Quantitative measurement of finger usage in stroke hemiplegia using ring-shaped wearable devices

Naoya Yamamoto  
Shonan Keiiku Hospital

Takato Matsumoto  
Tokyo University of Agriculture and Technology

Tamami Sudo  
Tokyo University of Agriculture and Technology

Megumi Miyashita  
Tokyo University of Agriculture and Technology

Toshiyuki Kondo  
Tokyo University of Agriculture and Technology

Research Article

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Quantitative measurement of finger usage in stroke hemiplegia using ring-shaped wearable devices

Naoya Yamamoto¹,²†, Takato Matsumoto¹†, Tamami Sudo¹, Megumi Miyashita³ and Toshiyuki Kondo¹*
Abstract

Background:
Positive use of affected limbs in daily life is important to improve the affected upper limb function in post-stroke rehabilitation. Several studies have been conducted to quantitatively evaluate the amount of upper limb activity, but few have measured the finger usage. In this study, we measured the upper limb and finger usage simultaneously in hospitalized hemiplegic stroke patients with a ring-shaped wearable device and investigated the association with the finger usage and general clinical evaluation.

Methods:
Twenty stroke hemiplegic patients staying in an inpatient hospital participated in this study. All patients wore a ring-shaped wearable device on both hands for 9 hours on the day of the intervention and the finger usage was recorded. For the outcome assessments of the rehabilitation, Fugl-Meyer Assessment Upper Limb (FMA-UL), Simple Test for Evaluating Hand Function (STEF), Action Research Arm Test (ARAT), Motor Activity Log-14 (MAL), and Functional Independence Measure Motor (FIM-m) were employed and were evaluated on the same day as the intervention.

Results:
The finger usage of affected hand was moderately correlated with STEF ($r = 0.48, p < .05$) and STEF ratio ($r = 0.47, p < .05$). The finger usage ratio was moderately correlated with FMA-UL ($r = 0.56, p < .05$) and ARAT ($r = 0.53, p < .05$), and strongly correlated with STEF ($r = 0.80, p < .01$) and STEF ratio ($r = 0.80, p < .01$). The upper limb usage of affected side was moderately correlated with FMA-UL ($r = 0.46, p < .05$), STEF ($r = 0.55, p < .05$) and STEF ratio ($r = 0.54, p < .05$), and strongly correlated with ARAT ($r = 0.57, p < .01$). The upper limb usage ratio was moderately correlated with ARAT ($r = 0.48, p < .05$) and STEF ($r = 0.55, p < .05$), and strongly correlated with STEF ratio ($r = 0.61, p < .01$). By contrast, MAL has revealed no correlation with any of the measurements.

Conclusions:
These results suggest that this measurement technique is able to provide useful information that are not biased toward the subjectivity of patients and therapists.

Keywords: Physical activity; Activity of Daily Living; Finger; Upper limb; Rehabilitation; Stroke
Background

Stroke is one of the most common diseases in the world [1]. Most of the stroke survivors experience some degree of upper limb dysfunction due to motor paralysis [2, 3]. Patients with stroke hemiplegia are tend to reduce the frequency of use of the affected upper limbs in activities of daily living, and to use only the unaffected limbs, resulting in a learned nonuse phenomenon [4, 5]. Learned nonuse is one of the major clinical problem impeding the recovery of motor function in the affected limb and reducing the patient’s quality of life (QOL) [6]. As indicated by previous reports that active use of the affected limb promotes use-dependent plasticity of the cerebral cortex [7–9], increasing the frequency of use of the affected limb in daily life is crucial for preventing the learned nonuse and recovering from the motor dysfunction. Another study reported that increased frequency of use of affected hands rather than improved function of affected hands contribute to the QOL of the patients [10]. Therefore, encouraging the use of the affected limb in daily life is one of the vital issues in rehabilitation.

