Study of surface electromyography sensor (sEMG) from E.M.I.L solution: validity and reproducibility during quadriceps exercises

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Abstract

Electromyography analysis (EMG) is widely spread in clinical and sports environments. Physiological data can be recorded thanks to state-of-the-art EMG sensors like E.M.I.L (© 2023 Optimergo, ElectroMyographie Intelligente et Ludique). This latter is composed of Bluetooth sEMG sensors and mobile software. It gives signal information to the user at the end of the acquisition. This study aims to assess the validity of E.M.I.L© sensor measurement relative to other commercials and validated sEMG sensors: MuscleBAN© and Shimmer3©. For this study, leg extension exercises have been carried out by twelve subjects in different conditions: isometric (IC) and dynamic (DC). IC consists of doing a maximum voluntary contraction (MVC) and maintaining 50% of MVC. DC consists of doing leg extension exercises with and without training band, respectively WL and FL). The rectus femoris (RF) muscle activity is observed with two sensors positioned according to a normalized proximal-distal scheme. Results are delivered via numerous indexes: Standard Error Measurement (SEM) of Root Mean Square (RMS) to highlight sensor reproducibility; Intra-class Correlation Coefficient (ICC) to assess the sensor repeatability; Absolute Bias (AB) of RMS average and Pearson correlation coefficient (r) to point out similarities between E.M.I.L© and both markets sensors MuscleBAN© and Shimmer3©. Results show excellent correlation (AB: 0.52% ± 1.86 %, r = 0.947) of recorded EMG data by E.M.I.L© solution concerning the MuscleBAN© sensor. Results also show a great correlation (AB: 1.50% ± 1.77 %, r = 0.856) of recorded EMG data by E.M.I.L© concerning Shimmer3© in dynamic condition (DC – WL). In addition, very good reproducibility of data values and excellent repeatability have been demonstrated in dynamic and isometric conditions for the quadriceps without considering the intensities.

Keywords: sEMG, Validity, Repeatability, E.M.I.L©, Wireless sensors

1. Introduction

Over the past years, physiological wireless sensors have been developed to meet the growing demand from clinical and sports structures. As a result, surface electromyography (sEMG) is now well widespread. sEMG is a non-invasive diagnostic method to measure muscle activity during the contraction cycle and muscle relaxation [1]. EMG signal shows electric activity produced by action potentials of motor units inside the corresponding muscle [2,15]. EMG studies permit better acknowledgment of some muscular and neuromuscular pathologies' origin and observation of the effect of different movement execution strategies [3]. sEMG contribution to non-invasive muscular characterization has been demonstrated by numerous authors [4,5]. Over the past decade, the EMG acknowledgments have been improved thanks to a better comprehension of the physiological process that generates EMG signals, improvement of signal processing, and a finer understanding of the different clinical software in which it can be used. The rapid growth of software numbers highlights the great potential of sEMG as a non-invasive tool to evaluate neuromuscular systems.

Despite widespread sEMG in clinical, science, and sports environments, some constraints can make its use difficult. The skin must be cleaned, and the sEMG sensor requires single-use Ag/AgCl electrodes. These latter are attached to a data acquisition system that constrains subject motion and the environment around them. Furthermore, additional signal processing must be carried out by an expert to exploit the raw data recorded. To conclude, the material cost, the equipment complexity, and the processing signal make sEMG analysis difficult outside a laboratory or a clinic.

New technologies of physiological measurement and human neurology study arise thanks to progress in miniaturization components, light materials development, and manufacturing method improvement [20]. These latter give the possibilities to reduce sEMG cost and complexity to enable measuring on the ground on a bigger scale.

E.M.I.L© (© 2023 Optimergo) (ElectroMyography Intelligente et Ludique) solution is among these new technologies. OPTIMERGO© sells a solution that combines a wireless sEMG sensor connected by Bluetooth with mobile software. It records and displays data in real-time and produces post-treatment results at the end of acquisition. Thus, E.M.I.L© gives access to sEMG measurements to everyone in real-time. However, no previous study about the reproducibility of this sensor has been carried out.

This study aims to assess the validity and reproducibility of sEMG sensor measurements of E.M.I..L© solution. This latter will focus on leg extension exercises in isometric and dynamic conditions with different intensities. The results will be compared to other commercial and validated sensors (MuscleBAN© BE, Shimmer3© ECG/EMG).

