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# Temporal Motor Coordination in the Ankle Joint Following Upper Motor Neuron Lesions

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**Abstract.** [Purpose] We compared ankle temporal motor coordination between stroke, spinal disease and healthy elderly groups, and investigated the relationship between motor impairments and gait speed. [Subjects] Twenty-four patients with stroke, 19 post-operative spinal disease patients and 17 healthy elderly subjects participated. [Methods] Ankle temporal motor coordination of the three groups was assessed using the simple reaction time, the foot-tapping test, and a rhythm task. Rhythm error and rhythm variation were analyzed using the results of the rhythm task. Isometric muscle strength, spasticity, muscle stiffness, somatosensory and 10-m gait speed of the stroke and spinal disease subjects were also measured. [Results] Only the stroke group showed significant reductions in temporal accuracy and consistency in the rhythm task. Simple reaction time and the rhythm task were significantly poorer in the stroke group, whereas the foot-tapping test was not. Stepwise multiple regression analysis indicated gait speed was explained by rhythm error and plantarflexor strength in the stroke group, and rhythm error and simple reaction time in the spinal disease group. [Conclusion] Poor performance in simple reaction time and the rhythm task in the stroke group suggest these tasks are controlled by the supraspinal central nervous system. Negative features, particularly motor coordination, are more associated with gait speed than positive features.
**Key words**: Motor coordination, Ankle joint, Upper motor neuron lesion

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## INTRODUCTION

Motor impairments following upper motor neuron syndrome are classified into three types of features: positive, negative, and adaptive[1)]. Positive features represent newly emerging phenomena due to upper motor neuron lesions, such as spasticity. Negative features represent the loss of previously existing abilities, as seen in muscle weakness, paresis, and loss of dexterity. Adaptive features are secondary phenomena, such as muscle contracture, as a result of disuse or immobilization. Traditional rehabilitation for patients with upper motor neuron syndrome has emphasized positive features. Under the assumption that exercise that requires high-level effort would aggravate abnormal muscle activity, clinicians have paid less attention to negative or adaptive features[2, 3)]. Negative features are currently widely accepted to be more likely than positive features to disturb motor performance[4–6)]. Although the importance of muscle strength is well recognized, motor coordination rarely gains attention. Motor coordination is defined as the ability to adjust precisely and quickly to a changing environment, and can be divided into temporal and spatial components[7, 8)]. Canning et al. revealed that muscle strength and motor coordination are distinct phenomena, and suggested that impairment of each should not be confounded[7)]. Based on the definition of motor coordination, the present study conducted three assessments to measure temporal ankle motor coordination in a clinical situation: simple reaction time (SRT), the foot-tapping test (FTT), and a rhythm task (RT). SRT is a well-known and widely accepted method of measuring the latency from stimulation to the onset of response[9)]. FTT is also a popular method of measuring ankle motor coordination, and a poor performance implies a lesion in the pyramidal tract[10)], with the magnitude reflecting the severity of cervical myelopathy[11)]. We also conducted a RT, the reliability of which has already been reported[12)].

Previous studies have reported a relationship between some motor impairments and gait speed. As for negative features, some reports have shown the contributions of plantarflexor[13, 14)] and dorsiflexor[15)] strength to the gait speed of stroke patients. On the other hand, in terms of positive features, spasticity might have less effect on gait speed, since one meta-analysis[16)] reported that improvements in spasticity of stroke patients, after injection of botulinum toxin into the gastrocnemius, resulted in limited changes in gait speed. Nevertheless, to the best of our knowledge, no study has shown a relationship between gait speed and motor impairments, including motor coordination, using multiple regression analysis. By analyzing multiple motor impairments at the same time, we can gain a better understanding of the dominant factors determining gait speed. We investigated the ankle joint: because ankle dorsiflexion reflects gross lower limb motor function in stroke patients[17)]; and to examine correlations between motor impairments and gait

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speed[18]. The aim of this study was to compare ankle temporal motor coordination among stroke, spinal disease and healthy elderly subjects, and to investigate the relationship between motor impairments and gait speed, using multiple regression analysis.

