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Method for Evaluating Motor Synchronization and Short-Term Motor Memory Based on Forearm Synchronization Process to Sinusoidal Motion Visual Stimulus

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Abstract: Neurological problems can manifest in body movements. Pronation and supination of the forearms are used to evaluate the performance of diadochokinesis. Diagnosis in the clinic is subjective and nonquantitative. Introducing a sinusoidal visual stimulus, a novel measuring and evaluating method for human motor control function in a motor synchronization process has been proposed. The Non-Smoothness Measure (NSM) and movement speed measure (P3r) are confirmed in this study as promising evaluation parameters based on experiments on age groups.

Keywords: pronation and supination, sinusoidal visual stimulus, motor synchronization, short-term motor memory, quantitative evaluation

1. Introduction

This study proposes a method for evaluating human motor control function by observing the synchronization process to others' movements. For evaluating the synchronization, the movement process must be measured and analyzed.

Dysdiadochokinesia is found in patients with disorders of motor control systems in the central nervous system. For evaluating the performance of diadochokinesis, pronation and supination of the forearm is well used in clinical diagnosis. In addition, finger tapping is used. Speech fluency is another parameter representing the performance of diadochokinesis [1], [2].

In the Unified Parkinson's Disease Rating Scale (UPDRS), the performance of pronation and supination is subjectively evaluated by a doctor on a 5-point scale [3], [4]. The finger tapping test is evaluated based on the number of taps. In the UPDRS, the number of taps in 5 seconds is used for evaluating diadochokinesis performance. In speech diadochokinesis, the number of syllables in a second is used [2]. However, no objective method exists for evaluating the movement process in the UPDRS.

We can not only imitate other's movements, but also synchronize them with each other as in a group dance. This synchronization is realized based on the integration of various aspects of our motor control function. To synchronize our movements with each other's, we should remember the movements by observing others' movements, generate the movements based on the memorized movements, evaluate the difference between the two, and compensate for the differences with proper feedback and feed forward. The differences include differences in timing and differences in the movements.

Based on a proper stimulus, the evaluation of the response is easy, and the evaluated results are easy to understand. Tapping tests are viewed as a step response observation method in the communication field. This observation has enough precision in the time domain. However, this method only measures two states: "on" and "off" of a switch. There are no analogous measurements.

By observing gesture reactions, our body works as a strong low-pass filter. In the environment, step and impulse response observations can used to observe the response of a body. However, meticulously observing the response of motor control function is difficult. Therefore, we must select other signal as the stimulus.

The authors have proposed a visual stimulus and hand gesture reaction task which measures the performance of human motor control function using pure sinusoidal pronation and supination images of the forearm as the input signal (stimulus). The participants' forearm movements synchronizing to the stimulus are the output signal (response).

This study proposes a novel method for measuring and evaluating a subject's ability to synchronize their movements to others' movements of human motor control function based on not only the timing, but also the movement

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Fig. 1 Stimulus hands images

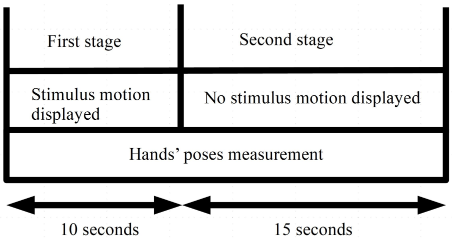

Fig. 2 Structure of proposed task

processes using a visual stimulus of sinusoidal pronation and supination. The proposed method generates objective generalized measures based on the signal processing model.

In the following section, this study introduces the outline of the motor control function measuring method after which the measuring and evaluating methods for motor control function are discussed. Next, the evaluation parameters representing the synchronization of the movements and short-term memory of the movement are discussed. Finally, we provide our conclusions.

2. Measuring and Evaluating Methods for Motor Control Function

2.1 Outline of the measuring method for motor control function

The trial of the motor control function measuring method consisted of a visual stimulus and hand motor reaction task, which evaluated the hand motion processes based on the visual stimulus. The participants were instructed to move their hands according to the images of periodic pronation and supination of the hands displayed (**Fig. 1**) and to continue their movements even after the displayed stimulus image was removed. In an entire trial, the pronation and supination movements of the participants' hands were measured. It was a type of visual synchronization task as required vision, motion recognition, short-term motor memory, and motion generation. After the removal of the stimulus image, the blocks in the dashed box does not work. Two stages were generated in the visual synchronization task to measure the detailed performance of motor control function. **Fig. 2** shows the outline of the proposed task.

