Research article

# Intersession reliability of thoracolumbar multisegmental motor responses

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Study design: Experimental design.
Objective: To determine test-retest reliability across sessions of the thoracolumbar multisegmental motor responses (MMR) in the upper and lower limbs of healthy subjects. Test-retest reliability of MMR has not been established or examined in previous studies.
Settings: Neuro Laboratory of the Texas Woman's University (School of Physical Therapy, Houston, TX, USA).
Methods: The MMR of 15 healthy subjects were tested over two sessions. T11–12 vertebral segments were electrically stimulated using surface electrodes. MMR signals of the upper and lower limbs were recorded, using surface electrodes, from the upper extremity muscles (abductor pollicis brevis, flexor carpi radialis, biceps brachii, triceps brachii), and from the lower extremity muscles (vastus medialis obliqus, medial hamstring, soleus, tibialis anterior). The peak-to-peak maximum amplitude and deflection latency were the dependent parameters. Data from the first session was compared with a second session (on a different day), using interclass correlation coefficient (ICC), to evaluate the reliability across sessions. In addition, data from the right limbs were compared with the left limbs.
Results: MMR of the right and left, upper and lower extremities were comparable between limbs in all subjects. Further, signals were highly correlated between days of testing (ICC = 0.58–0.99) and was not statistically different between the two sessions in the same subject.
Conclusion: These results indicate that MMR studies could be useful for serial testing of patients with neurological disorders, such as spinal cord injuries and diseases.

**Keywords:** Multi-segment motor response, Reliability, Correlation, Spinal cord, Thoracic

## Introduction

Electrophysiological testing of the spinal cord circuitries could complement clinical and imaging findings. A newly developed electrophysiological test is the multisegmental motor responses test (MMR). MMR includes percutaneous electrical stimulation of the spine that can be applied at the C7, the T11–T12 vertebral levels, and recording upper and lower limb muscular signals simultaneously from proximal and distal muscles.[1,2] Limb muscle responses using MMR have been recorded at variable amplitudes and latencies[1,2] in response to a single electrical stimulus (ES). Findings indicate that signal latency of the muscle response is compatible with the distance of the muscle from the generator source at the spinal cord.[1,2] These signals hold promise for identifying neurological disorders, especially for patients with spinal cord injuries and diseases. For example, recording the upper limb signal during T11–T12 stimulation may evaluate the integrity of the ascending spinal pathways to the upper limbs. Similarly, recording upper limb MMR with C7 stimulation may evaluate the integrity of the descending or the direct spinal pathways to upper limb muscles. The descending spinal pathways may also be evaluated by the C7 stimulation and by recording lower limb MMR (the focus of future report). Therefore, MMR signals may be useful in testing different spinal levels with a single ES thereby saving valuable clinical time and providing detailed information on spinal circuitries.

The major drawback of the MMR test is that it requires accurate placement of the electrically-stimulating electrodes at the T11–T12 vertebrae, compared with the prominent C7 vertebra. Similarly, stimulation and

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DOI 10.1179/2045772313Y.0000000121

recording electrodes placement and positioning can influence signal amplitude and shape thus affecting the reliability of the collected data across sessions. Recorded signals may also vary across sessions due to changes in the excitability of the spinal centers,[3–6] resulting in smaller or larger signal amplitudes. Such signal variability could negatively affect serial testing of patients and may discredit the accuracy of such electrophysiological procedures. Serial testing of spinal cord injury patients for example, demands reliable procedures that are consistent across sessions. Therefore, before MMR can be used as a routine diagnostic tool, its reliability must be established in healthy individuals. Given that such reliability has not been studied previously, our first aim is to investigate intersession reliability of thoracic MMR (TMMR) in healthy subjects.

Limb dominance and the fact that right and left limb muscles may have different strength levels, due to differences in training, function, and neural control may cause signal asymmetries between healthy and injured subjects.[7–10] Therefore, it is important to test MMR signal from opposite upper and lower extremities. To address the existing gap in the literature, the second aim of this study is to investigate reliability of MMR across left and right upper and lower limbs in healthy subjects.

## Materials and methods

Fifteen healthy subjects (seven men and eight women; age = 31 ± 10.4 years, height = 167.7 ± 9.9 cm, weight = 67.4 ± 13.2 kg) signed informed consent forms, thereby agreeing to participate in this study. All subjects were right handed. Subjects were excluded if they had a history of neck, back, or limb pain, a history of metabolic, neurological disease (including radiculopathy), arthritis, or any form of cancer diagnosis within the previous 12