2. Materials and Methods

2.1 Experimental Data

Twelve adult volunteers took part in this experiment: 7 females (22 ± 3 y.o, 163 ± 10 cm, 62 ± 15 kg, 5 with dominant right leg and 2 with dominant left leg) - 5 males (26 ± 5 y.o, 181 ± 7 cm, 74 ± 11 kg, 4 with dominant right leg and 1 with dominant left leg). Subjects have no lower limb injury history over the past six months. Before the experiment started, they were well-informed of potential risks and agreed to the Helsinki Declaration.

2.2 Materials

Subjects were installed on a weight bench with a fixed lower limb locking element, a training band, and a protective foam. The extension angle between the femur and the tibia was set thanks to an inclinometer with an accuracy of ± 0.1° [2]. A metronome was used to beat the pace during dynamic leg extensions.

Three sensors were used in this experiment: E.M.I.L©, Shimmer3©, and MuscleBAN©. The latter two sensors were chosen because of their market validation and widespread with similar features. Data were recorded at 1,000Hz for each of them. Adhesive electrodes H124SG from Kendall – Cardinal Health© (24 mm ø) were used for each sensor. Table 1 shows all the features of each sensor. All data were acquired with its corresponding software and a tablet (Galaxy TAB S8).

All computations were processed with MATLAB r2022b (© 1994-2023 The MathWorks)

Table 1. Sensors features.

	E.M.I.L©	MuscleBAN©	Shimmer3©
Dimensions (mm)	*53 x 25.6 x 14,5*	*70 x 31 x 11*	*65 x 32 x 12*
Mass (g)	*19*	*29*	*29*
Electrode connection	*Wireless*	*Wireless*	*Wired*
Memory (Gb)	*8*	*Non specified*	*2*
Resolution (bit)	*12*	*16*	*24*
Gain (ø)	*7.5*	*10*	*1, 2, 3, 4, 6, 8, 12*
Bandwidth (Hz)	*1 – 1,000*	*1 – 1,000*	*1 – 8,400*
Sample frequency (Hz)	*100; 250; 500; 1,000*	*80; 160; 200; 400; 800; 1,000*	*125; 250; 500; 1,000; 2,000; 4,000; 8,000*
Communication	*Bluetooth Low Energy*	*Bluetooth Low Energy*	*Bluetooth – RN4678*

2.3 Experimental Protocol

The current study aims to compare sEMG measurements between E.M.I.L© and the reference sensors MuscleBAN© and Shimmer3© on the same contractions [2]. Subjects were asked to perform leg extension exercises with their dominant leg evaluated via a balance test. First and foremost, subjects had a warm-up session before the experiment: 3 series of 20 seconds of high stepping, then 15 lunges, and 15 squats with 10 seconds of recovery between each exercise. Next, the skin's subjects were razed, abrased, and cleaned with alcohol to eliminate most of the skin dirt to get reliable sensor fixation on the skin. Then, subjects were equipped with sensors attached to the rectus femoris (RF) (Appendix 1). Sensors were attached to the skin according to SENIAM recommendation [6]. The best electrode location is between the innervation zone and tendinous endings. EMG variable estimation is less affected by noise signals and tiny electrode displacements with this prior protocol to position sensors [7]. Electrodes and sensors were attached in series (proximal-distal) [2] around the landmark of the middle line starting from the anterior iliac spine to the patella superior part [6] (Appendix 1). Finally, electrodes were aligned with muscle fibers and positioned with a 2.0 cm inter-electrode distance [8]. This electrode's location is normalized and applied to the three sensors. Shimmer3© requires a supplementary ground electrode attached to the patella.

The experiment is carried out under two conditions: isometric (IC) and dynamic (DC) [9].

For IC, the weight bench is set to obtain a knee extension angle between the femur and the tibia of 125° ± 0.1°. This setting is inspected before each condition with the inclinometer. The subject is positioned on the weight bench with a hip opening of 90°, knee extension of 125°, hands on hips, and opposite foot lying flat on the ground with knee extension of 90°. A protective foam is used at the contact point between the tibia and the lock element. Subjects are asked to carry out two efforts. First, it is a series of three maximal voluntary contractions (MVC) of 5 seconds with 5 minutes of recovery between repetitions. Second, it is a voluntary contraction of 50% of MVC that lasts 10 seconds on three repetitions (IC-50); the subject evaluates the contraction intensity without feedback access.

