Chapter 7

Normalization of EMG Signals: To Normalize or Not to Normalize and What to Normalize to?

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Additional information is available at the end of the chapter

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1. Introduction

Electromyography (EMG) has been around since the 1600s [1]. It is a tool used to measure the action potentials of motor units in muscles [2]. The EMG electrodes are like little microphones which "listen" for muscle action potentials so having these microphones in different locations relative to the muscle or motor units affects the nature of the recording [3]. The amplitude and frequency characteristics of the raw electromyogram signal have been shown to be highly variable and sensitive to many factors. De Luca [4] provided a detailed account of these characteristics which have a "basic" or "elemental" effect on the signal dividing them into extrinsic and intrinsic sub-factors. Extrinsic factors are those which can be influenced by the experimenter, and include: electrode configuration (distance between electrodes as well as area and shape of the electrodes); electrode placement with respect to the motor points in the muscle and lateral edge of the muscle as well as the orientation to the muscle fibres; skin preparation and impedance [5, 6]; and perspiration and temperature [7]. Intrinsic factors include: physiological, anatomical and biochemical characteristics of the muscles such as the number of active motor units; fiber type composition of the muscles; blood flow in the muscle; muscle fiber diameter; the distance between the active fibers within the muscle with respect to the electrode; and the amount of tissue between the surface of the muscle and the electrode. These factors vary between individuals, between days within an individual and within a day in an individual if the electrode set up has been altered. Given that there are many factors that influence the EMG signal, voltage recorded from a muscle is difficult to describe in terms of level if there is no reference value to which it can be compared. Therefore, interpretation of the amplitude of the raw EMG signal is problematic unless some kind of normalization procedure is performed. Normalization refers to the conversion of the signal to a scale relative to a known and repeatable value. It has been reported [8] that normalized EMG signals were first presented by Eberhart, Inman & Bresler in 1954 [9]. Since then, there have been a number of methods used to normalize EMG signals with no consensus as to which method is most appropriate [8]. In this chapter, we will outline when the presentation of raw EMG is acceptable and when normalization is essential as well as the various methods used to normalize EMG signals. A discussion of the advantages and disadvantages of each method and examples of its uses will be provided.

2. Raw EMG signals (without normalization)

As indicated in the introduction, there are many factors that influence the EMG signal. However, it is generally accepted that within a data collection session and within an individual where no changes have been made to the configuration of the EMG set-up (electrode placement, amplification, filtering etc), under constant temperature and humidity conditions and within a short period of time, the raw EMG can be used for limited comparisons such as:

1. the analysis of the frequency content of the EMG signal. In this type of analysis, the power spectrum of the EMG signal can be obtained by applying a Fast Fourier Transform to the EMG signal. The power density function of the EMG provides a distribution of the signal power as a function of frequency. Changes in the shape of the power density function of the EMG is usually analysed and shifts in the power density to lower frequencies is associated with fatigue. Since the shape of the power spectra is what is important, the amplitude of the EMG signal is not critical and EMG normalization is not required.
2. the decomposition of the EMG into wavelets for an analysis of motor unit firing patterns, or cross talk between muscles. In this analysis, the EMG signal is decomposed into small wavelets (small waveforms). The wavelets are then used to identify and characterize motor unit action potentials by compressing and/or rescaling the wavelets and identifying them in the EMG signal. Again, the amplitude of the EMG signal is not critical and EMG normalization is not required.
3. the time of the initiation of muscle activation. This type of analysis does not require EMG normalization as the time of activation is usually identified from the raw signal e.g. when the raw EMG signal amplitude reaches 2 [10] or 3 [11] standard deviations of the mean above baseline levels.
4. amplitude comparisons of signals from a given muscle between short term interventions/movements within an individual in the same session under the same experimental conditions without changes to the EMG electrode set-up [12] e.g. when comparing the EMG signal between different interventions/movements in a given muscle in each individual [13-16]. Because the absolute amplitude of the signal is meaningless, one cannot evaluate the level of activity in the muscle, but only that it is more or less active in one intervention/movement compared to the other. Therefore, comparison of muscle activity levels between muscles or individuals is not valid.

