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Normalizing gastrocnemius muscle EMG signal: an optimal set of maximum voluntary isometric contraction tests for young adults considering reproducibility

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Abstract

Background: Even though most studies normalize the surface EMG signal of the gastrocnemius muscle using a single position of maximum voluntary isometric contraction (MVIC), several studies tend to indicate that several positions are in fact needed to obtain a maximal voluntary activation (MVA) for most of the subjects. However, no combination of positions has already been described.

Research question: A combination of MVIC positions to normalize the EMG signal of the gastrocnemius muscle is investigated. the influence of using several positions on the reproducibility of the normalization process is evaluated.

Methods: Twenty healthy volunteers (45% female – 55 % male, 25.4 years (SD 4.3), 72.6 kg (SD 13.9), 1.78 m (SD 0.12)) were recruited. Six positions for MVIC were compared and the effect of several normalization combinations on a functional task (gait) was evaluated.

Results: Several positions are needed to obtain at least 90% of the MVA for 90% of the volunteers even though the use of a single well-chosen position (unipodal standing position with knee fully extended and ankle fully plantar-flexed) will lead to no statistically significant differences of the gait evaluation during stance phase. For each position, five repetitions of the MVIC are recommended to obtain a valid MVA.

Significance: This study confirms that using several MVIC positions is recommended when possible to normalize the gastrocnemius muscle EMG signal. However, in the situation of a patient where limited MVIC attempts are possible, using a single well-chosen position should not significantly influence the amplitude and the reproducibility of the measures.

1 Introduction

The lower limb muscles play an important role in the quality of gait but also in all sort of activities such as running and jumping. Muscle activation may reflect disorders or pathologies [1]. Surface electromyography (EMG) is commonly used to evaluate the muscle contraction intensity and timing [2]. However, there is no unequivocal relationship between the amplitude of the electrical signal and the force exerted by the muscle because of intrinsic and extrinsic factors [3]. Consequently, surface electromyographic recordings need to be normalized if comparisons, between subjects or times, are sought. Maximal voluntary isometric contractions (MVIC) are commonly used [4] because they allow comparing muscle activity levels between muscles, tasks and individuals [3].

Most studies based EMG signal normalization on a single MVIC position [5]. However, a few studies [6,7] have shown that several positions are needed to obtain a maximal activation for most individuals for the triceps surae muscle. Therefore, these authors recommended to use more than one position to normalize the EMG signal. However, to date, the effectiveness of combining several MVIC positions on the intersession reproducibility has not been explored for the lower limb. Most studies have only focused on comparing the relative reproducibility of several normalization approaches (i.e. isometric vs. isokinetic vs. dynamic actions …) [8–10]. The ability to obtain reliable measurements over time is a key factor to use EMG evaluations for rehabilitation or clinical trials purposes.

In addition to the positions used, the number of MVIC attempts might also influence the maximal activation obtained during the MVIC procedure. For quadriceps muscle, 25% of the individuals may not generate maximal force after three attempts [11]. For triceps surae muscle, maximal activation is almost equally obtained during each of three attempts [12].

The objectives of this study were firstly to evaluate the influence of combinations of MVIC positions on the normalization of gastrocnemius EMG signals. The criterion retained for evaluation was the level of MVA achieved, the percentage of the population achieving maximal activation, and repeatability. Secondly, the effect of the number of MVIC attempts on the normalization was also evaluated. A functional task (gait) was included to assess the practical consequences of the normalization choices on the EMG signal interpretation.

2 Material and methods

2.1 Participants

Twenty volunteers (45% female – 55 % male, 25.4 years (SD 4.3), 72.6 kg (SD 13.9), 1.78 m (SD 0.12)) were included. The volunteers should have a recreational practice of sport (from 1.5 to 6 hours per week). None of them had a history of surgery or injury at their lower limbs. The study was approved by the local ethics committee, and each participant was informed of the details of the study.

2.2 Instrumentation

Surface EMG signal was collected with Trigno Standard sensors (Delsys, Boston, MA, USA) using silver-contact wireless bipolar bar electrodes with fixed 10 mm inter-electrode spacing. The two heads of the gastrocnemius muscle were investigated. Electrodes were positioned following Barbero et al. recommendations [13]. Only one leg was studied for each subject (equal repartition of the dominance). Data were acquired at a sample frequency of 1000 Hz.