For DC, subjects are asked to perform ten leg extensions (extension, then flexion of the knee) in two different conditions: free leg (FL) and weighted leg (WL) with training band (strength: 15kg measured at 200% of elastic elongation). Subjects start at 90° knee flexion to reach 180° knee extension and return to the initial position; this represents one repetition. The pace is set to 30 repetitions per minute via a metronome. Subjects are asked to perform smooth knee extension and flexion.
Each condition is executed twice by exchanging EMG sensors to average data recorded in both positions [8]. The experiment is achieved twice with 48h delay for every subject to carry both comparisons: E.M.I.L© - Shimmer3© and E.M.I.L©-MuscleBAN© [2,10]. The order and start position (proximal-distal) were randomized. The experiment protocol is shown in Figure 1.

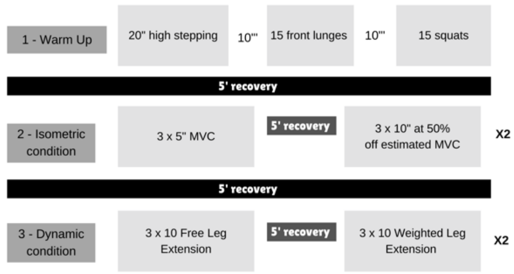

Figure 1. Experiment protocol

2.4 Data recording and signal processing

Data recording was carried out with respective sensors software: E.M.I.L© solution for E.M.I.L©, OpenSignals for MuscleBAN©, and Shimmer3Capture for Shimmer3©. All sensors were calibrated at 1,000 Hz sample frequency. All data were normalized post-acquisition by dividing data values by corresponding gain because the gain was not modulable pre-acquisition for each sensor except Shimmer3© (figure 1).

In addition, each sensor has a different bandwidth to filter data (figure 1). Fast Fourier Transform was applied on sEMG signals [11] to extract frequency features. Filter parameters choice was made with a subjective observation pre-test. After this empiric signal analysis and protocols acknowledgment from literature, EMG signals were filtered with an order 3 Butterworth bandpass filter between 10 Hz and 240 Hz [2, 12, 13] and a Butterworth bandstop filter at 50 Hz to attenuate noise (outlier frequencies).

The EMG signal is smoothed on a 200 ms window by moving average (MOV); the maximum of this smoothness corresponds to the MVC. IC-50 data is processed by getting the RMS of the 10 seconds that outreaches 30% of MVC.

For DC, data is split in contraction envelopes defined by a threshold of 30% of 10 RMS peak mean values. RMS is calculated for each ten contractions envelope. These RMS values are stored to be compared to other sensors.

Data obtained from proximal and distal positions are averaged to normalize sensor location in each condition, each subject, and each sensor [8]. After this latter step, normalized data samples are obtained for statistical assessment of the validity and reproducibility of similar contraction data.

2.5 Statistical indexes

All statistical analyses were processed with MATLAB r2022b (© 1994-2023 The MathWorks). A Shapiro-Wilk test was applied to the data to verify whether they followed a normal distribution.

The Standard Error Measurement (SEM) and the Intra-class Correlation Coefficient (ICC) are determined for intra-sensor analysis. The mean of Absolute Bias (AB) and Pearson correlation coefficient are calculated for inter-sensor analysis.

The SEM index shows absolute reproducibility and allows an accurate assessment of the measurement system and its variability [14]. It is obtained from the standard deviation of data RMS. It is expressed in the percentage of MVC (%). A SEM inferior to 2% shows excellent reproducibility for low-intensity effort. It was agreed that a SEM lower than 5% shows excellent reproducibility for high intensity.

The ICC index quantifies the similarity degree between observations within the same sensor. It allows sensor repeatability validation. A value superior to 0.90 is considered excellent. This index is unitless and ranges from 0 to 1. The degree of correlation corresponds to the following scale: [0; 0.50]: weak,]0.50; 0.75]: moderate,]0.75; 0.90]: good,]0.90; 1.00]: excellent [18].

The mean of AB is an index of absolute measurement validity. It mixes random and consistent errors. A value equal to zero means perfect similitude: the bias decreases as the similitude increases.

The Pearson correlation coefficient (r) shows a linear relationship between two continuous variables. Null value reflects no relation between both variables; positive value implies that both values are linked positively (if one increases, the other one too); as for negative value, it indicates that both values are connected negatively (if one increases, the other one decreases). It is derived from data envelope RMS for each sensor. This index is unitless and ranges from 0 to 1. The degree of correlation corresponds to the following scale: [0; 0.20]: very weak,]0.20; 0.40]: weak,]0.40; 0.70]: moderate,]0.70; 0.90]: strong,]0.90; 1.00]: very strong [17].

