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Reliability and interpretation of single leg stance and maximum voluntary isometric contraction methods of electromyography normalization

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ABSTRACT

Normalization of electromyographic (EMG) amplitudes is necessary in the study of human motion. However, there is a lack of agreement on the most reliable and appropriate normalization method. This study evaluated the reliability of single leg stance (SLS) and maximal voluntary isometric contraction (MVIC) normalization methods and the relationship between these measures for the gluteus maximus (GMax), gluteus medius (GMed), rectus femoris (RF), vastus lateralis (VL), hip adductor group (ADD), and biceps femoris (BF). Surface EMG was recorded in 20 subjects during three 5 s trials of SLS and MVIC. SLS and MVIC methods both demonstrated good-to-excellent reliability in all muscles (ICCs > 0.80). Intrasubject coefficients of variation were lower for the MVIC method (9–36%) than for the SLS method (20–59%). EMG amplitudes during MVIC and SLS were significantly correlated for all muscles (Pearson r's = 0.604–0.905, $p < 0.005$) except GMax ($r = 0.250$, $p = 0.288$). Use of SLS normalization for the RF, VL, and BF is not recommended due to a lack of measurement precision. However, this method is justified in the GMax, GMed, and ADD and may provide a better representation of coordinated muscle function during a functional task.

1. Introduction

Surface electromyography (EMG) is useful in the study of human movement as it is a non-invasive method used for evaluating the timing of muscle activation and activation amplitude during walking (Benoit et al., 2003; Santilli et al., 2005), running (Mann et al., 1986), and rehabilitation exercises (Arokoski et al., 2004; Sakamoto et al., 2009), and as a measure of skeletal muscle fatigue (Bosch et al., 2009; Ebaugh et al., 2006). Though the EMG signal can be easily obtained, there exist a multitude of threats that can potentially alter its amplitude and frequency characteristics (De Luca, 1997). Extrinsic factors like the electrode configuration and location are controllable, while intrinsic physiological factors like the amount of subcutaneous tissue, muscle fiber type, fiber diameter, and blood flow within the muscle cannot be controlled by the researcher (De Luca, 1997; Rainoldi et al., 2004). Due to these inherent problems associated with acquisition of the EMG signal, it is necessary to normalize the signal amplitude to a standard value when comparing different subjects, muscles, and studies, or conducting repeated measures across different testing sessions (Fernández-Peña et al., 2009; Knutson et al., 1994; De Luca, 1997; Burden and Bartlett, 1999; Soderberg and Knutson, 2000).

While consensus exists regarding the need to normalize EMG amplitudes, there are numerous methods described in the literature on how this should be accomplished. Maximal voluntary isometric contraction (MVIC) appears to be the most common normalization method used (Fernández-Peña et al., 2009; Yang and Winter, 1983; Knutson et al., 1994; Araujo et al., 2000; Soderberg and Knutson, 2000). However, this method assumes that subjects are able to provide a true maximal effort, thus its use may be limited in subjects who are either unable or unwilling to provide such an effort (Yang and Winter, 1984; Soderberg and Knutson, 2000; Bolgla and Uhl, 2007). As a result, other researchers have investigated alternative normalization methods including submaximal isometric contractions (Yang and Winter, 1983, 1984), peak EMG amplitude during dynamic activities (Yang and Winter, 1984; Kadaba et al., 1989; Benoit et al., 2003; Bolgla and Uhl, 2007), and mean EMG amplitude during dynamic activities (Kadaba et al., 1989; Neumann et al., 1992; Benoit et al., 2003; Bolgla and Uhl, 2007). It has been suggested that EMG amplitudes derived from these dynamic activities may provide a better representation of coordinated muscle activity compared with the isolated MVIC method (Benoit et al., 2003).

Reliability refers to the consistency, repeatability, or reproducibility of a measure over time (Thomas and Nelson, 2001), and

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has been assessed in both MVIC and dynamic methods of EMG normalization using the intraclass correlation coefficient (ICC) (Fernández-Peña et al., 2009; Kollmitzer et al., 1999; Bolgla and Uhl, 2007), coefficient of multiple correlations (Kadaba et al., 1989), intersubject coefficient of variation (CV) (Yang and Winter, 1983; Winter and Yack, 1987; Burden and Bartlett, 1999), and intrasubject CV (Fernández-Peña et al., 2009; Yang and Winter, 1984) with equivocal results. However, the appropriateness of assessing consistency using some of these techniques is questionable. Specifically, the intersubject CV is not a true measure of reliability, as it is indicative of consistency of the data across subjects, not across trials. Similarly, the intrasubject CV is representative of the precision rather than the reliability of a measure, with a low intrasubject CV indicative of greater stability and less discordance across repeated measures (Knutson et al., 1994). The ICC directly assesses the reliability of two or more quantitative measures and is not subject to the errors in judging agreement that are present when using the Pearson correlation coefficient (r) (Müller and Büttner, 1994), and therefore is the most appropriate means by which to assess reliability.