## SUBJECTS AND METHODS

This study was conducted as a cross-sectional observational investigation of motor impairments and gait speed of stroke, spinal disease patients and healthy adults. Both the stroke and spinal disease participants were recruited from a hospital, and the healthy adults were recruited from among participants in community activities. Measurements of the stroke and spinal disease subjects were performed at a hospital, and the same measurements were performed at a community center for the healthy adults.

The participants were 24 subjects with stroke, 19 postoperative spinal disease subjects, and 17 healthy elderly subjects. Subjects were excluded if they had both stroke and spinal disease, or if they had cognitive, language comprehension or auditory deficits. Stroke patients with cerebellar or brainstem lesions were excluded from this study. To maintain the generality of findings, we did not exclude subjects on the basis of severity of motor impairments such as spasticity or muscle strength. Measurements of the spinal disease subjects were conducted 14 days postoperatively. The most common spinal disease in the group was cervical myelopathy, while other patients showed ossification of the posterior longitudinal ligament and yellow ligament. Table 1 shows a summary of the characteristics of each group. The research ethics administration at Harunaso Hospital approved all study protocols (No. 110104), and informed consent was obtained from all participants prior to data collection.

Motor coordination was measured for all three subject groups. The remaining measurements (muscle strength, spasticity, muscle stiffness, somatosensory function and gait speed) were performed only for the stroke and spinal disease group subjects. In the stroke group, the leg on the paretic side was tested. In the spinal disease and healthy elderly groups, the leg on the dominant side was tested. Foot dominance was determined by self-report as the leg normally used to kick a ball.

Motor coordination was assessed using three DIFFERENT methods. For simple reaction time, subjects sat in a relaxed position, with their feet on the ground. Subjects responded with ankle dorsiflexion to the sound produced by an electronic metronome (DB-30, Roland), as soon as possible. The metronome emits a light when it produces a beep. A video of each trial was recorded in the sagittal plane at 210 fps using a digital camera (EX-FC100, Casio) placed about 1 m from the chair, and the captured images were analyzed using Image J software (National Institute, USA). Duration from the onset of the light sign (i.e., beep) until the head of the fifth metatarsal bone left the ground was defined as the reaction time. The measurement was conducted 3 times, with an interval of 30 s of rest between trials.

The foot tap test was used as an indicator of movement speed. The FTT is a test of subjects' ability to switch between ankle dorsi- and plantar-flexion, and reflects the level of coordination between agonist and antagonist muscles. Numasawa et al. reported that the results of FTT correlate with the physical function of patients with cervical myelopathy, and performance deteriorates with aging[11]. Although most previous studies have measured FTT in the largest range of motion (ROM), this method might be confounded by muscle strength. Subjects sat in a relaxed position, with their feet on the ground, then tapped the required foot by switching between dorsi-and plantarflexions as many times as possible in 10 s, regardless of the ROM, in order to differentiate motor coordination between agonist and antagonist muscles from muscle strength.

The rhythm task (RT) was undertaken to assess subjects'

**Table 1.** Characteristics of the groups

| | Stroke | Spinal disease | Healthy elderly |
|---|---|---|---|
| Age (years) | 68.8±10.9<br>(64.1, 73.5) | 67.8±10.0<br>(62.8, 72.8) | 80.1±5.1<br>(77.5, 82.8) |
| Sex (male:female) | 10:14 | 8:11 | 0:17 |
| Diagnosis*<br>(number of subjects) | Infarction: 13<br>Hemorrhage: 11 | OPLL: 5<br>OYL: 1<br>CSM: 9<br>TDH: 2<br>Tumor: 4 | – |
| Test side (right:left) | 15: 9 | 17: 2 | 17: 0 |
| Length from onset/operation (days) | 240.7±287.4<br>(116.4, 364.9) | 36.9±27.7<br>(23.5, 50.3) | NT |
| Active ROM of dorsiflexion (degrees) | 8.8±11.5<br>(3.9, 13.6) | 14.5±7.4<br>(10.9, 18.1) | NT |
| Fugl-Meyer assessment (/34) | 29.7±4.6<br>(27.8, 31.7) | NT | NT |

