemoglobin based on the measurement of this absorbance by NIRS. In NIRS, the cranial target area of the subject is overlaid with a special holder for optical fibers, which are inserted into the holder at selected measurement positions on the scalp, thus enabling non-invasive measurement of NIRS incidence and reception. This configuration places little or no restriction on the bodily movement of the subject, and the measurements can therefore be made with the subject in a natural state of posture and movement. As such, in the present study, we used NIRS to determine the state of hemoglobin oxygenation at the cerebral surface and, on that basis, performed real-time color mapping of the state of brain activity (the brain activation response) in the target regions.

2.2 Handle rotation trials A

In trials involving crank handle rotation, NIRS measurements were performed while the subject rotated a handle under several different loads. The handle was of the same configuration as handles actually used in lathes. The handle torque was 0.009, 0.025, 0.651, or 1.332 Nm. Figure 1 shows the handle that was used for the trials. We used two healthy right-handed volunteers in age of 25 and 26. At the time of the trial, the subjects were instructed to rotate the handle using their left and right hands alternately for 30 s. The direction of rotation was counterclockwise, and no instruction was given as to the speed of rotation. We placed 21 transmission-receiving probes in a reticular pattern on the cap. Different areas in the brain are specialized for different functions (11). The premotor cortex is activated by the sensory guidance of movement and control of trunk muscles of the body (11). Thus, the measurement region was the motor cortex, as shown in Fig. 2. The interval of the probe was set to be 30 mm, and total number of measurement channels was 45. The locations of the probes are based on the international 10-20 system.

Figure 3 shows the oxyHb change in Subject A as he rotated the handle using his right
hand. In the first 4 to 5 s after beginning the task, oxyHb increased. Throughout the course of the task, oxyHb increased and decreased, but remained higher than before the task began. However, oxyHb did not decrease to the base level that existed before the task until after completion of the task. Thus, the results indicate that it is possible to determine the change in oxyHb in the motor cortex related to handle rotation. Moreover, as shown in Figure 3, increasing the handle torque resulted in a greater change in oxyHb. In summary, the performance of the handled rotation caused oxyHb to increase in the motor cortex, and the degree of increase was largely dependent on the force used to rotate the handle.

2.3 Handle rotation trials B

In trials involving crank handle rotation, NIRS measurements were performed while the subject rotated a handle. We used five healthy right-handed volunteers in age of 24~26. At the time of the trial, the subjects were instructed to rotate the handle using their left or right hands for 30 s. As shown in Fig. 4, we placed 21 and 27 transmission-receiving probes in a reticular pattern on the cap. The interval of the probe was set to be 30 mm. The measurement region was the motor cortex and frontal lobes, as shown in Fig. 5. The direction of rotation and number of rotations were instructed before the trial (instruction trial). In case of number of rotation were not instructed, the subjects simply cranked handle for 30 s (non-instruction trial).

Figure 6 shows the oxyHb change in the frontal lobes and Fig. 7 shows the oxyHb change in the motor cortex as the subject A cranked the handle. In the case of non-instruction trial, the oxyHb tended to decrease in frontal lobes. In order to investigate
whether the decrease in oxyHb was attributable to the handle rotation task, a test for significant difference between oxyHb during the task and oxyHb during rest was performed using the Holm-Bonferroni method. The level of significance was taken as 1%. The results of the test revealed that there isn’t a significant difference at almost all of the measurement positions in the frontal lobes. Thus, the results indicate that the oxyHb level did not change in the non-instruction trial. Meanwhile, in case of instruction trial, the oxyHb increase in the frontal lobes. In this case, we also use the Holm-Bonferroni method to investigate whether the increase in oxyHb was attributable to the task. The level of significance was taken as 1%. The test results showed a significant difference between the rest period and the task period at nearly all measured positions in the frontal lobes, indicating that the increase in oxyHb was actually caused by the handle rotation task. The frontal lobe is the region that associates with planning, attention, and short-term memory tasks. Therefore, we can conclude that the frontal lobe is activated by the instruction. In case of the motor cortex, the oxyHb level increase in both the instruction trial and non-instruction trial. Because the motor cortex response to movement, the oxyHb level increased as the subjects cranked the handle in both trials.