The position of the foot was measured using 3D cameras (CX1 units, Charnwood Dynamics, Rothley, UK) at a frequency rate of 100 Hz. Two markers were placed on the posterior part of the heel and at the top of the hallux of the studied foot. This 3D system has been shown to be an accurate evaluation tool [14].

2.3 MVIC tests

Six MVIC positions were evaluated in this study (Figure 1). The task acronyms were defined as follows: the value following the “K” and “A” letters indicate the knee and ankle angles, respectively. “uni” and “bi” specified whether the standing position was unipodal or bipodal. To limit a possible investigator’s influence, the MVIC positions were maintained using a steel structure rather than a manual resistance. The structure did not apply extra-weight. It was possible to adapt the structure to both the test positions and the specific size of the volunteers. Before starting the MVIC tests, the volunteers performed a warm-up composed of 20 plantar flexions to reach a tiptoe position and 20 plyometric jumps on a 20 cm step. Before each position, the volunteers were asked to perform three increasing sub-maximum trials to get used to the exercise. Then, three trials of five seconds were performed for each position. For the bipodal upright position with the knees fully extended only, ten repetitions were performed. The total number of MVICs was 25. The volunteers were asked to increase the exerted force during the first second and maintain maximal force during the last four seconds. During the trials, the volunteers received verbal encouragement. As previously recommended [15], to avoid fatigue, a minimum of 30 seconds and three minutes rest intervals were provided between each trial and each MVIC test position respectively. The order of the positions was randomized across the volunteers.