OPLL, ossification of posterior longitudinal ligament; OYL, ossification of the yellow ligament; CSM, cervical spondylotic myelopathy; TDH, thoracic disc herniation.
* Includes multiple diseases in the same subject.

ability to adjust movement timing to a given rhythm. Subjects were seated on a chair, with their feet on the ground. An electric metronome was used to present the subjects with three different rhythms: 0.8 Hz, 1.6 Hz, and 2.4 Hz. These target timings were chosen based on a previous study[12]. Subjects were instructed to perform alternate dorsi- and plantarflexion as accurately as possible by tapping the foot at the given metronome rhythm. Subjects were not explicitly asked to tap the foot with the largest ROM possible, to minimize the influence of muscle strength on the test. One or two practice sessions were conducted prior to data collection. For each session, the subject had to perform 21 tapping repetitions. An interval of 30 s was given between sessions. A video of each trial was recorded in the sagittal plane at 30 fps using the digital camera placed about 1 m from the chair, and the captured images were analyzed using Image J software. Rhythm error (RE) and rhythm variation (RV) were calculated as indicators of temporal accuracy and consistency of the task, respectively. These parameters were calculated for each rhythm condition, using the following formulae:

$$RE\ (s) = |(\text{Target interval}) - (\text{Mean of tap-to-tap interval})|$$

$$RV = \text{Standard deviation of tap-to-tap interval} / \text{Mean of tap-to-tap interval}$$

A hand-held dynamometer ($\mu$TAS F-1, ANIMA) was used to measure force during isometric dorsiflexion and plantarflexion. Subjects lay in the supine position, extending the knee for plantarflexion measurements, while slightly (10–30°) flexing the knee using a pillow for support in the dorsiflexion trials, to exclude the influence of antagonist

**Table 2.** Summary of test results

| | | Stroke | Spinal disease | Healthy elderly |
|---|---|---|---|---|
| Simple reaction time (s)* | | 0.30±0.07 | 0.25±0.05 | 0.22±0.02 |
| | | (0.27, 0.33) | (0.22, 0.28) | (0.21, 0.23) |
| | | | ** | ** |
| Foot tapping test* | | 23.0±10.8 | 29.7±7.9 | 27.3±5.6 |
| | | (18.3, 27.6) | (25.9, 33.5) | (24.4, 30.2) |
| Rhythm error (s)* | 0.8 Hz | 0.05±0.10 | 0.01±0.01 | 0.01±0.01 |
| | | (0.01, 0.10) | (0.00, 0.01) | (0.01, 0.01) |
| | | | ** | |
| | 1.6 Hz | 0.04±0.07 | 0.01±0.03 | 0.01±0.01 |
| | | (0.01, 0.08) | (0.00, 0.03) | (0.00, 0.01) |
| | 2.4 Hz | ** 0.08±0.13 | 0.03±0.07 | 0.01±0.02 |
| | | (0.02, 0.14) | (0.00, 0.06) | (0.00, 0.02) |
| Rhythm variety* | 0.8 Hz | 0.10±0.06 | 0.07±0.02 | 0.08±0.03 |
| | | (0.07, 0.13) | (0.06, 0.08) | (0.07, 0.10) |
| | 1.6 Hz | ** 0.13±0.12 | 0.07±0.03 | 0.08±0.05 |
| | | (0.07, 0.18) | (0.05, 0.08) | (0.06, 0.11) |
| | 2.4 Hz | ** 0.20±0.15 | 0.09±0.03 | 0.10±0.05 |
| | | (0.13, 0.27) | (0.07, 0.10) | (0.08, 0.13) |
| | | | ** | ** |
| Strength (% body weight)* | D/F | 0.13±0.09 | 0.13±0.06 | NT |
| | | (0.29, 0.49) | (0.37, 0.52) | |
| Stretch reflex (/4) † | KE | 0.0 (1.0) | 1.0 (1.0) | NT |
| (APTS) | KF | 0.5 (1.8) | 1.0 (2.0) | NT |
| Middle range resistance (/4) † | KE | 0.0 (0.8) | 0.0 (0.0) | NT |
| (APTS) | KF | 0.0 (0.0) | 0.0 (0.0) | NT |
| Final range resistance (/4) † | KE | 0.0 (2.0) | 0.0 (1.0) | NT |
| (APTS) | KF | 0.0 (0.8) | 0.0 (0.0) | NT |
| Passive ROM (degree)* | KE | 12.7±8.5 | 15.5±4.7 | NT |
| | | (3.9, 13.6) | (10.9, 18.1) | |
| | KF | 23.3±7.5 | 25.2±6.0 | NT |
| | | (20.2, 26.5) | (23.4, 27.6) | |
| Somatosensory function (/6) † | | 6.0 (2.7) | 5.0 (1.0) | NT |
| (Fugl-Meyer assessment set) | | | | |
| Gait speed (s)* | | 19.6±22.2 | 10.2±7.6 | NT |
| (10-m gait time) | | (7.8, 31.4) | (6.5, 13.9) | |

