Establishment of vestibular function multimodality platform

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Abstract

Background: The technology of using inertial measurement units (IMUs) to detect motions in different body segments has drawn enormous attention to research and industry. In our previous research, we have applied IMUs in evaluating and treating patients with vestibular hypofunction. Furthermore, according to the research, when a person's head rotates over 60° on either side in the horizontal plane, and desires to focus vision on any targets, then the function of gaze shift comes in to operation. Herein, we aimed to use IMUs to build up a system to evaluate vestibular ocular reflex (VOR) during gaze shifting maneuver.

Methods: In this study, we developed a platform, which combines the features of gaze shift and computerized dynamic visual acuity (cDVA), called the gaze shift DVA (gsDVA) platform. The gsDVA platform measures the orientations of the subject's head by IMU, and executed the evaluation according to the algorithm that was developed by us. Finally, we used the VICON system to validate the performance of gsDVA platform.

Results: The performance of the accuracy was 2.41° ± 1.08°, the maximal sensor error was within 4.25°, and highly correlated between our platform and VICON ($p < 0.05$, R = 0.99). The intraclass correlation coefficient (ICC) of between-day and within-day was 0.984 and 0.999, respectively. Furthermore, the platform not only executed the evaluation automatically but also recorded other information besides the head orientation, such as rotation speed, rotation time, reaction time, and visual acuity.

Conclusion: In this study, we demonstrated the utility of vestibular evaluation, and this platform can help to clarify the relationship between gaze shift and VOR. This methodology is useful and can be applied efficiently to different disease groups for interactive evaluation and rehabilitation programs.

Keywords: Inertial measurement unit (IMU); Vestibular ocular reflex (VOR); Visual acuity; Vestibular hypofunction

1. INTRODUCTION

In the past decade, inertial measurement unit (IMU) has drawn a vast attention and has been wildly utilized in many fields. In industrial applications, the IMU was worn on the workers wrist and measured the information of the worker's activities in assembly lines.[1] Some microsurgical instrument also used the IMU to distinguish and compensate the tremor in doctor's hand.[2] Even in military application like Doppler radar, star trackers aid the flight vehicle to land.[3] In addition, the IMU was used to develop the navigation system and integrated into the global positioning system to enhance the performance of localization.[4–7] In the research applications, the IMU worked as sensor for assessing the orientations of body segments,[8] as well as measuring the trajectory of center of mass.[9] One report indicated the IMU represents a reliable sensor to measure the cervical spine range of motion,[10] evaluate the motor function of upper limb,[11] and analyze the kinematic of lower limb.[12] Some research executes the gait analysis by using IMU, and they estimate step length, step distance, walking speed and detect the gait phase in walking and running conditions.[13–18]

Furthermore, there has been many research integrated IMU into other device to enhance the performance of assessment. For example, the IMU was fixed on the unstable chair to assist the experiment of the trunk postural stability test,[19] the electromyogram sensors and IMU were used to evaluate the people balance,[20] and the system for detecting gait phase was built by force-sensing resistor and IMU.[21] Additionally, in rehabilitation application, the IMU is used as the system for assessing the effectiveness and providing feedback during the physical therapy exercises.[22] The IMU also integrates into other devices such as potentiometer bend sensors for stork rehabilitation,[23] the force plate or wii remote for hypofunction of vestibular,[24,25] and the virtual reality (VR) for low back pain or stroke.[26,27] As mentioned earlier, IMU has been successfully applied in many territories because of its advantage in providing not only the information of position and velocity three dimensionally but also about wearable and suitable indoor and outdoor environments.[3] Furthermore, the IMU has strong tendency for measuring movement related to the optical motion capture system.[28]

The vestibular ocular reflex (VOR) helps to stabilize the surrounding images in the fovea. During walking with horizontal head rotation, human use gaze shift strategy to see clearly. Compared with the computerized dynamic visual acuity (cDVA) test, gaze shift is a more functionally relevant task for evaluation of vestibular function. Therefore, in this study, we aimed to develop a system that incorporated the characteristics of cDVA and gaze shift for evaluation of vestibular function during head rotation and walking on a treadmill.

2. METHODS

The gaze shift dynamic visual acuity (gsDVA) contains three subsystems (Fig. 1). The IMU was the sensing system used to measure the head rotation angle, transmit the signal to the control system, perform the evaluation according to the algorithm, and finally it displays the instruction on the display system.

