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Differences in Maximum Voluntary Excitation Between Isometric and Dynamic Contractions are Age-Dependent

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Obtaining true maximum voluntary excitation appears to be more difficult in older populations than in young populations. The aims of this study were (1) to determine whether differences in maximum voluntary excitation obtained from maximum voluntary isometric contraction (MVIC) and (sub-)maximum voluntary dynamic contraction [(s-)MVDC] are age dependent, and (2) to determine how normalizing electromyographic 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 10 young women, and MVIC and s-MVDC were recorded in 19 older women. A significant age × contraction mode interaction effect was found for vastus lateralis ($P = .04$). In young women, MVDC elicited the highest maximum voluntary excitation for vastus lateralis and rectus femoris ($P < .05$). In older women, no differences in maximum voluntary excitation were found ($P > .05$). Normalization to dynamic contractions resulted in lower between-participant variance of electromyography amplitudes, though not for all muscles, and decreased the number 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; however, overall dynamic contractions may be preferable over isometric contractions for normalization purposes.

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

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 contraction[1] instead of measuring force directly (eg, 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 produced.[2] 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 normalized.[4] 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 muscle.[5]

The most commonly applied method of normalization is to express 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 (maximum voluntary isometric contraction, MVIC) or dynamically (maximum voluntary dynamic contraction, MVDC). To date, there is no clear consensus on which EMG normalization method is best. A general conclusion could be that both MVIC and MVDC have advantages and disadvantages.[5] Although physical limitations might make it difficult to obtain a true maximum voluntary excitation,[8] 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 MVICs.[4] This method is commonly applied because 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 muscles.[11] This limitation can be addressed by measuring maximum voluntary excitation at several joint angles to allow for angle-specific normalization. However, this is rarely performed, because it is a time-consuming process, and muscle fatigue may affect the EMG signals obtained.[11] 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 MVIC.[7] For some muscles, studies have found activation reaching up to 300% of predetermined maximum voluntary excitation during dynamic task performance,[7] leading to overestimations of the proportion of individual muscle capacity required for dynamic task performance.[5] In addition, participants are usually unfamiliar with isometric contractions, which can lead to a 20% to 30%

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reduction in maximum contraction performance.[10] 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 common.[13]

An important issue when selecting a normalization method is that little is known about how factors such as age affect the difference between isometric and dynamic normalization. Age-related differences in maximum excitation may be partly accounted for by differences in the thickness of subcutaneous fat layers and skin impedance,[3] 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 the maximum excitation obtained from isometric contractions differs from that obtained from dynamic contractions, comparisons of outcomes obtained with 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 submaximum 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, because the age-related loss of muscle mass, which generally accelerates after menopause,[17] inevitably results in a lower number of motor units firing simultaneously, and conductivity between the skin and electrodes decreases due to a relative increase in subcutaneous adipose tissue.[15]

So far, no studies have investigated whether 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 for age and contraction mode. The second objective was to assess how normalization using different contraction modes would affect between-participant variance of normalized EMG signals and to see which method resulted in the lowest number 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 number of normalized signals exceeding 100% for both age groups.

Methods

Participants

Ten healthy young women (22.9 [1.6] y) and 19 healthy community-dwelling older women (69.1 [3.1] y) were recruited around Leuven, Belgium. Data from the older women were reported previously.[18] Potential participants were excluded if they had any medical contraindications for resistance exercise or if they had participated in a structured strength training program in the last 6 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. 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, Denmark) were then placed, in parallel to the muscle fiber direction, on the muscle belly with an interelectrode distance (center to center) of 25 mm. EMG was amplified 1000× and band-pass filtered between 10 and 500 Hz. EMG was recorded with a telemetric system (ZeroWire®; Aurion, Milan, Italy) with a sampling rate of 1000 samples per second. Subsequently, all recorded EMG signals were high-pass filtered with a first-order Butterworth filter with a cutoff frequency at 20 Hz,[1] full-wave rectified, and smoothed with a 100-millisecond moving average window using MATLAB R2014b (MathWorks, Inc, Natick, MA).

Prior to testing, all participants performed a 5-minute warm-up on a cycle ergometer with moderate resistance at 70 to 80 RPM. After warming up, individual 1-RM was estimated for each resistance exercise using a formula by Brzycki.[19] In order to ensure the accuracy of the estimates, 5-repetition maximum (86% of 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, Italy; Figure 1). Due to limitations of older adults in performing maximum contractions,[1,15] the weight corresponding to 80% of 1-RM, (sub-)maximum voluntary dynamic contraction, (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.

