Neuroscience Letters 803 (2023) 137186

Contents lists available at ScienceDirect

Neuroscience Letters

journal homepage: www.elsevier.com/locate/neulet

Mirror movements – A simple algorithm for mirror activity signal processing and normative values

José Castro [a,b,*], Tomás Pedrosa [c], Isabel de Castro [a,b], Michael Swash [d], Mamede de Carvalho [a,b]

[a] Instituto de Fisiologia, Instituto de Medicina Molecular João Lobo Antunes, Faculdade de Medicina, Universidade de Lisboa, Lisbon, Portugal
[b] Department of Neurosciences and Mental Health, Centro Hospitalar Universitário de Lisboa Norte, Lisbon, Portugal
[c] Departamento de Bioengenharia, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
[d] Departments of Neurology and Neuroscience, Barts and the London School of Medicine, Queen Mary University of London, United Kingdom

ARTICLE INFO

Keywords:
Mirror activity
Mirror movements
Emg
Signal processing
Normative values

ABSTRACT

Mirror activity is an involuntary activation of a muscle when the respective contralateral muscle is contracting. This phenomenon has been described primarily in children and in disease states, and, more recently, also in healthy adults. Different ways of assessing mirror activity have been described.

In this work we propose a simple protocol for quantifying the amount of mirror activity during a brief isolated full force isometric contraction of a given muscle. The signal was analyzed by a custom-built algorithm that detects the beginning and the end of muscle contraction. The amount of EMG signal on the mirror muscle in relation to the amount of EMG signal of the active muscle is then calculated.

We studied 57 right-handed healthy subjects. Mirror activity was evaluated in the Abductor digiti minimi (ADM) and Tibialis anterior (TA) muscles during a 2–3 s full force isometric contraction. The intensity of mirror movement was represented as a percentage of the signal from maximal voluntary contraction.

The performance of the algorithm for the detection of the beginning of muscle contraction was very good, when compared to 2 human operators. Intraclass correlation coefficient was excellent (0.998). The Bland-Altman plots showed similar performances of the algorithm and the human operators.

We found a significant correlation of mirror activity with intensity and age. There was significantly more intense mirror activity in the left limbs (non-dominant) when compared to the right limbs.

The upper limits of normality for mirror EMG signal was 27.4% for right ADM, 15.4% for left ADM, 10.4% for right TA and 2.1% for left TA.

This simple protocol allows for an objective measurement of the amount of mirror activity. We propose this technique for investigation of neurological disorders.

1. Introduction

During unilateral contraction of a given muscle, involuntary activation of the contralateral homologous muscle can occur [6,13]. This phenomenon has been named in several different ways – motor overflow, mirror activity or mirror movements. Although first thought to occur only in healthy children and in several neurological conditions [6,10,13], the presence of this mirror activity has since been described in normal adults [5,11,27], albeit to a much lesser extent [5,21].

Two possible pathophysiological mechanisms have been proposed for this phenomenon [8,28]. One possible explanation relies on an uncrossed corticospinal projection from the voluntarily activated motor cortex to the ipsilateral lower motor neuron [10,20]. Another possibility proposed is the activation of the contralateral motor cortex through transcallosal pathways, due to reduced interhemispheric inhibition [14].

Assessment of this mirror activity has been reported either by clinical observation [15,16,31], by force transduction measurements [5,29], or by recording surface electromyographic (EMG) signal [6,7,14,15,30]. In patients, mirror movements have been described mainly in the hands [10,26], although there have been reports of the presence of this activity in the lower limbs [9,19].

Most EMG recording paradigms reported for the assessment of mirror movements are based on phasic hand muscles activation or execution of

---

* Corresponding author at: Institute of Physiology, Faculty of Medicine - University of Lisbon, Av. Professor Egas Moniz, Lisbon 1649-028, Portugal.
E-mail address: jose.zecastro25@gmail.com (J. Castro).

https://doi.org/10.1016/j.neulet.2023.137186
Received 15 December 2022; Received in revised form 13 February 2023; Accepted 10 March 2023

complex finger sequences, while recording muscle activation from the contralateral (mirror) hand. Some protocols require some degree of contraction, around 10% to 20% of maximum voluntary contraction, of the mirror hand [8].

