Differences in maximum voluntary excitation between isometric and dynamic contractions are age dependent

Remco J. Baggen^{1,2}, Jaap H. van Dieën², Sabine M. Verschueren³, Evelien Van Roie¹,
Christophe Delecluse¹

¹ Department of Movement Sciences, Physical Activity, Sports and Health Research Group,
KU Leuven

² Faculty of Behavioural and Movement Sciences, Department of Human Movement
Sciences, Amsterdam Movement Sciences, Vrije Universiteit Amsterdam

³ Department of Rehabilitation Sciences, Research Group for Musculoskeletal Rehabilitation,
KU Leuven

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Correspondence Address:

Remco J. Baggen, MSc.

ORCID: 0000-0002-1034-8997

Tervuursevest 101 – bus 1501

3001 Leuven, Belgium

Phone: +32 16 37 73 77 Email: remco.baggen@kuleuven.be

Running Title: Considerations for EMG normalization in young and older adults

Abstract

In older populations, obtaining true maximum voluntary excitation appears more difficult than in young populations. The aims of this study were to determine whether differences between maximum voluntary excitation obtained from voluntary isometric contractions (MVIC) versus (sub-)maximum voluntary dynamic contractions (s-)MVDC) are age-dependent, and how normalizing EMG signals to corresponding maximum voluntary excitations affects variance between participants and the likelihood of normalized signals exceeding 100%. MVIC, s-MVDC and MVDC were recorded in ten young women, and MVIC and s-MVDC in nineteen older women. A significant age x contraction mode interaction effect was found for vastus lateralis ($p = 0.037$). In young women MVDC elicited highest maximum voluntary excitation for vastus lateralis and rectus femoris ($p < 0.05$). In older women, no differences in maximum voluntary excitation were found ($p > 0.05$). Normalization to dynamic contractions resulted in lower between-participant variance of EMG amplitudes, though not for all muscles, and decreased the amount of normalized signals exceeding 100% in young women. These findings indicate that differences in maximum voluntary excitation across contraction modes are age-dependent. Therefore, one should be cautious when comparing normalized signals between age groups, but overall dynamic contractions may be preferable above isometric contractions for normalization purposes.

Keywords: surface electromyography, normalization, older adults, young adults

Introduction

Surface electromyography (EMG) is commonly used to measure muscle activation during task performance. It is often used to indirectly estimate individual muscle forces during a contraction¹ instead of measuring force directly (e.g. with a dynamometer). This is likely because direct force measurements are difficult to obtain and are subject to effects of co-contraction of synergistic and antagonistic muscles that modulate the net force produced². However, the absolute value of surface EMG signals (obtained in V or mV) can be affected by many factors such as variation in EMG electrode placement, skin preparation, and impedance of the skin interface and tissue layer between electrodes and muscle^{1,3}. To allow for comparisons of muscle activation between participants and within participants between different measurement sessions, EMG signals need to be normalized⁴. Normalization is usually performed by expressing the magnitude of activation from a specific muscle as a percentage of the EMG signal obtained from a reference contraction of the same muscle⁵.

The most commonly applied method of normalization is by expressing activation as a percentage of maximum voluntary excitation, obtained during a maximum voluntary contraction^{6,7}. This maximum voluntary contraction can be performed either isometrically (MVIC) or dynamically (MVDC). To date, there is no clear consensus on which EMG normalization method is the best. A general conclusion could be that both MVIC and MVDC have advantages and disadvantages⁵. Even though physical limitations might make it difficult to obtain a 'true' maximum voluntary excitation⁸, one should strive to normalize to a value that is as close as possible to the true maximum. This will reduce the number of normalized signals obtained from dynamic activities that exceed 100% of the predetermined maximum and limit between-participant variance, enabling researchers to more accurately assess individual muscle contributions to a motor task, and provide more accurate force estimations^{1,7,9}.