3. Normalization of EMG signals

To be able to compare EMG activity in the same muscle on different days or in different individuals or to compare EMG activity between muscles, the EMG must be normalized [4, 17, 18]. Normalization of EMG signals is usually performed by dividing the EMG signals during a task by a reference EMG value obtained from the same muscle. By normalizing to a reference EMG value collected using the same electrode configuration, factors that affect the EMG signals during the task and the reference contraction are the same. Therefore, one can validly obtain a relative measure of the activation compared to the reference value.

The common consensus is that a "good" reference value to which to normalize EMG signals should have high repeatability, especially in the same subject in the same session, and be meaningful. By choosing a reference value repeatable within an individual, one can compare the levels obtained from any task to that reference value. The choice of reference value should allow comparisons between individuals and between muscles. To be able to do so, the reference value should have similar meaning between individuals and between muscles. The choice of normalization method is critical in the interpretation of the EMG signals as it will influence the amplitude and pattern of the EMG signals [8]. Unfortunately, there is no consensus as to a single "best" method for normalization of EMG data [8, 18] and a variety of methods have been used to obtain normalization reference values:

1. Maximum (peak) activation levels during maximum contractions
2. Peak or mean activation levels obtained during the task under investigation
3. Activation levels during submaximal isometric contractions
4. Peak to peak amplitude of the maximum M-wave (M-max)

3.1. Maximum (peak) activation levels during maximum contractions

3.1.1. Maximal voluntary isometric contractions

The most common method of normalizing EMG signals from a given muscle uses to the EMG recorded from the same muscle during a maximal voluntary isometric contraction (MVIC) as the reference value [19-23]. The process of normalization using MVICs is that a reference test (usually a manual muscle test) is identified which produces a maximum contraction in the muscle of interest. Based on the repeatability between tests measures, it is recommended that at least 3 repetitions of the test be performed separated by at least 2 minutes to reduce any fatigue effects [12]. The EMG signals are then processed either by high-pass filtering, rectifying and smoothing or by calculating the root mean square of the signal. The maximum value obtained [12] from the processed signals during all repetitions of the test is then used as the reference value for normalizing the EMG signals, processed in the same way, from the muscle of interest. This allows the assessment of the level of activity of the muscle of interest during the task under investigation compared to the maximal neural activation capacity of the muscle [24-26].

This method sounds simple enough. However, when trying to implement it, investigators are faced with an important question: *What test should be used to produce maximum neural activation in a given muscle?* The choice of MVIC should reflect the maximal neural activation capacity of the given muscle [27]. Unfortunately, there is no consensus as to which test produces maximal activation in all individuals in any given muscle. Table 1 provides some examples of different tests that have been used for the same muscle in different studies. Note the number of different reference tests used for each muscle indicating the lack of consensus as to what test generates maximum activity in any given muscle.