* Mean ± standard deviation (95% confidence interval: lower limit, upper limit)
† Median (interquartile range)
** $p<0.05$
D/F, dorsiflexion; P/F, plantarflexion; KE, knee extended; KF, knee flexed; NT, not tested.
HHD, hand-held dynamometer; APTS, Ankle Plantarflexors Tone Scale; ROM, range of motion.

stiffness[19]. The dynamometer was anchored stably, using a belt to ensure reliable results. The test was performed at 0° dorsiflexion for 3 sessions, and the maximum values were chosen as representative values.

Spasticity was measured by the Ankle Plantar Flexors Tone scale (APTS), developed by Takeuchi et al., as an assessment tool for measuring muscle tone in the plantar flexors[19]. This scale was developed to distinguish reflex and non-reflex components of muscle tone by stretching the muscle at different velocities; its validity and reliability have been already reported[20]. Stretch reflex, as an indicator of spasticity, was measured with the knee both extended and flexed in the supine position. Muscle stretch was performed rapidly to induce spasticity.

Both middle-range resistance and final-range resistance on the Ankle Plantar Flexors Tone scale were measured as indicators of muscle stiffness. In addition, passive ROM of ankle dorsiflexion was measured. Each test was conducted with the knee both extended and knee flexed in the supine position. Stretch was performed at a very slow speed in order to avoid confounding muscle stiffness with spasticity.

The lower limb motor item of the Fugl-Meyer assessment[21] was assessed in the stroke group, as a profile of gross lower limb function. Active ROM (AROM) of dorsiflexion was measured using goniometry as an indicator of ankle motor function in the supine position in both the spinal disease and stroke group subjects.

Sensory items of the Fugl-Meyer assessment were also assessed. Fine touch and proprioception of the lower limb were tested in the supine position.

The 10-m walking time (10MWT) was measured using a stop watch. Subjects were allowed to use walking aids, such as a cane or brace, if needed. Subjects were instructed to walk as quickly as possible at a safe speed for 14 m. Subjects' gait was timed between the 2 m and 12 m marks to eliminate acceleration and deceleration effects[22].

Spearman correlation coefficients were computed to test the relationships of motor coordination measurements among the three subject groups. The Friedman test was used to compare RE and RV among the different rhythms (0.8, 1.6 and 2.4 Hz) in each group. The Wilcoxon matched pairs test was used to test items determined significant by the Friedman test and the significance level was corrected using Bonferroni inequality. Analysis of variation and multiple comparisons were performed to compare SRT and FTT among the groups. The Kruskal-Wallis test was conducted to compare RE and RV among the subject groups. The Mann-Whitney test was used to test significance identified by the Kruskal-Wallis test and the significance level was corrected by Bonferroni inequality. Multiple regression analysis was carried out using a stepwise method, to determine correlations with gait speed. Gait speed was submitted as a dependent variable, and the results for SRT, FTT, 2.4-Hz RE, 2.4-Hz RV, passive ROM (knee extension), stretch reflex (knee extension), dorsiflexion strength, plantarflexion strength and total score of the Fugl-Meyer sensory items were submitted as independent variables. All statistical analyses were performed using IBM SPSS Statistics 17.0 for Windows. Statistical significance was accepted for values of $p<0.05$ in all tests.

