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Objective Assessment of Motor Ataxia via Quantitative Analysis of Romberg's Test Utilizing Webcam-Based Motion Capture with AI

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Non-invasive technologies have significantly influenced the advancement of electromagnetics- and optics-based diagnostic methodologies in clinical settings. While the Romberg test is a pivotal preliminary screening tool for motor ataxia, its intrinsic subjectivity and constrained diagnostic sensitivity, owing to its reliance on visual appraisal by clinicians, critically limit its efficacy. To surmount these limitations, this study instituted a webcam-based quantitative diagnostic approach to capture and analyze human motion. Precise analytical procedures using artificial intelligence were devised to examine skeletal joint-position variance, culminating in a comparison of individuals exhibiting normal and control signs. Rigorous statistical scrutiny via Mann–Whitney U testing substantiated statistically significant divergences between the two cohorts ($p<0.001$), thereby validating this technological advancement's potential in capturing nuanced movements traditionally challenging to qualitatively assess. This endeavor fortifies the Romberg test's diagnostic capabilities and extrapolates the significance of non-invasive technologies, albeit without direct implications on treatment, in enhancing clinical diagnostic protocols.

Keywords : magnetic, romberg test, quantitative assessment, webcam-based analysis

1. Introduction

In cases where abnormalities arise in the cerebellum, which plays a role in observing body movements, motor dysfunction syndrome can develop. Motor dysfunction syndrome refers to a condition where no abnormalities exist in the muscles; however, muscle movement control is disrupted, leading to issues with delicate movements and maintaining balance [1]. This syndrome potentially manifests owing to abnormalities in peripheral organs that provide information; complications along the spinal cord, which serves as the pathway for transmitting such information to the cerebellum; and/or abnormalities in the cerebellum itself. Therefore, determining and differentiating the specific area(s) with abnormalities is essential. Diagnostic and testing methods encompass various examinations, including, magnetic resonance imaging (MRI), electromyography (EMG), and nerve conduction studies, among others. Among these, the Romberg test serves as a rapid clinical tool for assessing motor dysfunction syndrome. Apart from the Romberg test, methods that evaluate motor dysfunction syndromes such as ataxia, including the finger-to-nose and heel-to-shin tests, are available. The finger-to-nose test is a clinical tool for assessing cerebellar issues where the examinee, with outstretched arms, touches their nose alternately with their index fingers. The heel-to-shin test involves the supine patient lifting one leg and using the heel to slide down the opposite shin, commencing from the knee. In patients with motor dysfunction, a phenomenon is observed where the foot tends to drop near the patella during this task, indicating impairment [2].

The Romberg test is employed to investigate the causes of motor dysfunction based on the premise that at least two out of three sensory systems—visual, proprioceptive, and vestibular senses—are necessary for maintaining

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balance while a person is standing. In the first position of the Romberg test, the patient stands with their shoes removed and feet together. During this stage, their arms can be placed at their sides or crossed in front of their body. Subsequently, the clinician assesses the patient's balance with their eyes open and then with their eyes closed [3]. In this context, if the patient can maintain relatively good balance within a specified period while their eyes are open but sways or falls when their eyes are closed, it is considered a positive result. Nevertheless, if they do not sway or fall, it is deemed negative. This helps in identifying the underlying causes of motor dysfunction [4].

However, the Romberg test possesses a predominantly qualitative nature as it relies on visual assessment by the clinician without the aid of specific tests. Additionally, it has limitations in terms of reliability and validity owing to the absence of standardized validation. Furthermore, it has the drawback of low sensitivity in diagnosis, since a positive result requires the participant to actually fall [5].

Evidently, tools that quantitatively assess motor dysfunction are available, unlike the Romberg test, which is not quantitative in nature. A clinical tool called the Tinetti test evaluates the participant's gait ability and balance. The therapist observes the patient's movements and assigns scores ranging from 0 to 2 points. Subsequently, the total score is used to determine the patient's overall condition [6]. In contrast to the Romberg test, which is merely based on whether the patient falls or not, the Tinetti test allows for a more quantitative analysis. However, like the Romberg test, the Tinetti test still relies on the therapist's observation, rendering it challenging to achieve complete objectivity. Its limitation lies in the fact that scores can vary depending on the therapist's experience and expertise, potentially leading to inconsistent scoring [7].