In this work, we developed a simple mathematical algorithm to quantify EMG mirror activity during short isometric maximum voluntary contractions of the abductor digiti minimi (ADM) and the tibialis anterior (TA) muscles. Based on our data, we also propose normative values for these measurements.

2. Methods

2.1. Subjects

Fifty-seven subjects (42 females; mean age 56.9 ± 13.8 SD; 20–83) were recruited. In 41 subjects, the upper limbs were studied. In a subset of 16 subjects, all 4 limbs were evaluated. Subjects with a history of neurological disease or who were taking drugs that could alter central nervous system excitability were excluded. Subjects gave their informed consent, and all experiments were performed according to the Declaration of Helsinki.

The protocol was approved by the local Ethics Commission.

All subjects were right-handed, according to the Edinburgh Handedness Inventory [24].

2.2. Motor task and EMG recordings

Subjects were lying supine, in a quiet room, with arms stretched along the body, and hands resting comfortably on the bed, while trying to relax as much as possible. They were instructed to perform brief, 2 to 3 s, isometric full force contractions of only one hand (finger abduction) or one foot (foot dorsiflexion). This was considered the active muscle. No instruction was given regarding the contralateral limb, which was considered the mirror muscle. Three trials were performed considering one side as active, followed by three consecutive recordings with the other side as active. Order (right-left and hand-foot) was randomly chosen between subjects. An interval of 5 to 10 s was allowed for resting between each trial.

Surface electrodes (reference 9013L0203, Natus Inc) were used for recording EMG activity. For the upper limb, recordings were made with the active electrode over the belly of the ADM muscle, while the reference electrode was placed on the volar side of the proximal interphalangeal joint of the 5th finger. The ground electrode was placed on the wrist. For the lower limb, recordings were performed with the active electrode over the belly of the TA muscle and the reference electrode 5–7 cm distally, over the tibial bone. The ground electrode was placed on the ankle. Standard amplifier filter settings of 30-Hz and 10-kHz were used. Signals were digitized at sampling frequencies of 3 kHz and 24 kHz in order to assess the algorithm performance in commonly used ranges of sampling frequencies in clinical neurophysiology. Recordings were made on a 10 s window and stored for offline analysis.

Additionally, two experienced neurophysiologists (JC and IdeC), independently marked the beginning of muscle activation, for comparison with the proposed algorithm.

2.3. Mathematical Algorithm for signal analysis

The signals obtained were stored and exported as txt files, which were then analyzed offline using a custom built MatLab algorithm (MatLab R2018a, The Mathworks, Inc., Natick, Massachusetts).

The calculations of the starting and finishing points of muscle activation were based on a mathematical formula previously described in the literature [12]. In a small percentage of signals analyzed (6%), it was necessary to apply a 50 Hz band pass filter to the signal due to the presence of electrical artifacts. Latency determinations were defined by the algorithm and both operators who were blind to the algorithm results and to the other operator determination.

The MatLab *trapz* function was used to estimate the amount of EMG signal in both sides, by calculating the area under the curve of the absolute value of the raw EMG signal during the estimated active muscle contraction. To control for differences in force across subjects, the amount of EMG signal in the mirror muscle during the motor task was defined as a percentage of the EMG signal of the active muscle according to the formula: $MirrorEMG = \frac{EMGsignalofthemirrormuslce}{EMGsignalofthetargetmuscle}x100$.

An example of the custom function output can be seen in Fig. 1.

The detailed code used for the construction of the algorithm, along with comments, can be found in the supplementary material.