Muscles investigated	Manual muscle test
upper trapezius	• shoulder shrug [28, 29] • combined shoulder elevation/arm flexion/abduction in the scapular plane at 90° abduction [30] • shoulder abduction in scapular plane at 90° abduction [31, 32] • lumbar extension [33]
supraspinatus	• shoulder abduction at 90°, internal rotation (seated) [28] • shoulder abduction at 90°, elbow flexed to 90° (seated) [34] • shoulder external rotation and abduction, shoulder abducted to 20°, elbow flexed to 90°, no shoulder flexion [29]
infraspinatus	• shoulder external rotation, arm at side, elbow flexed to 90° (seated) [28, 31, 34] • shoulder external rotation, shoulder abducted to 45°, elbow flexed to 90°, no shoulder flexion [29]
subscapularis	• shoulder internal rotation, arm at side, elbow flexed to 90° (seated) [28, 34] • shoulder internal rotation, shoulder abducted to 45°, elbow flexed to 90°, no shoulder flexion [29]
latissimus dorsi	• shoulder depression with resistance or adduction and internal rotation, arm at side (seated) [28] • shoulder extension and internal rotation with arm straight, abducted to 30° in the coronal plane and internally rotated [29] • shoulder extension (prone lying) [35, 36]
serratus anterior	• scapular protraction, shoulder abducted to 90°-100° (seated) [28] • scapular protraction, elbow flexed to 45°, shoulder abducted to 75° and internally rotated to 45° [29]
upper rectus abdominis	• trunk flexion, hips and knees flexed to 90°, feet supported, trunk in full flexion (supine) [35, 36] • trunk flexion, legs bent at 45°,and secured, trunk position not mentioned (supine) [37]
internal oblique	• trunk flexion and lateral flexion, hips and knees flexed to 90°, feet supported, trunk in full flexion and rotated contra-laterally (supine) [35] • trunk flexion and lateral flexion, hips and knees flexed to 90°, feet supported, trunk in full flexion and rotated ipsi-laterally (supine) [36]
gluteus maximus	• hip extension, hip flexed 45° (prone) [38] • back extension, hip flexed 30° (seated) [39] • hip abduction at 10° abduction, leg fully extended (side lying) contra-lateral knee and hip flexed 30° [40]
gluteus medius	• hip abduction at 10° abduction, leg fully extended (side lying) contra-lateral knee and hip flexed 30° [40, 41] • hip abduction at 25° abduction, leg fully extended (side lying) [42]

Muscles investigated	Manual muscle test
vastus lateralis	• knee extension, knee flexed 90°, hip flexed 90° (sitting) [38, 43] • knee extension, knee flexed 60°, hip flexed 90° (sitting) [44, 45] • knee extension, knee flexed 45° (sitting) [37]
vastus medialis	• knee extension, knee flexed 60° (sitting) [44, 45] • knee extension, knee flexed 90°, hip flexed 90° (sitting) [43]
rectus femoris	• knee extension, knee flexed 90°, hip flexed 80° to 90° (sitting) [35, 36, 38, 43] • knee extension, knee flexed 60°, hip flexed 90° (sitting) [44-46]
lateral hamstring (biceps femoris) long head	• knee flexion, knee flexed 90°, hip flexed 90° (sitting) [38] • knee flexion, knee flexed 60° (sitting) [44, 46] • knee flexion, knee flexed 60° (prone) [45] • knee flexion, knee flexed 90°, hands clasped behind head (prone) [37]
gastrocnemius lateralis	• ankle plantar flexion, ankle -15°, knee flexed 30° [44] • ankle plantar flexion, mid ankle position (standing unilateral – body weight) [47] • ankle plantar flexion, ankle, knee and hip in neutral position (prone) [45]
gastrocnemius medialis	• ankle plantar flexion, ankle, knee and hip in neutral position (prone) [38, 45] • ankle plantar flexion, ankle -15°, knee flexed 30° [44] • ankle plantar flexion, mid ankle position (standing unilateral – body weight) [47] • ankle plantar flexion (supine) [33]
soleus	• ankle plantar flexion, mid ankle position (prone) [38] • ankle plantar flexion, ankle in neutral position; knee and hip flexed 90° (quadruped position) [45, 46]
tibialis anterior	• ankle dorsi flexion, ankle, knee and hip in neutral position (supine) [45] • ankle dorsi flexion, ankle in neutral position; knee and hip flexed 90° (quadruped position) [46]

Table 1. Examples of MVIC tests used to generate maximum activity levels in various muscles

Although the repeatability of the EMG recorded during MVICs within individuals on the same day has been questioned [34], the majority of studies indicate that the reliability of MVICs within individuals on the same day is high [42, 48, 49]. High repeatability requires proper guidance of the subjects to perform the tests identically with each repetition, familiarity of the subjects with the production of maximum effort and the avoidance of fatigue.