To overcome these limitations, several quantitative research approaches have been attempted. In one study, a force plate under the feet was employed to assess center-of-pressure shifts, pathways, oscillation areas, and mean velocities [8]. In another investigation, inertial sensors were attached to the patient's occiput to measure x, y, and z values in three planes and determine whether the graphs altered according to the direction of the movement [9]. Unfortunately, these sensors and wearable devices have not been widely adopted in clinical settings, limiting their generalizability.

Therefore, this study aimed to quantitatively evaluate the Romberg test using easily deployable and cost-effective webcams in a clinical environment. Our goal was to identify metrics based on joint angles and variations that could differentiate healthy participants with negative signs from participants with positive signs. We sought to demonstrate the potential of quantifying the Romberg test using webcams by comparing the two groups. Furthermore, our objective was to quantitatively establish differences between the two groups. In other words, this study endeavored to develop a technological tool that quantitatively analyzes joint movements using a webcam to assist in diagnosing Romberg test assessments.

2. Materials and Methods

2.1. Experimental Setup

We captured human motion using a single webcam (Logitech c922). The webcam was positioned at a height of approximately 100 cm, with the distance set to ensure that the participant's entire body, from head to toe, was visible within the frame. In this study, we selected and analyzed a specific Romberg test maneuver wherein each participant stood with both feet placed parallel on the floor and their hands placed on their chest.

2.2. Data Acquisition

For the normal group, we recruited 11 healthy participants and recorded their motions using the webcam. Each participant initially had their eyes open, and after 5 s, they closed their eyes to assess the degree of body sway. In the control group, various social media sites, such as YouTube, were used to download videos wherein actual patients recorded their symptoms. In these videos, the entire body of the patient was captured on camera, and only those videos containing the before-and-after states of the symptoms were selected. We analyzed 11 videos featuring individuals with actual impairments.

2.3. Analysis Methodology

2.3.1. Calculation of Angles for the Four Elements (Nose, Shoulders, Pelvis, and Knees)

To analyze each participant's motion in the Romberg test, we measured the angles of the nose, right shoulder, left shoulder, right pelvis, left pelvis, right knee, and left knee. Each element was calculated using a total of two coordinates: one representing the joint's position and another representing a fixed coordinate that formed a vector. For the human model, we extracted skeleton points using MediaPipe's core [10] and subsequently performed angle calculations based on joint coordinates. A total of four equations were used to generate vectors between two points, with each angle calculated as the dot product angle between these vectors [11]. The first 10 frames were established as the reference for the fixed