2.1. Sensing system

As a starting point, high precision and flexible measurement are needed. Therefore, IMU that is manufactured by PNI Sensor Corporation was used as the sensing system. The IMU with 3-axis accelerometer, 3-axis Gyroscope, and PNI's Geomagnetic Sensor Suite can provide reliable orientation data with quaternion. The sampling rate was 125 Hz, and the data were transmitted to the control system by USBUART.

2.2. Display system

Three screens were used to display the optotypes (ie, letter E) with different orientation and size.

2.3. Control system

The computer was the core processing platform. It received signals from the sensing system, calculated user's head orientation, altered the orientation and size of the optotypes randomly, showed the optotypes at the correct monitor, and recodes the experimental data.

2.4. Controlling algorithm

We developed the control algorithm, and used the LabVIEW 2013 software (National Instruments Corporation). The flow

Fig. 1 Architecture of gaze shift dynamic visual acuity (gsGVA). The gsDVA contains three subsystems, the sensing system was the IMU and transmitted the orientation signal to the control system, and then the control system with algorithm that can instruct the subject to perform the experiment by display system.

chart of the algorithm is shown in Fig. 2B. First, the quaternion data of head orientation were transmitted to the control system as the input signal, and then the quaternion data were transformed to the direction cosine matrix. After that, the built in function "Direction Cosine to Euler Angles" was used to calculate the rotation angle degree of the Yaw axial (Horizontal plane). The rotation order was the "Z-X-Y", which could avoid the gimbal lock to disturb the Yaw axial. Then, the data of the Yaw axial as the input reference and the algorithm based on the reference are used to set a desired order and target (optotypes with different orientation and size) for the correct screen which in turn instructed the subject to finish the test.

2.5. System verification

The system was verified by using the VICON computer-assisted video motion analysis system (VICON Motion Systems, Oxford, UK). As shown in Fig. 3A, the subject wore the sensing helmet, and three markers were attached at the sagittal plane. The angle of head rotation was determined by using the global coordinate system. As shown in Fig. 3B, first, the subject looked forward as the initial position (0°); then rotated to right side and rotated to the opposite side; and finally back to the initial position. All the signals were simultaneously recorded by the PC. The sampling rate of VICON was 100 Hz, and our sensing system was 125 HZ. Therefore, we would resample both data by interpolation before our verified process.

2.6. Statistical analysis

The results are reported as mean ± SD and correlation coefficient. Statistical analysis was performed using Pearson correlation and intraclass correlation coefficient (ICC) was calculated for within-day and between-day.

3. RESULTS

3.1. System verification

As mentioned earlier, the function of gaze shift will be triggered when the head rotation angle was >60° in the horizontal plane. It means the good performance of the sensing system was the most important fact of the gsDVA. The performance of the IMU is evaluated in our VICON Motion system. A typical angle relationship between IMU and VICON is shown in Fig. 4A, the blue line was the rotation angle of the VICON and the red line was the IMU; 0° was the initial position, rotating right is positive and rotating left is negative. Obviously the angle variation of IMU is associated with the change of VICON, the maximal value of error was 4.25° (Fig. 4B) and the error of the mean ± SD was 2.41° ± 1.08°. There was high correlation between IMU and VICON ($p < 0.05$, R = 0.99), and the ICC of between-day was 0.984 and within-day was 0.999.

As noted earlier, the results demonstrated that the system integrated by ourselves could work collectively and correctly. As shown in Fig. 4, it can be seen that the value of IMU will alter with the angle of head rotation no matter whether the subject rotates to right side or left side. The result of the error was 2.41° ± 1.08°, which was similar to the manufacturer's datasheet indicating the resolution of IMU as 2°. Although the maximal error was 4.25°, the value was not serious because the total rotation angle was 60° and the movement of 5° was not obviously in the head rotation. Furthermore, the ICC was almost perfect, since we asked the subject to perform the head rotation only in horizontal plane (Yaw axial) as far as possible, which would reduce the interference from other axle's rotation.