In most research and clinical settings, signal normalization is performed using MVICs⁴. This method is commonly applied since it is easy to perform in a standardized manner^{7,10}. MVICs are often recorded at specific joint angles, despite the fact that the ability to achieve maximum excitation may depend on joint angle and this dependency may differ between synergistic muscles¹¹. This limitation can be addressed by measuring maximum voluntary excitation at several joint angles to allow angle-specific normalization. However, this is rarely performed since it is a time consuming process, and muscle fatigue may affect EMG signals obtained¹¹. The absence of joint angle-specific methods could cause severe underestimation of the true maximum voluntary excitation, resulting in normalized signals that exceed the predetermined 'maximum' excitation obtained through MVIC⁷. For some muscles, studies have found activation reaching up to 300% of predetermined maximum voluntary excitation during dynamic task performance⁷, leading to overestimations of the proportion of individual muscle capacity required for dynamic task performance⁵. Additionally, participants are usually unfamiliar with isometric contractions, which can lead to a 20-30% reduction in maximum contraction performance¹⁰. In contrast with MVIC, normalizing to a MVDC usually results in fewer recordings that exceed 100% of the predetermined maximum^{5,12}. MVDCs can be performed with an isokinetic dynamometer, but one-repetition maximum (1-RM) testing is more common¹³.

An important issue when selecting a normalization method is that little is known about how factors like age affect the difference between isometric and dynamic normalization. Age-related differences in maximum excitation may in part be accounted for by differences in thickness of subcutaneous fat layers and skin impedance³, which is why signal normalization is essential when comparing between age groups. Nevertheless, these confounders would be expected to have an equal impact on maximum voluntary excitation regardless of the contraction mode. However, if the age-related decline in maximum excitation obtained from isometric

contractions would differ from that obtained from dynamic contractions, comparisons of outcomes obtained from different normalization methods would be inherently skewed. Differences in the ability to assess ‘true’ maximum activation are likely to be more pronounced in populations such as older adults and patients with pain-related inhibition, because it is more difficult for these populations to perform maximum voluntary contractions (either isometrically or dynamically) ^{14–16}. For this reason, normalization to a well-defined sub-maximum contraction is often advised. This reference contraction should not exceed 80% of maximum because EMG signals and force are exceptionally unstable above this level ^{1,6}. Examining the age-related differences between normalization methods is especially relevant in the female population as the age-related loss of muscle mass, which is generally accelerated after menopause ¹⁷, inevitably results in a lower number of motor units firing simultaneously, while conductivity between the skin and electrodes is decreased due to a relative increase in subcutaneous adipose tissue ¹⁵.

So far, no studies have investigated if differences in maximum voluntary excitation between isometric and dynamic contractions are age-dependent. Therefore, the first objective of this study was to determine if there is an interaction effect of age and contraction mode. The second objective was assess how normalization using different contraction modes would affect between-participant variance of normalized EMG signals and which method resulted in the least amount of normalized signals exceeding 100%. We hypothesized that dynamic contractions would yield higher EMG amplitudes than isometric contractions, that age would show a significant interaction effect with contraction mode, and that normalization to dynamic contractions would result in lower between-participant variance, and a lower amount of normalized signals exceeding 100% for both age groups.

Methods

Participants: Ten healthy young women ($22.9\text{y} \pm 1.6$) and nineteen healthy community-dwelling older women ($69.1\text{y} \pm 3.1$) were recruited around Leuven, Belgium. Data from the older women were reported previously¹⁸. Potential participants were excluded if they had any medical contra-indications for resistance exercise or if they had participated in a structured strength training program in the last six months. This study was approved by the Human Ethics Committee of KU Leuven in accordance with the Declaration of Helsinki. All participants provided signed informed consent before participation.

Protocol: All data were collected at the Movement and posture Analysis Laboratory Leuven (MALL). EMG was recorded from the rectus femoris, vastus lateralis and gluteus medius. Electrode placement sites were first shaved and thoroughly scrubbed with isopropyl alcohol. Bipolar pre-gelled disposable surface EMG electrodes (Ambu® BlueSensor P Ag/Ag-Cl electrodes, Ballerup, DK) were then placed, in parallel to the muscle fiber direction, on the muscle belly with an inter-electrode distance (center to center) of 25 mm. EMG was amplified 1000x and band-pass filtered between 10–500 Hz. EMG was recorded with a telemetric system (ZeroWire®, Aurion, Milan, IT) with a sampling rate of 1000 samples/s. Subsequently, all recorded EMG signals were high-pass filtered with a 1st order Butterworth filter with a cut-off at 20 Hz¹, full-wave rectified and smoothed with a 100 ms moving average window using MATLAB R2014b (MathWorks®, Natick, USA).