While normalization of EMG amplitudes to MVIC is the prevailing method of choice, this method may not be the most appropriate technique in some instances due to the previously stated limitations. There is also the potential for differing interpretations of EMG activity during dynamic activities based upon the normalization method utilized. This is due to the fact that the MVIC method measures EMG activity during separate, isolated isometric contractions, while functional normalization methods, such as single leg stance (SLS), measure simultaneous EMG activity of multiple muscles as they function in a coordinated manner during a functional task. Differences in muscle coordination strategies employed by individuals in order to meet the demands of the task could affect the relationship between functional and MVIC normalization reference values between subjects, and alter the subsequent interpretation of normalized EMG activity amplitudes measured during experimental tasks. In this investigation, SLS was chosen as the functional normalization task as it allows for measurement of coordinated lower extremity muscle function in response to a relatively standardized demand, while minimizing differences in joint position between subjects. Currently, the reliability and precision of a SLS method of normalization, the relationship between normalization values obtained using SLS and MVIC techniques, and the effect of using these different methods on the interpretation of the EMG signal in the lower extremity are unknown. Therefore, the purpose of this study was to evaluate the within-session reliability and precision of SLS and MVIC EMG amplitude normalization methods and the relationship between values obtained using these methods in six muscles of the lower extremity. We hypothesized that SLS and MVIC would demonstrate good reliability and high measurement precision, but that there would not be a significant relationship between MVIC and SLS normalization values for all muscles.

2. Methods

2.1. Subjects

Ten males ((mean ± SD) age: 20.6 ± 3.4 years; height: 1.77 ± 0.07 m; mass: 70.7 ± 4.6 kg) and 10 females (age: 20.8 ± 0.4 years; height: 1.66 ± 0.05 m; mass: 62.1 ± 8.7 kg) participated in this study after reading and signing a consent form approved by the University of North Carolina at Chapel Hill, Institutional Review Board. All subjects were healthy and physically active (participating in at least 30 min of physical activity three times per week), with no history of neurological disorder, lower extremity surgery, or lower extremity injury within the six months preceding data collection.

2.2. Subject preparation

Prior to data collection, preamplified/active surface EMG electrode configurations (DelSys Inc., Boston, MA: interelectrode distance = 10 mm; amplification factor = 10,000 (20–450 Hz); CMMR at 60 Hz > 80 dB; input impedance > 10^{15} Ω/0.2 pF) were placed over the muscle bellies of the gluteus maximus (GMax), gluteus medius (GMed), rectus femoris (RF), vastus lateralis (VL), adductors (ADD), and long head of the biceps femoris (BF) parallel to the direction of action potential propagation. When applicable, electrodes were placed between the innervation zones described by Rainoldi et al. (2004) and the distal attachments of these muscles in the dominant leg of each subject, defined as the leg that would be used to kick a ball for distance. Proper electrode placement was verified via manual muscle testing (Hislop et al., 1995).

Additionally, subjects were outfitted with a standard retroreflective marker set (25 static, 21 dynamic) placed bilaterally on the acromion process, anterior superior iliac spine, greater trochanter, anterior thigh, medial and lateral epicondyles, anterior shank, medial and lateral malleoli, calcaneus, 1st and 5th metatarsal heads, and the sacrum. These markers were used to measure hip and knee kinematics during the SLS normalization procedure using a seven camera motion capture system (Vicon Inc., Centennial, CO).

2.3. Experimental procedures

Surface EMG amplitudes of the GMax, GMed, RF, VL, ADD, and BF along with hip and knee kinematics were measured concomitantly during SLS as subjects stood on the dominant leg with the hands on the hips and the non-dominant knee flexed to 90°. Subjects were instructed not to allow the non-dominant leg to contact the dominant leg and to remain as still as possible. Three 5 s trials were recorded with at least 30 s of rest between trials.

