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The association between upper-limb motor estimation error specific to the paralyzed side and cognitive and motor functions in patients with stroke

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Abstract

This study examined differences in upper-limb motor estimation errors (difference between the motor imagery task and actual task) on the paretic and non-paretic sides, as well as the associations between these errors and cognitive, and motor functions in patients with stroke. Thirty-four patients participated in the cross-sectional study. The imagined and actual peg tasks were performed with the paretic and non-paretic upper limbs, and the motor estimation error was calculated using the imagined and actual peg tasks. As a results, motor estimation error was significantly greater on the paretic side than the non-paretic side ($P = 0.021$). On the paretic side, motor estimation error positively correlated with the Trail Making Test (TMT) –A ($\rho = 0.431$), TMT–B ($\rho = 0.491$, $p < 0.05$). The difference in inter-limb estimation error negatively correlated with motor paralysis of upper limb ($\rho = -0.530$), motor paralysis of fingers ($\rho = -0.595$), touch sensory ($\rho = -0.478$), and position sensory ($\rho = -0.494$, $p < 0.05$). In conclusions, these findings suggest that the upper-limb motor estimation errors associated with motor and cognitive functions in patients with stroke.

Keywords: stroke, motor imagery, upper limb, motor function, cognitive function, motor estimation error

Introduction

Motor imagery, defined as the mental simulation of movement without actual movement, contributes to motor planning, feedforwards, and motor learning [1-4]. Consistent with this definition, neuroimaging studies have indicated that motor imagery activates neural regions

involved in motor planning and internal action representation, including the supplementary motor area, premotor cortex, parietal cortex, basal ganglia, and cerebellum [3,4]. These findings support the notion that motor imagery relates to internal models and predictive sensorimotor processing.

Within this framework, the comparator model is often used to explain the consistency between motor imagery and motor execution [5, 6]. When an action is initiated, the motor command generates an efferent copy that provides feedforward information about the outcome of the movement and the resulting sensory feedback. These predictions are then compared with sensory feedback during execution, which enables the detection of mismatches and adjustment of the feedforward information. However, since motor imagery does not generate actual movement, it lacks sensory feedback [7, 8]. However, feedforward information maintains active states, enabling the evaluation of feedforward information even without overt motor execution [9]. Therefore, motor imagery can be conceptualized as the generation of predicted movement based solely on feedforward information.

Mental chronometry (MC) compares the duration of imagined and executed movements. It is considered a behavioral indicator that indirectly reflects the comparator model [2]. MC is also widely cited as a measure of motor estimation error [10-14]. When imagined and executed movement times align, it is estimated that the feedforward information is being appropriately updated based on feedback information during motor execution. Conversely, discrepancies between imagined and actual movement duration is thought to reflect the integration of feedforward information generated from the internal model with feedback information following motor execution, and the resulting prediction error. MC has been shown to exhibit a strong correlation between imagined and executed walking times in healthy adults ($r = 0.89\text{--}0.99$) [2]

99 and mild subacute stroke patients ($p = 0.96$) [15]. This indicates that matching of feedforward
100 and feedback is largely maintained in familiar tasks.

101 However, previous studies using motor estimation errors have largely focused on gross
102 motor tasks, such as walking and balance [10-15]. In the upper limbs, Stinear et al. used the box
103 and block test to examine differences in movement estimation errors between the paralyzed and
104 non-paralyzed sides, reporting that movement estimation errors were larger in the paralyzed
105 upper limb [16]. However, factors related to the estimation error of movement between the
106 paralyzed and non-paralyzed upper limbs remain unclear. Additionally, although motor imagery
107 is influenced by age [17], cognitive function [18], motor impairment [19], and sensory
108 impairment [20], the underlying related factors of motor estimation errors in patients with stroke,
109 particularly in regard to differences between paralyzed and non-paralyzed limbs, remain unclear.
110 In patients with stroke, the unaffected limb generally retains motor and sensory function. This
111 allows both feedforward and feedback information to contribute to error detection and internal
112 model updating [21, 22]. In contrast, the paralyzed limb cannot obtain sufficient sensory
113 feedback due to motor paralysis and sensory deficits. This limits error correction and hinders the
114 refinement of feedforward predictions. Furthermore, since motor imagery generates feedforward
115 information, cognitive functions may also be involved [18]. These differences suggest that motor
116 estimation errors may vary between limbs and be related to cognitive, motor, and sensory
117 functions.