2.4. Statistical analysis

Descriptive data is shown with mean values and standard deviations, or median with interquartile range (IQR), as appropriate. Inter-rater reliability was assessed with a two-way mixed model Intraclass Correlation Coefficient (ICC (2,k); Absolute Agreement) [23]. ICC reliability was considered poor for values lower than 0.5, moderate for values between 0.5 and 0.75, good for values 0.75–0.9 and excellent for values higher than 0.9 [25].

We used the 95% Limits of Agreement, as proposed by Bland and Altman [18], to evaluate the mean differences in the latency of the beginning of muscle activation as marked by the proposed algorithm and by the two neurophysiologists.

Regarding the amount of mirror EMG signal, the Shapiro-Wilk test was applied to test for the normality of data distribution. Given that the data was not normally distributed, non-parametric tests were used. Differences in gender and sides were assessed with a Mann-Whitney *U* test. Correlation of mirror activity with age was evaluated with a Spearman rank-order correlation. A p value < 0.05 was considered statistically significant.

For calculations of normative data, we performed a logarithmic transformation $\log(x + 1)$ of the mirror muscle signal amplitudes [22]. The resulting data followed a normal distribution. After the analysis, the data was back-transformed, in order to obtain meaningful values.

All analyses were performed in IBM SPSS for Microsoft Windows, Version 26.0 (Armonk, NY: IBM Corp).

3. Results

Recordings were obtained from bilateral ADM and TA muscles at sampling frequencies of 3 and 24 Hz, as detailed in Table 1.

3.1. Latency measurements

ICC values for the onset latency (proposed algorithm and both operators), were calculated for the ADM muscles, considering all recordings done in both sampling frequencies. For both 3 Hz and 24 Hz, the ICC value was 0.998 ($p < 0.001$). Concordance between the ADM measurements of the Algorithm against both operators, for the two frequencies, can be seen in Figure S5 (Supplementary material).

Bland-Altman plots were constructed in order to further evaluate the agreement in measurements. We compared measurements from one operator (JC) against the other operator (IdC) and against the Algorithm for both frequencies (Fig. 2).

The limits of agreement were very similar for both comparisons JC vs IdeC 82.9 ms and JC vs Algorithm 88.4 ms for 24 Hz and JC vs IdeC 63.9 ms and JC vs Algorithm 83.5 ms for 3 Hz.

3.2. Amplitude measurements

Given the similar results in latency measurements between both frequencies analyzed, amplitude measurements were evaluated in 3 Hz signals. For each subject, the amplitude considered was the mean of the

