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Original Article

Relationship between correcting error and smoothness of movement in the process of motor learning

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Abstract. [Purpose] Improvement in the smoothness of movement is a motor learning outcome. This study sought to clarify the relationship between motor skills and smoothness of movement in motor learning. [Participants and Methods] We subjected 12 healthy adults to a task in which they had to learn the sensation of a load while standing up and sitting down. We attached triaxial accelerometers to the seventh cervical spine and the third lumbar spinous process of the participants prior to measurement. We took the measurements over two successive days and used absolute error and variable error as indicators of motor learning outcomes. In addition, we used entropy, calculated from the results of the power spectrum analysis of acceleration changes, as an indicator of the smoothness of the movement. [Results] In the test sessions, absolute and variable errors showed a significant reduction. Entropy also showed a similarly significant decrease, although the change in errors and entropy showed different transitions. [Conclusion] Qualitative indicators of motor learning captured an aspect of motor learning that one cannot capture by quantitative indicators. In the future, qualitative indicators will be necessary to judge the outcomes of motor learning.
Key words: Entropy, Motor learning, Smoothness

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INTRODUCTION

The concept of motor learning is very important in physical therapy. Motor learning is the process by which a patient attempts to reacquire activities of daily living through movement practice, or the process by which a physical therapist assists the patient to acquire activities of daily living efficiently through movement instruction for the patient. In the 1970s, Carr and Shepherd et al. reported a psychological theory of motor skill acquisition and efficient practice methods as the Motor Relearning Program, and this motor learning theory has been applied in physical therapy[1–3)]. In 1990, the Special Therapeutic Exercise Project (IISTEP) was presented at a conference in the United States as a theory of therapeutic exercise for central nervous system diseases[4)]. Consequently, a paradigm shift occurred in the theoretical system of central nervous system function, and physical therapy based on systems theory and motor learning theory is being discussed, and motor learning research in physical therapy has flourished in recent years[5)].

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Various factors have already been examined as influences on motor learning. The method of providing feedback (FB), including the frequency and timing of FB[6], the arrangement of tasks, such as block design and random design[7], attentional focus[8], and optimal task difficulty[9] affect the efficient learning of the task.

Physical therapists must generate practice plans according to the progress of motor learning, which should include the method of providing FB and the placement of tasks, so that patients can efficiently reacquire activities of daily living. Therefore, it is necessary to assess the patient's ability to perform the movement appropriately.

Previous evaluations of motor learning have been based on quantitative aspects of the process, such as the number of errors and the error range. However, progress in motor skills needs to be evaluated not only quantitatively, but also qualitatively, such as by gauging the smoothness of movements. It has been reported that improvement in the smoothness of movements reflects motor learning characteristics[10]. In physical therapy, motion analysis by visual inspection is often used to assess the quality of movement. However, Keenan et al. have reported that the results of visual inspection of motion analysis are subjective assessments by the physical therapist and unreliable[11]. Therefore, it is necessary to use large-scale devices, such as three-dimensional motion analysis to evaluate the quality of movement objectively. In a previous study, the use of Jerk Cost[12, 13] and the Jerk Index[14] was reported as a method for evaluating the smoothness of movement using a three-dimensional motion analysis system. Jerk shows the time rate of change in acceleration, while Jerk Cost is the sum of the squares of the Jerk, and the Jerk Index is the Jerk Cost corrected by the movement time and distance. However, these indicators are difficult to apply in physical therapy due to time and environmental constraints. Accordingly, it has been reported that accelerometers can be used to measure the smoothness of a movement[15–17]. Triaxial accelerometers are small and inexpensive and allow easy measurement without any limitation of the measurement environment. Kojima et al. proposed a method for evaluating the smoothness of movement by assessing entropy, based on the spectrum changes of the acceleration time-series during movements[18]. Entropy is a measure that estimates the amount of information and is a fundamental concept in the theory of information and communication proposed by Shannon[19, 20]. If a normalized probability curve is expressed in terms of entropy, the entropy value increases with the extent of equivalence in the occurrence probability of each event. If many high-frequency components are involved in the fine adjustment of movements, the entropy would be large, indicating movements with low smoothness.

In addition, it has been reported that improvement in the smoothness of movements indicate that the learner's effort had decreased[21–23]. Accordingly, it has been suggested that improvement of motor skills is accompanied by an increase in movement smoothness. In previous studies, National Aeronautics and Space Administration-Task Load Index (NASA-TLX) has been used as a method for evaluating the level of effort of learners. The NASA-TLX is an indicator of mental workload and is a scale comprised of six items: mental demand, physical demand, time pressure, performance, effort, and frustration[24].