118 Based on this theoretical background, we hypothesized that motor estimation errors
119 would be greater in the paralyzed upper limb than in the non-paralyzed limb in patients with
120 stroke. Furthermore, we hypothesized that increased motor estimation errors, particularly on the
121 paralyzed side, would be associated with reduced executive function, greater motor impairment,

and sensory dysfunction in patients with stroke. The aims of this study are twofold: (1) comparing motor estimation errors between paralyzed and non-paralyzed upper limbs in patients with stroke and (2) examining the relationship between motor estimation errors and cognitive, motor, and sensory functions.

Results

A total of 74 patients with stroke were enrolled in this study (mean age, 68.4 ± 13.2 years; male, $n = 41$; female, $n = 33$; mean time since stroke, 80.7 ± 47.8 days; hemorrhagic, $n = 53$; infarction, $n = 21$; right hemiplegia, $n = 36$; left hemiplegia, $n = 38$). 30 patients with stroke were excluded because of age ($n = 1$) and data missing ($n = 29$). Finally, 34 patients with stroke were analyzed in this study (mean age, 69.9 ± 13.0 years; males, 23; female, 11; mean time since stroke, 73.7 ± 46.9 days; hemorrhage, 13; infarction, 21; left hemiplegia, 20; right hemiplegia, 14) (Table 1).

The cognitive functions of 34 patients with stroke were mild to moderate MMSE scores, TMT part A and B, and FIM cognitive part scores (Table 2).

The motor functions were mild to moderate degree of paralysis, mild sensory deficits, and FIM motor part scores (Table 2).

The Shapiro-Wilk test revealed that the motor estimation error and the image and actual peg task were a normal distribution ($P > 0.05$).

The number of actual pegs task on the paralyzed side was 10.7 ± 6.5 , while the number on the non-paralyzed side was 12.3 ± 5.1 . The number of actual pegs task on the paralyzed side was significantly lower than the number on the non-paralyzed side ($t = -2.48$, $P = 0.018$, Figure 1A). However, there was no significant difference in the number of imaged pegs task between the paralyzed and non-paralyzed sides ($t = -0.96$, $P = 0.344$, Figure 1A). Motor estimation error

was greater on the paralyzed side compared to the non-paralyzed side (the paralyzed side: 0.21 ± 0.13 , the non-paralyzed side: 0.16 ± 0.10 , $t = 2.43$, $P = 0.021$, Figure 1B).

Regarding the results of the correlation analysis, the motor estimation error on the paralyzed side was positively correlated with TMT part A ($\rho = 0.431$, $P = 0.016$), TMT part B ($\rho = 0.291$, $P = 0.016$), and TMT part B-A ($\rho = 0.416$, $P = 0.014$, Figure 2). However, no correlation was observed between motor estimation error on the paralyzed side and the MMSE scores ($\rho = -0.214$, $P = 0.223$) and the FIM cognitive part ($\rho = -0.133$, $P = 0.455$). After controlling for the number of pegs on the non-paralyzed side and age as covariates, partial correlation analysis showed that motor estimation error on the paralyzed side was positively correlated with TMT part A ($\rho = 0.468$, $P = 0.007$) and TMT part B ($\rho = 0.479$, $P = 0.006$).

The motor estimation error on the non-paralyzed side was positively correlated with TMT part A ($\rho = 0.580$, $P = 0.016$), TMT part B ($\rho = 0.535$, $P = 0.001$), and TMT part B-A ($\rho = 0.399$, $P = 0.019$, Figure 3). However, no correlation was observed between motor estimation error on the non-paralyzed side and the MMSE scores ($\rho = -0.218$, $P = 0.214$) or the FIM cognitive part ($\rho = 0.000$, $P = 0.999$). After controlling for the number of pegs on the non-paralyzed side and age as covariates, no correlation was observed between motor estimation error on the non-paralyzed side and TMT part A ($\rho = 0.192$, $P = 0.294$) and TMT part B ($\rho = 0.272$, $P = 0.132$).

Motor estimation error differed between the paralyzed and non-paralyzed sides by 0.05 ± 0.02 , showing a negative correlation with BRS upper limb ($\rho = -0.530$, $P = 0.001$), fingers ($\rho = -0.595$, $P < 0.001$), upper limb touch sense ($\rho = -0.478$, $P = 0.004$), and position sense ($\rho = -0.494$, $P = 0.003$, Figure 4).