Because the test that will yield maximal activation in any given muscle is not known, many studies report EMG levels during various tasks that are >100% MVIC particularly during rapid, forceful contractions [18] or eccentric contractions [50]. For example, Jobe et al. [51] reported EMG signals from serratus anterior and triceps brachii during the acceleration phase of the over arm throw to be 226% and 212% respectively of the EMG from maximal manual muscle tests which were not described. Reported normalized EMG signals >100% indicate that the normalization test used to generate the MVIC is not accurately revealing the maximum muscle activation capacity. If maximum activity in each muscle is not obtained during the normalization contractions, a systematic error will be introduced which leads to an over estimation of activation levels [30]. This could lead to an incorrect interpretation of the intensity of the muscle activity required to perform a given task. In addition, if the activity in all muscles is not being referenced to the same activity level, e.g. maximum capacity, comparison of activity levels between muscles is not valid.

The problem of not eliciting maximum capacity in each muscle tested would be avoided if standard tests that reliably elicit maximum activation levels were identified [52]. A number of studies have attempted to identify voluntary isometric tests that produce maximum activation levels in various muscles. These studies have shown that multiple tests can produce maximum recording from any given muscle [52-56] and that no specific test produces maximum recording from a given muscle in all individuals tested [27, 53, 54, 56-63]. These findings indicate that the use of single MVIC test to identify maximum activity in a given muscle is not valid and that sets of tests are required in order to ensure maximum activity in a given muscle is recorded from all subjects. Table 2 summarizes the sets of MVIC tests that have been shown to produce maximum activity in face, trunk, shoulder and leg muscles.

Provided that maximum neural activation is achieved in all muscles and individuals tested, using MVICs is a highly reliable method to normalize EMG data and can be used to compare activity between muscles, between tasks and between individuals. To achieve the maximum neural activation in all muscles and individuals, sets of MVIC tests that produce maximum activation in each muscle need to be identified. The highest value recorded for each muscle from at least 3 attempts at these MVIC tests should be used as the normalization value to ensure that the recorded values reflect maximum neural activation levels.

Study	Muscles investigated	MVIC test	Isometric tests that produce maximum EMG in the muscles investigated
O'Dwyer et al (1981) [56]	levator labii superiori zygomaticus major buccinator risorius orbicularis oris superioris orbicularis oris inferioris depressor anguli oris depressor labii inferioris mentalis intrinsic tongue muscles anterior genioglossus styloglossus/hyoglossus geniohyoid mylohyoid digastric (anterior belly) internal (medial) pterygoid temporalis	Maximum EMG from each muscle across all tests	1. unilateral snarl 2. broad laugh 3. puff out cheeks, mouth closed 4. broad smile, mouth closed 5. compress upper lip against upper incisors 6. compress lower lip against lower incisors 7. depress comers of mouth 8. depress lower lip, jaw closed 9. raise and evert lower lip while wrinkling chin 10. curl sides of tongue up 11. saliva swallow 12. gentle tongue protrusion 13. lower jaw against resistance 14. intercuspal bite on hard object 15. clench jaw.