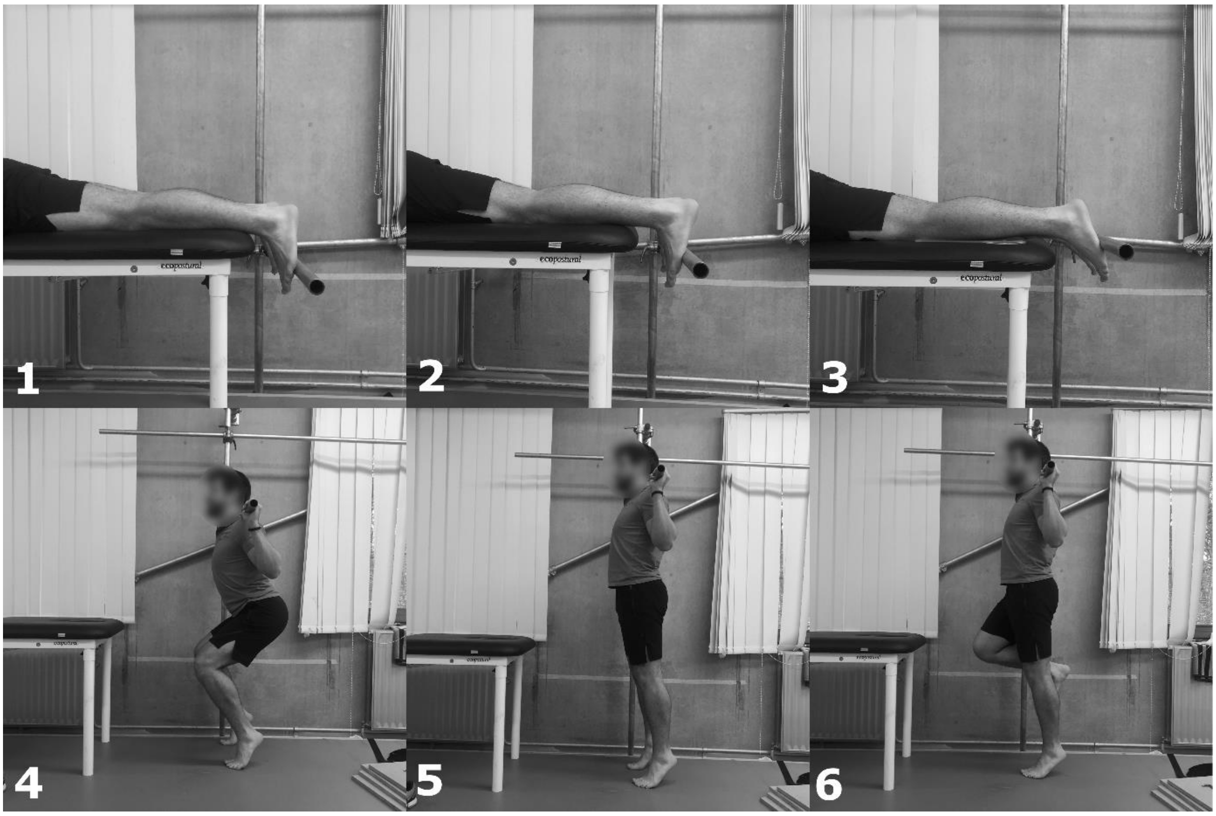

Figure 1: *The six maximum voluntary isometric contraction positions. 1) [K0 A0] prone position, knee fully extended (0°), ankle in neutral position (0°), 2) [K0 Amax] prone position, knee fully extended (0°), ankle in maximal dorsal flexion, 3) [K0 A30] prone position, knee fully extended (0°), ankle at 30° of plantar flexion, 4) [K90 Amax bi] upright bipodal position, knee at 90°, ankle in maximal plantar flexion, 5) [K0 Amax bi] upright bipodal position, knee fully extended (0°), ankle in maximal plantar flexion, 6) [K0 Amax uni] upright unipodal position, knee fully extended (0°), ankle in maximal plantar flexion. No motion was performed during the acquisitions*

To evaluate the repeatability of the MVA estimations, the volunteers were evaluated again with the same protocol (same order of MVIC tests as during the first session) seven days after the first test.

2.4 Functional test

The volunteers were asked to perform three gait trials at a self-selected comfort speed. The length of the gait was approximately 15 m and the central steps were retained for analyses to avoid the acceleration and deceleration phases. These tests were performed during both sessions.

2.5 Signal and statistical analyses

The EMG signal was first band pass filtered (20 - 500 Hz, zero-phase 4th order Butterworth) and then processed using a root-mean-square algorithm (50 ms moving window) [16]. Then, the average EMG envelope over a time window of one second (moving average filter) was calculated during each MVIC trial for each muscle. The activation level of each muscle was then defined as the peak value of the processed signal among the three MVIC trials. The muscle activation level during each MVIC trial was then expressed as a percentage of the maximum activity found among all the MVIC trials [7].

All the combinations of MVIC tests were investigated for the following criteria: percentage of muscle activation level, percentage of volunteers achieving specified activation levels, intersession reproducibility. To assess the reproducibility of the maximal muscle activation, a Bland and Altman approach [17] was used as described previously [18]. The 90% limits of agreement of the Bland and Altman statistics were computed. Then, the maximum of the absolute value of the upper and lower bounds of the limits of agreement were kept (a measure of 'total error' [17]). This approach provides an estimation of the reproducibility error which applies to at least 90% of the volunteers. To assess muscle activations during gait, one-dimensional statistical parametric mapping [19,20] (parametric paired t-tests (SnPM{t})) was used. One-tailed t-tests were applied when we had a priori knowledge of the direction of the normalization effect. Statistical significance occurs when the SnPM curves cross the critical threshold. The associated p- values are calculated using Random Field Theory. This approach allows comparing the complete gait cycle rather than a limited number of features such as the muscle activation peak. As the gastrocnemius muscle mainly contributes to the stance phase in normal gait [21], we only performed the analysis during this phase.

The EMG signals were normalized with the values obtained during the MVIC tests and then expressed relatively to a gait cycle. Gait events (heel strike and toe off) detection was based on the method described by O'Connor et al [22] using the 3D markers placed on the feet.

3 Results

3.1 Individual MVIC positions evaluation

None of the MVIC positions taken individually produced at least 90% of the MVA for at least 90% of the volunteers (Figure 2). For both gastrocnemius lateralis and medialis muscles (GL and GM), the unipodal upright position [K0 Amax uni] provided the best maximal activation. Our results showed that for GL, 65% (85% for GM) of the volunteers achieved at least 90% of MVA in unipodal standing with a mean activation of 94.2% MVA (95.4% MVA for GM).

The reproducibility results demonstrated large 90% confidence intervals for all positions (Figure 2). The upper value of the confidence interval of the most reproducible position, [K0 Amax uni], was 18.8% MVA.