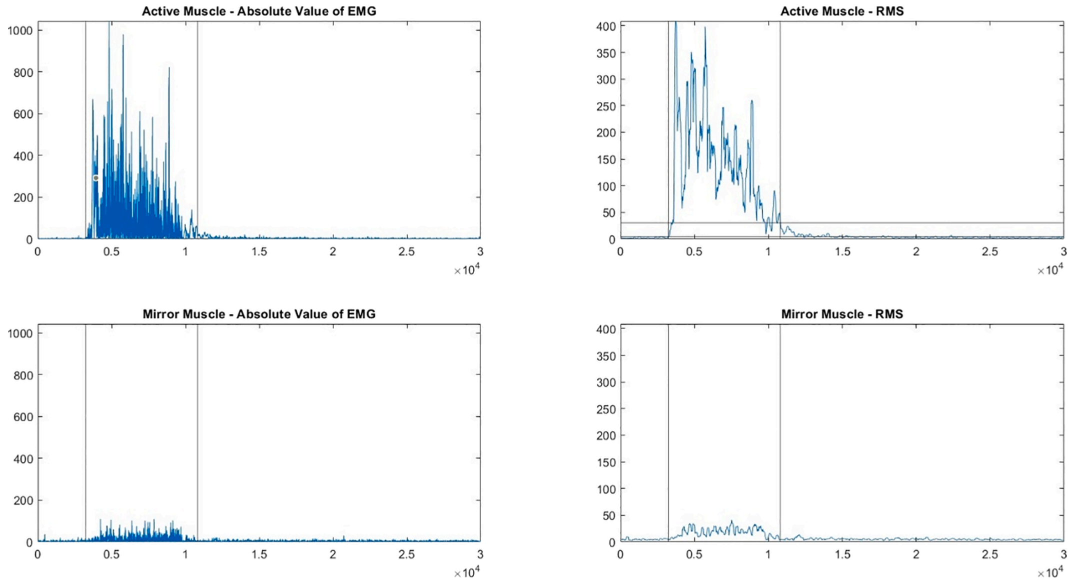

Fig. 1. Example of our custom algorithm output; RMS – root mean square.

Table 1
Number of muscles recorded in each sampling frequency; Age values are mean and SD; ADM – Abductor digiti minimi; TA – Tibialis anterior.

	3 Hz				24 HZ	
	Right ADM	Left ADM	Right TA	Left TA	Right ADM	Left ADM
Gender	29 ♀14 ♂		10 ♀6 ♂		29 ♀12 ♂	
Age	56.6 (15.1)		53.8 (17.2)		57.3 (12.5)	
Muscles	43	43	16	16	41	41

three recordings. The amount of EMG mirror signal for each muscle as a percentage of the full contraction signal is displayed in Table 2.

There was no difference in amplitude of the mirror activity between genders. A Spearman's rank-order correlation was run to assess the relationship between age and the amount of mirror activity. Preliminary analysis showed that all relationships were monotonic, as assessed by visual inspection of a scatterplot. There was a statistically significant, moderate positive correlation between age and mirror activity in the ADM ($r_s(86) = 0.300$, $p = 0.005$) and in the TA ($r_s(32) = 0.475$, $p = 0.006$) muscles (Fig. 3). Regarding difference between sides, there was significantly more mirror activity in the right muscles (when the left muscle was active). Differences between mirror activity, regarding the active side, were assessed with the Mann-Whitney U test. In the upper limbs, median mirror activity in the right ADM (6.4%) was significantly higher than in the left ADM (2.6%), $U = 577$, $z = -3.002$, $p = 0.003$. In the lower limbs, median mirror activity in the right TA (2.1%) was significantly higher than in the left TA (0.8%), $U = 64.5$, $z = -2.399$, $p = 0.016$ (Fig. 4).