Motor Activity Log have been widely used as an evaluation method for assessing the amount of upper limb activity in daily life. The Motor Activity Log, developed by Taub et al [11], is a semistructured interview for hemiparetic stroke patients to assess the use of their paretic arm and hand from two aspects, amount of use (AOU) and quality of movement (QOM). Motor Activity Log-14 (MAL), which is generalized and commonly used, allows patients to self-evaluate AOU and QOM on a 6-point scale from 0 to 5 for 14 activities of daily living movement items [12, 13], and has been reported high reliability and excellent validity [14, 15]. Since MAL is an interview-style subjective evaluation scale, there is a potential problem that the answer is significantly influenced by a patient’s cognitive level and subjectivity. Therefore, it is more effective to use together the directly measuring the amount of real-world arm use as an objective quantitative evaluation.

Accelerometry is a method of recording the usage of the upper limbs using a watch-type wearable device embedded with an accelerometer [16, 17]. It is small, lightweight, and can implicitly measure the amount of affected limbs usage, so often applied as devices to measure the usage of upper limbs in daily life. Changes in upper limb usage after rehabilitation intervention could be quantified, and the measurement data in clinics and research institutes reported a high correlation with...
the assessments of upper-extremity function [18–20]. However, this method is unable to measure the finger usage during skilled movements since the accelerometer attached to the wrist. Several devices, such as Data Glove [21–23], Leap Motion [24, 25], have been recently developed for accurate finger motion sensing and measuring the individual finger motions. Although these devices realized accurate finger motion measurements, they are not well-suited for continuous measurement of finger usage in stroke hemiplegic patients because the daily usage had not been so considered. Manumeter [26, 27] is a daily usable method measuring the extent of the wrist and finger usage using a magnetic field sensor and a ring-shaped magnet. However, the correlation between the estimated and actual finger angles was not high ($R^2 \leq 0.61$), and it would be difficult to measure multiple points simultaneously because of the interference among the magnetic fields. With this background, in this study, we focused on a newly developed ring-shaped wearable device for a constant measurement of finger usage in daily life [28]. This device has many advantages such as high measurement accuracy, easy attach-detachment, and constant measurement, so that suitable for quantitative approach of the amount of finger usage in daily life after stroke.

In this study, to clarify the amount of finger usage in daily life in hemiplegic stroke patients, quantitative measurements were carried out for subacute phase hemiplegic patients by wearing the ring-shaped wearable device. In addition, the correlation between daytime finger usage measured by the devices and respective clinical assessments were investigated based on the hypothesis that patients with higher clinical evaluation scores tend to use more fingers. This measurement technique is expected to contribute to providing universal evaluation results that are not biased toward the subjectivity of patients and therapists.

**Methods**

**Participants**

Twenty stroke hemiplegic patients staying in an inpatient hospital participated in this study. Inclusion criteria were (1) first-ever stroke (infarction or hemorrhage), (2) paralysis of one side only, (3) no serious neurological or musculoskeletal problems prior to stroke, (4) no problem with cognitive function (Mini Mental State Examination $>23$), (5) Mild to moderate upper limb paralysis (FMA-UL $>23$) [29].
Exclusion criteria were (1) with unstable medical conditions, (2) restricted upper or lower limbs for fluid treatment. The sample size was determined by considering effect size (0.6), power (0.8) and significance level (0.05). Based on the Declaration of Helsinki, all participants were informed of the study protocol, stress, possible risks, and being able to interrupt at any time by their own will, and gave their written informed consent. This study was conducted with the approval of the ethics committee of the Shonan Keiiku Hospital (19-002).

Devices

We developed a ring-shaped wearable device capable of measuring hand movement and estimating the flexion angle of each finger [28]. As shown in Fig. 1A, the device consists of a light emitting diode (LED) (Osram, SFH4550) and a phototransistor (Honeywell, SD5410). It was worn at the proximal phalanx of the index finger of the dominant hand (Fig. 1B). The microcomputer (Adafruit, Feather M0 Adalogger) and a LiPo battery (3.7V, 400mAh) were installed in a white wrist box.

The ring-shaped device measures the distance between the fingertip and the device at 100 Hz. Based on the distance, the flexion angle of proximal inter-phalangeal (PIP) joint can be estimated. While the cumulative angular change is recorded as finger usage, the cumulative norm of the accelerometer on the wrist is simultaneously recorded as upper limb usage. Simultaneous measurement with wrist and finger sensors makes it possible to separate finger movements from whole upper limb movements.