However, it is not clear how the qualitative aspects of movement (e.g., smoothness) relate to changes in the quantitative aspects of movement (e.g., error). The purpose of this study was to investigate the relationship between correcting movement error during motor tasks and changes in the smoothness of movement. In addition, NASA-TLX was used to examine the participants' efforts on the learning task. The results of this study will help us to judge motor learning outcomes by clarifying the relationship between quantitative and qualitative aspects of motor learning.

PARTICIPANTS AND METHODS

Twelve healthy adults (age 22.1 ± 1.4 years, weight 59.4 ± 14.3 kg) with no history of neurological or orthopedic diseases were included. Participants had to have no previous experience with the task used in this study. The participants were informed about the contents of the study and the handling of the results, and their written consent for participation was obtained. This study was approved by the Ethics Committee of Ibaraki Prefectural University of Health Sciences (approval number: 896).

The load data from a force plate (Kistler Instruments AG, Winterthur, Switzerland) were transmitted to the floor reaction-force measurement computer through a charge amplifier for the force plate and recorded using BioWare ver. 3.27 (Kistler Instruments AG). The sampling frequency was set to 60 Hz.

Acceleration data were recorded using a Trigno Wireless system device (Trigno Lab, Delsys, Inc., Natick, MA, USA). The external dimensions were 37.0 mm (width) × 26.0 mm (depth) × 15.0 mm (height), and the weight was 14 g. The Trigno Wireless system used in this study has a piezoelectric acceleration sensor and can measure the vertical component (X-axis), the left–right component (Y-axis), and the front–back component (Z-axis) in three axes. The measurement range was set to ± 1.5 G and the sampling frequency was set to 148 Hz.

In this study, we performed a sensation of load learning task during a standing up and sitting down movement. In the starting position, participants sat in a 40-cm-high chair on a force plate, with the left foot on the 5-cm blocks and the right foot on the force plate (Fig. 1). Participants were instructed to perform the standing up and sitting down movement four times consecutively constituting one series. One series of the movement was performed for 5 seconds, in time with a metronome (60 bpm). During the movement, the participants were asked to keep the load on both feet even. There was a 5 second interval between each series of movements. Participants were required to learn the sensation of equal load during the standing up and sitting down movement in an asymmetrical posture. In this study, the target load was defined as 50% of each participant's body weight.

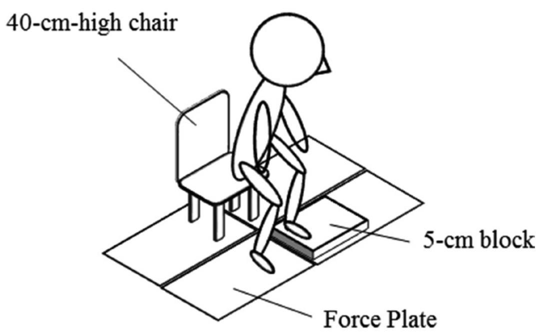

Fig. 1. Measurement environment.
The participant performed standing-up and sitting-down movements with the right foot on the force plate, weighted to 50% of the participant's body weight. The floor reaction force meter of the right foot was used to measure the amount of load weight and the floor reaction force meter of the hip was used to determine the start and end of the load on the right foot.

Accelerometers were attached to the participants before the measurement started. Based on a previous study, acceleration sensors was attached to the skin overlying the seventh cervical spinous process (C7) and the third lumbar spinous process (L3), and were fixed with tape and a belt so that the attachment position did not change during task implementation[25–27].

The measurement was performed over 2 days: Pre-test, practice sessions, and a short-term retention test (Post 1) were performed on the first day, and a long-term retention test (Post 2) and practice session were performed on the second day. The pre-test and retention test included five trials each. The first day's practice sessions included 25 trials, and the second day's practice sessions included 15 trials, and each of the aforementioned tasks were conducted. The practice attempt began 3 minutes after the pre-test ended. For practice sessions, five trials were considered as one block, and 3 minutes of rest was given between blocks.

FB was given after the end of the first and fourth trials of each block. As FB, the load on the right foot was displayed on the monitor after completion of the trial, so that the error between the target load and the measurement result could be visually confirmed. In this study, the short-term retention test was conducted 5 minutes after the end of the practice trial and the long-term retention test was conducted 24 hours later. NASA-TLX was measured after the practice trials on days 1 and 2. It is measured on a line segment, where the right end of each line segment is 0 and the left end is 100. The position marked on the line segment is read as a number between 0 and 100, constituting the score for each item. In this study, NASA-TLX was determined after the practice trials on days 1 and 2.