3.2. Features of the gsDVA

The function of gaze shift will be induced in both conditions, first is over 45° rotation in horizontal plane and the second is the target display at the edge of the vision. Therefore, the gsDVA had two characteristics: first, the platform could measure the movement of subjects' head such as the rotation angle (horizontal
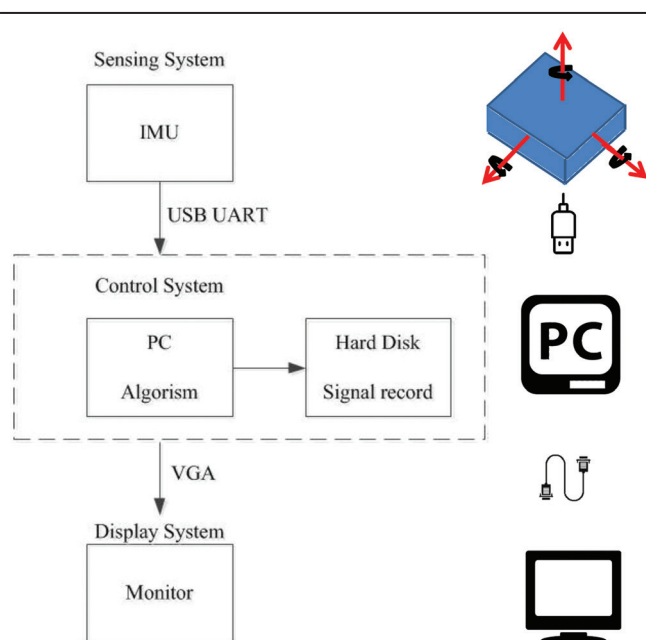
A

$$DCM = \begin{bmatrix} q_3{}^2 + q_0{}^2 - q_1{}^2 - q_2{}^2 & 2(q_0q_1 + q_3q_2) & 2(q_0q_2 - q_3q_1) \\ 2(q_0q_1 - q_3q_2) & q_3{}^2 - q_0{}^2 + q_1{}^2 - q_2{}^2 & 2(q_1q_2 + q_3q_0) \\ 2(q_0q_2 + q_3q_1) & 2(q_1q_2 - q_3q_0) & q_3{}^2 - q_0{}^2 - q_1{}^2 + q_2{}^2 \end{bmatrix}$$
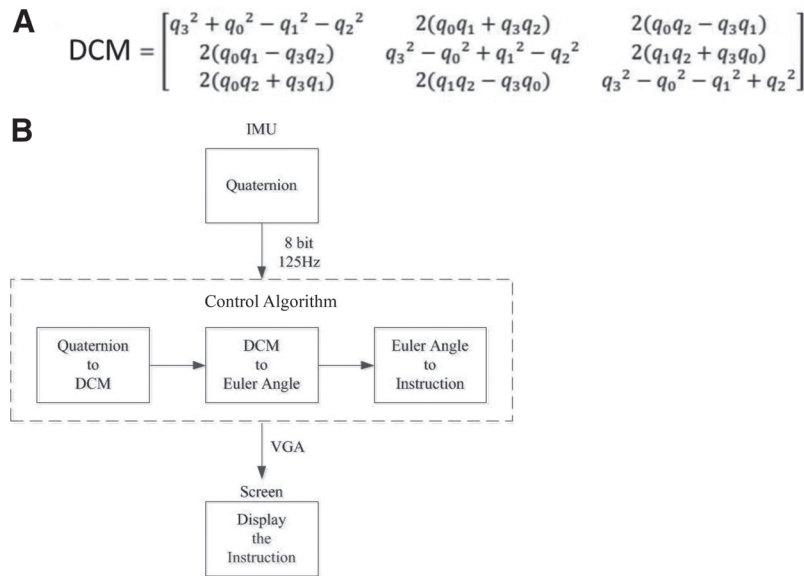
B

Fig. 2 The controlling algorithm. A, The transformed equation for direction cosine matrix (DCM). The quaternion data was transformed to the DCM by this equation. The quaternion data with four parameters were the Q_w, Q_x, Q_y, and Q_z; they were the q_0, q_1, q_2, and q_3, respectively. B, The flow chart of control algorithm. The orientation data were transferred to DCM and was used to calculate the Euler angle, which decides the instruction displayed in the screen.

plane), rotation velocity, rotation time, reaction time, and the visual acuity (dynamic and static); second, the platform was applicable in various subject's features.