Procedures

All patients were wearing the ring-shaped devices on both hands during the intervention period, for a total of 9 hours from 8:00 to 20:00, excluding the 3 hours of rehabilitation intervention. For the outcome assessments of the rehabilitation, Fugl-Meyer Assessment (FMA) [30], Simple Test for Evaluating Hand Function (STEF) [31], Action Research Arm Test (ARAT) [32], MAL, and Functional Independence Measure Motor (FIM-m) [33] were employed and were evaluated on the same day as the measurement. The reliability of each test has already been confirmed. The evaluation of MAL was conducted by trained therapists (the author NY). Other assessments (FMA, STEF, ARAT and FIM-m) were conducted in routine clinical
practice by physical therapists, occupational therapists, and speech therapists under the supervision of the author NY.

Statistical analysis

The Shapiro-Wilk test was used to evaluate the normality of the dataset distribution. Because all clinical measures were not normally distributed, a Wilcoxon signed-rank test was used to assess the difference in frequency of use between affected and unaffected hands. Finger usage, upper limb usage, and all clinical measures were assessed using Spearman’s correlation test. Significance level was set at $p < 0.05$. Statistical analyses were carried out using SPSS (Version 26, IBM SPSS Statistics).

Results

Table 1 shows the characteristics of participants and their respective scores for clinical assessments. Figure 2A shows the amount of the finger usage of affected and unaffected hand per hour of the measured day (total of 9 hours). The amount of the finger usage of affected hand was significantly smaller than the one of unaffected hand ($p < 0.01$). Figure 2B shows the amount of the upper limb usage of affected and unaffected hand per hour of the measured day. The amount of the upper limb usage of affected hand was significantly smaller than the one of unaffected hand ($p < 0.01$).

Table 2 shows the results of the correlation analysis between the finger usage, the finger usage ratio (affected hand / unaffected hand) and each clinical assessment measures. The finger usage of affected hand was moderately correlated with STEF ($r = 0.48, p < 0.05$) and STEF ratio ($r = 0.47, p < 0.05$). The finger usage ratio was moderately correlated with FMA-UL ($r = 0.56, p < 0.05$) and ARAT ($r = 0.53, p < 0.05$), and strongly correlated with STEF ($r = 0.80, p < 0.01$) and STEF ratio ($r = 0.80, p < 0.01$). On the other hand, neither the finger usage on the affected hand nor the finger usage ratio were significantly correlated with MAL AOU (finger usage: $p = 0.41$, finger usage ratio: $p = 0.27$) and MAL QOM (finger usage: $p = 0.42$, finger usage ratio: $p = 0.29$).

Table 3 shows the results of the correlation analysis between the upper limb usage, the upper limb usage ratio (affected hand / unaffected hand) and each clinical assessment measures. The upper limb usage of affected side was moderately correlated with FMA-UL ($r = 0.46, p < 0.05$), STEF ($r = 0.55, p < 0.05$) and STEF ratio
\( r = 0.54, p < .05 \), and strongly correlated with ARAT \( r = 0.57, p < .01 \). The upper limb usage ratio was moderately correlated with ARAT \( r = 0.48, p < .05 \), and strongly correlated with STEF ratio \( r = 0.61, p < .01 \). On the other hand, neither the upper limb usage on the affected side nor the upper limb usage ratio were significantly correlated with MAL AOU (UL usage: \( p = 0.30 \), UL usage ratio: \( p = 0.66 \)) and MAL QOM (UL usage: \( p = 0.26 \), UL usage ratio: \( p = 0.67 \)).

Figure 3A shows the relationship between the finger usage ratio and STEF ratio as a representative example showing a strong correlation with finger usage ratio. The relationship with MAL (AOU) is shown in Figure 3B as a representative example that showed no correlation. Figure 4A shows the relationship between the upper limb usage ratio and STEF ratio as a representative example showing a strong correlation with upper limb usage ratio. The relationship with MAL (AOU) is shown in Figure 4B as a representative example that showed no correlation.

Discussion

In most previous studies, the amount of real-world arm use was estimated by wearing an accelerometer on the wrist. On the other hand, the present study has tried to record the activities such as the skilled motor activities of fingers separately from the wrist using the new developed ring-shaped wearable device. As a result of investigating the relationship between the quantitative measurement by the devices and each clinical measurement scores, the following was clarified.