In this study, the floor reaction force obtained from force plate at each sampling frequency was divided by the gravitational acceleration to determine the load. The indices for evaluating motor learning were the deviation between the target load weight (target load weight; LWt) and the actually obtained load weight (load weight results; LWr) per trial multiplied by the absolute value and divided by the number of samples (absolute error), and the standard deviation (variable error) of the deviation between the target load weight and the actually obtained load weight divided by the number of samples (Equations 1 and 2, respectively):

$$\text{Absolute Error (AE)}=\frac{1}{N}\Sigma\left|LWt-LWr\right| \quad (1)$$

$$\text{Variable Error (VE)}=\sqrt{\frac{1}{N}\Sigma(\overline{LWt}-LWr)^2} \quad (2)$$

The analysis sections were the second and third of the four consecutive standing and sitting movements, and the interval from the point where the floor reaction force from the chair was zero when the participant started the standing movement to the point where the reaction force from the chair occurred during the sitting movement was analyzed.

After the acceleration data were transmitted from the accelerometer to the measurement computer, the data from the start of the second standing up movement to the end of the third sitting down movement was extracted using Delsys Analysis (Delsys, Inc). This analysis software was built into the measurement computer. After the data were confirmed by the investigator, the interval between the end of the second sitting down movement and the start of the third standing up movement in the extracted data was removed using the software. The data were further extracted by moving averages and then power spectrum analysis in Delsys Analysis. The entropy of C7 and L3 in each direction (back and forth, right and left, and up and down) was then calculated by the following equation (Equation 3):

$$H=-\textstyle\sum_i(P_i\times\log_2 P_i) \quad (3)$$

where H is entropy, and P_i is the i-th element of the spectrum.

NASA-TLX calculated the scores for each item on days 1 and 2. In order to confirm the motor learning effects of the loads in the test and practice sessions, and to ascertain the effects of practice, the dependent variables were set as the absolute and variable errors and were compared by repeated-measures one-way analysis of variance for each dependent variable. The items with a main effect were subjected to multiple comparisons by Dunnett's method for each measurement period as a subtest. In order to confirm the smoothness of the movement during standing up and sitting down in the test and practice sessions, the entropy in each of three directions (X, Y, and Z axes) of C7 and L3 was set as the dependent variable, and each dependent variable was compared by repeated-measures one-way analysis of variance. The items with a main effect were subjected to multiple comparisons using the Dunnet method for each measurement period as a subtest. The items of NASA-TLX were compared between days 1 and 2, using a paired t-test, to determine if the task difficulty on the practice trials had changed between days 1 and 2.

Statistical analyses were performed using SPSS ver. 24 software (IBM Corp., Armonk, NY, USA), and the significance level was set at 5%.

RESULTS

Table 1 shows the results of the absolute error of loadings and variable loadings in test sessions. The results of the absolute error of the loadings shows repeated-measures one-way analysis of variance revealed a significant main effect ($F_{2, 6.629}$=14.044, p<0.001, η_p^2=0.561). Consequently, multiple comparisons were made using Dunnett's post hoc test, which revealed a significant difference between the pre-test, short-term retention test, and long-term retention test (all p<0.001). The results of the variable error of the loadings shows repeated-measures one-way analysis of variance revealed a significant main effect ($F_{2, 1.565}$=19.545, p<0.001, η_p^2=0.640). Multiple comparisons with Dunnett's method as a post hoc test revealed a significant difference between the pre-test, short-term retention test, and long-term retention test (all p<0.001).

The change in entropy is shown in Table 2. Repeated-measures one-way analysis of variance revealed a significant main effect on L3-X ($F_{2, 0.190}$=3.603, p<0.05, η_p^2=0.247). Because a significant main effect was found, multiple comparisons were made using Dunnett's method as post hoc test. The results showed a significant difference between the pre-test and long-term retention test (p<0.05). Repeated-measures one-way analysis of variance showed no significant main effects for other factors.

The results of the absolute error and variable error of loadings in practice session are shown in Table 3. The results of the absolute error of the loadings shows repeated-measures one-way analysis revealed a significant main effect ($F_{7, 0.836}$=2.816, p<0.05, η_p^2=0.204). Because a significant main effect was found, multiple comparisons were made using Dunnett's method as post-hoc test. There were significant differences between block 1 and blocks 5, 6, 7, and 8 (all p<0.05). The results of the variable error of loadings shows repeated-measures one-way analysis of variance revealed a significant main effect ($F_{3.081, 1.171}$=4.462, p<0.05, η_p^2=0.289). As a significant main effect was found, Dunnett's post hoc test for multiple comparisons was performed, and showed significant differences between block 1 and blocks 5, 6, 7, and 8 (all p<0.05).