As mentioned earlier, the gsDVA was developed with three subsystems as shown in Fig. 5. The sensing system was assembled by the IMU and the helmet, since that helmet was easy to wear and adjust. The display system used the screen to display the optotypes. The distance and angle between the subject and screen and the horizontal level of the screen were adjusted according to subject's features. The control system and its control algorithm were developed in the Microsoft Windows environment, which is easily applied to other PC.

Furthermore, the LabVIEW could provide the information of time and the precision in millisecond, and we compared the precision between the VICON and the sensing system. As shown in Fig. 6, the blue bar was the time of the rotation recorded by VICON and the red was recorded by IMU; the left group was the time interval from initial position to the left side and then back to the initial position; the right group is with the same protocol but in opposite direction. The rotation time interval was 6.68 seconds in IMU and 6.59 seconds in VICON. The difference was 0.09 seconds. Hence the gsDVA could measure and record those parameters by means of the time and IMU information. The parameters were the following:

1. Visual acuity: Includes static and dynamic visual acuity. The LogMAR score based on the randomly optotypes with an interval seconds by a computer generated automatically.
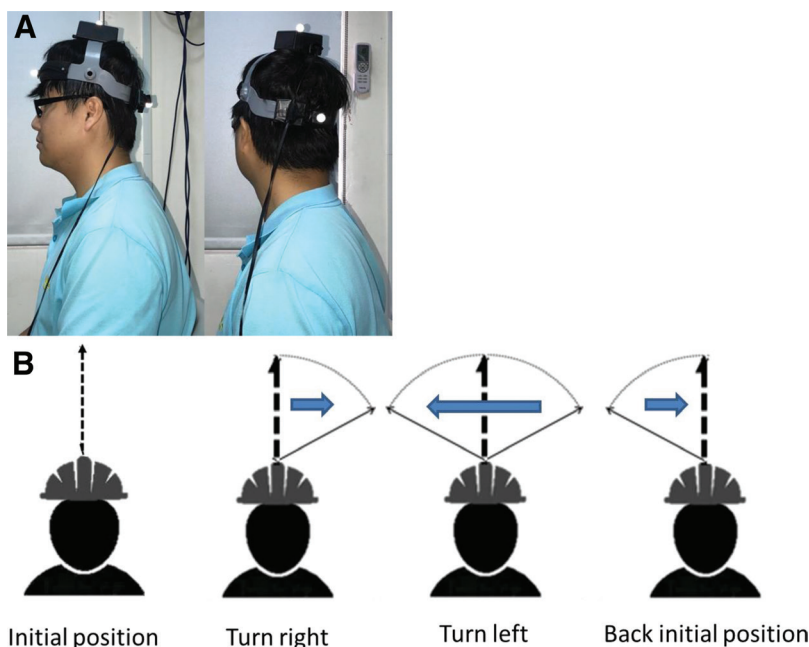