2.6 Data analysis

Intra-sensors indexes (SEM - ICC) and inter-sensors indexes (AB – r) are derived for each condition (IC and DC) and each exercise (IC-50, DC-WL, DC-FL).

The SEM and the ICC are calculated for E.M.I.L©, MuscleBAN©, and Shimmer3© sensors. Two data samples are acquired for each measurement: the sensor in the proximal position and the sensor in the distal position. For the E.M.I.L© sensor, four data samples are obtained due to protocol repetition by 48h intervals. The value of "x" from equation (3) corresponds to the RMS value from the EMG envelope (see Appendix 3).

AB and r are computed between E.M.I.L© - MuscleBAN© and between E.M.I.L© - Shimmer3©. The value of "x" from equation (6) corresponds to the RMS value from the EMG envelope (see Appendix 3). Reference sensor (x_{ref}) is MuscleBAN© for E.M.I.L© - MuscleBAN© comparison and Shimmer3© for E.M.I.L© - Shimmer3© comparison.

3. Results

	IC – 50	***DC – FL***	***DC – WL***
E.M.I.L	3.455	0.953	1.648
MuscleBAN	3.673	1.017	1.916
Shimmer3	3.215	0.931	1.330

Table 1. SEM (% of MVC); IC-50 = Isometric Condition 50% MVC; DC-FL = Dynamic Condition Free Leg; DC-WL = Dynamic Condition Weighted Leg

	IC – 50	***DC – FL***	***DC – WL***
E.M.I.L	0.980	0.985	0.988
MuscleBAN	0.976	0.983	0.986
Shimmer3	0.984	0.975	0.986

Table 2. ICC (ø); IC-50 = Isometric Condition 50% MVC; DC-FL = Dynamic Condition Free Leg; DC-WL = Dynamic Condition Weighted Leg

	IC – 50	***DC – FL***	***DC – WL***
E.M.I.L – MuscleBAN	0.15 ± 2.89	0.14 ± 1.20	0.52 ± 1.86
E.M.I.L – Shimmer3	1.02 ± 4.12	1.01 ± 1.29	1.50 ± 1.77

Table 3. AB (% of MVC); IC-50 = Isometric Condition 50% MVC; DC-FL = Dynamic Condition Free Leg; DC-WL = Dynamic Condition Weighted Leg

	IC – 50	***DC – FL***	***DC – WL***
E.M.I.L – MuscleBAN	0.939	0.924	0.947
E.M.I.L – Shimmer3	0.930	0.774	0.856

Table 4. r (ø); IC-50 = Isometric Condition 50% MVC; DC-FL = Dynamic Condition Free Leg; DC-WL = Dynamic Condition Weighted Leg

3.1 Intra-sensors analysis

SEM index:

The Standard Error Measurement (SEM) for each sensor and each condition are displayed in Table 2.

For IC-50, SEM is 3.455% for E.M.I.L©, 3.673% for MuscleBAN©, and 3.215% for Shimmer3©.

For DC-FL, SEM is 0.953% for E.M.I.L©, 1.017% for MuscleBAN©, and 0.931% for Shimmer3©.

For DC-WL, SEM is 1.648% for E.M.I.L©, 1.916% for MuscleBAN©, and 1.330% for Shimmer3©.

Shimmer3© has better reproducibility results, followed respectively by E.M.I.L© and MuscleBAN©. This ranking remains the same for each condition.

It can be observed that values vary with effort intensity: IC-50 >> DC-FL >> DC-WL. Higher EMG values will imply higher absolute variations.

ICC index:
The Intra-class correlation coefficient (ICC) for each sensor and each condition are displayed in Table 3.

For IC-50, ICC is 0.980 for E.M.I.L©, 0.976 for MuscleBAN©, and 0.984 for Shimmer3©.

For DC-FL, ICC is 0.985 for E.M.I.L©, 0.983 for MuscleBAN©, and 0.975 for Shimmer3©.

For DC-WL, ICC is 0.988 for E.M.I.L©, 0.986 for MuscleBAN©, and 0.986 for Shimmer3©.

All sensors expose excellent repeatability results in both conditions (isometric and dynamic): all values range from 0.975 to 0.988.

3.2 Inter-sensors analysis

AB index
The Absolute bias (AB) between E.M.I.L© and the reference sensors is displayed in Table 4.

For IC-50, AB is 0.15% ± 2.89% for E.M.I.L© - MuscleBAN©, and 1.02% ± 4.12% for E.M.I.L© - Shimmer3©.