## RESULTS

The demographic and test results of the study groups are summarized in Table 1. Gross lower limb function was high in the stroke group. The results of AROM indicated that ankle motor function was high in the spinal disease group, while some stroke subjects could not actively dorsiflex the ankle. Spasticity and muscle contracture ranged from mild to moderate in both the stroke and spinal disease groups. No severe sensory disorder was observed in either patient group.

Only the stroke group showed significant differences among the three rhythms. The spinal disease and healthy elderly groups did not show significant differences in RE or RV among the three rhythms.

The results of single regression analysis are presented in Table 3. In the stroke group, RE and RV showed moderate to strong correlations. The relationships of RE and RV to SRT and FTT were weak to moderate. In the spinal and healthy adult groups, relationships between all measurements were weak.

SRT in the stroke group was significantly delayed compared to the spinal disease and healthy adult groups ($F=10.121$, $p<0.01$). RE at 0.8 Hz ($\chi^2=11.390$, $p<0.01$) and RV at 2.4 Hz ($\chi^2=9.792$, $p<0.01$) in the stroke group were significantly impaired compared to the spinal disease and healthy elderly groups (Table 2). We also compared differences in RE and RV among the three rhythms in each subject group. A significant difference was found only in the stroke group, between 1.6 Hz and 2.4 Hz in RE ($\chi^2=9.789$, $p<0.01$), and between 0.8 Hz and 1.6 Hz and 2.4 Hz in RV ($\chi^2=17.789$, $p<0.01$).

Table 4 shows the results of stepwise multiple regression analysis for both patient groups. Both 2.4-Hz RE and plantar flexor strength were identified as independent factors by stepwise multiple regression analysis in the stroke group. This model accounted for 90.9% of the variation in gait speed between subjects ($R^2_{adj}=0.909$). The same multiple regression analysis was undertaken for the spinal disease group and 2.4-Hz RE and SRT were identified as independent factors. This model explained 81.6% of the variation in gait speed ($R^2_{adj}=0.816$).

## DISCUSSION

Recent studies have revealed that negative features, which have not traditionally received much attention, are more related to functional performance than positive features. Most studies have reported muscle strength as representative of negative features. However, motor coordination is rarely discussed. We therefore measured all three features, positive, negative and adaptive features, in the same subjects, all of whom had a history of upper motor neuron lesions. We adopted three measurements for motor coordination, orientated to distinguish results from muscle strength. Associations among RE, RV, SRT and FTT were weak to moderate, suggesting that each variable was relatively independent and reflected different aspects of ankle

**Table 3.** Relationships of motor coordination measurements among the three subject groups

| | | | RE | | | RV | | | SRT | FTT |
|---|---|---|---|---|---|---|---|---|---|---|
| | (Hz) | | 0.8 | 1.6 | 2.4 | 0.8 | 1.6 | 2.4 | | |
| RE | 0.8 | St | | 0.491* | 0.610* | 0.503* | 0.492* | 0.625* | 0.310 | −0.239 |
| | | SD | | −0.035 | 0.281 | 0.112 | 0.260 | 0.088 | 0.300 | −0.443 |
| | | HA | | −0.016 | −0.022 | 0.297 | 0.201 | −0.344 | −0.016 | −0.098 |
| | 1.6 | St | | | 0.808* | 0.220 | 0.672* | 0.627* | 0.363 | −0.581* |
| | | SD | | | 0.392 | −0.099 | 0.491* | 0.500* | 0.364 | −0.258 |
| | | HA | | | 0.384 | 0.306 | 0.319 | 0.231 | 0.316 | −0.452 |
| | 2.4 | St | | | | 0.189 | 0.781* | 0.777* | 0.478* | −0.526* |
| | | SD | | | | −0.042 | 0.329 | 0.471* | 0.395 | −0.547* |
| | | HA | | | | 0.314 | 0.414 | 0.263 | −0.136 | −0.118 |
| RV | 0.8 | St | | | | | 0.614* | 0.471* | 0.133 | −0.307 |
| | | SD | | | | | 0.253 | 0.198 | −0.366 | 0.059 |
| | | HA | | | | | 0.306 | −0.196 | −0.178 | 0.014 |
| | 1.6 | St | | | | | | 0.746* | 0.394 | −0.556* |
| | | SD | | | | | | 0.227 | 0.233 | −0.245 |
| | | HA | | | | | | 0.401 | 0.020 | −0.336 |
| | 2.4 | St | | | | | | | 0.259 | −0.470* |
| | | SD | | | | | | | −0.181 | −0.113 |
| | | HA | | | | | | | 0.322 | −0.380 |
| SRT | | St | | | | | | | | −0.230 |
| | | SD | | | | | | | | −0.545* |
| | | HA | | | | | | | | −0.372 |