Study	Muscles investigated	MVIC test	Isometric tests that produce maximum EMG in the muscles investigated
McGill (1991) [59]	rectus abdominis external oblique internal oblique latissimus dorsi upper erector spinae (T9) lower erector spinae (L3)	1,2,6,7 1,2,5,6,7 1,3,5,6,7 2,3,6,7 3,4,7 4	1. resisted bent-knee sit-up (feet restrained trunk at 30º hands behind head). 2. standing pelvis fixed flexing forward 3. standing pelvis fixed lateral bend 4. hanging over the edge of the test table in a prone posture and extending upward against resistance 5. hanging over the edge of the test table supine and flexing upward against resistance 6. hanging over the edge of the test table on side and lateral bending upward against resistance 7. clockwise and anticlockwise trunk twist at 0º and pre-rotated at ± 30º
Nieminen et al (1993) [61]	supraspinatus infraspinatus upper trapezius middle trapezius lower trapezius anterior deltoid middle deltoid pectoralis major	5,6,7,8 2,5,6,7 5,6,7,8 2,3,4,6,7 1,2,5,6,8 3,5,6,7 2,3,5,6,7 1,4,5,9	1. internal rotation shoulder at 0º abduction, elbow at 90º flexion 2. external rotation shoulder at 0º abduction, elbow at 90º flexion 3. abduction shoulder at 0º abduction 4. shoulder elevation 5. flexion arm horizontal 6. flexion hand 25 cm above and 25 cm right of horizontal 7. flexion hand 25 cm above and 25 cm left of horizontal 8. flexion hand 25 cm below and 25 cm right of horizontal 9. flexion hand 25 cm below and 25 cm left of horizontal
Kelly et al 1996 [54]	supraspinatus infraspinatus subscapularis anterior deltoid middle deltoid posterior deltoid latissimus dorsi pectoralis major	7-9,12-14 10-12 16,17 1-9 7 12 16,17 15	Coded: Activity at shoulder abduction angle; humeral rotation angle 1. abduction at 0º; -45º 2. abduction at 0º; 0º 3. abduction at 0º; +45º 4. abduction at 45º; -45º 5. abduction at 45º; 0º 6. abduction at 45º; +45º 7. abduction at 90º; -45º 8. abduction at 90º; 0º 9. abduction at 90º; +45º 10. external rotation at 0º; -45º 11. external rotation at 45º; -45º 12. external rotation at 90º; -45º 13. external rotation at 90º; 0º 14. external rotation at 90º; +45º 15. internal rotation at 0º; 0º 16. internal rotation at 90º; -45º 17. internal rotation at 90º; 0º

Study	Muscles investigated	MVIC test	Isometric tests that produce maximum EMG in the muscles investigated
Ekstrom et al (2005) [27]	upper trapezius middle trapezius lower trapezius serratus anterior	1,2,3,4,5,7 5,6,7 1,2,3,5,7,8 1,2,3	1. shoulder flexion at 125º with scapula resistance 2. shoulder abducted to 125º scapular plane 3. shoulder abducted to 90º with the neck side bent, rotated to the opposite side, and extended 4. scapula elevated with the neck side bent, rotated to the opposite side, and extended 5. shoulder horizontally abducted and externally rotated 6. shoulder horizontally abducted and internally rotated 7. arm raised above the head in line with the lower trapezius muscle 8. shoulder externally rotated at 90º abduction
Hsu et al (2006) [45]	tibialis anterior lateral gastrocnemius medial gastrocnemius soleus vastus lateralis vastus medialis rectus femoris lateral hamstrings (biceps femoris) medial hamstrings (semitendinosus)	Maximum EMG from each muscle across all tests	1. entire leg flexion and extension, seated with backrest reclined 45º, hip flexed 110º, knee flexed 60º, ankle neutral. 2. knee flexion and extension, seated with backrest vertical, knee flexed 60º
Boettcher et al 2008 [53] and Ginn et al 2011 [57]	supraspinatus infraspinatus subscapularis lower subscapularis upper trapezius middle trapezius lower trapezius serratus anterior latissimus dorsi rhomboid major teres major anterior deltoid middle deltoid posterior deltoid pectoralis major (clavicular head)	Maximum EMG from each muscle across all 5 tests provides >95% chance of eliciting maximum for all muscles	1. shoulder extension seated with the arm at 30º abduction, elbow fully extended, and thumb toward the body; arm extended as resistance applied over the distal forearm. 2. shoulder abduction at 90º with internal rotation 3. shoulder internal rotation in 90º abduction 4. shoulder flexion at 125º with scapula resistance 5. shoulder horizontal adduction at 90º flexion
Chopp et al (2010) [52]	anterior deltoid middle deltoid pectoralis major (clavicular head) pectoralis major (sternal head)	1,4-6,10 2-6 7-12 7,8,10	1. Coded: force direction – shoulder flexion angle – horizontal abduction angle 2. UP-45-0 3. UP-45-45 4. UP-45-90 5. UP-90-0 6. UP-90-45 7. UP-90-90