The stimulus image is a strong basis of motion generation. After the removal of the stimulus image, only the remembered motion in the motor memory becomes the basis for motion generation. In the stage where the stimulus image is shown, the entire motor control function is evaluated. The remembered motion is updated at each cycle of pronation and supination of the stimulus image. In the first stage, an extremely short-term motor memory (approximately 1 second) affects the whole performance. This short-term motor memory is a part of motor recognition. In the second stage where the stimulus image is removed, the remembered movement from the stimulus image decays over time. The whole performance is affected by the decay of the memorized movement. The difference between the first and second stages represents the performance of short-term motor memory approximately five or more seconds.

2.2 Stimulus movement

The periodic pronation and supination of the hands were purely controlled sinusoidally on their rotation angles for ease of analysis and evaluation of motor control function.

Because a stimulus is purely controlled sinusoidally, in the measured rotation of the hands of the participants, the components of the stimulus signal and other noises are well defined. We can easily distinguish the signal component from other noise components in the measured rotations of the participant's hands.

A synchronization of periodic movements is more difficult than simple movement imitation. To generate synchronized movements, the periodic motion to be synchronized has to be observed and remembered. The generated movements have to be similar to the stimulus motion based on the memorized movements. Additionally, it has to be ensured that the generated motion synchronizes with the stimulus motion, estimate the divergence between the generated motion and the stimulus motion, and correct the generated motion based on the stimulus motion. The speed of motion synchronization has to be controlled. These functions make the feedback loop. However, to compensate for the brain's processing delay, the delay itself has to be estimated to make proper corrections.

2.3 Task structure

The motor control function measuring method has two stages (Fig. 2). In the first stage, the participant sees, and remembers the displayed stimulus motion and generates a motion that synchronizes with the stimulus motion. In the second stage, the displayed stimulus motion is removed. The participant continues to move their hands based on the mental image of the stimulus movement. The mental image is an expression of motor memory. Through a task, the poses and positions of the participant's hands and the displayed motion can be measured and recorded.

In the first stage, a feedback loop connects the participant's movement and the stimulus movement. In the second stage, the stimulus motion is removed. The participant makes the movement based only on a mental image of the stimulus movement shown in the first stage.

2.4 Task parameters

In the task, an image showing pronation and supination of the hands is set to take one second. In preliminary experiments, healthy participants in their 20s reported that one pair of pronation and supination shown in $\leq 2/3$ second is too fast.

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Healthy participants needs approximately three cycles of pronation and supination to synchronize their movements with the stimulus movement. Therefore, the length of the task should be more than three cycles. To evaluate the performance of motor control function using a stimulus, the length of the first stage was set to be 10 cycles. Therefore, the duration of the first stage was ten seconds.

To evaluate changes in the performance of motor control function after the disappearance of the stimulus image, the length of the second stage was set to be 15 seconds. As a result, the total length of the trial was 25 seconds. Using a longer task helped generate precise results. The participants reported that a task lasting 25 seconds only is long.

The measuring system was set to measure the participants' hand movements in 25 seconds before and after the disappearance of the stimulus images.

2.5 Experimental setup

2.5.1 Visual stimulus generation

Images showing slow pronation and supination of the model's hands were taken with pronation and supination observation without stimulus images. In each image, the pose of the hand was recorded. The number (N) of images used to generate the stimulus was decided. In this experiment, N was approximately 60. From the images, for each non-negative integer i of less than $N + 1$, the image where the recorded rotation angle best fit $PI \times \cos(PI \times i/N)$ was selected and numbered i. Each selected image was then connected with its mirror image. The connected images showed both hands where their poses were the same.

Using a personal computer, the best fit hand image was displayed for the decided amount of time. The length of a pair of pronation and supination was t seconds. When s seconds had passed since the stimulus started, r was defined as the fractional part of s/t. If r was less than or equal 0.5, the stimulus image numbered $int(2\times r\times N)$ was displayed. Otherwise, the stimulus image numbered $2N-int(2\times r\times N)$ was displayed. When the stimulus images were not displayed, a solid gray image instead of the stimulus images was displayed.