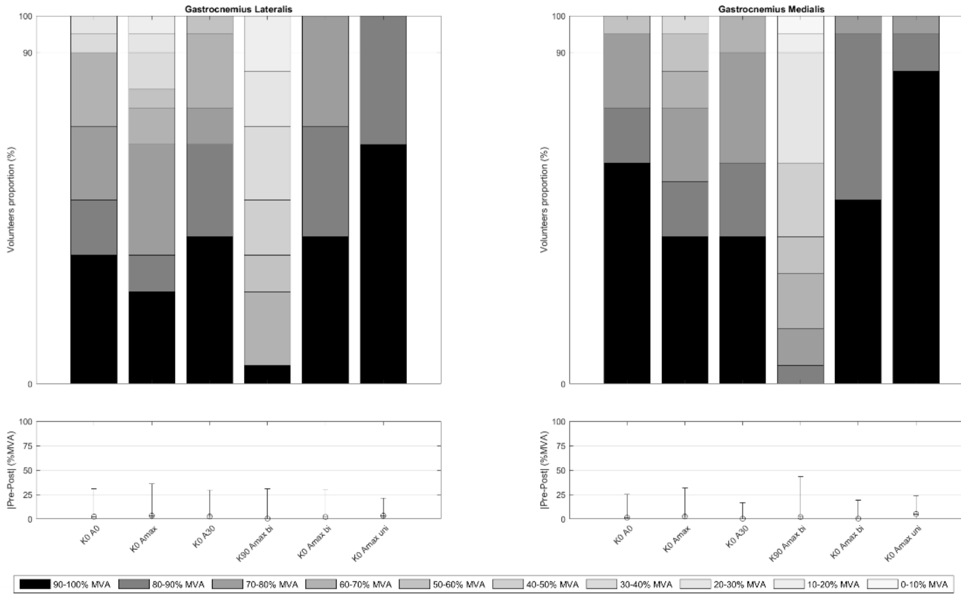

Figure 2: *Level of muscle maximal voluntary activation and reproducibility during the six individual isometric tests (gastrocnemius lateralis muscle on the left and gastrocnemius medialis muscle on the right) . The stacked bars represent the percentage of volunteers within activation level ranges of 10%. The error bars represent the absolute value of the difference (and 90% confidence interval) of normalized activation between the pre- and post-tests.*

3.2 Contribution of MVIC combination

The evaluation of all the possible combinations of MVIC positions showed that at least a combination of three positions, all including [K0 Amax uni], was required to obtain at least 90% of MVA for at least 90% of the volunteers for GL. For instance, for [K0 A0] + [K0 A30] + [K0 Amax uni], the mean activation was 98.4% MVA, 95% of the volunteers achieved at least 90% MVA and the upper value of the confidence interval of the reproducibility error was reduced to 11.9% MVA). Only two positions were needed for GM, all including [K0 Amax uni] (i.e. [K0 A0] + [K0 Amax uni]).

When considering the gait trials, using single positions for normalization led to significant differences in comparison to using a combination of positions (Figure 3). However, the level of significance and the differences between the curves varied depending on the chosen position. The peak activity obtained using only [K0 A0] for normalization was 18.4% MVA (SD: 22.9) higher than the peak obtained when using a combination of three positions (SPM analysis: from p = 0.02 to p < 0.01). The same difference was only 1.6% MVA (SD: 2.6) for the position [K0 Amax uni] (SPM analysis: p = 0.05).