Initial position Turn right Turn left Back initial position

Fig. 3 The protocol of the sensing system verification. A, The setting of the experiment. The subject wore the sensing helmet that was assembled with the inertial measurement unit (IMU) and helmet, and three markers were attached to the helmet in the same plane. B, The protocol of the experiment: first, look forward as the natural position; second, rotate to right side from natural position; third, rotate from right to left side; finally, rotate back to the natural positon and finish the experiment.
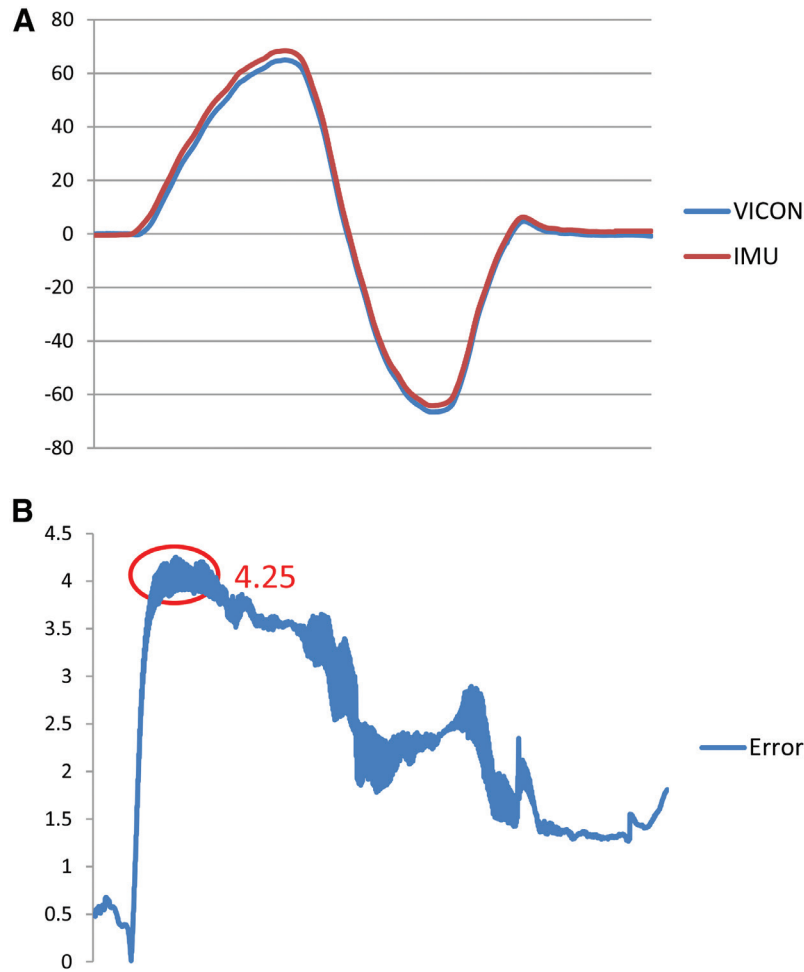
Fig. 4 The result of the system verification. A, The angle degree records the movement of the rotation as displayed in Figure 3. The red line was the degree variety of the inertial measurement unit (IMU) and the blue line was the VICON data. The mean ± SD was 2.41 ± 1.08. B, The error degree between the IMU and VICON. The maximal value was 4.25.

2. Reaction Time: This includes the time from which the subject saw the optotypes to answer from the position of 15° to 60°.
3. Head rotate angle: The subject faced forward as the initial position (0°), rotated to left as the plus and right as the minus.
4. Head rotate speed: The average velocity from the position of 15°to 60°.

Additionally, the system could automatically instruct the subject to perform the visual acuity test. The test protocol is as follows (Fig. 7): Step 1, central monitor displayed the right arrow, prompted the subject in rotating to right side from the initial position (0 ± 15°); Step 2, when subjects are rotated to the green area (over 15°), the arrow disappears and avoids affecting the subject; Step 3, when subjects are rotated to the blue area (over
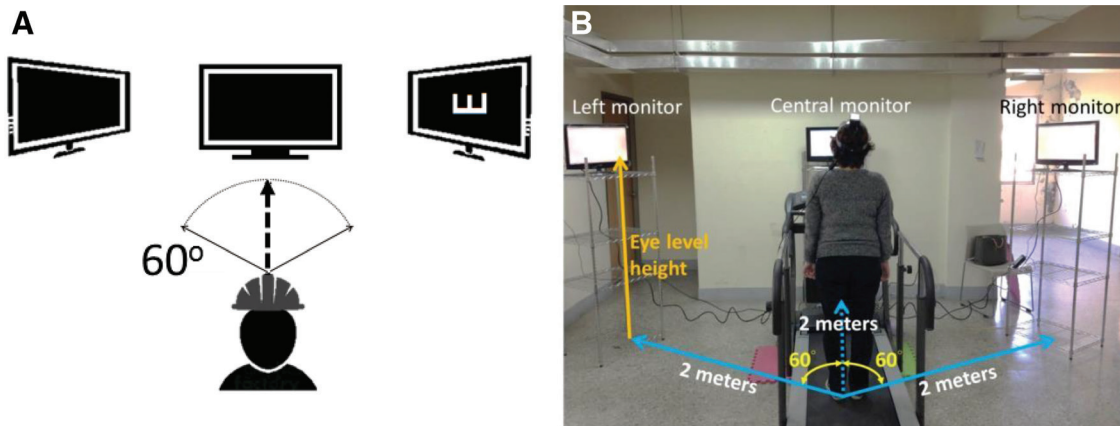