First, both of the finger usage and the upper limb usage on affected side was significantly smaller than on unaffected side. In the previous study by Lang et al.[18], measured the real-world arm use with an accelerometer, the usage ratio on the on affected hand compared with the unaffected hand reported about 55%. In this study, the amount of the finger usage on the affected hand was about 59% compared to the unaffected hand, and the amount of the upper limb usage on the affected side was about 58% compared to the unaffected side, so the results were similar to those of Lang et al.

Secondly, the finger usage ratio measured in this study showed a correlation with FMA, ARAT and STEF, and the upper limb usage ratio also showed a correlation with ARAT and STEF. The correlation between the clinical measurements of upper
limb function and the finger usage in daily life was consistent with our hypothesis. Previous studies that used accelerometers to measure the amount of real-world arm use showed a correlation with FMA [34] and ARAT [18], almost consistent with this study. Regarding STEF, there has been no previous study comparing with the amount of activity in daily life. Thus, this study is the first to investigate the correlation between the finger usage and STEF. Among the clinical measures used, STEF showed the highest correlation with the finger usage. Since STEF is mainly used to evaluate finger function in the upper limbs, it is considered that a high correlation was revealed. FMA, ARAT, and STEF are specific measures indicating the function of the upper limbs. Overall, the result that these measures showed a correlation with the finger usage supports the construct validity of this study.

Third, this is the most notable result of this study, and contrary to our hypothesis, no correlation was found between the finger and upper limb usage and MAL scores. This means that there was a dissociation between MAL, that is the subjective evaluation of the real-world arm use, and a quantitative evaluation of the finger and upper limb usage measured in this study. MAL is the most standard clinical evaluation for assessing the amount and quality of use of affected limbs in daily life. Previous studies measuring upper extremity usage with an accelerometer found a moderate correlation between the real-world arm use and MAL [13, 35–37]. Therefore, it was also expected that there was a correlation with the finger usage measured in this study, but no correlation was observed. The following two points can be considered as the results. One is that all subjects in this study were patients. In most previous studies, MAL was evaluated in community-dwelling stroke patients with calm condition [13, 35, 36]. The MAL is a clinical measure asking the amount and quality of use for 14 items in daily life. During hospitalization, much of daily life is restricted and the range of activities is narrowed. Therefore, some actions not performed during hospitalization were included among the 14 items, which is considered to have affected the MAL score. There is also one study that measures the amount of activity in hospitalized stroke patients with an accelerometer [37], but this previous study targeted patients in the acute phase shortly after onset, and the measurement timing was significantly different from that of the present study. These differences in patient characteristics are considered to have caused these dif-
ferent results. Another point is that MAL is an interview-style evaluation. Stroke\(^1\) patients occasionally have memory problems, aphasia, dementia, and so on. Since\(^2\) MAL is an evaluation asking subjectively for such patients how much their own\(^3\) hands have been used [38, 39], it is necessary to determine whether the patients\(^4\) properly evaluate the real-world arm use in daily life. Also, when assessing MAL,\(^5\) it is necessary to be aware of the effects of Hawthorne effect [40] caused by the\(^6\) patient feeling that the therapists are expecting the outcome of the intervention.\(^7\) The irrelevancy with the finger usage measured as the objective evaluation in this\(^8\) study suggests that it should be noted whether the patients were able to perform\(^9\) an appropriate self-evaluation in MAL, and the problem of MAL as the evaluation\(^10\) tool was also highlighted.

No correlation was revealed between both of the finger and upper limb usage and\(^11\) FIM-m. The result in this study indicates that the higher self-care independence\(^12\) does not mean more frequent the affected limb use. FIM-m is an evaluation that\(^13\) reflects the amount of assistance required in daily life, but the evaluation target\(^14\) is the entire motor activity including the affected and unaffected sides. Therefore, it\(^15\) has the characteristic of showing a high score even in the case of independent by\(^16\) compensatory movement without using the affected limb. The previous study by\(^17\) Lang et al. [18], showed the correlation between FIM and upper extremity use measured using an accelerometer. This previous study has targeted patients in the acute\(^18\) phase, a period focused on restoring function through the positive use of the affected\(^19\) limb, it is considered that the upper limb usage of affected side have influenced the\(^20\) independence. On the other hand, the subacute phase patients participated in this\(^21\) study were in a rehabilitation program with an emphasis on independence, and\(^22\) there were no specific instructions to recommend the use of the affected limb or\(^23\) limit compensatory movements of the unaffected limb in this measurement.