For DC-FL, AB is 0.14% ± 1.20% for E.M.I.L© - MuscleBAN©, and 1.01% ± 1.29% for E.M.I.L© - Shimmer3©.

For DC-WL, AB is 0.52% ± 1.86% for E.M.I.L© - MuscleBAN©, and 1.50% ± 1.77% for E.M.I.L© - Shimmer3©.

Results highlight a better likeness between E.M.I.L© and MucsleBAN© sensors than between E.M.I.L© and Shimmer3©. A Bland-Altman diagram can be found in Appendix 2 to illustrate this repartition [19]. The AB is close to 0 for E.M.I.L© - MuscleBAN© for each condition, whereas the AB is around 1% for E.M.I.L© - Shimmer3©. This systematic error may be derived from the Shimmer3© reference electrode that contributes to signal noise reduction.

The table also shows an increase in the AB in DC-WL. It could derive from dynamic motions that induce vibrations during efforts or internal filter differences between sensors.

r Index:
The Pearson coefficient (r) results between E.M.I.L© and reference sensors are exposed in Table 5.

For IC-50, r is 0.939 for E.M.I.L© - MuscleBAN©, 0.930 for E.M.I.L© - Shimmer3©.

For DC-FL, r is 0.924 for E.M.I.L© - MuscleBAN©, and 0.774 for E.M.I.L© - Shimmer3©.

For DC-WL, r is 0.947 for E.M.I.L© - MuscleBAN©, and 0.856 for E.M.I.L© - Shimmer3©.

This latter result confirms the very high similitude between E.M.I.L© and MuscleBAN© (r > 0.90, for each condition). As for E.M.I.L© - Shimmer3©, similitude is very high in IC, and declines but remains elevated in DC (between 0.70 and 0.90).
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Conclusion

This comparative study of different EMG sensors (E.M.I.L©, MuscleBAN©, and Shimmer3©) reveals a predominant similitude between E.M.I.L© and MuscleBAN© for isometric and dynamic conditions that do not imply high induced vibrations. However, the results show differences between both sensors when the exercise intensity increases and generates induced vibrations. As for E.M.I.L© and Shimmer3©, it produce identical similitude with an additional systematic bias primarily due to the reference electrode of Shimmer3©. Moreover, all sensors have excellent repeatability (ICC) and reproducibility (SEM) indexes.

Results allow validity and repeatability establishment of EMG data recorded by E.M.I.L© solution regarding MuscleBAN© and Shimmer3© in both isometric and dynamic conditions. Nevertheless, it is worth noting the difference in validity from E.M.I.L© data concerning Shimmer3© that presents a systematic bias of around 1% primarily due to the reference electrode from Shimmer3©.

According to this study, E.M.I.L© is a highly reliable and repeatable sensor in both isometric and dynamic motions with or without resistance. Thus, the reliability and the speed of execution of the E.M.I.L© solution create new opportunities in EMG use on the ground: rehabilitation, physical preparation, and workstation adaptation. For physiotherapists or sports coaches, the E.M.I.L© solution offers the possibility to follow patients' rehabilitation and to imply them in different exercises by biofeedback. For ergonomists, the solution allows workstation studies while being as least invasive as possible for workers who can carry out their tasks without being annoyed. It quantifies the muscular loads of workers in their daily tasks and helps specialists to adjust their working conditions. Future comparative works between the E.M.I.L© sensor and the Trigno Aventir Sensor© from Delsys© will be interesting. This latter is the reference in research. Also, it would be relevant to study thinner muscles to know whether the results will remain accurate.