The changes in entropy is shown in Table 4. Repeated-measures one-way analysis of variance for all items showed no significant main effect.

The NASA-TLX results are shown in Table 5. The results of the paired *t*-test showed that effort declined significantly between days 1 and 2 (p<0.05). There were no significant differences in the other items.

DISCUSSION

This study investigated the relationship between qualitative and quantitative aspects of movement. We found that the qualitative indicators of motor learning captured an aspect of motor learning that could not be captured by quantitative indicators, suggesting that qualitative indicators should also be considered when judging the outcomes of motor learning, such as during physical therapy.

The task used in this study was estimated to be more challenging due to the different heights of the lower limb from the ground between the normal standing and sitting position. However, the NASA-TLX scores in this study were 33 points on day 1 and 34 points on day 2. Akizuki et al. reported that the optimal task difficulty for making motor learning more efficient is 51.5 points on the task achievement item[28]. Therefore, this task was considered to be a relatively low-difficulty task. In this study, there was a significant reduction in absolute and variable error in the test session. One of the factors that reduced the errors in loading was the fact that the participants were given appropriate FB. In this study, visual FB was used, at a frequency of 40% FB, after the end of the trial. For simple tasks, giving visual FB after the end of the trial has been reported to improve its effectiveness[6]. In terms of the frequency of giving FB, based on the guidance hypothesis, it is possible that giving FB at a lower frequency participants may have reduced their dependence on FB[29]. Hence, the absolute and variable errors may have been reduced. There was no reduction in error in the practice session between days 1 and 2. Both absolute and variable error results showed a decrease in error on day 1 in practice blocks 1 to 4, but no decrease in error for block 5 and for day 2 practice blocks. The fact that the reduction in the difference was as close to zero as possible, suggested that a floor effect in performance had occurred.

However, the NASA-TLX results showed a significant decrease in effort on days 1 and 2. Effort reflects the aspect of the

Table 1. Results of the absolute error (AE) and variable error (VE) in the test sessions

	Pre	Post 1	Post 2
AE (kgf)	3.19 ± 0.77	2.01 ± 0.35**	2.01 ± 0.61**
VE (kgf)	2.61 ± 0.43	1.87 ± 0.34**	1.88 ± 0.42**

Mean ± SD. **p<0.001.

Table 2. Results of entropy in the test sessions

	Pre	Post 1	Post 2
C7-X (bit)	2.74 ± 0.14	2.72 ± 0.16	2.62 ± 0.26
C7-Y (bit)	3.38 ± 0.24	3.11 ± 0.50	3.21 ± 0.64
C7-Z (bit)	2.93 ± 0.21	2.74 ± 0.42	2.64 ± 0.42
L3-X (bit)	2.78 ± 0.18	2.65 ± 0.36	2.52 ± 0.36*
L3-Y (bit)	3.24 ± 0.26	3.14 ± 0.28	3.06 ± 0.35
L3-Z (bit)	2.71 ± 0.15	2.73 ± 0.15	2.63 ± 0.14

Mean ± SD. *p<0.05.

Table 3. Results of the absolute error (AE) and variable error (VE) in the practice session

	Block 1	Block 2	Block 3	Block 4	Block 5*	Block 6*	Block 7*	Block 8*
AE (kgf)	2.89 ± 0.42	2.33 ± 0.38	2.67 ± 0.94	2.40 ± 0.71	2.16 ± 0.40	2.16 ± 0.47	2.27 ± 0.54	2.11 ± 0.64
VE (kgf)	2.59 ± 1.02	2.37 ± 0.83	2.43 ± 0.77	2.45 ± 0.94	2.04 ± 0.72	2.12 ± 0.97	2.09 ± 1.02	1.74 ± 0.70

Mean ± SD. *p<0.05.
Block 1 to Block 5 shows data from Day 1 and Block 6 to 8 shows Blocks 1, 2 and 3 from Day 2.