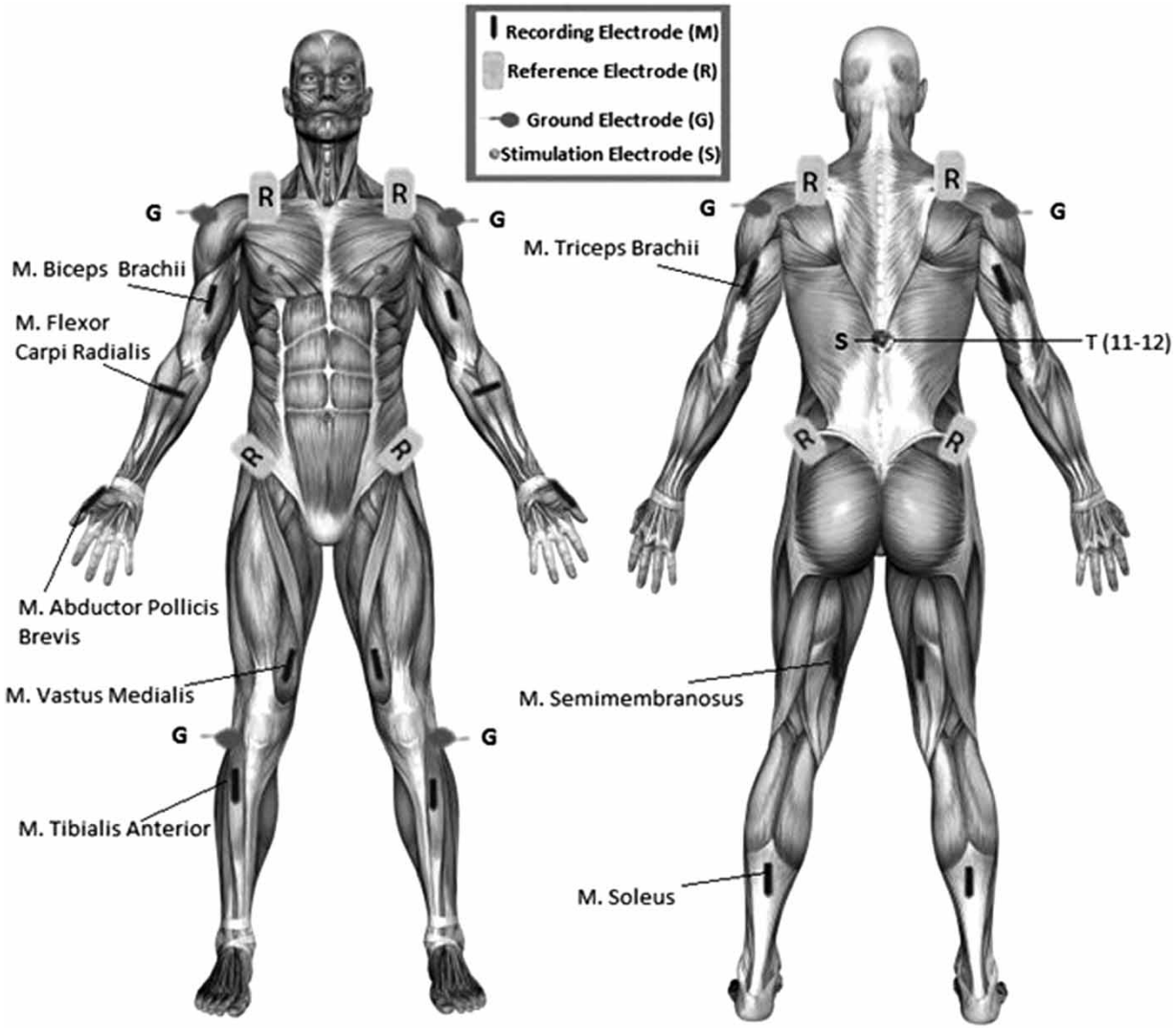


**Figure 1 Recording set-up for T11–T12 MMR in healthy subjects.**

months, or if they were obese (BMI > 30). Subjects were able to tolerate strong ES to the thoracolumbar spine.

### *Electrical stimulation and recording*

The T11–T12 vertebral segments were electrically stimulated with 1-ms square-wave pulses at 0.2 pps at the maximum muscular response (muscle action potential (MAP)). Maximum MAP was determined by increasing the strength of the ES until the EMG signal amplitude increased and reached a plateau that would no longer change with increased ES, at a tolerable level. The T11–T12 spinous processes were palpated during flexion/extension of the trunk. A cup electrode was affixed to the intervertebral space. For accurate and effective stimulation and recording, all electrodes (cathodes) were tightly fixed to the skin throughout the entire session. The reference electrode (anode) was a $5 \times 9$-inch square, pre-gelled flexible pad (similar to those used for transcutaneous electrical stimulation) that was attached to the corresponding acromion process (for upper extremity stimulation) or the anterior superior iliac spine (for lower extremity stimulation). Stimulation was the most critical step of this experiment.