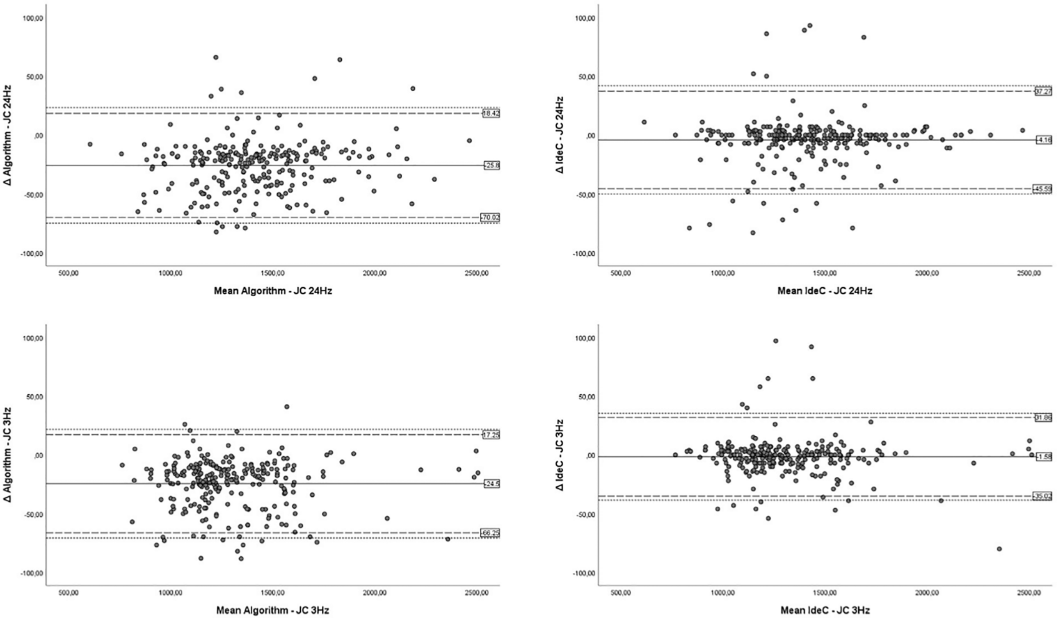

Fig. 2. Bland-Altman plots of the difference in latency as marked by the custom algorithm vs one operator (JC) as well as one operator (JC) vs other operator (IdeC), for both sampling frequencies. Solid lines represent the mean difference; Upper dashed lines represent the mean differences + 1.96 SD (with upper 95% CI – dotted line), and lower dashed lines represent the mean differences – 1.96 SD (with lower 95% CI – dotted line).

Table 2

Median and IQR of the amount of mirror activity; Mean ± standard deviation and 95% limits of normality for both the transformed and the exponentiated variables (all values are in % of the amount of EMG from the active muscle); ADM – Abductor digiti minimi; TA – Tibialis anterior.

		Mirror activity Mirror EMG (%)	Logarithmic scale (%)	After exponentiation (%)
Mirror muscle	Right ADM	6.43.0–10.2	0.83 ± 0.310.09–1.19	6.8 ± 2.01.7–27.4
	Left ADM	2.61.6–5.0%	0.64 ± 0.280.22–1.44	4.4 ± 1.91.2 – 15.4
	Right TA	2.10.8–4.0	0.49 ± 0.29-0.08–1.06	3.1 ± 1.90.8 – 10.4
	Left TA	0.80.5–1.2	0.26 ± 0.120.02–0.50	1.8 ± 1.31.1 – 2.1

Given the non-normality of the amount of mirror signal distribution, we performed a logarithmic transformation of the data, for the calculation of normative data.

We chose a log10 transformation for this purpose. Given the small amount of mirror EMG signal in some subjects, we opted for a $\log(x + 1)$, to avoid the approach to negative infinity as × approached 0. The resulting variables were approximately normally distributed (Shapiro-Wilk test $p > 0.01$, Skewness and Kurtosis < 1).

Normative data was calculated as Mean ± 1.96SD in the transformed data. Values in logarithmic scale and after exponentiation are presented in Table 2. The upper limit of normality for mirror EMG signal in our group was 27.4% for right ADM, 15.4% for left ADM, 10.4% for right TA and 2.1% for left TA.

4. Discussion

In this work, we describe a simple algorithm to quantify the amount of EMG activity in a muscle (mirror) when performing an isometric full force contraction of the contralateral muscle (active).

The performance of the algorithm regarding latency was excellent, with very high ICC values between automated and manual measurements. The analysis of the Bland-Altman plots showed that the 95% limits of agreement between the algorithm and an experienced human operator were very similar to those comparing two experienced human operators. The performance of the algorithm was similar for both sampling frequencies tested. Despite this good performance, there were a small number of issues with latency markings, particularly when the beginning of the contraction was not very well defined. This is a limitation of this method since in cases where the subject starts activating the muscle with a low degree of force before the full contraction, erroneous results can be obtained. In contrast, in cases where there was incomplete relaxation or spontaneous muscle activity, e.g., fasciculations, the algorithm ignored this unwanted activity and correctly identified the beginning of muscle contraction.