Prior to testing, all participants performed a 5-minute warm-up on a cycle ergometer with moderate resistance at 70-80 RPM. After warming-up, individual 1-RM was estimated for each resistance exercise using a formula by Brzycki¹⁹. In order to ensure accuracy of the estimates, five-repetition maximum (86% 1-RM) was the minimum intensity used to calculate the 1-RM. The testing protocol consisted of a unilateral seated knee extension and a unilateral standing hip abduction, performed with an adapted cable jungle (Technogym®, Gambettola, IT) (Figure

1). Due to limitations of older adults in performing maximum contractions ^{1,15}, the weight corresponding with 80% 1-RM (s-MVDC), which was the maximum intensity employed in the older cohort, was calculated. Consequently, to allow for comparisons between both age groups, s-MVDCs were also included for the young cohort.

Figure 1 - Older participant performing standing hip abduction (left) and seated knee extension (right).

MVIC values for the vastus lateralis and rectus femoris were recorded in seated position with a knee angle of 90° while the hip and ankle were fixated. For the gluteus medius, participants laid on a bed sideways with their dominant side up. The hip and ankle were fixed with the knee fully extended. MVIC was recorded twice during 5 seconds of maximal contraction and the highest value was used for normalization. For (s-)MVDC, each participant performed three separate repetitions of knee extension and hip abduction at an intensity of 80% and 100% of 1-RM. The order of exercise intensities was randomized to avoid fatigue bias.

Each repetition was timed at one second concentric action and one second eccentric action, indicated by a metronome, to avoid differences in peak excitation due to repetition speed. Participants also performed three repetitions of forward and lateral stepping onto an elevated platform for each riser height (10, 20 and 30 cm). Stepping was timed at one second for ascent, one second stance and one second descent, indicated by a metronome to match concentric contraction speed with the 1-RM trials. The EMG signals obtained from these stepping tasks were normalized to the maximum voluntary excitation obtained from each contraction mode to assess between-participant variance. The amount of dynamic trials for which activation exceeded 100% of maximum voluntary excitation provided an indication of underestimation of the true maximum by each normalization method. Forward stepping was chosen specifically because of its functional similarity to stair climbing^{20,21}, a daily activity which requires a relatively high effort for older adults^{22,23}. Lateral stepping was added because it was found to elicit additional gluteus medius activation¹⁸.

Data analysis: Statistical analysis was performed with SPSS (IBM® SPSS v23 Statistics for Windows, Armonk, USA). All data were checked for normality with a Kolmogorov-Smirnov test. Non-normalized signals more than 2 standard deviations from the mean were removed from the analyses. Two-way ANOVA was used to test for main effects of contraction mode and for age x contraction mode interaction effects. In view of the sample size²⁴, post hoc tests consisted of paired samples t-tests within groups. Within-group analyses of the normalized signals were performed using Friedman tests for the young adults and Wilcoxon Signed Rank tests for the older adults. Overall level of significance was set at $p = 0.05$.

Results

A significant main effect of contraction mode on obtained peak excitation was found for vastus lateralis ($p = 0.001$) and rectus femoris ($p = 0.018$) but not for gluteus medius ($p = 0.964$). There was a significant age x contraction mode interaction effect on vastus lateralis peak excitation ($p = 0.037$) but not on rectus femoris and gluteus medius peak excitation ($p > 0.05$; Table 1).

Table 1: Mean and standard deviation of peak EMG per muscle obtained from each normalization method (MVIC, s-MVDC and MVDC) for young and (MVIC and s-MVDC) for older women.

		Peak amplitude (mV)			Significance of Difference			Interaction effect ^a
Muscle		MVIC	s-MVDC	MVDC	MVIC/s-MVDC	MVIC/MVDC	s-MVDC/MVDC	
Vastus lateralis	Young women	2.1 ± 0.7	3.6 ± 1.8	4 ± 1.8	0.040	0.009	0.011	0.037
	Older women	1.8 ± 0.9	2 ± 0.6		0.117			
	Women							
	Sig. Diff. Y/O	0.126	0.005					
Rectus femoris	Young women	2.6 ± 1.9	3.4 ± 1.4	4.1 ± 1.8	0.177	0.009	0.029	0.249
	Older women	1.6 ± 0.9	1.9 ± 0.6		0.099			
	Women							
	Sig. Diff. Y/O	0.164	< 0.001					
Gluteus medius	Young women	3.3 ± 1.5	3.4 ± 2.2	3.6 ± 2.3	0.887	0.585	0.076	0.721
	Older women	1.5 ± 1	1.4 ± 0.7		0.968			
	Women							
	Sig. Diff. Y/O	< 0.001	< 0.001					

The p -values of differences between methods for young and older women are displayed on the right and p -values of difference between age groups for each method are displayed below. Significant differences are indicated in bold. ^a age x contraction mode.