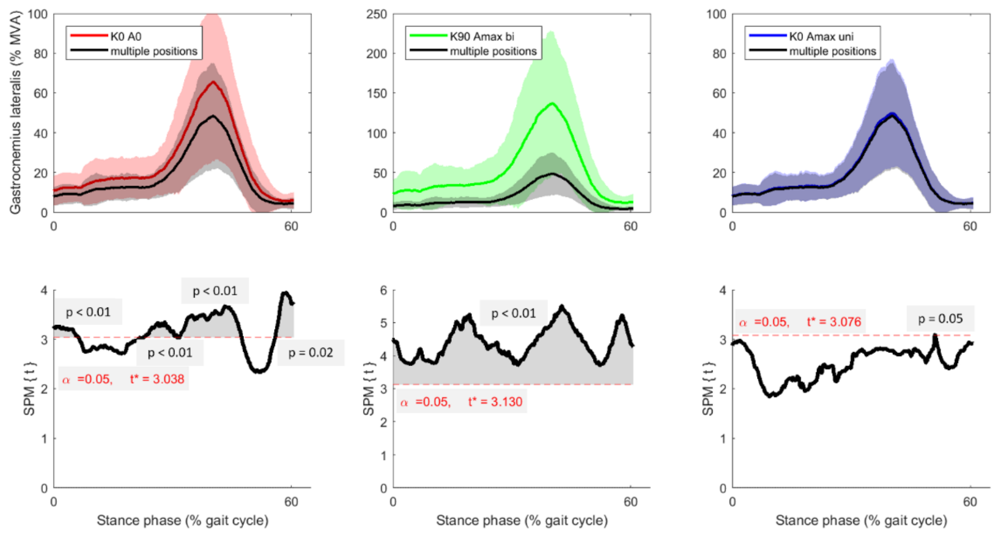

Figure 3: *Effect of the number of MVIC positions on the normalized activity of the gastrocnemius lateralis muscle during the gait stance phase. Upper row: muscle activity during stance phase (multiple positions: [K0 A0] + [K0 Amax bi] + [K0 Amax uni]), lower row: 1D statistical parametric mapping shows statistical differences when the solid thick line is over the horizontal dashed line.*

The comparison of the EMG curves (Figure 4) did not reveal significant differences (p > 0.05) between the intersession errors of several normalization strategies. However, the intersession errors were approximatively 1.5 to 1.8 times higher when the [K0 A0] position was used rather than the [K0 Amax uni] or multiple positions.

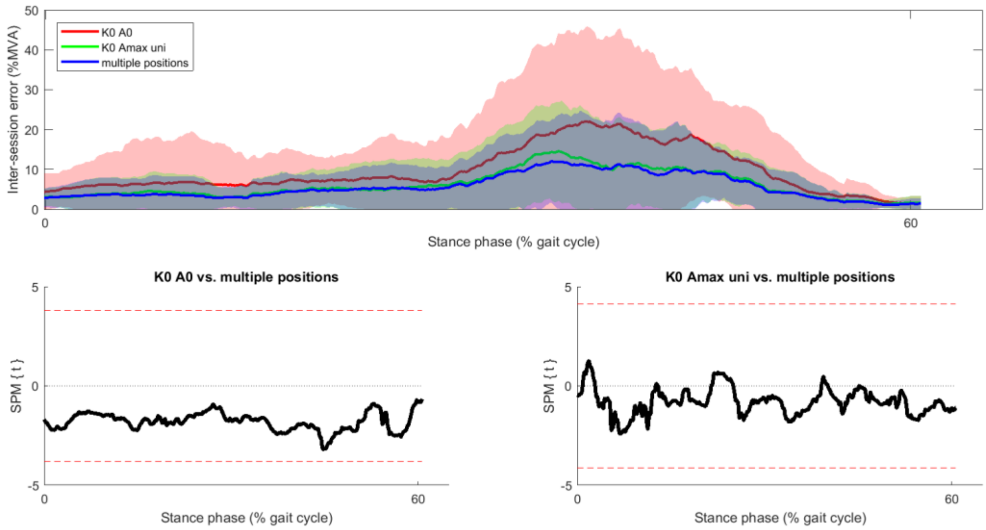

Figure 4: *Intersession error of the normalized activities of the gastrocnemius lateralis muscle during the gait stance phase. Upper row: pre-post absolute difference of the normalized muscle activity during stance phase (multiple positions: [K0 A0] + [K0 Amax bi] + [K0 Amax uni]), lower row: 1D statistical parametric mapping shows statistical differences when the solid thick line is over the horizontal dashed line.*

3.3 Influence of the number of MVIC attempts

The number of MVIC attempts used to normalize the EMG signal of GL and GM can significantly influence the normalized muscle activity during gait. Results (Figure 5) showed that for GL and GM, at least five attempts were required to achieve 90% of the MVA for 90% of the population. Using only one attempt for GL led, on average, to 86.3% of the MVA. Our results also demonstrated that all the repetitions have equal chances to elicit the MVA (ANOVA 1, p = 0.92 and p = 0.76 for GL and GM muscles respectively).