Maximum MAP values were recorded using a four-channel Cadwell EMG unit (Cadwell Laboratories, Kennewick, WA, USA). Surface silver–silver chloride cup electrodes with gel were applied on the muscles using 3M hypoallergenic tape. A metal ground electrode (3 cm diameter) with gel was applied to the subject's upper and lower extremities (Fig. 1). Signal-to-noise ratio was improved by sanding the skin electrode sites with light-grade sandpaper and cleaning with alcohol. Signal artifacts were minimized by positioning the ground electrode between the stimulation and recording sites and by using the split screen technique of the Cadwell EMG unit, if necessary, to suppress these artifacts. In our previous study,[2] we established and recorded upper and lower extremity MMR during ES at the T11–T12 vertebral level. Therefore, to acquire TMMR, MAP was recorded from common motor points of the right and left upper extremity including the abductor pollicis brevis, flexor carpi radialis, and biceps brachii and triceps. For the lower extremity,

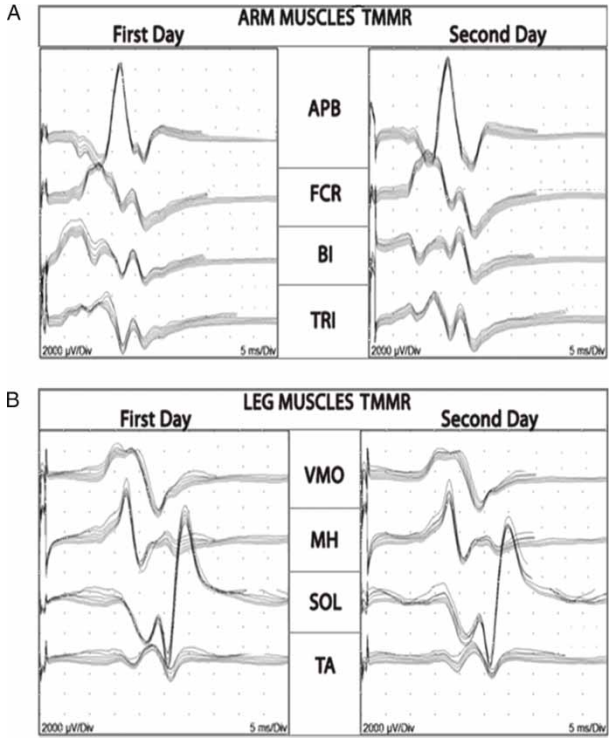


**Figure 2.1 Sample traces for T11–T12 MMR for right upper extremity for days 1 and 2 (A) (APB, abductor pollicis brevis; FCR, flexor carpi radialis; BI, biceps brachii; Ch 4: TRI, triceps muscle MMR), and T11–T12 MMR for right lower extremity (B) (VMO, vastus medialis obliques; MH, medial hamstring; SOL, soleus; TA, tibialis anterior) in two different days.**

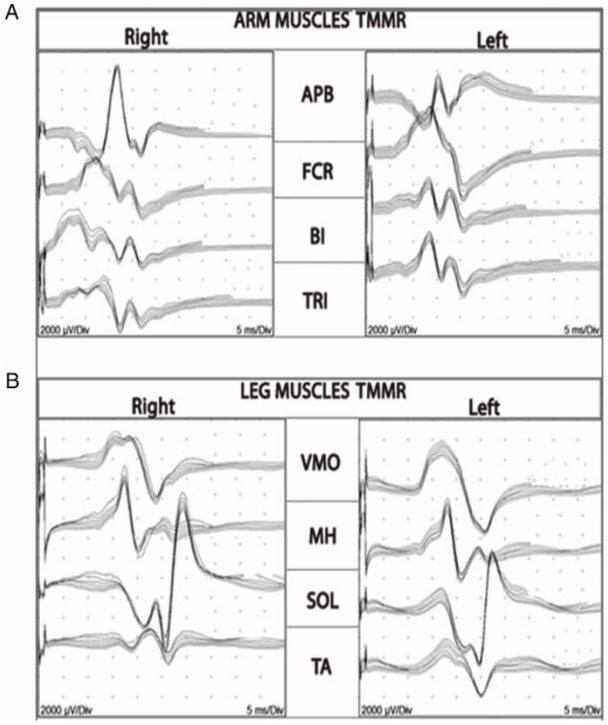


**Figure 2.2 Sample traces of T11–T12 stimulation (A) upper extremity (TMMR-upper) (right) (left) (Ch1: APB, abductor pollicis brevis; Ch2: FCR, flexor carpi radialis; Ch 3: BI, biceps brachii; Ch 4: TRI, triceps muscle MMR), (B) lower extremity (TMMR-lower) (right) (left) (Ch 1: VMO, vastus medialis obliques; Ch 2: MH, medial hamstring; Ch 3: SOL, soleus; Ch 4: TA, tibialis anterior).**

**Table 1 Interclass correlations table for TMMR amplitudes and latency for the right and left arms in the first and second days**