Study	Muscles investigated	MVIC test	Isometric tests that produce maximum EMG in the muscles investigated
			8. IN-45-0 9. IN-45-45 10. IN-45-90 11. IN-90-0 12. IN-90-45 13. IN-90-90
Vera-Garcia et al (2010) [64]	upper rectus abdominis lower rectus abdominis lateral external oblique medial external oblique internal oblique latissimus dorsi (T9) erector spinae (T9) erector spinae (L5)	1,2,6 1,2,3,4 1,3,4,5,6,10 1,3,5,6 2,3,5,6 3,4,5,9 7,8,9 7,8	1. upper trunk flexion 2. lower trunk flexion 3. upper trunk twisting 4. lower trunk twisting 5. upper trunk bending 6. lower trunk bending 7. upper trunk extension 8. lower trunk extension 9. shoulder rotation and adduction 10. abdominal hollowing
Rutherford et al (2011) [58]	lateral gastrocnemius medial gastrocnemius vastus lateralis vastus medialis rectus femoris lateral hamstrings (biceps femoris) medial hamstrings (semitendinosus)	2,4,5,6,7,8 4,5,6,7,8 1,2,3,7,8 1,2,3,7,8 1,2,3 4,5,6 4,5,6	1. knee extension at 45º knee flexion in sitting 2. combined knee extension + hip flexion at 45º knee flexion in sitting 3. knee extension at 15º knee flexion in supine position 4. knee flexion at 15º knee flexion in supine position 5. knee flexion at 55º knee flexion in sitting 6. knee flexion at 55º knee flexion in prone position 7. plantar-flexion at neutral ankle, knee and hip in supine position 8. unilateral plantar-flexion in standing

Table 2. Examples of studies that have identified tests that produce maximum recordings from given muscles and recommend the use of multiple tests to make sure maximum activation is produced by all individuals tested.

3.1.2. The maximum activation obtained during the task under investigation performed at maximum effort

To reduce the possibility of obtaining normalized EMG levels during a task greater than 100%, investigators have used the EMG obtained during the task under investigation performed at maximum effort as the normalization value. For example, maximum EMG recorded during isometric shoulder abduction has been used to normalize the EMG during submaximal abduction [65], maximum crunch exercise for submaximal crunch exercise [66], maximum sprinting for normalizing the EMG during walking [44, 67] and maximum sprint cycling for normalizing the EMG during cycling [38].

This method of normalizing EMG data produces high reliability between trials [44, 67] and greatly reduces the possibility of obtaining EMG levels during the task of interest greater than the reference value. However, the maximum activation levels of muscles are unknown since maximum force production during the task under investigation does not necessarily produce a maximum activation level in any of the muscles under investigation [8]. In addition, different individuals may use different muscle control strategies to produce the same movement, resulting in different activation levels during the reference contraction in a given muscle between individuals. Therefore, although highly reliable, the use of this method to normalize EMG data to compare muscle activation levels between individuals and between muscles in the task being investigated is not valid. In addition, because this reference value is task dependent, it cannot be used to compare muscle activation levels between different tasks.

3.1.3. The maximum activation obtained at a range of joint angles under maximum effort during dynamic contraction

There is a debate about whether isometric contraction can be used to obtain reference EMG levels for use during dynamic tasks [25]. Some research has found that the EMG levels change with muscle length [68-71], while other studies indicate that joint angle has little effect on maximum EMG levels [72-74] or that there is no consistent pattern of change in the EMG levels with joint angle [74-76]. To address this potential problem, it has been recommended that maximum dynamic (usually isokinetic) contractions be used to obtain reference EMG levels in order to normalize EMG data obtained during movement [77]. In this method, the individual performs a maximum isokinetic contraction at a speed similar to the dynamic task under investigation. The activation levels vs joint angle curve generated from the maximum dynamic contraction is then used to normalize the EMG data [77].