The aforementioned algorithm was implemented using Python and Pyglet, which worked in real-time. When t was one second, the displayed timing error of the stimulus image was less than $1/2/60 = 0.0083$ second. In other words, the frame rate to generate the stimulus images was larger than 120 frames per second. This frame rate was enough for our experiments.

A normal personal computer cannot refresh the displayed image as fast as 120 fps. However, the display rate of the stimulus images was fast enough for human participants.

2.5.2 Pronation and supination observation

Using the Leap Motion Controller, a motion sensor with the same personal computer that displayed the stimulus hand, the positions and poses of participants' hands were measured and recorded with time [5]. The sensor measured the positions and poses each 1/100 of a second. The number of measurements depended on the load situation of a computer.

The Leap Motion Controller measured the rotation angle with an error of five degree, which was an error rate of approximately 2% in 180 degree rotations. In the following data analysis, a group of 100 measurements was processed using the fast Fourier transformation (FFT) algorithm. The resulting low-frequency components kept four significant digits. This accuracy was sufficient for this study.

2.5.3 Experimental system

The experimental system used was constructed from the control front end, the visual stimulus generator and the hand pose-measuring system. The front end controller started the visual stimulus generator and the hand pose-measuring system and stopped them.

2.6 Basic evaluation

The measured hand poses were not acquired at equal intervals. From the start of the stimulus, hand poses at each 100th of a second were calculated with linear interpolation from before and after the time. The results were the sequence of hand poses at each 100th a second.

In total, 2500 pairs of hand poses were generated in the entire trial. At every second from the start of the stimulus, we generated 100 pairs of participants' hand poses.

At each second of participants' hand pose measurements, sequences of hand poses were processed using the FFT algorithm. From the FFT, we obtained a pair of power and phase of each frequency component. The frequency component ranged from 0 Hz to 50 Hz in 1 Hz increments in 100 measurements within a second. We generated 51 pairs of power and phase at each second in each hand.

A 0 Hz component represents the average pose of a hand. Therefore, 0 Hz components were omitted from our analysis. As a result, 50 components in a second were analyzed in each hand. This FFT results excluded movements slower than the stimulus movements.

To obtain information on movements slower than the stimulus movement, in each continuous three seconds of hand pose measurements, hand pose sequences were processed using the FFT. FFT results described frequencies ranging from 0 Hz to 50Hz in 1/3 Hz increments. Therefore, we had power and phase of 1/3 Hz and 2/3 Hz movements in components slower than the stimulus movement. These FFT results represented the movements slower than the stimulus movement.

2.7 Evaluation parameters at each stimulus cycle

The number of parameters in each second was $50 \times 2 \times 2$ for the stimulus movement component and those with higher frequencies than the stimulus movements. For analyzing slower movements, the number of parameters in every three seconds period was $150\times 2\times 2$. However, in higher frequency components, noise in the measurement process increased. Therefore, 26 Hz and higher components were excluded from our analysis. In the analysis of slower movements, only 1/3

Hz, 2/3 Hz, and 1 Hz components were used. As a result, for higher frequency movements analysis, $25 \times 2 \times 2$ values were used in each second. For the analysis of lower frequency movement, $3 \times 2 \times 2$ values were used. The total number of parameters was 1,276 in a trial. To evaluate the performance of a participant, 1,276 parameters were too large for easy understanding of motor control function. At each stimulus cycle, the ratio of the total power of faster movement components to the power of the stimulus movement component was computed to evaluate the non-smoothness of each participant's movements, also called Non-Smoothness Measure (NSM)(1).

$$NSM = \frac{P_2 + P_3 + P_4 + ... + P_{25}}{P_1} \quad (1)$$

In (1), NSM is the Non-Smoothness Measure. P_n represents the power of the n Hz component. The stimulus movement is controlled as a 1 Hz sinusoidal movement. Therefore, the FFT result of the stimulus movement had only 1 Hz components. Higher frequency components had no power. NSM represented the noises of each participant's movements relative to the stimulus movements.