| T11–12 upper extremity multisegmental motor responses | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Amplitude (mV) | | | | Latency (seconds) | | | | *P* |
| Muscles | First day (mean ± SD) | Second day (mean ± SD) | ICC | *F* | First day (mean ± SD) | Second day (mean ± SD) | ICC | *F* | |
| APB (R) | 9.8 ± 4.7 | 9.5 ± 5.1 | 0.904 | 0.181 | 10.7 ± 2.3 | 10.9 ± 2.3 | 0.990 | 2.437 | |
| APB (L) | 8.3 ± 4.4 | 8.5 ± 3.7 | 0.913 | 0.193 | 10.5 ± 2.6 | 10.6 ± 2.4 | 0.971 | 0.200 | |
| FCR (R) | 4.4 ± 2.3 | 4.7 ± 2.8 | 0.937 | 0.815 | 7.2 ± 1.5 | 7.3 ± 1.6 | 0.940 | 0.353 | $P < 0.05$ |
| FCR (L) | 4.6 ± 2.8 | 5.0 ± 3.2 | 0.967 | 2.371 | 7.1 ± 1.4 | 7.1 ± 1.5 | 0.939 | 0.024 | |
| BI (R) | 4.3 ± 3.1 | 3.8 ± 2.8 | 0.924 | 1.098 | 5.1 ± 1.5 | 5.1 ± 1.5 | 0.975 | 0.115 | |
| BI (L) | 4.6 ± 3.5 | 4.8 ± 3.2 | 0.940 | 0.143 | 5.1 ± 1.5 | 5.2 ± 1.6 | 0.985 | 0.896 | |
| TRI (R) | 5.2 ± 4.2 | 6.1 ± 4.2 | 0.890 | 1.682 | 4.9 ± 1.6 | 4.6 ± 1.1 | 0.918 | 0.896 | |
| TRI (L) | 5.3 ± 3.7 | 6.3 ± 4.5 | 0.896 | 2.321 | 4.6 ± 1.7 | 4.7 ± 1.7 | 0.991 | 0.152 | |

All values shown as subjects (15 people) mean ± standard deviation.

MAP was recorded after T11–T12 stimulation using common motor points including: vastus medialis obliques, medial hamstrings, soleus, and tibialis anterior muscles. Recording parameters were 100–1000 μv/div (sensitivity) with sweep speed of 5 ms/div, and the signal was band-passed filtered using a 10 Hz–10-KHz Butterworth filter.

### *Experimental procedures*

For testing, subjects were seated in an armless chair with the arms resting on a pillow on the lap. Stimulation and recording sites were shaved when necessary, cleansed with fine-grade sandpaper, and then wiped with alcohol and dried. Thereafter, electroconductive gel was applied to the electrodes and were taped to the skin sites with 3M tape.

TMMR upper (right and left) and lower (right and left) extremity recordings were performed in order, for a total of four sets of tests. Subjects rested for 3–5 minutes after each limb test. They were instructed to relax and refrain from any limb or head movements during the testing. Before subjects were dismissed, all electrodes were removed and the skin was cleansed. The same procedures were repeated in a second session at least 3 days later. To ensure similar electrode placements in each session bony landmarks (for ES) at the costovertebral junction were used as a guide. Recording electrode placements were carried out according to our previous protocol.[2] Active electrodes were applied on the same location of the common motor points of the muscles, which are usually located at the middle of the muscle bulk and the reference electrode applied 3 cm distal to it. With FCR muscle recording reference