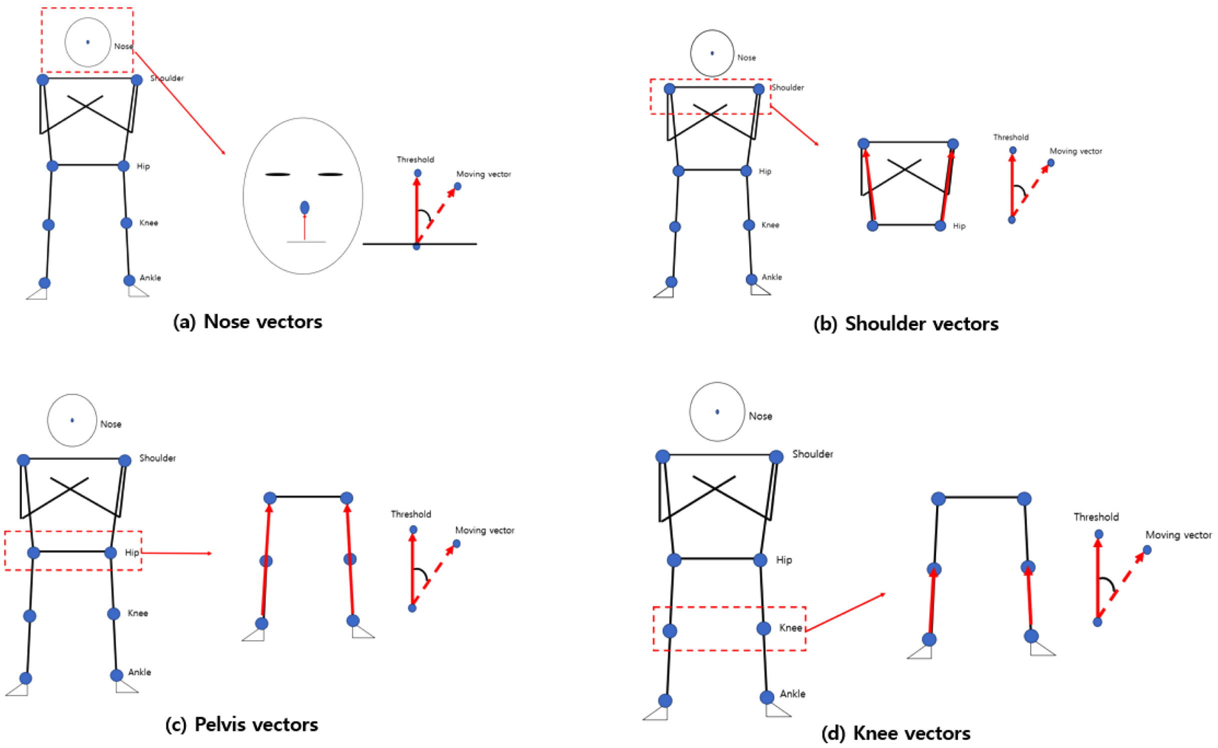

Fig. 1. (Color online) Vectors used for each element's analysis. (a) presents the vector configuration for calculating the angle of the nose. (b) presents the vector configuration for calculating the angle of each shoulder. (c) presents the vector configuration for calculating the angle of the pelvis. (d) presents the vector configuration for calculating the angle of each knee.

vector because participants have typically been observed to remain motionless for at least 10 frames. To calculate nose movement, the midpoint between the two points representing the corners of the mouth was used, as no other points were directly connected to the nose. For the shoulders, we considered the vector connecting the shoulder and hip joints. The pelvic angle was based on the vector linking the pelvis and ankle joint, whereas for the knees, the vector connecting the knee and ankle was utilized (Fig. 1).

2.3.2. Calculation of Variance for the Angles of the Four Elements

To calculate the extent of each participant's movement during the task, we used Eq. (1) to compute the variance from the total angles during the task. Variance was employed to determine each participant's degree of movement, calculated as the average of the squared deviations. In Eq. (1), "x_i" represents the measurement of the i-th individual, while "$\bar{x}$" signifies the mean value of the group. The symbol "n" represents the number of individuals in the group. A higher variance value indicated irregular alterations in the angles, allowing us to determine the extent to which the participant's body swayed. The mean of the extracted angles for each joint was computed, and the difference between the mean and moved angle value was used in the calculation.

$$\text{Variance} = \sum \frac{(x_i - \bar{x})^2}{n} \quad (1)$$

3. Results

3.1. Comparison of Angle Measurements for the Four Elements Between the Normal and Control Groups

Comparison of the four elements—nose, shoulders, pelvis, and knees—between the normal and control groups revealed that normal participants exhibited relatively minor angle variations compared with control participants. Control participants displayed more erratic angle fluctuations, while normal participants maintained angles within the 0-2° range. Fig. 2(a) illustrates the nose angles of normal participants, while Fig. 2(b) presents those of control participants. Fig. 3(a), (b) depicts the shoulder angles of the normal and control groups, while Fig. 4(a), (b) displays their pelvic angles. Fig. 5(a), (b) presents the knee angles of the normal and control groups.