The phase and power of the stimulus movement component were bases to evaluate each performance of the movements. The parameters describing each participant's movements at each stimulus cycle were the following:

- NSM
- Phase of the stimulus movement component
- Power of the stimulus movement component

In each continuous three seconds, the components with lower frequencies than the stimulus movement were useful parameters for evaluating the movement speed of each participant. The powers of 1/3 Hz, 2/3 Hz and 1 Hz components of the stimulus movement were used. These parameters were obtained from the movements in each continuous three seconds section. Therefore, these parameters were obtained at each second before the last two seconds of the entire measurement. At each second, we have NSM, phase, power, and three more parameter describing the status of slower movements. The 53 parameters were put together into six parameters fro each hand at each second. The total number of parameters in a second was reduced to 12 for both hands. However, approximately 300 parameters were obtained in an entire trial. This number of parameters was too large to treat directly. The parameters had to be reduced much more.

2.8 Evaluation periods

Twenty five cycles were too many for easy implementation. The entire trial was divided into four periods for easy evaluation.

The first period is the same term as the first stage. In the first period, a stimulus video was presented. The presented motion on a display was the strongest standard for generating motion.

Preparatory experiments showed that a participant needed three cycles to synchronize their movements to the stimulus movement. The three cycles (3 seconds) of hands pose measurements were excluded from our evaluation. The remaining seven seconds composed one group for evaluation.

The second stage was 15 seconds long. After the removal of the stimulus image, changes in the movement were important. Therefore, the second stage was divided into three continuous periods: the second, third, and fourth periods of an entire trial. Each group was comprised continuous five seconds of hand pose measurements. At the beginning of the second period, the stimulus image was removed. The continuous five seconds of each period corresponded to the timing of the five pairs of pronation and supination of the stimulus movement. In these periods, no stimulus image was displayed. Each participant performed their hand movements based on their motor memory. The second period started after the removal of the stimulus movements, followed by the third and fourth periods. In these periods, only the mental image of the stimulus movement was used as the basis for generating movements in each participant.

2.9 Evaluation parameters at each period

The first and second stages together comprised four periods. In each period, mean and other statistical parameters were obtained.

The three slower parameters were reduced into one parameter. The value describing the movement speed named $P3r$ (power of 3 cycles in ratio) was defined as (2). $P3r$ is the power of the stimulus in the three slower components in a ratio. $P3r$ was averaged in each period. Therefore, an average $P3r$ was the representative parameter of the slower movements.

$$P3r = \frac{P3_3}{P3_1 + P3_2 + P3_3} \quad (2)$$

In (2), $P3_n$ represents the power of the $n/3$ Hz component. When a participant followed the stimulus movement completely, no slower movements were generated. $P3_1$ and $P3_2$ were zero. Therefore, $P3r$ was 1.0.

The means alone were large enough. The number of means in a trial was $3 \times 2 \times 4 + 4 \times 2 = 32$. These means were analyzed in this study. The correlation between the movements of both hands was large enough. Therefore, only the movements of the right hand were used in this study.

2.10 Change ratio between periods

To evaluate motor memory, the change ratio between periods was defined as (3).

$$CR(a, b) = \frac{2(b - a)}{a + b} \quad (3)$$

In (3), a is a standard. b is a reference. With this change ratio, $CR(a, b) + CR(b, a) = 0$. This characteristic was important in statistical processing.

3. Experimental Method

The proposed method for measuring and evaluating human motor control function generated several evaluation pa-

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Table 1 Number of trials in age groups

Age range	#Participants	Trials	Mean Age
20-29	4	10	24.8
30-39	13	24	35.6
40-49	34	73	44.7
50-59	70	156	54.7
60-69	194	409	65.4
70-79	234	513	74.5
80-89	98	220	83.0
90-99	14	24	91.6
Total	661	1,429	68.8

rameters. These parameters evaluated many aspects of motor control function. The validity of these parameters was checked in the experiments.

Based on the assumption that the performance of motor control function declined with aging, the effectiveness of the proposed evaluation parameters was confirmed.

3.1 Participants

In this study, 1429 valid measurements were achieved after obtaining approval from the Ethical Council of Utsunomiya University during the period from March 2017 to May 2017 in an internal medicine clinic. The number of participants was 661. The average number of trials per participant was 2.16. The ages of the participants ranged from 21 years to 94 years. The mean age was 68.8 years.

All participants visited the hospital and were in good physical condition. Every participant had no subjective symptoms, including fever or cough. **Table 1** shows the distribution of the participants and trials.