Discussion

The purpose of this study is to clarify differences in motor estimation errors between the paralyzed and non-paralyzed upper limbs and to examine how these differences relate to cognitive, motor, and sensory functions in patients with stroke. As predicted, the number of actual pegs task was significantly lower on the paralyzed side than on the non-paralyzed side, while no difference was observed between sides in imagined pegs task. Consequently, motor estimation error was significantly larger in the paralyzed side upper limb in patients with stroke. These findings indicate a disassociation between imagined and actual movement in patients with stroke and support the usefulness of motor estimation error as a behavioral marker of impaired internal motor representation.

Our results are consistent with the findings of Sterner et al, who demonstrated larger motor estimation errors in the paralyzed side upper limb during a box-and-block test in subacute patients with stroke [16]. In current study, although no bilateral difference (paretic and non-paretic) was observed in imagined pegs performance, actual pegs performance was significantly impaired on the paralyzed side. However, a new finding in this study was that different factors were involved in the motor estimation errors of the paralyzed and non-paralyzed upper limbs. Motor imagery is generally thought to rely on feedforward information predicting sensory outcomes prior to motor execution [7, 33]. After stroke, while motor intent can be generated, motor paralysis and sensory deficits interfere with error learning through motor execution and sensory feedback [7, 8, 21, 22, 34]. This mismatch between intended and actual movement may have not detect the updating of feedforward information, leading to movement overestimation on the paralyzed side in patients with stroke.

Furthermore, to indirectly assess this mechanism, we examined the relationship between interlimb differences in motor estimation error and cognitive and motor function in patients with stroke. The difference of motor estimation error of interlimb was moderately associated with both motor paralysis and sensory deficits, suggesting that impaired sensorimotor feedback hindered internal model updating. These findings support the concept that patients continue to expect movement of the paralyzed limb at pre-illness levels despite actual motor deficits [35].

Motor estimation errors on the paralyzed side remained significantly associated with attention and executive function even after adjusting for motor function and age, whereas these relationships were not significant on the non-paralyzed side. Previous studies have demonstrated that motor imagery is associated with cognitive function [36, 27]. Attention or executive dysfunction may be inhibiting the updating of feedforward information [36, 37]. Moreover, previous study have shown that motor imagery in the paralyzed limb relies more heavily on cognitive resources due to impaired sensory-motor feedback and failure to update body representations [38]. When feedforward information cannot be corrected by sensory feedback, attentional and executive functions such as attention control and set shifting may assist in generating feedforward information [39]. In contrast, the non-paralyzed limb retains motor and sensory functions, allowing the internal model to be updated [40]. Consistent with findings in healthy populations, the execution of motor imagery in the non-paralyzed limb appears to depend primarily on actual motor ability rather than higher-order cognition [1]. Therefore, controlling for motor execution ability may have eliminated the relationship between motor estimation error and executive function.

The limitations of this study are as follows: First, the motor imagery ability assessment conducted solely on mental chronometry. Clinical assessments of motor imagery include

different aspects assessments such as vividness and modality (visual vs kinesthetic). However, mental chronometry, like other motor imagery assessments, remains an evaluation reflecting the participant's motor function [12-15] Future research will implement multifaceted motor imagery assessments and introduce multidimensional assessment methods using neurophysiological techniques to assess motor imagery processes more comprehensively. Secondary, the cross-sectional study design limits the ability to infer causal relationships between motor estimation errors and cognitive, sensory, or motor impairments. Future longitudinal or intervention studies will clarify whether improvements in attention and executive function or sensory feedback led to reductions in motor estimation errors. Finally, this study did not evaluate upper limb usage frequency in daily life (i.e., motor activity log). Evaluating this would have clarified the impact of motor estimation errors on daily activities, so future research will include this assessment.

In conclusions, this study indicates that motor estimation error, particularly on the paretic side, is associated with attention and executive function and sensory-motor function in patients with stroke.