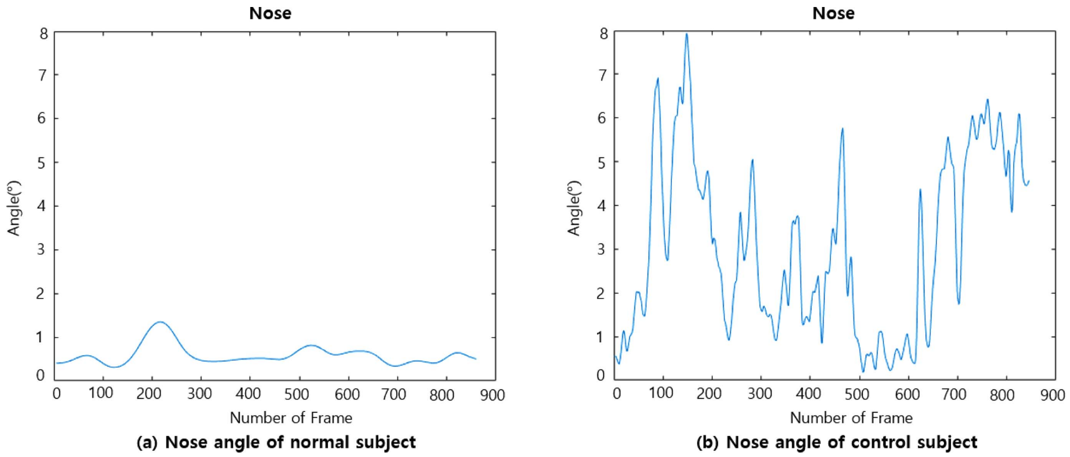

Fig. 2. (Color online) Nose angles of normal and control participants. (a) presents the nose angles of normal participants, while (b) displays the nose angles of control participants.

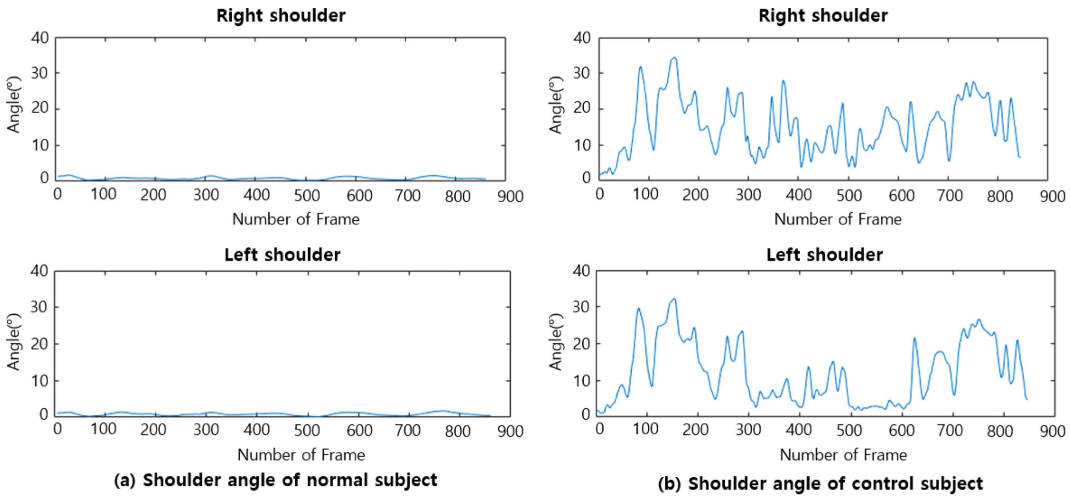

Fig. 3. (Color online) Shoulder angles of normal and control participants. (a) illustrates the shoulder angles of normal participants, while (b) depicts the shoulder angles of control participants. The top graphs present the right shoulder angles, while the bottom graphs present the left shoulder angles.