For young women, MVDC elicited significantly higher excitation than MVIC in vastus lateralis and rectus femoris, and s-MVDC elicited higher excitation than MVIC, although this difference was only found to be significant in vastus lateralis. Excitation obtained from MVDC in the quadriceps muscles was also significantly higher than s-MVDC. The same trend was visible for gluteus medius, but these differences were not statistically significant (Table 1). Normalized data from the stepping trials (Figure 2) show that signals from the vastus lateralis were significantly higher when normalized to isometric contractions compared with signals normalized to either maximum or sub-maximum dynamic contractions (with more excursions above 100%). Normalization to isometric contractions also resulted in the highest between-participant variance. The same trend was visible for the rectus femoris. However, differences were not statistically significant for each step height. No differences or signals exceeding 100% were found for gluteus medius.

In contrast with the results obtained in the young cohort, no significant differences were found in maximum voluntary excitation between both normalization methods for the older adults in any of the three muscles (Table 1). Normalized signals (Figure 2) show no significant differences between methods. However, both methods resulted in frequent excursions above 100% (~40 and 54% of all normalized trials) in vastus lateralis and, to a lesser extent, in rectus femoris and gluteus medius. Variance of the normalized signals was lower for s-MVDC in each task, with exception of the gluteus medius during lateral stepping.

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213 **Figure 2** – Mean and standard deviations of EMG (in % of maximum voluntary excitation; MVE), recorded during dynamic tasks, normalized to
 214 maximum voluntary excitation obtained from MVIC or (s-)MVDC, for young (top) and older women (bottom). Dynamic tasks consisted of forward
 215 (Fstep) and lateral (Lstep) stepping at step heights of 10, 20 and 30 cm. * indicates significant effect of normalization method at $p < 0.05$, **
 216 indicates significance at $p < 0.01$.

Discussion

Despite the available knowledge about the advantages and disadvantages of using isometric or dynamic contractions for signal normalization ⁵, no studies have investigated whether differences in maximum voluntary excitation between contraction modes are age-dependent and the implications for signal normalization. Therefore, the main aims of this study were to determine if age shows an interaction effect with contraction mode and which normalization method results in the lowest between-participant variance and least amount of signals exceeding 100%. These are important considerations when selecting the most appropriate way to normalize EMG signals from dynamic trials in young and older populations.

The results from this study show that differences in maximum excitation between contraction modes are age-dependent in the vastus lateralis, and that in both age groups, dynamic contractions elicit excitation equal to, or greater than isometric contractions. Additionally, dynamic normalization resulted in lower between-participant variance, though not for all muscles, and resulted in less signals exceeding 100% in young women.

One important concern with the comparison between isometric and dynamic contractions is that joint angles may affect the detection volume due to changes in relative position of the muscle to the electrodes ⁷. This study used MVICs recorded at a single joint angle, which is the most common approach to isometric normalization and is least time-consuming and susceptible to effects of fatigue ¹¹. Second, even though MVDC appears to be the best method to reduce variance between participants, there are still some practical downsides which might limit clinical applicability compared to MVIC. For example, 1-RM estimation requires more time to perform and is likely more expensive due to the fact that some form of equipment, like an isokinetic dynamometer or a strength training device, is required to assess maximum voluntary excitation. 100% 1-RM contractions are also hard to achieve by older adults and might lead to injuries ^{14–16}. Therefore, MVDCs were not included in the older cohort. Third, this study did

not take into account the possibility that older adults modulate motor strategies due to reduced musculoskeletal capacity to allow stepping task performance within their individual constraints²⁵. The relatively high excitation of the gluteus medius and larger number of dynamic trials exceeding 100% MVE in the elderly, as opposed to the young cohort, for all normalization methods might be attributable to altered motor strategies. Finally, this study only included data obtained from young and older women since women show higher age-related declines in muscle mass¹⁷.