Methods

This study was a prospective cross-sectional study design and was conducted at four hospitals. Data collection started on March 11, 2024, and was completed by October 31, 2025. The inclusion criteria were as follows: (a) diagnosis of first-ever stroke, (b) one or more pegs can be grasped, (c) age > 18 years, (d) absence of orthopedic disease, and e) presence of hemiplegia. The exclusion criteria were as follows: (a) diagnosis of dementia, (b) diagnosis of high brain dysfunction (e.g., unilateral spatial neglect, apraxia and aphasia), (c) presence of a visual field defect, (d) age > 90 years, and (f) data missing. The purpose of this study was explained to all participants, and written informed consent was obtained before starting the study. Furthermore,

the study was approved by the ethics committee of Tokyo Metropolitan University (approval numbers: 23820) and publicly registered in UMIN Clinical Trials Registry (trial registration ID: UMIN000053805). The study was conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki.

Assessments

The assessments were conducted within 10 days after patient registration. Motor estimation errors were assessed using the imaged peg task and actual peg task in the paretic and non-paretic upper limbs. Cognitive functions were assessed the Mini-Mental State Examination (MMSE), Trail Making Test part A and B, Functional Independence Measure (FIM) cognitive part. Furthermore, motor functions were assessed using the upper limb and finger parts of Brunnstrom Recovery Stage (BRS), Sensory part of Stroke Impairment Assessment Set (SIAS), and FIM motor part.

Regarding motor estimation error assessments, the imaged peg task of paretic and non-paretic side were initially performed once, then, the actual peg task of paretic and non-paretic side was also performed once. Because performing the movement first changes the motor imagery [10-15]. For the peg task, the participants sat at a table and used a pegboard placed on the table. The participants used fingers from either the paralyzed or non-paralyzed side to take only one peg from the tray and insert it into the top hole of the column. Next, following the same procedure, the participant took pins from the tray and inserted them sequentially into the holes from the top, performing this for one minute. The therapist used a stopwatch to measure the one-minute duration and counted how many pegs were inserted into the holes [23]. For the imagined peg task, the participant imagined performing the task with their paralyzed or non-paralyzed fingers while looking at the pegboard on the table (kinesthetic imagery) [24]. The participant told

the therapist how far they could insert the peg into the holes. The therapist used a stopwatch to time the task for one minute and recorded how far the peg was inserted into the holes.

Cognitive functions

The MMSE assessed global cognitive function. MMSE was a total score of 30 points indicates good cognitive functions [25].

In TMT part A, participants connected circled numbers (from 1 to 25) in sequence as quickly as possible [26]. In TMT part B, participants connected numbers and letters alternately in sequence as quickly as possible.

FIM is used to measure the ability to perform activities of daily living [27]. It comprises 18 items, including 13 motor (FIM motor) and five cognitive (FIM cognitive) part. It is used to rate each item on a six-point scale, with a minimum score of 1 and a maximum score of 7. The highest possible scores for FIM motor and FIM cognitive parts are 91 and 35, respectively. A higher FIM score indicates better function in activities of daily living.

Motor and Sensory Functions

BRS was used to assess the degree of paralysis and categorized upper-limb, finger, and lower-limb functions on a six-point scale, and higher scores (range, 1–6) indicated better motor functions [28]. This study measured only the upper limbs and finger parts.

SIAS is classified into nine types of functional disorders and includes 22 items [29]. This study measured only the sensory function item (i.e., touch and position senses) was used. Sensory function is rated on three-point scale, with a minimum score of 0 and a maximum score of 3, and higher scores indicate better sensory function.

283

284 *Data and Statistical Analysis*

285 For the sample size of paired t-test was calculated using a power of 0.95, $\alpha = 0.05$, and a $d = 1.18$
286 using G power 3.1.9.2 (Düsseldorf University; Düsseldorf, Germany) [13]. Therefore, the sample
287 size was more than 12 participants. Furthermore, the sample size of correlation analysis was
288 calculated using a power of 0.95, $\alpha = 0.05$, and a correlation coefficient of 0.492 using G power
289 3.1.9.2 [12]. Therefore, the sample size was more than 30 participants.

290 The estimation error was calculated using the following formula: (imagined peg
291 task – actual peg task)/ (imagined peg task + actual peg task)/2 [30-32]. Subsequently, the motion
292 estimation error was converted to its absolute value. A value close to zero indicates a smaller
293 motor estimation error, while a value close to 0.5 indicates a large motor estimation error. In
294 other words, the values of the motor imagery and the actual motor execution are similar.