![Fig. 6 Change in oxyHb levels in the frontal lobes](image)

(a) VR environment

(b) real environment

![Fig. 7 Change in oxyHb levels in the motor cortex](image)

(a) VR environment

(b) real environment

Fig. 6 Change in oxyHb levels in the frontal lobes (the standard error of each time point from trials average)

Fig. 7 Change in oxyHb levels in the motor cortex (the standard error of each time point from trials average)
3. Measurement of brain activation response during lathe operation by NIRS

3.1 VR system for transmission of lathe operating skill

During these trials, the operator stood in front of a screen wearing polarized glasses and a head tracking device that enables detection of the position and orientation of his head. The operator therefore had a stereoscopic view of the lathe image, which was projected onto the screen, and could manipulate the model handles, which were located near the operator’s hands, as shown in Fig. 8, and synchronized with the screen image. One handle was modeled on the carriage handle of an actual lathe for longitudinal movement, and the other was modeled on a toolpost handle for transverse movement. Each handle unit contained a handle, a magnetic brake, and an encoder. The handle and the magnetic brake were attached coaxially on the same crankshaft, and the encoder was linked to each crankshaft by coupling. The magnetic brakes imparted a sensation of a force on the operator when he rotated the handle. Simultaneously, a signal was sent from the encoder, the information was read by a Peripheral Interface Controller (PIC), and the rotational speed was transmitted to a personal computer (PC). Based on the rotational speed, the number of rotations was determined, and the depth of the cut was computed from the positional relationship of the tool bit and the workpiece. Based on this information, an image of the processing state was constructed and projected onto the screen. Figure 9 shows the projected screen image. Scale markings are present on actual lathe handles, but none were provided on the fabricated system handles, and so these markings were shown in the image. As an added training function in the virtual system, which simulated one aspect of OJT, it was possible to show not only a reproduction image of the actual object but also the feed rate in comparison with
the feed rate of the recommended cutting conditions. During the operation, processing sounds were provided by an ITU-R5.1ch speaker system in order to present changes in sound when the tool bit came into contact with the workpiece and various sounds that depend on the cutting state. In this manner, it was possible to present haptic, visual, and auditory information to the trainee.

3.2 Measurement of brain activation response by NIRS during lathe operation

In the experiments of the present study, the NIRS instrument used for the measurement was the Shimadzu FOIRE-3000. The subject was a male in his twenties with little experience in lathe operation. We measured the brain activation level of the subject during lathe operation in the VR lathe environment and in the actual lathe environment. Each experiment was performed in alternating segments of observation of another person operating the lathe and operation by the subject himself. Measurement positions by NIRS were the entire brain. We set sixteen pairs of transmission-receiving probes in a reticular pattern on the cap. The interval of the probe was set to be 30 mm, and total number of measurement channels was 100. The locations of the probes are based on the international 10-20 system. Figure 10 shows the measurement positions, and each experiment was performed twice. In these experiments, the workpiece material was aluminum. The cutting conditions, which were taught to the subject in advance, were a cutting depth of 0.2 mm and a cutting length of 20 mm. As shown in Fig. 11, the subject performed the lathe operation task in 40 s, and the non-operating time was 80 s.

3.3 Analysis of brain activation response during lathe operation

3.3.1 Trials in the VR lathe environment

Figure 12 shows the changes in oxyHb levels in the motor cortex and the frontal lobes during the observation by another person of operation in the VR environment. As shown in the figure, oxyHb in the motor cortex tended to decrease in both the right and left hemispheres. A decrease in oxyHb in the frontal lobes was also observed. In order to investigate whether the decrease in oxyHb was attributable to the observation task, a test for significant difference between oxyHb during the task and oxyHb during rest was performed using the Holm-Bonferroni method. The level of significance was taken as 1%. The results of the test revealed a significant difference at almost all of the measurement positions in the frontal lobes and motor cortex between the task time and the rest time. Thus, the decrease in oxyHb was actually attributable to the observation task. Moreover, in regard to the positions in which there was no significant difference, a test performed under the assumption that the task-time oxyHb increased showed no significant difference from the oxyHb change during the rest time. In summary, the results indicate that, in the case of watching another person operate the lathe in the VR lathe environment, oxyHb in the motor cortex and the frontal lobes decreased or did not change.

Figure 13 shows the results for the motor cortex and the frontal lobe measurements during operation of the VR lathe by the subject himself. In this case, oxyHb increased at almost all measurement positions in both the motor cortex and the frontal lobes. In these trials, we use the Holm-Bonferroni method with a significance level of 1%. A significant difference was found between the task period and the rest period in almost all of the measured positions in the motor cortex and the frontal lobes. Therefore, we can conclude that the increase in oxyHb, as measured by NIRS, was attributable to the performance of the lathe operation. In the motor cortex, the positions in which the increase in oxyHb was particularly large were in the temporal region, which corresponds to hand movement, and the parietal region, which corresponds to trunk movement. The increase in oxyHb during lathe operation was larger than the oxyHb changes during observation of lathe operation by another person.
Change in oxyHb level in the motor cortex

Change in oxyHb level in the frontal lobes

Fig. 12 Brain activation response during observation in the VR environment

Change in oxyHb level in the motor cortex

Fig. 13 Brain activation response during operation in the VR environment
Taken together, the results of the trials in the VR environment reveal that oxyHb in an individual tends to decrease while watching another person operate the lathe but increases substantially in an individual operating the lathe. In short, the results reveal that brain activity is greater while operating the lathe, as compared to watching another person operate the lathe.