Fig. 5 The overview of gaze shift dynamic visual acuity (gsGVA). A, The concept diagram of the gsDVA. B, The reality picture of our system. The gsDVA includes the sensing helmet that was worn on the subject, three monitors were set in front of the subject and each interval was 60°. Furthermore, the distance and the horizontal level of the screen were adjustable.
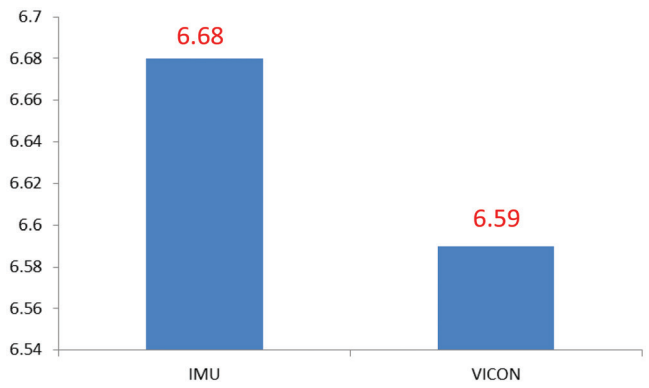
Fig. 6 The result of the time resolution. The left bar was the rotation time interval measured by inertial measurement unit (IMU) that was 6.68 s, the right bar was the result of VICON that was 6.59 s. The difference was 0.09 s.

60°), the optotypes are displayed. The subjects identified the orientation of the optotypes, and the researcher recorded the answer. Step 4, when the researcher recorded the answer, the optotypes will disappear. Simultaneously, subjects are back to the initial position and they wait for the next instruction.

4. DISCUSSION

IMU was used to estimate the orientation information in a variety of territories and had excellent performance. The applications include industry assemble lines, military submarines, missiles and unmanned air vehicles,[29] research, and clinical applications for measuring different physiological responses. In our daily activity, gaze shift and VOR are the main function to efficiently follow a target. The function of gaze shift was synchronized with the movement of head and eye; however, the VOR generated the movement of eye with same speed but in the opposite direction of the head.[30–33] Currently, there are many methods to evaluate the ability of VOR, and those methods already proved their effects.[34] Yet, a more functional relevant maneuver such as gaze shift does not have an efficient tool for evaluation.

We developed the gsDVA platform used by the IMU to measure the head rotation angle. We also developed the control algorithm, which uses the sensing signal to control the display of optotypes in order to evaluate the static and dynamic visual acuity. The platform would guide the subject to perform the test and record the information automatically. The information includes rotation speed, rotation angle, rotation time, reaction time, and visual acuity. We hypothesized that the gsDVA could distinguish between the vestibular patients and healthy controls.

The result indicated the platform with the accuracy of head rotation degree was 2.41° ± 1.08°, the maximal value of error was 4.25°, the ICC of between-day was 0.984 and within-day was 0.999; the difference of time was 0.09 seconds. Even though the maximal of error angle was 4.25°, the difference was insignificant, since the total rotation angle was 60° in our experiment and the Pearson correlation coefficient represented the high correlation between our platform and VICON ($p < 0.05$, R = 0.99). In addition, the frequency was the main factor for maintaining the clear vision during head movement;[33] hence, the accuracy of time was the most important factor. As from our results, the difference of time was 0.09 seconds; however, the difference was the cumulative error over 6 seconds and the cumulative number was 125 per second. Hence, each time stamp with the difference was <1 millisecond; the performance was suitable for our requirement. According to the above-mentioned results, we demonstrated that the sensing system established by IMU could perform accurately in the measurement of orientation, angle, and
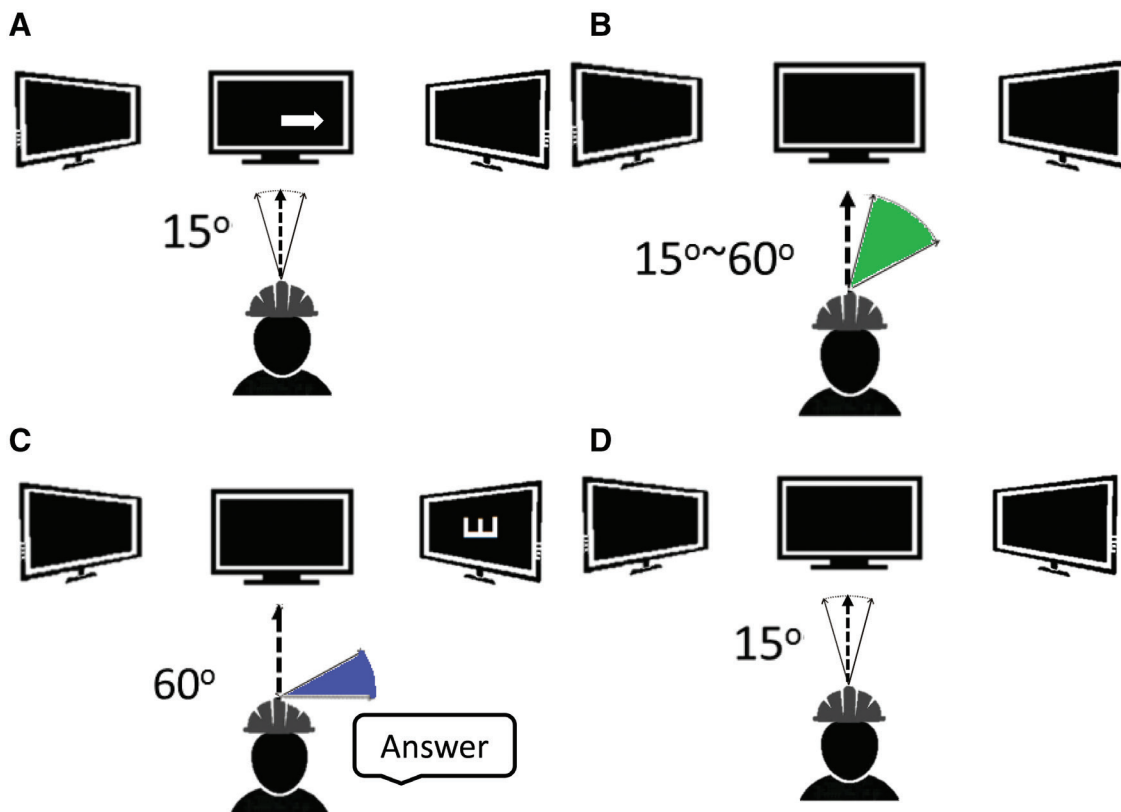