All clinical measures used in this study are assessed based on the therapist’s and\(^24\) patient’s subjective evaluation. Therefore, it needs to be carried out by an experienced and skilled evaluator. Alt Murphy et al., state that objective evaluations such\(^25\) as accelerometers enables to close the gap with the outcome of traditional clinical\(^26\) evaluations and improve the quality and accuracy of measurements [41]. The objec-

and between patients could be reduced compared to the scores of clinical evalua-
tions. In addition, it might be possible to provide useful information to patients and therapists by adding objective evaluations such as finger usage in daily life to the conventional subjective evaluations.

This study have several limitations. First, the participants in this study were recruited at only at a single institution. Therefore, their activities of daily living are restricted compared to community-dwelling patients, and their daily life schedule might have become similar with less individuality. Future investigations are needed to examine if the same trend extends to other types of institutions. Second, the subjects were not randomly selected, but recruited willed patients to participate in a clinical trial. From the patients, who had no voluntary upper extremity movements or who had recovered near-normal levels of upper extremity function were excluded. Therefore, all patients in this trial had mild to moderate hemiplegia, with a narrow range of severity. Although such patients are in appropriate target range because they have symptoms relevant to many studies of upper extremity rehabilitation, more studies are required to expand the target to patients with more diverse severity in the future.

Conclusions

The present study conducted the quantitative evaluation of the upper limb and finger usage in daily life in hemiplegic stroke patients, and our results have demonstrated that the new developed ring-shaped wearable devices has evaluated not only the amount of real world arm use but also the amount of finger use such as the skilled motor activities of fingers separately from the wrist. The results enable to provide an objective evaluation index for finger usage, which was conventionally obtained only from subjective self-reported evaluations. This measurement technique is expected to contribute to providing universal information without biases toward the subjectivity of patients and therapists.

List of abbreviations

- FMA-UL: Fugl-Meyer Assessment-Upper Limb
- STEF: Simple Test for Evaluating Hand Function
- ARAT: Action Research Arm Test
- MAL: Motor Activity Log-14
- AOU: Amount of Use
QOM: Quality of Movement
FIM-m: Functional Independence Measure Motor
QOL: Quality of Life
LED: Light Emitting Diode
PIP: Proximal Inter Phalangeal

Declarations

Ethics approval and consent to participate
This study was conducted with the approval of the ethics committee of the Shonan Keiiku Hospital (19-002).

Consent for publication
Not applicable.

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests
The authors declare that they have no competing interests.

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Author’s contributions
NY and TK considered the concept and design of the research. TM implemented the measurement device, and NY acquired the data. NY and TK analyzed and interpreted the data. NY, TS, and TK wrote the manuscript. All authors reviewed and approved the final manuscript.

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Not applicable.

Author details
1 Department of Computer and Information Sciences, Graduate School of Engineering, Tokyo University of Agriculture and Technology, 2-24-16, Naka-cho, Koganei, Tokyo, Japan. 2 Shonan Keiiku Hospital, 4360, Endo, Fujisawa, Kanagawa, Japan.

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Figure 1 The developed ring device. A: The ring device consists of an LED and a phototransistor. B: The ring device was worn at the proximal phalanx of the index finger of the dominant hand. A microcomputer, an accelerometer, and a battery were installed in a white wrist box.

Figure 2 Comparison of Finger usage (A) and Upper limb usage (B) between the affected side and the unaffected side.

Figure 3 Correlation analysis of Finger usage ratio and STEF/MAL(AOU).
Figure 4 Correlation analysis of Upper limb usage ratio and STEF/MAL(AOU).