St, stroke group; SD, spinal disease group; HA, healthy adult group
* $p<0.05$

**Table 4.** Results of multiple regression analysis

| | Stroke group | Spinal disease group |
|---|---|---|
| Dependent variable | 10-m gait time | 10-m gait time |
| Independent variables (Standard partial regression coefficient) | 2.4 Hz RE (0.885), Plantar flexor strength (−0.170) | SRT (0.514), 2.4 Hz RE (0.502) |
| *Adjusted* $R^2$ | 0.909 | 0.816 |
| *F* | 55.874 ($p<0.01$) | 40.821 ($p<0.01$) |

motor coordination.

Ada showed two sources of weakness following stroke[23]. Lesions of the neuromotor system lead to a reduction in the number of motor units available for recruitment. Lack of muscle activity and immobility results in secondary weakness. Because a long time had elapsed since stroke onset in the participants in this study, the influence of secondary factors may have been confounded.

In all groups, rhythmic accuracy (i.e., RE) and consistency (i.e., RV) decreased as the given rhythm increased. This result can be explained as a speed-accuracy trade-off. The decrease in temporal coordination was particularly obvious in stroke patients, because RE and RV were significantly disturbed as target rhythm increased, unlike in the spinal disease and healthy elderly groups. Faster rhythm made it more difficult for the stroke patients to correct movement errors in a given interval compared to the spinal disease and healthy adult groups. Furthermore, rhythmic accuracy and consistency were more impaired in the stroke group than in the other groups. SRT was significantly delayed in the stroke group, while FTT was not. These results suggest that supraspinal control plays an important role in SRT and RT, unlike FTT. Wirth et al. reported that rhythmic motor coordination is less impaired in individuals with incomplete spinal cord injury than in stroke subjects[24]. Considering these results, adoption of three measurements allowed successful differentiation of supraspinal motor coordination. This is the first study to investigate the differences in multiple measurements of motor coordination in the lower limb of the same subjects. For a better understanding of these findings, the relationship between brain lesion sites and loss of motor coordination needs to be clarified in the future.

Multiple regression analysis for both patient groups by stepwise multiple regression analysis indicated high validity of the present models, since the F values obtained were relatively high. The identified variables were only negative

features, indicating that motor coordination was probably the dominant factor explaining gait speed in both groups. Therefore, in addition to conventional findings that muscle strength is more strongly related to gait speed than positive features such as spasticity[13, 25], our findings suggest that motor coordination also plays a significant role in determining gait speed. Our findings are more likely to be valid, because we undertook stepwise multiple regression analysis with multiple impairments. These results successfully excluded spurious relationships between motor impairments and gait speed. Thus, interventions for improving gait speed should focus more on negative impairments, particularly on motor coordination, which is controlled by the supraspinal central nervous system. Further research is needed to clarify whether intervention emphasizing motor coordination can indeed effectively improve gait speed.

The present investigation had some limitations. We measured only temporal aspects of motor coordination at a single joint, so spatial factors at multiple joints should be taken into consideration in future research. Participants in both the stroke and spinal disease groups showed relatively high motor function of the lower limb. Future investigations including subjects with severe motor function are needed to generalize the findings in this study. Furthermore, we could not clarify the contribution of brain lesion site to motor coordination.

Each of the coordination tests, SRT, FPT and RT, reflect different aspects of temporal motor coordination at the ankle joint. SRT and RT are controlled at the supraspinal level. Negative features, particularly motor coordination, are more associated with gait speed than positive features. Intervention for improving gait speed should therefore focus more on negative impairments, particularly motor coordination, which is controlled at the supraspinal central nervous system.

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