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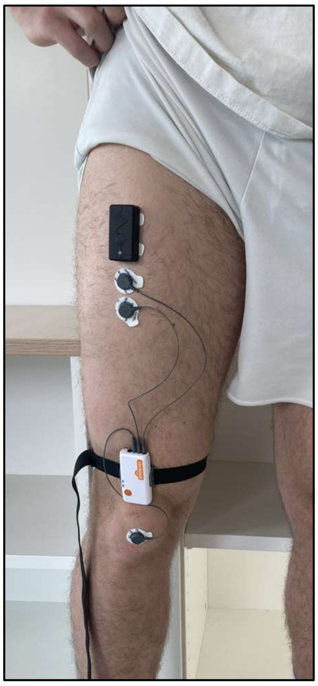
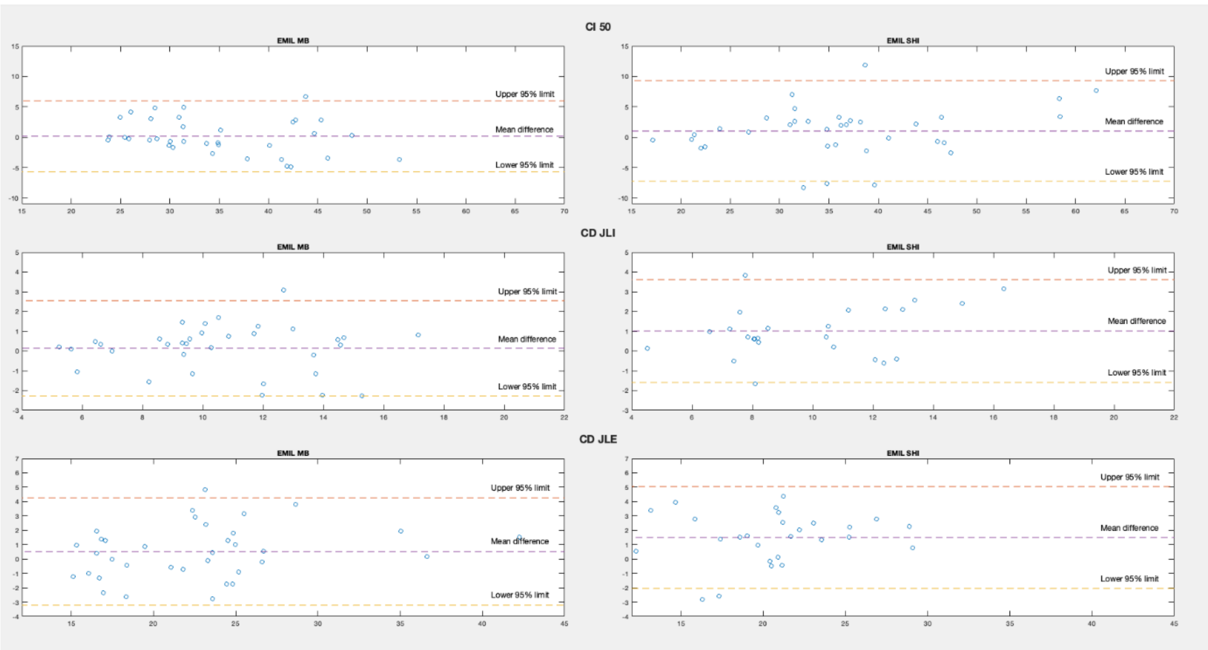
Appendix



Appendix 1: Sensors location on Rectus Femoris (E.M.I.L© et Shimmer3© ECM/EMG)



Appendix 2: Bland – Altman Diagram.

Appendix 3: Formula

$$MOV = \frac{\sum_{t_i}^{T} x_i}{T} \qquad (A)$$

$T: range\ of\ smoothing\ (200\ ms)$
$x_{t_i}: EMG\ filtered\ at\ t_i \in [O; T]$

$$RMS = \sqrt{\frac{\sum_{t_i}^{T} x_{t_i}^2}{T}} \qquad (B)$$

$T: envelope\ duration\ in\ milliseconds\ (ms)$
$x_{t_i}: EMG\ filtered\ at\ t_i \in [O; T]$

$$SD = \frac{1}{N}\sum_{i}^{N}(x_i - \bar{x}) \qquad (C)$$

$SD: Standard\ Deviation$
$N: Number\ of\ Subjects$
$x: Envelope\ RMS$
$\bar{x}: mean\ of\ RMS\ over\ all\ subjects$

$$SEM = \left|\frac{SD(x_{E.M.I.L} - x_{ref})}{\sqrt{2}}\right| \qquad (D)$$

$SD_i: standard\ deviation\ of\ data\ sample\ i$

$$ICC = \frac{SD^2 - SEM^2}{SD^2} \qquad (E)$$

$$AB = mean\left(x_{E.M.I.L} - x_{ref}\right) \qquad (F)$$

$$r = \frac{\sum_{i=1}^{n}\left(x_{E.M.I.L_i} - \overline{x_{E.M.I.L}}\right)\left(x_{ref_i} - \overline{x_{ref}}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_{E.M.I.L_i} - \overline{x_{E.M.I.L}}\right)^2} * \sqrt{\sum_{i=1}^{n}\left(x_{ref_i} - \overline{x_{ref}}\right)^2}} \qquad (G)$$

$r: Pearson\ Correlation\ Coefficient$