Table 1 Characteristics of participants.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>67.7 (13.6)</td>
</tr>
<tr>
<td>Gender (male/female)</td>
<td>11/9</td>
</tr>
<tr>
<td>Body mass index, kg/m²</td>
<td>22.6 (2.5)</td>
</tr>
<tr>
<td>Diagnosis (Infarction/Hemorrhage)</td>
<td>15/5</td>
</tr>
<tr>
<td>Dominant side (right/left)</td>
<td>20/0</td>
</tr>
<tr>
<td>Paresis side (right/left)</td>
<td>10/10</td>
</tr>
<tr>
<td>Days after the stroke</td>
<td>60.7 (32.3)</td>
</tr>
<tr>
<td>FMA-UL</td>
<td>52.1 (7.2)</td>
</tr>
<tr>
<td>STEF</td>
<td></td>
</tr>
<tr>
<td>Affected side</td>
<td>60.6 (17.2)</td>
</tr>
<tr>
<td>Unaffected side</td>
<td>92.8 (7.0)</td>
</tr>
<tr>
<td>Affected/Unaffected ratio</td>
<td>0.65 (0.19)</td>
</tr>
<tr>
<td>ARAT</td>
<td></td>
</tr>
<tr>
<td>Affected side</td>
<td>47.0 (17.1)</td>
</tr>
<tr>
<td>Unaffected side</td>
<td>57 (0)</td>
</tr>
<tr>
<td>Affected/Unaffected ratio</td>
<td>0.82 (0.14)</td>
</tr>
<tr>
<td>MAL</td>
<td></td>
</tr>
<tr>
<td>Amount of Use</td>
<td>2.7 (1.4)</td>
</tr>
<tr>
<td>Quality of Movement</td>
<td>2.7 (1.2)</td>
</tr>
<tr>
<td>FIM</td>
<td></td>
</tr>
<tr>
<td>Motor</td>
<td>80.1 (10.5)</td>
</tr>
<tr>
<td>Cognitive</td>
<td>34.2 (1.5)</td>
</tr>
</tbody>
</table>

The values are in mean (SD).
### Table 2  Correlation coefficients.

<table>
<thead>
<tr>
<th>Clinical measurements</th>
<th>Finger usage (Affected side)</th>
<th>Finger usage ratio (Affected/Unaffected side)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>FMA-UL</em></td>
<td>0.41</td>
<td>0.56*</td>
</tr>
<tr>
<td><em>ARAT</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Affected side</strong></td>
<td>0.44</td>
<td>0.53*</td>
</tr>
<tr>
<td><em>STEF</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Affected side</strong></td>
<td>0.48*</td>
<td>0.80**</td>
</tr>
<tr>
<td><strong>Unaffected side</strong></td>
<td>0.12</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Ratio (Affected/Unaffected)</strong></td>
<td>0.47*</td>
<td>0.80**</td>
</tr>
<tr>
<td><em>MAL</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Amount of Use</strong></td>
<td>0.20</td>
<td>0.26</td>
</tr>
<tr>
<td><strong>Quality of Movement</strong></td>
<td>0.19</td>
<td>0.25</td>
</tr>
<tr>
<td><em>FIM-m</em></td>
<td>0.43</td>
<td>0.25</td>
</tr>
</tbody>
</table>

* p < .05, ** p < .01

### Table 3  Correlation coefficients.

<table>
<thead>
<tr>
<th>Clinical measurements</th>
<th>Upper limb usage (Affected side)</th>
<th>Upper limb usage ratio (Affected/Unaffected side)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>FMA-UL</em></td>
<td>0.46*</td>
<td>0.37</td>
</tr>
<tr>
<td><em>ARAT</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Affected side</strong></td>
<td>0.57**</td>
<td>0.48*</td>
</tr>
<tr>
<td><em>STEF</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Affected side</strong></td>
<td>0.55*</td>
<td>0.55*</td>
</tr>
<tr>
<td><strong>Unaffected side</strong></td>
<td>0.19</td>
<td>0.21</td>
</tr>
<tr>
<td><strong>Ratio (Affected/Unaffected)</strong></td>
<td>0.54*</td>
<td>0.61**</td>
</tr>
<tr>
<td><em>MAL</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Amount of Use</strong></td>
<td>0.24</td>
<td>0.10</td>
</tr>
<tr>
<td><strong>Quality of Movement</strong></td>
<td>0.26</td>
<td>0.10</td>
</tr>
<tr>
<td><em>FIM-m</em></td>
<td>0.36</td>
<td>0.01</td>
</tr>
</tbody>
</table>

* p < .05, ** p < .01