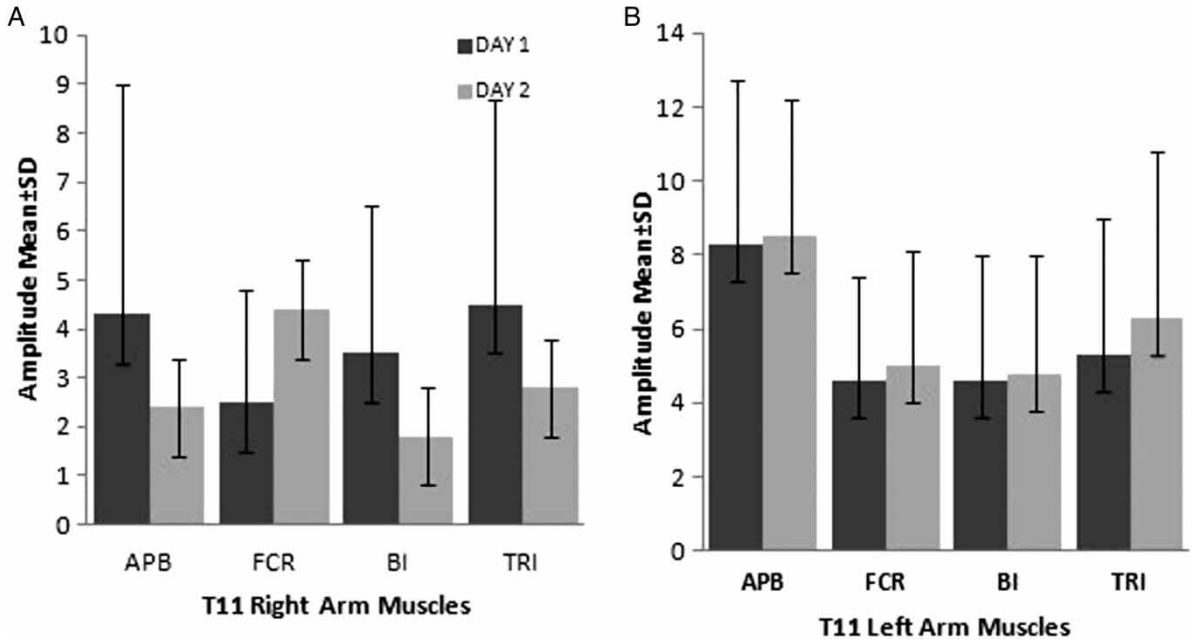


**Figure 3 T11–T12 upper extremity MMR amplitude (mean ± SD) values; (A) right and (B) left side for days 1 and 2.**

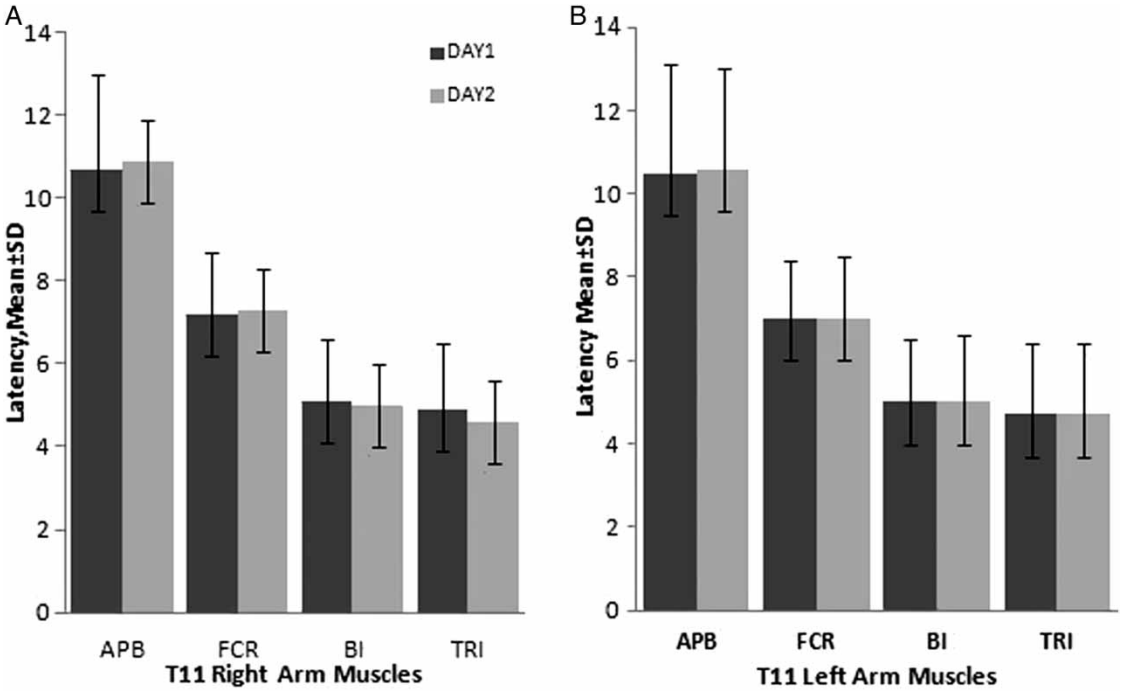


**Figure 4 T11–T12 upper extremity MMR latency (mean ± SD) values; (A) right and (B) left side for days 1 and 2.**

electrodes were applied 3 cm lateral to the active (using two electrodes embedded in a plexiglas rectangle base).

### *Signal and statistical analyses*

Five representative traces out of 10 consecutive stimuli were recorded for each muscle at the 5–10-second intervals necessary to assure capture of consistent traces. All stimuli evoked robust signals, as we employed maximum electric current. Selected traces of each muscle were averaged for each trial and compared using descriptive statistics at 0.05 alpha level. The peak-to-peak amplitude and deflection latency were the dependent parameters. The SPSS-20 statistical package (IBM SPSS Statistics for Windows, Version 20.0. IBM Corp., Armonk, NY) was used to determine interclass correlation coefficient (ICC, mixed model) for testing the intersession reliability. Pearson correlation (*r*) was used to establish the correlation between the dominant and non-dominant upper and lower extremities.

## Results

### *TMMR for upper extremities*

TMMR for the upper extremities resulted in large amplitude signals for all five traces, indicating no habituation to the repeated stimulation. Signals were comparable in shape, latency, and amplitude for the same muscle in both testing sessions (Fig. 2.1A).

ICC values indicated a significant correlation ($P < 0.05$) across sessions (Table 1), showing a strong intersession reliability of the dependent parameters for both upper extremities. The strong ICC was expected given similarities of average values for peak-to-peak amplitude (Fig. 3) and deflection latency (Fig. 4) in addition to the small variability values across sessions.