295 This study used the Shapiro-Wilk test to verify the normality of the data. The paired t-test
296 was used to determine between the motor estimation error, the actual pegs task, and imagined
297 pegs task of paretic and non-paretic side. Pearson or Spearman's rank correlation analysis were
298 used to evaluate the relationships between the motor estimation error and several variables
299 (MMSE, TMT part A and B, BRS of upper limb and finger parts, sensory items of SIAS, and
300 FIM motor and cognitive part). Furthermore, since the motor estimation error is associated with
301 age [17] and cognitive tests are associated with motor function in the non-paralyzed upper limb,
302 we performed a partial correlation analysis controlling for two factors.

303 Additionally, to identify factors associated with the difference in motor estimation error
304 between the paralyzed and non-paralyzed sides, we calculated the value obtained by subtracting
305 the non-paralyzed side motor estimation error from the paralyzed side value. We then conducted
306 a correlation analysis to examine its relationship with motor and cognitive function. All

statistical analyses were conducted using SPSS version 29.0 (IBM Corp., Armonk NY, USA).
Statistical significance was set at a P-value of < 0.05.

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Declaration of Interest

The authors report no conflict of interest.

Data availability statement

Provide the data as requested by the author.

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Author contributions

Conceptualization: Katsuya Sakai, Methodology: Katsuya Sakai, Formal analysis: Katsuya Sakai,
Investigation: Yusuke Harada, Validation: Junpei Tanabe, Kota Sawa, Yuki Fukumoto, Tsubasa
Kawasaki, Hiroyuki Hamada, Yusuke Harada, Data curation: Yusuke Harada
Writing – original draft: Katsuya Sakai, Writing – review & editing: Katsuya Sakai, Junpei Tanabe, Kota
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Supervision: Katsuya Sakai.

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Table

Table 1. Basic attributes

Variables	N = 34
Age (year)	69.9 ± 13.0
Sex (male/female)	11/23
Type of stroke (infarction/ hemorrhage)	21/13
Paretic side (right/left)	14/20
Time since stroke (day)	73.7 ± 46.9

Table 2. Cognitive and motor functions of the overall participants

Variables	N = 34
MMSE (Scores)	27.9 ± 2.7
TMT Part A (Sec)	66.5 ± 36.9
TMT Part B (Sec)	122.3 ± 70.3
TMT Part B-A (Sec)	55.8 ± 50.9
FIM cognitive (Scores)	32.3 ± 10.5
BRS upper limb	5 (2 - 6)
BRS finger	5 (2 - 6)
Touch sense	3 (1 - 3)
Position sense	3 (0 - 3)
FIM motor (Scores)	73.7 ± 16.9

Average ± standard deviation, median (min - max). MMSE: Mini-Mental State Examination, TMT: Trail Making Test, FIM:

Functional Independence Measure, BRS: Brunnstrom Recovery Stage.

Figure captions

Figure 1A. Comparison of the imaged peg task and the actual peg task between the paralyzed side and the non-paralyzed side

Light gray color indicates number of actual pegs task. Dark gray color indicates number of imaged pegs task. The number of actual pegs task on the paralyzed side was significantly lower than the number on the non-paralyzed side ($t = -2.48$, $P = 0.018$). However, there was no significant difference in the number of imaged pegs task between the paralyzed and non-paralyzed sides ($t = -0.96$, $P = 0.344$).

Figure 1B. Difference in motor estimation error between paralyzed and non-paralyzed sides

Dark gray color indicates paretic side. Light gray color indicates non-paretic side. Motor estimation error was greater on the paralyzed side compared to the non-paralyzed side ($t = 2.43$, $P = 0.021$).

Figure 2. Relationship between motor estimation error on the paralyzed side and cognitive function

The motor estimation error on the paralyzed side was positively correlated with TMT part A ($\rho = 0.431$, $P = 0.016$), TMT Part B ($\rho = 0.291$, $P = 0.016$), and TMT Part B-A ($\rho = 0.416$, $P = 0.014$).

Figure 3. Relationship between motor estimation error on the non-paralyzed side and cognitive function

The motor estimation error on the non-paralyzed side was positively correlated with TMT part A ($\rho = 0.580$, $P = 0.016$), TMT part B ($\rho = 0.535$, $P = 0.001$), and TMT part B-A ($\rho = 0.399$, $P = 0.019$).

Figure 4. Relationship between the difference in motor estimation error between the paralyzed and non-paralyzed sides and motor and sensory function

Difference of motor estimation error was negatively correlated with BRS upper limb ($\rho = -0.530$, $P = 0.001$), fingers ($\rho = -0.595$, $P < 0.001$), upper limb touch sense ($\rho = -0.478$, $P = 0.004$), and position sense ($\rho = -0.494$, $P = 0.003$).