3.2 Analysis method

A sufficient number of participants and trials had been obtained in the age group of 50 to 89 years. Participants aged 50–89 years were divided into four age groups: 50–59 years, 60–69 years, 70–79 years, and 80–89 years.

The age groups represented the normal changes due to aging. Therefore, motor control function of the age groups declines with aging.

Among the age groups and the evaluation periods, the mean NSM and P3r values were analyzed. To confirm the change between the age groups, the identity probability between distributions of two adjacent age groups was measured using the independent t-test.

4. Results and Discussions

4.1 Motor control function change with aging

4.1.1 Motor synchronization

NSM is the parameter describing the dissimilarity of the movement based on the stimulus movement. **Fig. 3** illustrates the changes in the mean NSM value with the period and aging. In Fig. 3, "Best" is the best trial. In every period, the mean NSM values increased as the age increased.

Table 2 shows the result of the independent t-test between adjacent age groups. The results of the independent t-test were significant when the probability was less than 0.05. In the table, significant values were emphasized. The

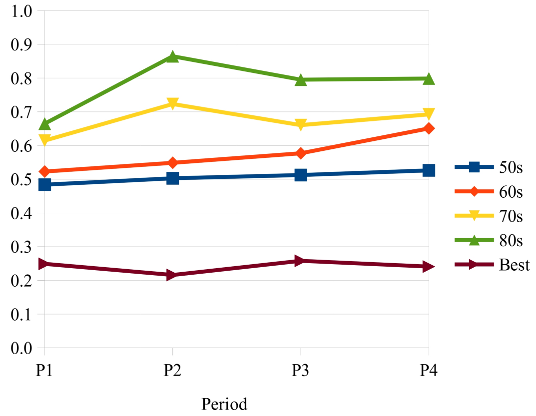

Fig. 3 NSM with aging and periods

Table 2 T-test identity probability of NSM between adjacent age group

	50s-60s	60s-70s	70s-80s
P1	0.2115	**0.0040**	0.3479
P2	0.1522	**0.0000**	**0.0168**
P3	**0.0255**	**0.0041**	**0.0038**
P4	**0.0040**	0.2738	**0.0275**

Table 3 T-test probabilities of P3r between adjacent age groups

Period	50s-60s	60s-70s	70s-80s
P1	0.359	**0.001**	**0.000**
P2	0.091	**0.000**	**0.000**
P3	**0.010**	0.066	**0.000**
P4	**0.011**	0.173	**0.000**

differences of the mean NSM values of the third and fourth periods were significant between the ages of 50s and 60s. The differences of the period 1, 2 and 3 are significant between the ages of 60s and 70s. The differences of the period 2, 3 and 4 are significant between the ages of 70s and 80s. In every evaluation period, the mean change in NSM with aging was confirmed.

4.1.2 Motor speed

P3r is the parameter that described the similarity of the movement speed relative to the stimulus movement. **Fig. 4** shows the changes in P3r among the periods and age groups.

Among all periods, P3r is the highest in the 50s age group, and decreases in the 60s, 70s, and 80s age groups. This reflects the deterioration of the ability to follow the stimulus movement speed with aging.

In all age groups, P3r is the highest in the first period with the stimulus movement, and decreases in the second, third and fourth periods. This reflects the decay of the short-term motor memory. This is discussed using the change ratio between adjacent periods in the following section.

Table 3 shows the result of the independent t-test between adjacent age groups regarding P3r changes. No differences were observed between the ages of 50s and 60s in the first and second periods. In the third and fourth periods, differences between the ages of 60s and 70s was confirmed in the first and second periods. In the third and fourth periods, no differences were found. This may represents that movements based on a motor memory over five seconds period show deterioration compared with the performance of

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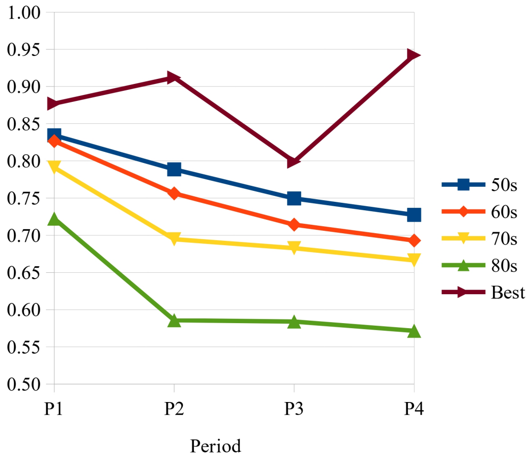