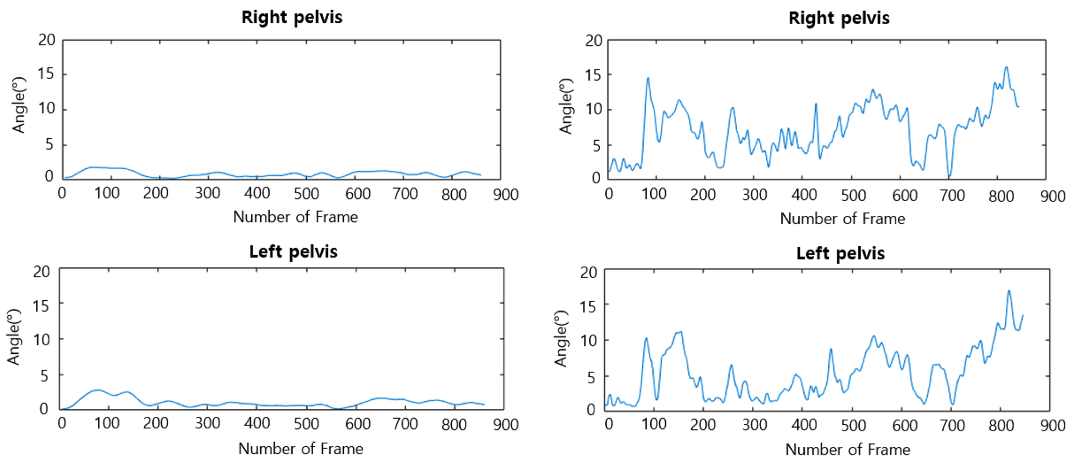

Fig. 4. (Color online) Pelvic angles of normal and control participants. (a) displays the pelvic angles of normal participants, whereas (b) presents the pelvic angles of control participants. The top graphs present the right pelvic angles, while the bottom graphs present the left pelvic angles.

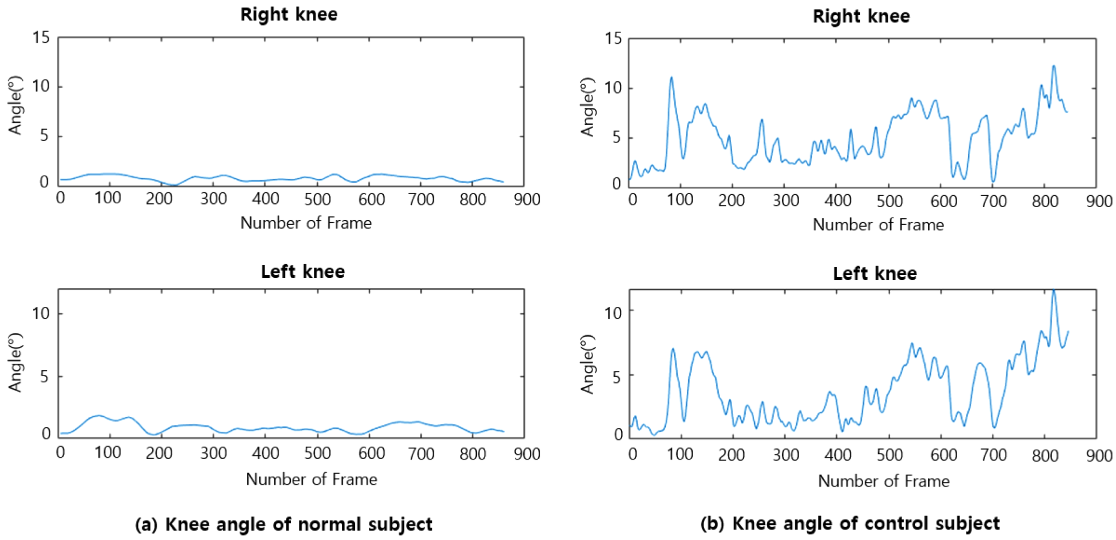

Fig. 5. (Color online) Knee angles of normal and control participants. (a) shows the knee angles of normal participants, while (b) illustrates the knee angles of control participants. The top graphs present the right knee angles, while the bottom graphs present the left knee angles.

3.2. Comparison of the Variance of the Angles Obtained for the Four Elements Between the Normal and Control Groups

The calculated variances for each participant revealed that normal participants did not exceed a variance value of 1, while among the control participants, some exhibited variance values > 100. Furthermore, normal participants exhibited relatively minor variations with variance values consistently at or < 1 for all elements. In contrast, significant discrepancies in the magnitude of the variance were noted among control participants. Table 1 summarizes the mean variances for the normal and control groups. To determine statistically significant differences between the two groups, we employed the Mann–Whitney U test. We compared the variances of the four elements between the control and experimental groups using the Mann–Whitney U test. Briefly, we calculated the mean of the variance values for each element across all participants in both groups. The comparison yielded p-values ≤ 0.001 for all elements, providing quantitative evidence of significant differences between the two groups.

4. Discussion

The cerebellum is one of the key organs responsible for regulating body movement. When the cerebellum is affected, motor dysfunction syndrome potentially develops, thus impairing the body's ability to maintain balance. This condition can be diagnosed via various tests, such as MRI and EMG. In addition to these methods, the Romberg test is available as a clinical tool for rapid assessment. In clinical practice, the Romberg test is primarily used to assess motor dysfunction based on proprioceptive and vestibular sensory systems. However, it is limited by its low diagnostic sensitivity emanating

Table 1. Comparison of Variance Values Between Normal and Control Participants.