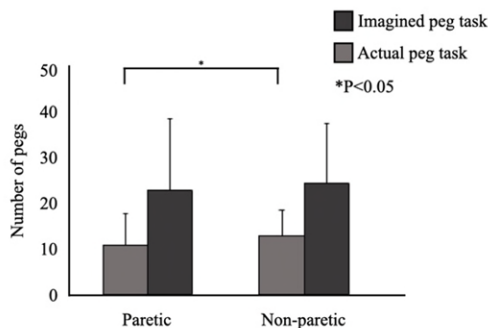


Figure 1A

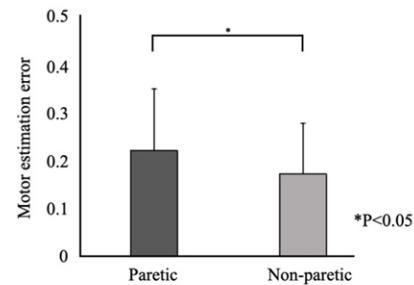


Figure 1B

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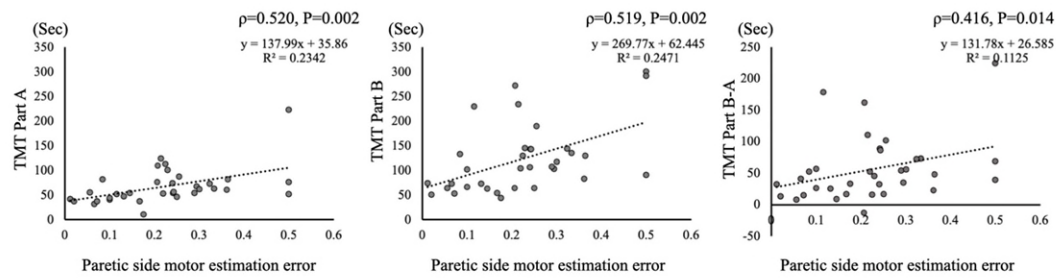


Figure 2

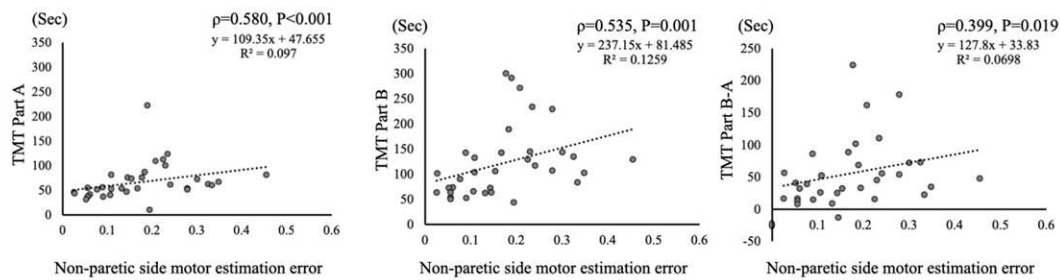


Figure 3

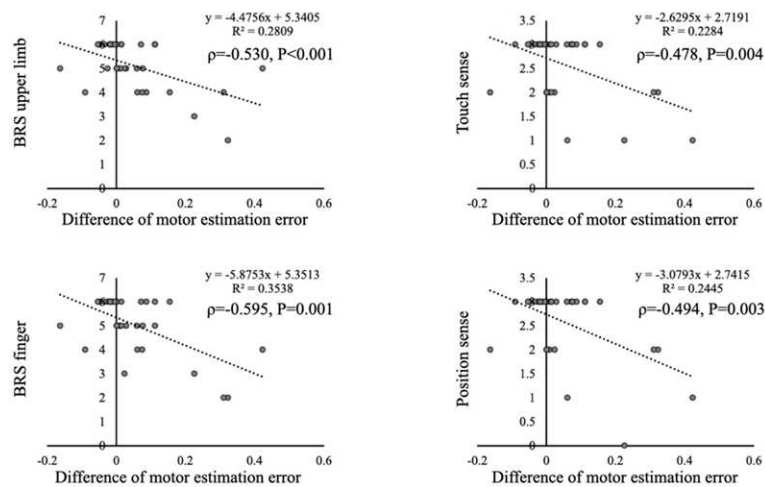


Figure 4