For amplitude measurement, we evaluated the mean of three recordings, in order to diminish interindividual variability of the recordings [17]. Given that we measured mean EMG values, the window length used for the RMS (150 ms in our algorithm), had a very small impact on the results [17]. We found no correlation in our data between the amount of mirror activity and gender. There were significant positive correlations with age, as expected, since it has been suggested that this mirror phenomenon may reappear in older adults [2]. When comparing sides, we found that when the left muscles were active, the amount of mirror activity was significantly greater. Given that all our subjects were right-handed, our findings are in accordance with what has been already reported, supporting a higher dominant-to-non dominant hemispheric inhibition [4,5]. Armatas et al [4], postulate that asymmetry in callosal interconnectivity, a possible result of hemisphere specialization [1], could account for this difference in mirror activity in the hands. Our study extends these findings, demonstrating that there is higher dominant-to-non dominant hemispheric inhibition in the lower limbs. From a physiological, and clinical, point of view, it would be interesting to integrate these findings with Transcranial Magnetic

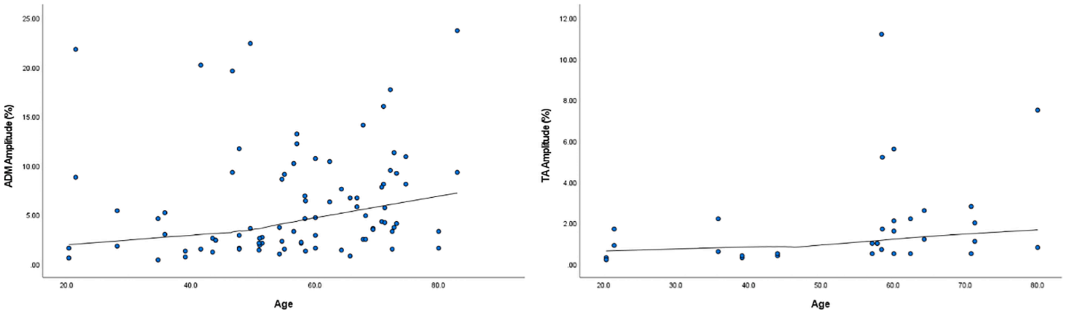

Fig. 3. Scatterplots of Age and mirror activity in the ADM and TA muscles. Values are represented as a percentage of the amount of EMG signal of the active muscle; ADM – Abductor digiti minimi; TA – Tibialis anterior; Trend lines were generated using loess modeling (90% of points fit, Epanechnikov kernel).

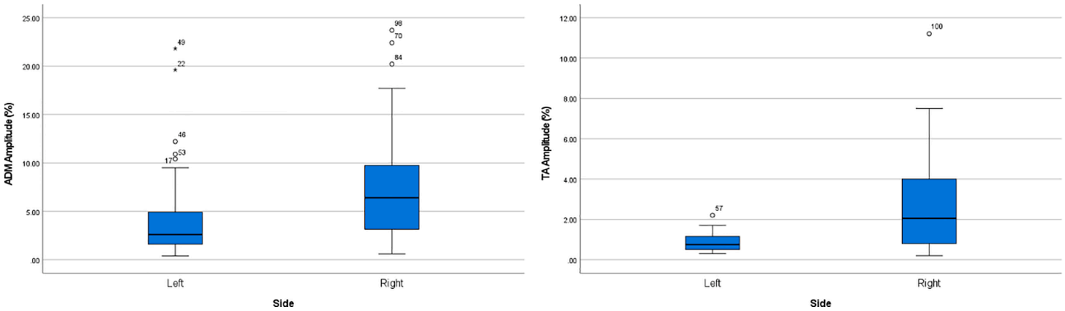

Fig. 4. Boxplot of the amount of mirror activity; Values are represented as a percentage of the amount of EMG signal of the active muscle; ADM – Abductor digiti minimi; TA – Tibialis anterior.

Stimulation (TMS), both in healthy subjects as well as in diseases that affect transcallosal inhibitory control, like motor neuron diseases.

In our data, the upper limit of normality for mirror activity is 27.4% for the right ADM, 15.4% for the left ADM, 10.4% for the right TA and 2.1% for the left TA.

Our study has some limitations. We did not measure the force of muscle contraction. However, we made every effort to encourage subjects to perform maximum contraction. Additionally, the number of muscles studied is not very large, particularly TA muscles, hindering the definition of normal values per age group.