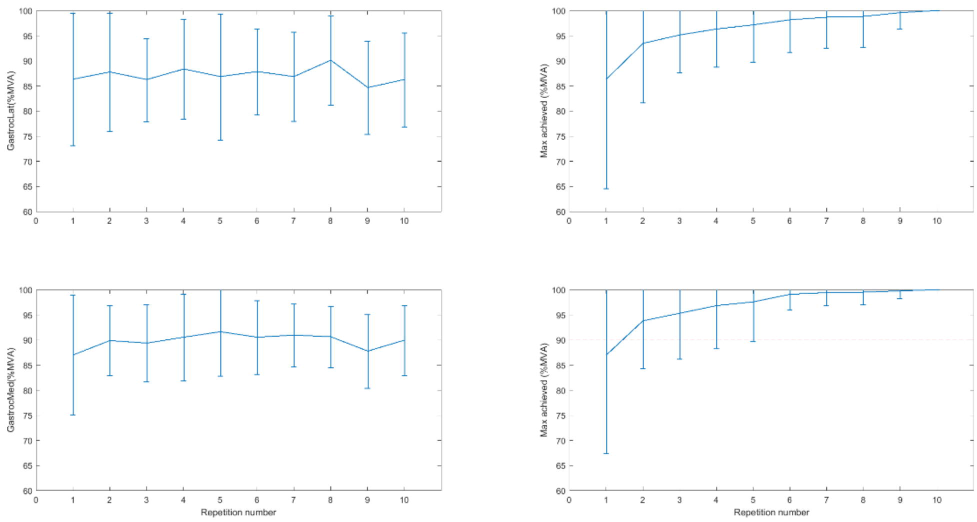

Figure 5: *Effect of the number of MVIC attempts [K180 Amax bi] on the achieved Maximal Voluntary Activity (MVA) of the gastrocnemius muscles. Left column: maximal muscle activity achieved at each single repetition. The error bars represent the standard deviation. Right column: maximal muscle activity achieved counting all previous repetitions. The error bars represent 1.645 times the standard deviation to cover 90% of the population. The horizontal dashed line represents the 90% MVA limit.*

4 Discussion

Previous studies have identified that several MVIC positions are needed to obtain a maximal activation of the gastrocnemius muscles [6,7]. However, the effect of selecting several MVIC tests to obtain the MVA of the gastrocnemius muscles on the intersession reproducibility has not been considered yet. This evaluation is of importance as it could significantly contribute to the definition of modalities able to evaluate the effect, over time, of clinical interventions on muscle activation patterns.

4.1 Individual evaluation of MVIC positions

Seated and standing positions have been studied in the literature and results have shown that standing positions usually lead to superior muscle activation [6,7]. The present study has compared lying and standing positions and has found that standing positions should also be favored to obtain a MVA. In the unipodal standing position with the knee fully extended, our results (mean activation of approximately 95% MVA) are similar to the one obtained by previous studies (mean activation was 85.6% MVA) [7]. Normalization using dynamic movements (maximal squat jump) has also been shown to be effective [23] to obtain MVA of the gastrocnemius muscles. Our results combined to the ones obtained previously in the literature tend to show that the positions leading to the largest loads (unipodal standing, jumping) provide larger activations with respect to positions implying lower loads (bipodal standing, sitting, lying). This situation could be problematic when evaluating individuals with pain or balance issues such as eldery or post-surgery populations. Indeed, using a less efficient (but less mechanically stressful) MVIC position would lead to an overestimation of the level of activity of a muscle and consequently complexify the clinical interpretation of data.

Our results confirm that no single MVIC position is able to elicit maximal gastrocnemius activation for all the volunteers. In Rutherford et al. [7], 49% (63%) of maximal activation was obtained in a unipodal standing position against 25% (18%) in a sitting one for GL (respectively GM). Similar conclusions have also already been found for other body parts such as reported by Vera-Garcia et al. [24] for the lower trunk and by Schwartz et al. [18] for the upper limb.

The evaluation of the intersession reproducibility of the MVIC positions demonstrates that even if no significant differences exists between some positions in terms of intersession errors, the magnitude of the errors may be affected. This result implies that if a non-optimal position (in terms of muscle activation) has to be used with a patient (because of pain, limited balance …) intersession comparisons could be used but should be interpreted with cautious.