This normalization method has been shown to have low within subject reliability [78] and, because EMG is depended on the velocity of movement for a given force level [79], normalization curves need to be generated for different speeds of movement.

The use of supramaximal stimulation to determine if voluntary contractions are being performed at maximum levels

Maximal voluntary activation can be assessed by interpolation of an electrical stimulus to all or part of the nerve supply to a muscle during maximum voluntary effort. Single electrical stimuli are delivered to the nerve that innervates the muscle during maximum voluntary contraction with increasing intensity until no additional increment in force can be seen. Then 2-4 electric stimuli trains (20 ms between stimuli) are delivered at that intensity as they produce substantially larger evoked responses [80-82]. If the stimulus fails to evoke an increment in force it can be deduced that all motoneurones innervating the muscle are recruited i.e. that the muscle is being maximally activated [83-85].

One criticism of this method of generating maximal activation in a given muscle is that the force output of a muscle during a synchronous activation of the motor neurons, due to the stimulation of a nerve, does not necessarily produce the same force as when the motor neurons are being asynchronously activated by the central nervous system [4].In addition, its use for some muscles will be problematic due to difficulty accessing the nerve/s supplying these muscles e.g. branches of the brachial plexus supplying shoulder muscles. It also has the disadvantage that strong contractions maintained for more than a few seconds will lead to muscle fatigue.

3.2. Peak or mean activation levels obtained during the task under investigation

The first report of normalized EMG signals [9] presented quadriceps EMG signals during walking as a percentage of the peak muscle activity that occurred during the gait cycle [8]. Since then, this method has been used to investigate muscle activation patterns during various activities e.g. walking [25, 86], cycling [87], biceps curl exercise [24] and kayaking [88]. In this method, the EMG data is normalized to the peak or mean activity obtained during the activity in each muscle for each individual separately.

Normalising to the peak or mean amplitude during the activity of interest has been shown to decrease the variability between individuals compared to using raw EMG data or when normalising to MVICs [24, 25, 86, 87]. Normalizing to the mean amplitude during the activity of interest has been reported to be either comparable to [34], or better than [24, 42, 89, 90], normalizing to the peak amplitude during the activity in reducing the variability between subjects. Although the within subject and within day reliability have been shown to be high for both peak and mean amplitude during an activity [42], it has also been shown that they may be less reliable between days in the same individuals compared to normalizing to MVICs [90].

However, the reduction in the variability between individuals by normalising to the peak or mean amplitude recorded during an activity is achieved by removing some real biological variation (e.g. strength difference) between individuals [24, 90]. The amount of muscle activity required to lift a given load, would vary according to each individual’s strength. As the reference value used in this method is relative to the task and not to the maximum capacity of the muscle, muscle activity levels cannot be compared between muscles, tasks or individuals. This method, however, can be used to compare patterns of muscle activation between individuals over time [24, 25, 42, 90].

3.3. Activation levels during submaximal isometric contractions

The use of maximal contractions to obtain reference EMG levels has been questioned because of difficulty in getting subjects to mobilize their maximal potential especially in symptomatic subjects who cannot perform a maximum contraction because of pain, muscle inhibition [42, 91] or risk of injury [91]. As a result, the use of tests at submaximal contraction levels have been used to produce reference EMG levels for the purposes of normalizing the EMG signals. De Luca [4] encouraged the use of EMGs from contractions < 80% of MVIC. However, there is no consensus as to whether submaximal contractions have higher within-day reliability than [23], or similar reliability to [92], maximal contractions. Commonly used submaximal isometric contractions include holding a limb against gravity [24, 26, 48, 87, 92] or holding a given load, either an absolute load [24, 93-95] or a relative load determined as a percentage of each individual’s maximum load [25]. The muscle activity recorded during the submaximal isometric contraction is then used to normalize the EMG in the same muscle while performing the task under investigation.