In this study we chose to analyze a simple isometric full force contraction given a lack of normative values of mirror activity for use in a clinical setting. Despite the recommendation for using more advanced kinematic paradigms for studying motor overflow [2], the use of a sustained strong effort has been shown to facilitate the presence of mirror activity [3] in healthy subjects. The proposed algorithm performs significantly well in defining the initiation of muscle contraction and allows for an objective measurement of the mirror activity in healthy subjects.

Electromyographic quantifying measurements of mirror activity, in both upper and lower limbs, will be interesting not only in patients with congenital mirror movements, but also in less well-defined motor overflow syndromes, as well as in patients with neurological diseases that might affect transcallosal inhibition. We propose that this protocol could be applied in future studies of various neurological disorders.

Author Contribution Statement

J.C. is responsible for conception, design, acquisition, analysis, interpretation of data, MatLab algorithm creation and manuscript draft. T.P. is responsible for algorithm coding, signal analysis and manuscript revision. IdeC is responsible for acquisition and manuscript revision. M. S. is responsible for interpretation of data and manuscript revision. M. de C. is responsible for conception, design, interpretation of data and manuscript revision. All authors reviewed the manuscript and approved the submitted version.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

This work was funded by the project “Spinal circuitry in Motor Neuron Disease: Changes in Spinal and Corticospinal Mechanisms in Amyotrophic Lateral Sclerosis and its variants” (sponsored by Biogen Inc).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neulet.2023.137186.

References

[1] F. Aboitiz, A.B. Scheibel, R.S. Fisher, E. Zaidel, Individual differences in brain asymmetries and fiber composition in the human corpus callosum, Brain Res 598 (1-2) (1992) 154–161.

[2] P.K. Addamo, M. Farrow, J.L. Bradshaw, N. Georgiou-Karistianis, Relative or absolute? Implications and consequences of the measures adopted to investigate motor overflow, J Mot Behav 43 (3) (2011) 203–212.

[3] Z. Arányi, K.M. Rösler, Effort-induced mirror movements A study of transcallosal inhibition in humans, Exp Brain Res 145 (1) (2002) 76–82.

[4] C.A. Armatas, J.J. Summers, J.L. Bradshaw, Handedness and performance variability as factors influencing mirror movement occurrence, J Clin Exp Neuropsychol 18 (6) (1996) 823–835.

[5] C.A. Armatas, J.J. Summers, J.L. Bradshaw, Mirror movements in normal adult subjects, J Clin Exp Neuropsychol 16 (3) (1994) 405–413.

[6] JOZEF Cernacek, Contralateral Motor Irradiation-Cerebral Dominance, Arch. Neurol. 4 (2) (1961) 165.

[7] M. Cincotta, F. Giovannelli, A. Borgheresi, F. Balestrieri, P. Vanni, A. Ragazzoni, G. Zaccara, U. Ziemann, Surface electromyography shows increased mirroring in Parkinson’s disease patients without overt mirror movements, Mov Disord 21 (9) (2006) 1461–1465.

[8] M. Cincotta, U. Ziemann, Neurophysiology of unimanual motor control and mirror movements, Clin Neurophysiol 119 (4) (2008) 744–762.

[9] A.J. Espay, J.Y. Li, L. Johnston, R. Chen, A.E. Lang, Mirror movements in parkinsonism: evaluation of a new clinical sign, J Neurol Neurosurg Psychiatry 76 (2005) 1355–1358.

[10] S.F. Farmer, D.A. Ingram, J.A. Stephens, Mirror movements studied in a patient with Klippel-Feil syndrome, J Physiol 428 (1990) 467–484.

[11] R. Forget, D. Boghen, E. Attig, Y. Lamarre, Electromyographic studies of congenital mirror movements, Neurology 36 (1986) 1316-1322.