Sample traces for the right and left upper extremities are demonstrated in Fig. 2.1A. A significant correlation was observed between the right and left upper extremities ($P < 0.05$) for the same muscles within and between sessions (Table 2). The strong correlation was

**Table 2 Correlations table for TMMR UE amplitude and latency for first and second day**

| | T11 UE MMR amplitude | | | | T11 UE MMR latency | | | |
|---|---|---|---|---|---|---|---|---|
| | First day *R* vs. L UE | | Second day *R* vs. L UE | | First day *R* vs. L UE | | Second day *R* vs. LUE | |
| Muscles | *P* value | *R* value | *P* value | *R* value | *P* value | *R* value | *P* value | *R* value |
| APB | 0.788** | 0.000 | 0.817** | 0.000 | 0.953** | 0.000 | 0.928** | 0.000 |
| FCR | 0.880** | 0.000 | 0.929** | 0.000 | 0.869** | 0.000 | 0.819** | 0.000 |
| BI | 0.925** | 0.000 | 0.880** | 0.000 | 0.960** | 0.000 | 0.961** | 0.000 |
| TRI | 0.581* | 0.023 | 0.921** | 0.000 | 0.984** | 0.000 | 0.882** | 0.000 |

*Correlation is significant at the 0.05 level (two-tailed).
**Correlation is significant at the 0.01 level (two-tailed).

**Table 3 Interclass correlations (ICC) table for the TMMR amplitude and latency for the right and left legs in the first and second days**

| T11–12 lower extremity multisegmental motor responses (MMRs) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Amplitude (mV) | | | | Latency (seconds) | | | | *P* |
| Muscles | First day (mean ± SD) | Second day (mean ± SD) | ICC | *F* | First day (mean ± SD) | Second day (mean ± SD) | ICC | *F* | |
| VMO (R) | 4.2 ± 3.7 | 4.3 ± 4.1 | 0.963 | 0.069 | 9.4 ± 2.3 | 9.6 ± 2.3 | 0.987 | 1.707 | |
| VMO (L) | 3.9 ± 3.5 | 3.8 ± 3.0 | 0.937 | 0.092 | 9.5 ± 2.1 | 9.4 ± 2.0 | 0.991 | 0.028 | |
| MH (R) | 4.4 ± 2.4 | 3.7 ± 3.0 | 0.952 | 6.945* | 8.3 ± 2.6 | 8.4 ± 2.6 | 0.988 | 1.214 | |
| MH (L) | 3.5 ± 1.9 | 3.4 ± 1.8 | 0.855 | 0.090 | 8.4 ± 2.5 | 8.7 ± 2.4 | 0.953 | 1.134 | $P < 0.05$ |
| SOL (R) | 6.9 ± 5.2 | 6.1 ± 3.3 | 0.856 | 0.943 | 15.5 ± 2.6 | 15 ± 3.1 | 0.877 | 1.162 | |
| SOL (L) | 6.0 ± 3.8 | 5.7 ± 3.3 | 0.917 | 0.247 | 15.2 ± 2.6 | 15.5 ± 2.8 | 0.961 | 2.149 | |
| TA (R) | 2.1 ± 2 | 1.9 ± 1.7 | 0.928 | 0.560 | 14.3 ± 2.1 | 14.2 ± 2.2 | 0.979 | 0.658 | |
| TA (L) | 2.1 ± 2 | 1.7 ± 1.5 | 0.987 | 1.707 | 14.0 ± 2.1 | 14.0 ± 2.0 | 0.909 | 0.004 | |

*$P = 0.02$.
All values shown as subjects (15 people) mean ± standard deviation.

expected given the similarities of average values for peak-to-peak amplitude (Fig. 3A and B) and deflection latency (Fig. 4A and B) and the small variability values across sessions.

### *TMMR for the lower extremities*

Results from lower extremity recordings after T11–T12 stimulation were similar to the above-mentioned results. No habituation was observed and signals were comparable in shape, latency, and amplitude (Fig. 2.1B).

The ICC values maintained their significance ($P < 0.05$) across sessions for the lower extremities (Table 3), showing a strong intersession reliability of dependent parameters for both lower extremities. Once again, similarities of average values for peak-to-peak amplitude (Fig. 5) and deflection latency (Fig. 6) and the small variability values across sessions were an indication of ICC significant.

The comparison of sample traces for the right and left lower extremities resulted in similar findings as those above wherein no significant differences were recorded (Fig. 2.2B). The correlation was also significant between both lower extremities ($P < 0.05$) for the same muscles within and between sessions (Table 4). Similarities of average values for peak-to-peak amplitude (Fig. 5) and deflection latency (Fig. 6) and their small variability values were also evident.