	Normal Group Variance Mean (SD)	Control Group Variance Mean (SD)	Mann–Whitney U test
Nose	0.15 (0.10)	4.42 (4.58)	0.001*
Shoulder_R	0.50 (0.34)	34.18 (32.04)	0.000*
Shoulder_L	0.51 (0.41)	31.33 (29.75)	0.000*
Hip_R	0.26 (0.22)	33.96 (71.87)	0.000*
Hip_L	0.33 (0.22)	15.1 (8.85)	0.000*
Knee_R	0.38 (0.26)	14.29 (27.82)	0.000*
Knee_L	0.41 (0.25)	6.86 (4.95)	0.000*

SD: standard deviation, R: right, L: left from its reliance on visual assessment without quantitative metrics. To circumvent this limitation, studies have investigated various sensors and wearables; nonetheless, the methods they applied have proven challenging to implement in clinical settings. Therefore, this study aimed to provide quantitative metrics for the Romberg test using a webcam, thus enhancing its applicability in clinical environments.

The results of this study, which analyzed Romberg motions in normal and control participants using a webcam, revealed meaningful differences. Normal participants exhibited minimal nose, shoulder, pelvic, and knee movements, whereas control participants displayed irregular and variable movements. On comparing variance as an indicator of the extent of movement, normal participants had an average value of 0.36, while control participants had an average of approximately 20. Notably, in the shoulders, which exhibited the most movement, normal and control participants had variance values of 0.5 and 34.18, respectively, indicating a significant difference between the two groups. Furthermore, the Mann–Whitney U test, which analyzed all elements, provided quantitative evidence of significant differences between the two groups. In a previous study utilizing pressure plates to quantitatively evaluate the Romberg test, significant differences were reported between normal and control participants [8]. Noteworthily, this study's results are consistent with those of previous studies.

Furthermore, in this study, we were able to quantitatively confirm a clear distinction between negative and positive cases using webcam-based Romberg test analysis. However, this study has certain limitations. The first regards the depth calculation. This study focused on quantitatively measuring body tremors using a webcam. While the Romberg test primarily assesses the extent of body sway, utilizing a single webcam limits the accurate determination of movement depth when the body sways forward or backward. However, this limitation can be overcome by using multiple webcams. Additionally, it is crucial for the entire body to be visible on the webcam, as partial visibility potentially disrupts body coordinates, rendering precise analysis challenging. The second limitation lies in the recruitment of participants. This study encountered challenges in recruiting control participants; hence, we had to improvise with videos of symptomatic patients for our analysis. Despite the inherent instability of human model implementation owing to the use of recorded videos, we were able to confidently distinguish negative from positive cases. Moreover, analysis using a webcam requires separate installation space. While some patients may exhibit resistance or hesitation because of the examination being conducted via a machine rather than a therapist, the advantage lies in deriving quantitative metrics from areas that have previously been challenging to subjectively assess. These quantitative metrics enable the calculation of average values based on specific individual characteristics. Consequently, generalizations based on these averages potentially pave the way for healthcare applications.

If applied in a clinical setting, this study's approach could yield average values when conducting the Romberg test on both normal participants and patients. These average values could subsequently be useful in healthcare applications. For instance, if the Romberg test score for a young adult is 20, while that for a patient or older individual is 50, then a young adult with a score approximating 30 potentially requires healthcare. In addition, since the Romberg test exhibits low sensitivity in diagnosis, determining the severity of a patient's condition is challenging. Therapists need to continually monitor the patient's movements, leading to potential fatigue. However, installing a webcam on one side of the hospital wall and having the patient perform the Romberg test in front of it may help classify the severity of the patient's condition using quantitative values. This approach also enables therapists to diagnose patients with relatively low fatigue levels.

5. Conclusion

This study developed a technique that quantitatively evaluates the Romberg test, comparing dispersion values for each joint between the control and normal groups. The findings demonstrate that this technique can quantitatively verify differences between these two groups. We believe that if implemented in clinical practice, this technology may establish itself as an assistive tool for occupational therapists.

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