[12] M.A. Garvey, U. Ziemann, D.A. Becker, C.A. Barker, J.J. Bartko, New graphical method to measure silent periods evoked by transcranial magnetic stimulation, Clin. Neurophysiol. 112 (8) (2001) 1451–1460.

[13] J.B. Green, An electromyographic study of mirror movements, Neurology 17 (1967) 91-94.

[14] A. Hubers, Y. Orekhov, U. Ziemann, Interhemispheric motor inhibition: its role in controlling electromyographic mirror activity, Eur J Neurosci 28 (2008) 364–371.

[15] K. Krampfl, B. Mohammadi, L. Komissarow, R. Dengler, J. Bufler, Mirror movements and ipsilateral motor evoked potentials in ALS, Amyotroph Lateral Scler Other Motor Neuron Disord 5 (3) (2004) 154–163.

[16] V.A. Magne, L. Adde, B. Hoare, K. Klingels, C. Simon-Martinez, L. Mailleux, S. Lydersen, A.-K. Elvrum, Assessment of mirror movements in children and adolescents with unilateral cerebral palsy: reliability of the Woods and Teuber scale, Dev Med Child Neurol 63 (6) (2021) 736–742.

[17] A. Mark Burden, S.E. Lewis, E. Willcox, The effect of manipulating root mean square window length and overlap on reliability, inter-individual variability, statistical significance and clinical relevance of electromyograms, Man Ther 19 (6) (2014) 595–601.

[18] J. Martin Bland, DouglasG. Altman, Statistical Methods for Assessing Agreement between Two Methods of Clinical Measurement, Lancet 327 (8476) (1986) 307–310.

[19] T. Maudrich, R. Kenville, J. Lepsien, A. Villringer, P. Ragert, C.J. Steele, Mirror Electromyografic Activity in the Upper and Lower Extremity: A Comparison between Endurance Athletes and Non-Athletes, Front Hum Neurosci 11 (2017) 485.

[20] M.J. Mayston, L.M. Harrison, R. Quinton, J.A. Stephens, M. Krams, P.M. Bouloux, Mirror movements in X-linked Kallmann’s syndrome. I. A neurophysiological study, Brain 120 (Pt 7) (1997) 1199–1216.

[21] M.J. Mayston, L.M. Harrison, J.A. Stephens, A neurophysiological study of mirror movements in adults and children, Ann Neurol 45 (5) (1999) 583–594.

[22] J.H. McDonald, Handbook of biological statistics, Vol. 2, sparky house publishing Baltimore, MD, 2009.

[23] K.O. McGraw, S.P.J.P.m. Wong, Forming inferences about some intraclass correlation coefficients, 1 (1996) 30.

[24] R.C. Oldfield, The assessment and analysis of handedness: The Edinburgh inventory, Neuropsychologia 9 (1) (1971) 97–113.

[25] L.G. Portney, Foundations of clinical research: applications to evidence-based practice, FA Davis, 2020.

[26] G.D. Schott, M.A. Wyke, Congenital mirror movements, J Neurol Neurosurg Psychiatry 44 (7) (1981) 586–599.

[27] G.D. Schott, M.A. Wyke, Obligatory bimanual associated movements, J. Neurol. Sci. 33 (3) (1977) 301–312.

[28] B. Sehm, M.A. Perez, B. Xu, J. Hidler, L.G. Cohen, Functional neuroanatomy of mirroring during a unimanual force generation task, Cereb Cortex 20 (1) (2010) 34–45.

[29] I. Uttner, N. Mai, O. Esslinger, A. Danek, Quantitative evaluation of mirror movements in adults with focal brain lesions, Eur J Neurol 12 (12) (2005) 964–975.

[30] A.N. Vardy, A. Daffertshofer, A. Ridderikhoff, P.J. Beek, Differential after-effects of bimanual activity on mirror movements, Neurosci Lett 416 (2) (2007) 117–122.

[31] B.T. Woods, H.L. Teuber, Mirror movements after childhood hemiparesis, Neurology 28 (1978) 1152-1157.