4.2 Contribution of MVIC combination

Performing MVIC tests is both time consuming and may induce fatigue. There is consequently a large consensus in the literature that an optimal set of MVIC tests containing a limited number of tests should be identified [6,7]. This study demonstrated that, based on an evaluation of all the combinations of the tested positions, at least three positions are needed to obtain at least 90% of the MVA for 90% of the volunteers for GL. For GM only two positions are needed. A lower inter-subject variability for GM is consistent with a previous study indicating that more volunteers produced a maximum activation in an unipodal standing position for GM compared to GL [7].

Significant differences were found between the use of a combination of MVICs positions and MVICs positions used alone to estimate muscles' activation during gait. For instance, using only one prone position to estimate MVA can lead to an increase of more than 35% of the muscle activation estimation during gait and consequently impair the clinical interpretation of the results. Ball et al. [10] have already stated that results obtained using different normalization methods (isometric, dynamic …) may not be comparable. The results of this study further demonstrate that data normalized using different MVICs protocols may not be comparable either and that the community would benefit from the standardization of the EMG normalization protocols. However, it should be noted that very limited differences of amplitude (and no significant statistical difference) are observed during gait when using the unipodal standing position alone for normalization in comparison with a combination of three positions. Therefore, in a situation where only one MVIC position needs to be kept (time constrains, risk of fatigue, risk of pain …) choosing the unipodal standing position is, based on the results of this study, the best compromise even if reproducibility is affected for some volunteers.

Adding an unreliable MVIC position to a combination of positions can reduce the overall reproducibility as previously suggested in the literature [23] even if MVA is sometime obtained. Therefore, there should be a compromise between maximal activation and increased reproducibility. In the present study, for the combination of positions [K0 A0] + [K0 Amax] + [K0 Amax uni] 90% of the volunteers have a mean MVA above 90% but a reproducibility of only 11.7% for GL. For the combination [K0 A0] + [K0 Amax bi] + [K0 Amax uni] only 80.0% of the volunteers have a mean MVA above 90% but the reproducibility is improved to 7.9%. These findings can be related to the instability of the EMG activity near maximal level as reported by De Luca et al. [2] who recommended using sub-maximal activation levels. Because of the importance of a good balance between reproducibility, MVA achievement and timing, our recommendations for MVICs combination are [K0 A0] + [K0 Amax bi] + [K0 Amax uni] for GM and [K0 A0] + [K0 A30] + [K0 Amax uni] for GL. This last combination is also valid if both GL and GM should be normalized at the same time. Better combinations using positions not tested in this study might however exist. For instance, Riemann et al. [5] have shown that foot orientation (internally or externally rotated) will favoured the activation of either the GL or the GM.

The present study was performed on young adults and the optimal MVIC combinations which are reported may not be optimal for other populations. Morphological differences as well as clinical interventions may modify the muscle activation patterns. One should therefore remain careful when extrapolating the results of reproducibility obtained in this study to other contexts.

4.3 Influence of the number of MVIC attempts

The literature show a large variability in the practice concerning the number of MVIC attempts used to obtain the muscle MVA. The number of attempts ranges from one [5] to four [23] including two [7,25] and three [6]. SENIAM general recommendations of three trials are in line with findings [6] showing that all (three) repetitions have equal chances to produce the maximal voluntary muscle activation. Our results confirm that several attempts are needed to obtain MVA. Our results demonstrate however that five repetitions, rather than three, are needed to obtain 90% MVA for nearly 90% of the volunteers. A single attempt only led, on average, to 86.3% of the MVA of GL. It should however be mentioned that the effect of the number of repetitions was only evaluated for one single position and that different results might be obtained for other positions.

5 Conclusion

Our results showed that three MVIC positions are needed to obtain a reproducible MVA for the gastrocnemius muscles and five MVIC attempts are recommended. A compromise needs to be performed between the evaluation of the maximal activation and the intersession reproducibility. When the evaluation of the MVA should be obtained in a limited number of attempts, our results demonstrated that, among the tested positions, the unipodal standing position is the best choice.

Conflict of interest statement

The authors have no financial and personal relationships with other people or organisations that could have inappropriately influence this work.

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