Fig. 4 P3r changes with aging

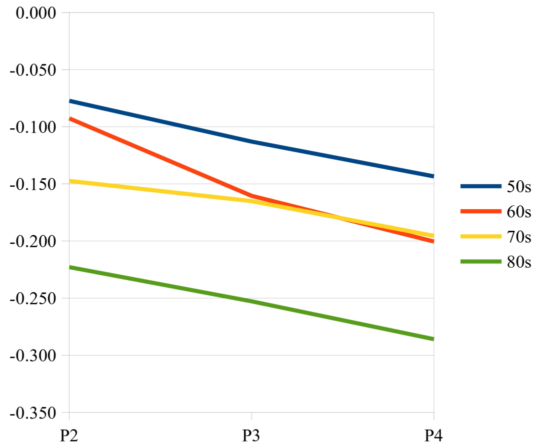

Fig. 5 P3r changes from Period1 to PeriodN

Table 4 T-test probabilities of P3r change from Period1 to PeriodN

	50-60	60-70	70-80
$CR(P1, P2)$	0.411	**0.001**	**0.001**
$CR(P1, P3)$	**0.026**	0.791	**0.000**
$CR(P1, P4)$	0.034	0.810	**0.001**

shorter motor memory and motor recognition in younger ages.

The NSM and P3r describe the deterioration of the motor control function with aging. Therefore, these parameters represented aspects of the performance of human motor control function. Many other parameters may describe various aspects of motor control function.

4.2 Motor memory

In the first period, the stimulus movement was memorized. In the second, third and fourth periods, a participant generated their movement based on the memorized stimulus movement. The changes from the first period to the Nth period represented the performance of motor memory.

Fig. 5 describes the ratio of change of P3r from the first period to the Nth period between adjacent age groups. **Table 4** shows the result of the independent t-test between adjacent age groups.

The change ratios of P3r from the first period to the second and the third period decreased as the age increased. However, the change between the ages of 50s and 60s was insignificant. The changes among the ages of 60s, 70s and 80s years were significant. In participants over 69 years old, the decay of motor speed memory under five seconds period was obvious in the P3r change ratio. Participants under 70 years old showed no obvious decay of motor speed memory under five seconds period. The change ratio from the first period to the third period is significant between the ages of 50s and the 60s. Participants under 70 years old showed a clear decay of motor speed memory after five seconds or more.

5. Conclusion

This study proposes a method for measuring and evaluating the performance of human motor control functions by observing the process of synchronizing a participant's movement to sinusoidal stimulus pronation and supination. The proposed measuring method needs only the hand movement and is completed in 25 seconds. Therefore, the proposed measuring method is safe, simple, and easy to complete. Several parameters for evaluating the motor control function are produced from the measured participant's movement based on the sinusoidal stimulus movement.

The proposed NSM represents the level of motor movement synchronization, and reflects the decline of motor control function as age increases. The proposed P3r represents the level of motor timing synchronization.

The change ratio from the first evaluation period to other evaluation periods represents the motor memory decay in a 5 seconds period. This short-term motor memory decay has not yet been measured and evaluated.

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References

[1] Montana, D., Campos-Roca, Y., Perez, C. J.: A Diadochokinesis-based expert system considering articulatory features of plosive consonants for early detection of Parkinson's disease, Computer Methods and Programs in Biomedicine, Vol.154, 2018, pp.89–97. (2018)

[2] Icht, M., Ben-David, B. M.: Oral-diadochokinesis rates across languages: English and Hebrew norms, Journal of Communication Disorders, Vol.48, pp.27–37. (2014)

[3] Fahn, S. et al: Unified Parkinson's Disease Rating Scale. In Recent Developments in Parkinson's Disease.Volume II. Fahn, S. et al (eds), Florham Park, Macmillan Healthcare Information pp.153–163. (1987).

[4] Goetz, C. G., et al: Movement Disorder Society-sponsored revision of the Unified Parkinson's Disease Rating Scale (MDS-UPDRS): Scale presentation and clinimetric testing results, Movement Disorders, Vol. 23, No. 15, pp.2129–2170. (2008)

[5] https://developer.leapmotion.com/documentation retrieved at 20210117.