The main limitation of using submaximal isometric contractions is that comparisons of activity levels between muscles and individuals are not valid because, once again, the reference value used in this method is not relative to the maximum capacity of the muscle. Lifting an absolute load of say 1 kg mass might require 10% of the maximum muscle capacity in a strong individual compared to say 40% of the maximum muscle capacity in another person who is not as strong. It is not possible to estimate maximum muscle activity from a relative submaximal contraction by linear extrapolation because the torque/EMG relationship is nonlinear [96]. Additionally, the lengths of muscle moment arms in individuals vary and since the EMG signal is related to the force produced by the muscle and not the torque produced by the limb, the force required by the muscle to produce a given torque would be different between individuals. Another limitation is that the motor strategy may not be the same between individuals or between sides within the same individual [95] during the reference submaximal contraction. This is not a problem during maximal contractions as heightened central drive engages all possible muscle resources to achieve the maximum force possible. Therefore, using submaximal isometric contractions as the reference for normalizing EMG data is reliable but doesn't allow valid comparisons between muscles or individuals.

3.4. Peak to peak amplitude of the maximum M-wave (M-max)

This method of normalizing EMG signals involves external stimulation of α-motor neurons. When a peripheral motor nerve is stimulated at a point proximal to a muscle it activates the muscle to contract. This signal is called the M-wave and can be recorded using EMG electrodes placed on/in that muscle. To obtain maximum activation in the muscle and produce a maximum M-wave (M-max), the amplitude of stimulation is increased until the peak to peak amplitude of the M-wave does not increase further. To ensure maximum simulation, the amplitude of the stimulation is increased by an additional 30%. The amplitude of the M-max is then used to normalize EMG signals from the same muscle during the tasks of interest [97]. Currently, this normalization method is problematic as the repeatability of the M-max is questionable. It seems to be less reliable as the background contraction level increases [98], decreases with time [99], and is dependent on muscle length [100-102] and the task performed [98, 102]. If these factors that affect the M-max values could be controlled resulting in more reliable measurements, this method to normalize EMG data has the potential to facilitate comparisons between muscle, between tasks and between individuals.

4. Summary

In summary, only the normalization method that uses MVICs as the reference level can be validly used to compare muscle activity levels and activation patterns between muscles, tasks and individuals, provided that maximum neural activation is achieved in all muscles and individuals tested. The use of peak or mean activation levels obtained during the task under investigation as the reference EMG level can be used to compare patterns of muscle activation between individuals over time with high reliability but does not allow comparisons of activity levels between muscles, tasks or individuals. The normalization methods of submaximal isometric contractions or maximum activation during the task under investigation performed at maximum effort also do not allow valid comparisons of muscle activity levels between muscles or individuals, and in addition, muscle activation patterns between individuals are potentially more variable because different individual motor control strategies may be used. Finally, the use of maximum activation levels obtained under maximum effort during dynamic contraction and the M-max methods to normalize EMG signals are associated with low within subject reliability and cannot be recommended.

5. EMG Normalization in clinical populations

Studies use EMG to identify differences in the activation levels and patterns between normal subjects and those with neuro-musculo-skeletal dysfunction with the aim of understanding the cause of the dysfunction and developing improved rehabilitation programs to treat the dysfunction. Since the use of MVICs is the most valid method to normalize EMG data allowing comparison of activity levels between muscles in different individuals, it should be the normalization method of choice when evaluating muscle function in clinical populations provided symptomatic individuals can produce MVICs. Indeed recent studies have shown that individuals from some clinical populations (moderate knee osteoarthritis [58], following knee surgery [103], back pain [104, 105], cerebral palsy [106], stroke [45, 107]), are able to produce maximum activation levels using the same MVIC tests as healthy individuals [8]. If symptomatic individuals are unable to elicit maximal contractions, e.g. as a result of pain due to illness or injury, then comparisons between these clinical populations and normal subjects can only be made using normalization to peak or mean activation levels obtained during the task under investigation. Under these circumstances comparisons of activity levels between muscles, between tasks and between individuals are not valid. Only comparison of muscle activation patterns between normal and symptomatic individuals can be made.

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