Table 4. Results of entropy in the practice session

	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Block 7	Block 8
C7-X (bit)	2.76 ± 0.13	2.77 ± 0.22	2.80 ± 0.16	2.79 ± 0.14	2.75 ± 0.18	2.69 ± 0.24	2.70 ± 0.23	2.69 ± 0.25
C7-Y (bit)	3.34 ± 0.30	3.31 ± 0.31	3.20 ± 0.44	3.28 ± 0.53	3.13 ± 0.44	3.32 ± 0.63	3.37 ± 0.59	3.28 ± 0.58
C7-Z (bit)	2.95 ± 0.25	2.94 ± 0.19	2.81 ± 0.44	2.81 ± 0.44	2.79 ± 0.44	2.77 ± 0.29	2.81 ± 0.29	2.78 ± 0.28
L3-X (bit)	2.78 ± 0.17	2.81 ± 0.19	2.72 ± 0.30	2.71 ± 0.36	2.70 ± 0.35	2.71 ± 0.32	2.74 ± 0.33	2.67 ± 0.32
L3-Y (bit)	3.18 ± 0.32	3.11 ± 0.33	3.09 ± 0.33	3.14 ± 0.40	3.08 ± 0.19	3.13 ± 0.41	3.02 ± 0.41	3.06 ± 0.44
L3-Z (bit)	2.72 ± 0.17	2.76 ± 0.19	2.76 ± 0.15	2.75 ± 0.16	2.72 ± 0.15	2.72 ± 0.16	2.74 ± 0.13	2.71 ± 0.17

Mean ± SD. Block 1 to Block 5 shows data from Day 1 and Block 6 to 8 shows Blocks 1, 2 and 3 from Day 2.

Table 5. Results of NASA-TLX

	Mental demand	Physical demand	Temporal demand	Performance	Effort	Frustration	RTLX
Day 1	57.5 ± 24.4	40.0 ± 18.5	24.6 ± 16.3	34.2 ± 12.0	61.3 ± 19.3	22.1 ± 11.4	44.6 ± 14.5
Day 2	49.2 ± 24.3	43.3 ± 20.6	24.2 ± 13.8	35.4 ± 19.8	48.3 ± 22.1*	29.2 ± 18.8	40.4 ± 20.9

Mean ± SD. *p<0.05.

participant trying to achieve what is required by the task, and includes mental and physical aspects[24]. The mental aspect represents cognitive effort and has been reported to be an important factor in motor learning[30]. The results may indicate that the participants were able to perform as well on day 2 as they did on day 1, even though they made less subjective effort in the task on day 2 as compared to day 1.

The results of this study showed a significant decrease in entropy in L3-X between the pre-test and the long-term retention test. In a previous study, it was reported that the smoothness of the movement depends on the task itself, and it is necessary to evaluate the characteristics of the task keeping this in mind[10]. In the standing up movement, the body is shifted upward after the center of gravity is shifted forward. In particular, participants were most likely to lose their balance immediately after their glutes had left the chair. The sitting movement is more difficult than the standing up movement, because the seating surface is not in sight, so that it is necessary to estimate the height of the seating surface from the floor while performing the movement. Properly timed joint movements and muscle strength moves the body's center of gravity from upward to downward, making stable sitting movements possible.

In this study, the decrease in entropy of L3-X may have decreased the fine adjustment of vertical movement, stabilized the body's center of gravity during sitting down and standing up movements, and improved the smoothness of movement. On the other hand, the change in entropy, a qualitative indicator, showed a different evolution from the loading error of the quantitative indicator. Load errors decreased from the early to the middle practice trials but did not change from the end of the practice to the test trials. However, entropy increased from the beginning to the middle of practice trials, and then decreased from the end of practice to the test trial. The qualitative indicators changed after quantitative indicators stabilized, while qualitative indicators changed after quantitative indicators stabilized. On the other hand, the change in entropy, a qualitative indicator, evolved differently from the load error of the quantitative indicator. Load errors showed a decrease in error from the early to middle practice trials but did not change from the end of practice to test trials. However, entropy increased from the beginning of practice to the middle of practice, and then decreased from the end of practice to the test trial. The results show that qualitative indicators changed after quantitative indicators stabilized, while qualitative indicators changed after quantitative indicators stabilized.

This study has some limitations. Measurements were taken in healthy adults using an easy task, but the study did not involve elderly people or patients who were considered to have impaired function. The elderly and those with impaired function may require more time to improve their motor skills than healthy adults, due to muscle weakness and impairment. Therefore, this study only captured the relationship of one of the qualitative aspects of motor learning with its quantitative aspect. In future, we will expand the scope of this study to include the elderly and impaired patients, and further study will be conducted.

Funding and Conflict of interest

There is no conflict of interests to declare and support with funding in this study.

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