3.3.2 Trials in the real lathe environment

The results obtained in the real lathe environment were similar to the results obtained in the VR lathe environment. Figure 14 shows the change in oxyHb level in the motor cortex and the frontal lobes while the subject observed the operation of the actual lathe by another person. OxyHb decreased in the motor cortex and remained at the same level in the frontal lobes. The decrease was again tested for significance using the Holm-Bonferroni method with a significance level of 1% in order to investigate whether the decrease was attributable to the performance of the task. The results revealed a significant difference between the task period and the rest period. Thus, the results indicate that oxyHb decrease was attributable to observation of the task being performed. In short, the results indicate that oxyHb in the motor cortex and the frontal lobes decreased or did not change in the real lathe environment while the lathe operation was viewed by another person.

Figure 15 shows the results for the motor cortex and the frontal lobes during real lathe operation by the subject. The results show that oxyHb increased in both the motor cortex and the frontal lobes while operating the actual lathe. In this case, we also use the Holm-Bonferroni method to investigate whether the increase in oxyHb was attributable to the performance of the task. The level of significance was taken as 1%. The test results showed a significant difference between the rest period and the task period at nearly all measured positions in the motor cortex and the frontal lobes, indicating that the increase in oxyHb was actually caused by the task performance. The measurement positions in the motor cortex that exhibited particularly large increases in oxyHb were in the temporal cortex. The results indicate that during both the real lathe operation and the VR lathe operation, the brain activation response was larger in an individual operating the lathe as compared to an individual watching someone else operate the lathe.

3.3.3 Brain activation response during VR lathe operation and real lathe operation

In the VR lathe operation by the subject, oxyHb increased greatly in the temporal region of the motor cortex. Similarly, in the real lathe operation, the increase in oxyHb was larger in the measurement positions in the temporal region of the motor cortex than in other regions. The temporal region of the motor cortex is the region of response to hand movement. In real lathe operation, the movement of both hands is the primary movement, since both hands must be used to manipulate the handles. The same circumstances applied in the VR lathe environment, the movement of both hands is the primary movement, and oxyHb was similarly found to increase greatly in the temporal region of the motor cortex. Figure 16 shows the oxyHb change in the motor cortex in the temporal region while the subject was operating the VR lathe and the real lathe, and Fig. 17 shows the oxyHb change in the frontal region. As shown in the figure, in both the real and VR environments, oxyHb tended to increase as the operation proceeded. As mentioned above, the frontal lobe is activated by the instruction. In the lathe trials, the subjects operated the lathe as instructed, thus the frontal lobe was activated in VR lathe and the real lathe trials.

Figure 17 also shows that the increase in oxy-Hb in the actual lathe environment was larger than that in the VR lathe environment. This was thought to occur because the torque produced by the VR lathe handle was smaller than produced by the handle of the actual lathe. In order to investigate whether the change in oxy-Hb in the VR lathe environment
Fig. 14 Brain activation response during observation in the real environment

Fig. 15 Brain activation response during operation in the real environment
was the same as that in the actual lathe environment, we took the largest change in oxyHb as 1 and normalized all values as shown in Fig. 18. Comparison of the results revealed qualitative agreement in oxyHb changes in the motor cortex and the frontal lobes between VR lathe operation and real lathe operation.

4. Conclusion

We measured brain activation responses by NIRS during the performance of turning the handle. The results revealed that the degree of change in oxyHb was governed largely by the level of force applied. We also measured brain activation responses during lathe operation in the VR lathe environment and the actual lathe environment. The results revealed qualitative agreement in the trends of oxyHb change for operation in the VR lathe environment and the real lathe environment. The results also revealed that, in both environments, lathe operation induces greater changes in oxyHb than watching the lathe operation.
being operated by another person. Therefore, the brain is more highly activated by the operating the lathe than by watching the lathe being operated by another person.

The results reveal that brain activation response during lathe operation in the VR environment is very similar to the results obtained during lathe operation in the actual environment, thereby indicating that training in such a VR environment will be effective and useful. In the future, we intend to perform more detailed analyses of movements performed during lathe operation and of the relationship between the process of developing lathe operation skills and brain activation responses.

References