Maximum voluntary isometric contraction values for the vastus lateralis and rectus femoris were recorded in a 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 3 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

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

1-second concentric action and 1-second eccentric action, indicated by a metronome, to avoid differences in peak excitation due to repetition speed. Participants also performed 3 repetitions of forward and lateral stepping onto an elevated platform for each riser height (10, 20, and 30 cm). Stepping was timed at 1 second for ascent, 1 second stance, and 1 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 in order to assess between-participant variance. The number of dynamic trials for which activation exceeded 100% of maximum voluntary excitation provided an indication of the 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 that requires a relatively high effort for older adults.[22,23] Lateral stepping was added because it was found to elicit additional gluteus medius activation.[18]

Data Analysis

Statistical analysis was performed with SPSS Statistics for Windows (version 23; IBM®, Armonk, NY). All data were checked for normality with a Kolmogorov–Smirnov test. Nonnormalized signals more than 2 SDs from the mean were removed from the analyses. Two-way analysis of variance was used to test for main effects of contraction mode and for age × contraction mode interaction effects. In view of the sample size,[24] 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 $P = .05$.

Results

A significant main effect of contraction mode on obtained peak excitation was found for vastus lateralis ($P = .001$) and rectus femoris ($P = .02$) but not for gluteus medius ($P = .96$). There was a significant age × contraction mode interaction effect on vastus lateralis peak excitation ($P = .04$) but not on rectus femoris and gluteus medius peak excitation ($P > .05$; Table 1).

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 the 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 submaximum 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 rectus femoris. However, the 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 the 2 normalization methods for the older adults in any of the 3 muscles (Table 1). Normalized signals (Figure 2)

Table 1 Mean (SD) of Peak EMG per Muscle Obtained From Each Normalization Method for Young (MVIC, s-MVDC, and MVDC) and for Older (MVIC and s-MVDC) Women

		Peak amplitude, mV			Significance of difference			
Muscle	Participants	MVIC	s-MVDC	MVDC	MVIC/s-MVDC	MVIC/MVDC	s-MVDC/MVDC	Interaction effect[a]
Vastus lateralis	Young women	2.1 (0.7)	3.6 (1.8)	4 (1.8)	**.04**	**.01**	**.01**	
	Older women	1.8 (0.9)	2 (0.6)		.12			**.04**
Significance of difference	Women Y/O	.13	**.01**					
Rectus femoris	Young women	2.6 (1.9)	3.4 (1.4)	4.1 (1.8)	.18	**.01**	**.03**	
	Older women	1.6 (0.9)	1.9 (0.6)		.10			.25
Significance of difference	Women Y/O	.16	**<.001**					
Gluteus medius	Young women	3.3 (1.5)	3.4 (2.2)	3.6 (2.3)	.89	.59	.08	
	Older women	1.5 (1)	1.4 (0.7)		.97			.72
Significance of difference	Women Y/O	**<.001**	**<.001**					

Abbreviations: EMG, electromyography; MVIC, maximum voluntary isometric contraction; (s-)MVDC, (sub-)maximum voluntary dynamic contraction; Y/O, young/older. Note: 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 × contraction mode.