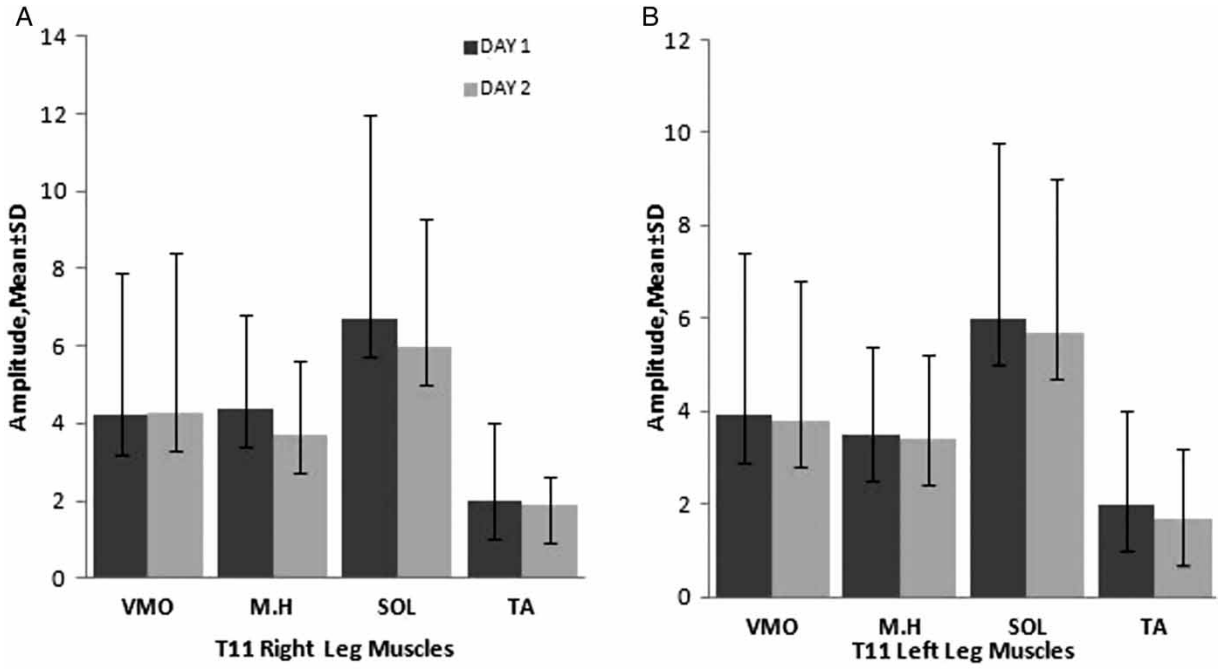


**Figure 5 T11–12 lower extremity MMR amplitude (mean ± SD) values; (A) right and (B) left side for days 1 and 2.**

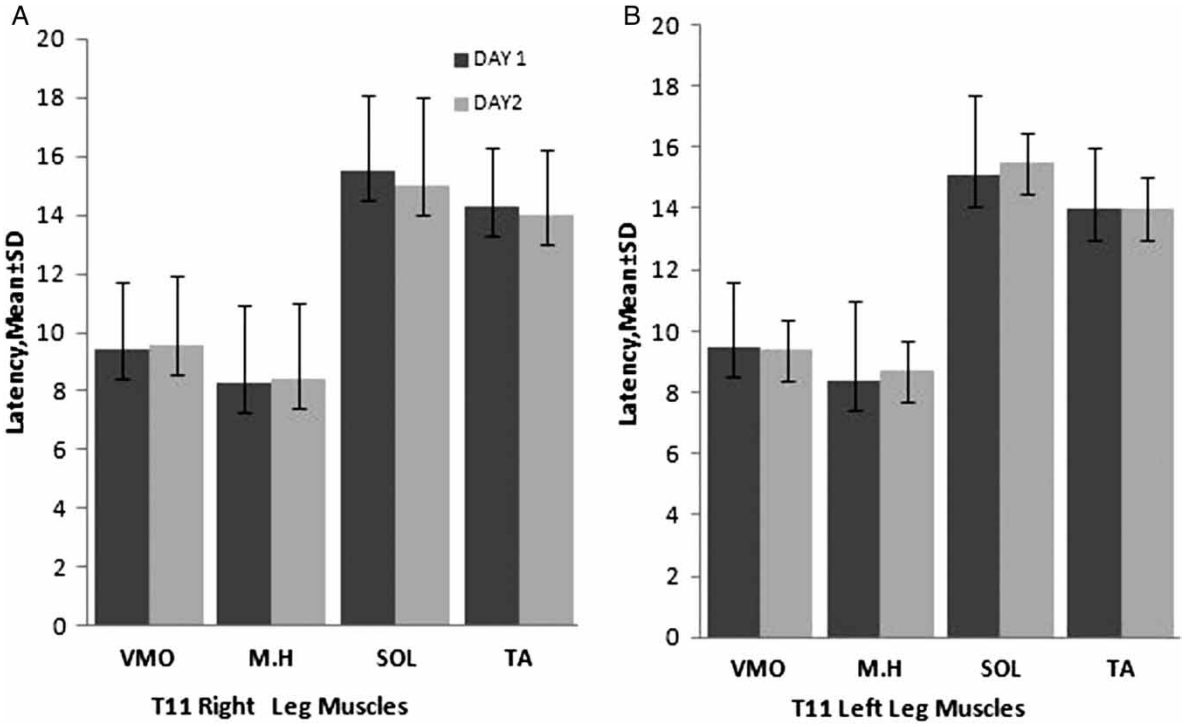


**Figure 6** T11–12 lower extremity MMR latency (mean ± SD) values; (A) right and (B) left side for days 1 and 2.

## Discussion

This study is one of the few to test spinal cord MMR in healthy individuals, and to our knowledge, it is the first to examine intersession reliability of MMR in the upper and lower extremity muscles for this population. Our results indicated significant test-retests reliability for signal amplitude and latency of MAP after TMMR (upper and lower). Furthermore, there was a significant correlation between signal amplitude and latency measures across opposite limbs. Therefore, limb dominance did not appear to affect muscular responses of the MMR as tested in this study.