Fig. 7 The protocol of visual acuity test. A, First step, the central screen displayed the arrow and the subject is rotated to the right side. B, second step, when subject is rotated over 15° (green area), the arrow will disappear. Avoid affecting the subject. C, third step, when subjects are rotated over 60° (blue area), the optotypes will be displayed and the subject needs to identify the orientation. The identified answer will be recorded in the system. D, The final step, when the system recorded the answer, the optotypes will disappear. The subjects are back to the initial position and are waiting for next instruction.

speed. However, the verification was executed in the sitting position not in the standing position or other dynamic states, and further research is still needed to verify the performance.

Furthermore, in this study, we have successfully established that a dynamic precision system incorporated the gaze shift strategy into the cDVA test, for measuring vestibular function, as well as the providing VOR's information including rotation speed, rotation angle, reaction time, and visual acuity. Moreover, the other important feature of gsDVA platform was the evaluation performed in the condition of standing and walking in order to simulate the real movements in our daily activities. As some study indicated the most DVA test has been executed with the sit condition,[24] and the performance of VOR was poor while stationary. Since the performance of execute the fine motor task was more important than maintain the VOR.[35]

The platform was developed with the sensing helmet and PC with screens. The sensing system was designed for plug and play with a portable helmet, the PC and screens were easy to get in many laboratory and clinical environment. Hence, the platform was easily reproduced providing with our execution program. In other words, it means the platform can transfer the experiment environment from indoor to outdoor conditions that make the experiment closer to reality. In addition, the platform not only could adjust the spatial relationship between the screen and the subject but also alter the arrangement of screens. Because some research indicated the direction of head rotate with different effect on vestibular system,[24,34] the screens could be aligned in the horizontal or vertical directions upon the user's needs, Besides, VR was wildly applied to many researches and clinical fields for evaluation and rehabilitation;[25–27] hence, our platform could vary the number or pattern of screen and easily integrate into VR for training purposes.

Nevertheless, it is worth noting that the performances of the gsDVA instruct the subject to perform the visual acuity test automatically and whether the system would really able to distinguish the subject with vestibular hypofunction still needs further clinical trial for validation.

In conclusion, we have successfully established the vestibular function multimodality system, which integrates the function of gaze shift into the cDVA test. This system may provide the utility of vestibular evaluation, as well as the potential of vestibular rehabilitation, for improving the vestibular hypofunction in the personalized medicine.

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