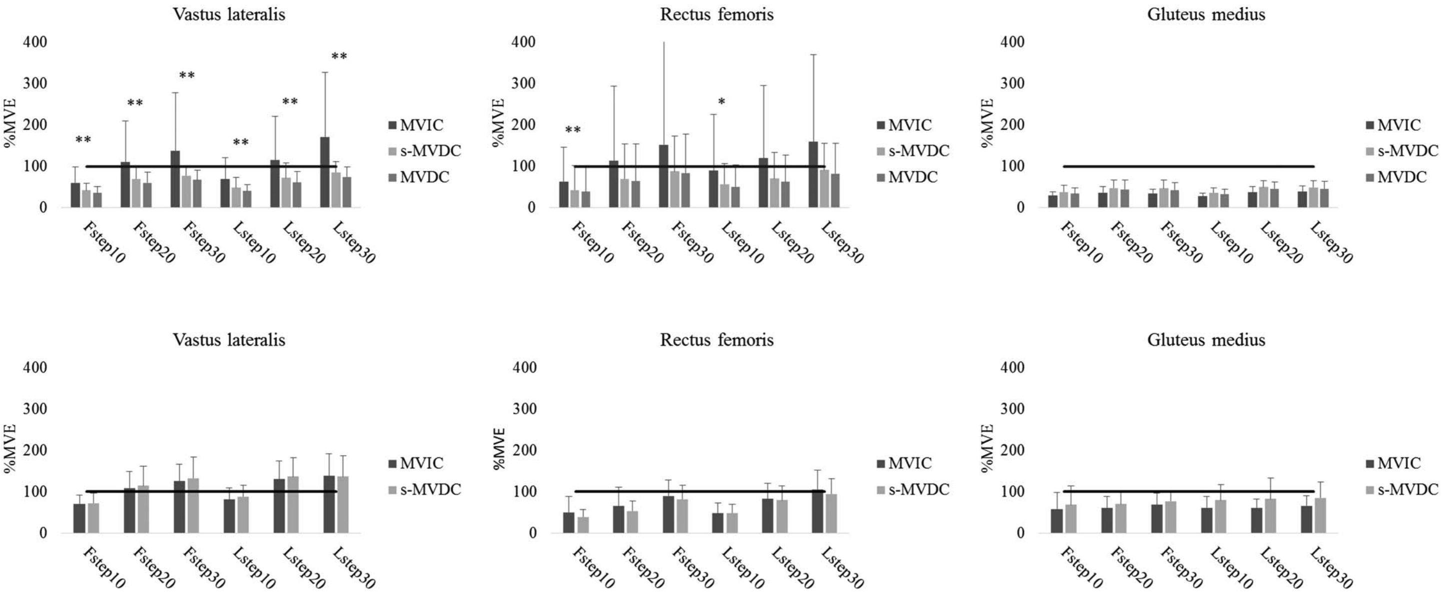

Figure 2 — Mean and SDs of EMG (in %MVE), recorded during dynamic tasks, normalized to MVE obtained from MVIC or (s-)MVDC, for young (top) and older women (bottom). Dynamic tasks consisted of forward (Fstep) and lateral (Lstep) stepping at step heights of 10, 20, and 30 cm. EMG indicates electromyography; MVE, maximum voluntary excitation; (s-)MVDC, (sub-)maximum voluntary dynamic contraction; MVIC, maximum voluntary isometric contraction. *Significant effect of normalization method at $P < .05$. $^{**}P < .01$.

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.

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 or 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 to determine which normalization method results in the lowest between-participant variance and lowest number 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. In addition, dynamic normalization resulted in lower between-participant variance, although not for all muscles, and resulted in fewer signals exceeding 100% in young women.

One important concern in comparing isometric and dynamic contractions is that joint angles may affect the detection volume due to changes in the position of the muscle relative 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 the method that is least time consuming and least susceptible to effects of fatigue.[11] Second, although MVDC appears to be the best method to reduce variance between participants, there are still some practical downsides that might limit clinical applicability compared with 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. Older adults have difficulty achieving 100% 1-RM contractions, and performing them might lead to injuries.[14–16] Therefore, MVDCs were not used with the older cohort. Third, this study did not take into account the possibility that older adults modulate motor strategies due to reduced musculoskeletal capacity in order to allow stepping task performance within their individual constraints.[25] The relatively high excitation of the gluteus medius and the larger number of dynamic trials exceeding 100% maximum voluntary excitation in the older cohort (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, because women show higher age-related declines in muscle mass.[17]

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 nonsignificant trend was found for the gluteus medius. These results are in line with findings by Hodder and Keir,[7] who found that maximum dynamic contractions yielded higher amplitudes more often than isometric contractions. Excitation of the gluteus medius during dynamic contractions may also be higher due to the increased recruitment needed for pelvic stabilization in the weight-bearing position (as opposed to the side-lying position more commonly used during isometric contractions).[26] When normalizing to a maximum contraction, the general assumption is that the obtained reference value should reflect 100% of the individual muscle's capacity.[6] If this is not the case, then normalization will lead to overestimation and misrepresentation of the EMG signal with regard 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 uncomfortable.[27] 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 nonsynchronous motor unit firing.[28] Consequently, normalized values are difficult to interpret. Therefore, this study only included voluntary contractions. In the young cohort, MVDCs elicited higher excitations and were better suited for reducing variance between participants than normalization to MVIC (Figure 2). This is in line with previous research on normalization using dynamic contractions.[10]

Normalization to submaximal 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 for estimating maximum voluntary excitation in the older cohort. Our data suggest that both methods underestimate true maximum excitation, which led 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 3 muscles does point toward s-MVDC as the best normalization method for the older cohort, with the exception of the 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 the gluteus medius, MVIC is deemed more reliable (lower within-participant variance) than dynamic normalization, but the latter is still recommended for reducing between-participant variance. Greater variance in normalized amplitudes with MVIC, combined with amplitudes exceeding 100%, indicate a lack of validity with 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 of whether there is an interaction effect between age and contraction mode on maximum voluntary excitation. Age-related differences in maximum excitation may be partly accounted for by differences in the 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, 2-way analysis of variance exploring the interaction effect of age × contraction mode (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 subcutaneous 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 sarcopenia.[30] In addition, motor unit firing rates decline with age[31] due to increased irregularity, likely caused by denervation of the muscle fibers.[32] The decrease in 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 the maximum voluntary excitation obtained during dynamic compared with 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; 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 for reducing between-participant variance and for allowing more accurate assessment of individual muscle contributions and force estimations during dynamic activities. By contrast, no differences were found between s-MVDC and MVIC in older women. The generally lower number of signals exceeding 100% and lower between-participant variance of the normalized EMG signals points toward s-MVDC as the most suitable normalization method overall.

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