As suggested in previous studies,[1,2] cervical MMR (CMMR) and TMMR involve different neural pathways. CMMR appears to involve direct spinal cord signals to upper extremity muscles from the cervical spinal segments, whereas TMMR to upper limbs may involve the ascending thoracolumbar-cervical pathways to those muscles. Similarly, TMMR to the lower extremities may involve direct spinal cord signals to lower limb muscles from the thoracolumbar spinal cord. Therefore, findings from this study suggest that MMR could be a reliable diagnostic tool for clinical purposes.

The amplitude and latency reflect the ability of viable axons to transit the electric signal to healthy muscle groups. Previous studies[1,2] have reported that reliability for signal latency is expected to be high because the latency value reflects the traveling distance between stimulation and recording sites. Such distances are always fixed and cannot be changed, thereby resulting in consistent latency values. However, the highly recorded reliability (test–retest) of the signal amplitude in all tested muscles for both upper and lower limbs was of great interest in this study.

The high test-retest reliability that we observed was probably due to the fact that maximum electrical stimulation intensity was used to activate all axons and to elicit a maximum response. Submaximal responses may vary between tests across sessions and affect MMR reliability.[11,12] Maximal muscular responses observed in this study suggest electric signal conduction from the spinal stimulation site to the recording site.[13] Other closely controlled factors that may have contributed to the significant test-retest reliability observed include room and skin temperature, obesity, precision in maintaining the same application site for stimulation and recording across sessions, adhering to standard procedures of electrode and skin preparation, placement and controlling for patient position, and eliminating any limb and neck movement during recording. Further, testers were the same for the two sessions, thus reducing the chance of technical variability. The above-mentioned are both physiological and non-physiological (mechanical) factors that can affect nerve conduction[14] and can, therefore, affect reliable testing.

The comparable signals observed between the right and left upper and lower extremities were probably due to equal distribution and activation of the electrical

**Table 4 Correlations table for TMMR LE amplitude and latency for first and second day**

| | T11 LE MMR amplitude | | | | T11 LE MMR latency | | | |
|---|---|---|---|---|---|---|---|---|
| | First day *R* vs. L UE | | Second day *R* vs. L UE | | First day *R* vs. L UE | | Second day *R* vs. L UE | |
| Muscles | *P* value | *R* value | *P* value | *R* value | *P* value | *R* value | *P* value | *R* value |
| VMO | 0.927** | 0.000 | 0.864** | 0.000 | 0.987** | 0.000 | 0.978** | 0.000 |
| MH | 0.900** | 0.000 | 0.723** | 0.002 | 0.991** | 0.000 | 0.901** | 0.000 |
| SOL | 0.895** | 0.000 | 0.705** | 0.003 | 0.865** | 0.000 | 0.916** | 0.000 |
| TA | 0.861** | 0.000 | 0.932** | 0.000 | 0.810** | 0.000 | 0.910** | 0.000 |

*Correlation is significant at the 0.05 level (two-tailed).
**Correlation is significant at the 0.01 level (two-tailed).

stimuli to the right and left contributing neural pathways. However, given that all of our subjects were right-handed, future studies including left-handed individuals would be recommended.

Results from this study support the reliability of repeated application of MMR in healthy subjects. Whether such reliability would be observed in patients whose spinal cord or nerve conduction have been affected by injury or disease has yet to be determined. If such test-retest reliability exists for those with compromised nervous systems, MMR could serve as a significant tool for testing and diagnosing level of impairment or even the plasticity of the spinal cord and associated pathways after treatment. It is important to reiterate that we consider the use of maximum stimulation and response to be the critical factor in determining reliability. Therefore, if this methodology is to be used for those with compromised nervous systems (e.g. spinal cord injury, radiculopathy, multiple sclerosis, myelitis), the intensity of stimulation must be carefully considered. Furthermore, the combined use of CMMR and TMMR is suggested for a comprehensive understanding of ascending and descending spinal pathways between the cervical and thoracolumbar spinal cord centers.

Limitations in this study include small sample size and a future study with a larger sample is needed for improved reproducibility of the results. Repeated application of electrodes in different sessions might contribute to the larger variability recorded in this study.

## Conclusions

This study is the first to report reliability of MMR in response to percutaneous spinal cord stimulation. The strong test–retest reliability of MMR to thoracic stimulations across sessions and the consistency of findings for opposite limbs suggest that MMR may be a valuable tool for clinical applications in diagnosis, evaluation, and treatment development for patients with neurological disorders. Reliable tools are critical foundations for making accurate diagnosis and delivering effective treatment. Future studies on larger populations and different levels of spinal cord stimulations could add to our understanding of MMR and its potential applications.

## Acknowledgments

Selda Uzun was supported by a grant from Scientific and Technological Research Council of Turkey (TUBITAK). We thank Kelly Angelone, who helped with subject recruitment, and Ambia Abdilahi, who provided technical support, and Zahra Kadivar, who helped with manuscript preparation.

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