In the young cohort, both MVDC and (s-)MVDC in vastus lateralis, and MVDC in rectus femoris elicited significantly higher excitation than MVIC and a similar but non-significant trend was found for the gluteus medius. These results are in line with findings by Hodder and Keir⁷ who found that maximum dynamic contractions more often yielded higher amplitudes than isometric contractions. Excitation of the gluteus medius during the dynamic contractions may also be higher due to increased recruitment needed for pelvic stabilization in the weight bearing position, opposed to the side-lying position more commonly used during isometric contractions²⁶. When normalizing to a maximum contraction, the general assumption is that the obtained reference value should reflect 100% of the individual muscle's capacity⁶. If this is not the case, then normalization will lead to overestimation and thus misrepresentation of the EMG signal with regards to muscular effort^{7,9}. Overestimation of normalized EMG signals could theoretically be solved by superimposing electrical stimulation onto the voluntary contraction. However, high-intensity stimulation is not possible for all muscles and is often perceived to be uncomfortable²⁷. In addition, after electrical stimulation motor units fire in synchrony, leading to EMG amplitudes (M-waves) that are different from EMG amplitudes in voluntary contractions with non-synchronous motor unit firing²⁸. Consequently, normalized values are difficult to interpret. Therefore, this study only included voluntary contractions. In the young cohort, voluntary maximum dynamic contractions elicited higher excitations and

were better suited to reduce variance between participants than normalization to MVIC (Figure 2). This is in line with previous research on normalization using dynamic contractions ¹⁰.

Normalization to sub-maximal contractions is often recommended for older adults ¹. However, no significant differences in peak excitation were found between MVIC and s-MVDC in the older cohort. This implies that both methods would be equally suitable to estimate maximum voluntary excitation in the elderly. Our data suggest that both methods underestimate true maximum excitation, leading to normalized signals exceeding 100% during the unloaded stepping tasks. The lower between-participant variance generally found in EMG when normalized to s-MVDC (Figure 2) for all three muscles does point towards s-MVDC as the best normalization method for the elderly cohort, with exception of gluteus medius during lateral stepping. This is in partial accordance with a study in osteoarthritis patients by French et al. ²⁹, who stated that in gluteus medius, MVIC is deemed more reliable (lower within-participant variance) than dynamic normalization, but the latter is still recommended to reduce between-participant variance. Greater variance in normalized amplitudes with MVIC, combined with amplitudes exceeding 100%, indicate a lack of validity of the MVIC normalization ²⁹. The different testing positions for dynamic and isometric contractions did not appear to have any effect on maximum excitation of the gluteus medius in this age group.

The skewed differences found between maximum excitations obtained from isometric versus dynamic contractions in each age group prompted the question; is there an interaction effect of age and contraction mode on maximum voluntary excitation? Age-related differences in maximum excitation may in part be accounted for by differences in thickness of subcutaneous fat layers and skin impedance ³. These confounding factors are the reason why signal normalization is essential when comparing between age groups. Nevertheless, age-related confounders would be expected to have an equal impact on maximum voluntary excitation regardless of the contraction mode. However, two-way ANOVA exploring the interaction effect

of age x contraction mode, and thus independent of age-related confounders, showed that the difference in maximum voluntary excitation between isometric and dynamic contractions in vastus lateralis was age-dependent. This indicates that, even when the same contraction mode is applied to obtain maximum voluntary excitation for normalization, caution should be taken when comparing normalized EMG between different age groups.

This age-dependent difference in magnitude of maximum voluntary excitation could be attributable to other physiological factors than skin impedance and sub-cutaneous fat. For example, magnitude of excitation depends on both the number of activated motor units (recruitment) and motor unit firing rates (rate coding)¹⁶. Recruitment is generally diminished with age due to a decline in the number of motor units through the process of sarcopenia³⁰. Additionally, motor unit firing rates decline with age³¹ due to increased irregularity, likely caused by denervation of the muscle fibers³². The decrease of motor unit firing rates in particular might explain why, in contrast with the young cohort, no differences were found in maximum voluntary excitation between MVIC and s-MVDC in the older cohort. In a study of motor unit firing rates of the soleus muscle of young adults, Kallio et al.³³ found that concentric dynamic contractions incited higher firing rates and thus higher muscle activity than isometric contractions at the same relative intensities. In older adults, the reduced firing rate capacity would have a relatively large impact on maximum voluntary excitation obtained during dynamic compared to isometric contractions, leading to more equal maximum voluntary excitations obtained from both conditions.

To summarize, this study shows that differences in maximum voluntary excitation between isometric and dynamic contraction modes are age-dependent and therefore, caution should be used when comparing signals obtained from different normalization methods between age groups. MVDCs elicited higher voluntary excitation than MVICs and s-MVDCs in young women. This indicates MVDC as a more suitable normalization method to reduce between-

participant variance and allow more accurate assessment of individual muscle contributions and force estimations during dynamic activities. In contrast, no differences were found between s-MVDC and MVIC in older women. The generally lower amount of signals exceeding 100% and lower between-participant variance of the normalized EMG signals point towards s-MVDC as the most suitable normalization method overall.

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