Following completion of the SLS trials, the retroreflective markers were removed so that subjects could be properly positioned for the assessment of MVICs in the following order; (1) RF and VL assessed concurrently, (2) ADD, (3) GMax, (4) BF, and (5) GMed by the same researcher. MVICs were performed against gravity and manual resistance in standardized testing positions as described by Hislop et al. (1995) using a short-seated position for RF and VL, side-lying positions for ADD and GMed, and a prone position with the knee flexed for GMax and BF. Three 5 s trials for each assessment were recorded with at least 30 s of rest between trials to reduce the likelihood of fatigue.

2.4. Data sampling and reduction

EMG and kinematic data were sampled at 1200 and 120 Hz, respectively, via Vicon Nexus motion capture software (Vicon Inc., Centennial, CO). Raw three-dimensional kinematic and EMG data were imported into The Motion Monitor motion analysis software (Innovative Sports Training, Chicago, IL). EMG data were corrected for DC bias and bandpass (20–350 Hz) and notch (59.5–60.5 Hz) filtered (4th order zero-phase lag Butterworth), while kinematic data were lowpass filtered at 12 Hz (4th order zero-phase lag Butterworth). Sagittal and frontal plane hip and sagittal plane knee joint angles were calculated using Euler angles in a Y (flexion/extension), X (adduction/abduction), Z (internal/external rotation) rotation sequence. Motion was defined about the hip as the thigh relative to the sacrum and about the knee as the shank relative to the thigh.

Custom computer software (LabVIEW, National Instruments, Austin, TX) was used to calculate the root mean square (RMS) EMG amplitude for each muscle over the middle 3 s of each SLS

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and MVIC trial. Mean hip and knee kinematics were also calculated over this same time interval for the SLS trials only.

2.5. Statistical analyses

Separate one-way repeated measures analyses of variance (ANOVA) were conducted to compare EMG amplitudes across trials for each muscle during SLS and MVIC normalization methods. These results were then used to calculate ICC (2, 1) and standard errors of measurements (SEMs) for each muscle and normalization method to assess the reliability and precision, respectively, of the measured EMG signals across trials. Intrasubject CVs were calculated by dividing the square root of the trial mean square error (MSE) by the overall mean EMG amplitude of each muscle during each method (Knutson et al., 1994). Intersubject CVs for each muscle and normalization method were calculated by dividing the standard deviation about the grand mean for all trials and subjects by the grand mean (Knutson et al., 1994). Finally, mean EMG amplitude for each muscle across the three trials of SLS and MVIC was calculated and used to evaluate the relationship between SLS and MVIC normalization methods using simple linear regression. Statistical analyses were conducted using SPSS Version 16.0 (SPSS Inc., Chicago, IL) with significance established *a priori* as α 0.05.

3. Results

Figs. 1 and 2 illustrate filtered EMG data from the six muscles of interest and hip and knee joint positions, respectively, during a representative SLS trial. These results demonstrate that muscle activity and joint position remained relatively constant over the course of the SLS trial and did not display large variations in joint position that would influence EMG amplitude appreciably. Mean hip and knee joint positions during SLS are presented in Table 1. The standard deviations for mean hip extension, hip abduction, and knee flexion were ±6.0°, ±6.0°, and ±4.1°, respectively. A summary of the ICCs and SEMs across trials for each muscle during the SLS and MVIC normalization methods are presented in Table 2. ICCs ranged from 0.80 to 0.94 during SLS and from 0.84 to 0.99 during MVIC. Intersubject and intrasubject CVs are presented in Table 3. Intersubject CVs ranged from 59% to 166 % for SLS and 61% to 118% for MVIC, while intrasubject CVs ranged from 20% to 60% for SLS and 9% to 36% for MVIC. Pearson product moment correlations (r) assessing the relationship between SLS and MVIC mean EMG amplitude for the three trials of each method are presented in Table 4. EMG amplitude during SLS and MVIC were significantly associated for GMed ($r = 0.905$, $p < 0.001$), RF ($r = 0.862$, $p < 0.001$), VL ($r = 0.743$, $p < 0.001$), ADD ($r = 0.604$, $p = 0.001$), and BF ($r = 0.673$, $p = 0.010$). However, there was no significant association between GMax SLS and MVIC EMG amplitudes ($r = 0.250$, $p = 0.288$).

4. Discussion

4.1. Subject positioning during SLS

For SLS to be a valid method for normalization of EMG, it is necessary that this procedure provide a consistent functional demand to all subjects. Qualitative analysis of hip and knee joint positions indicated that subjects performed the SLS procedure in very similar joint posi-

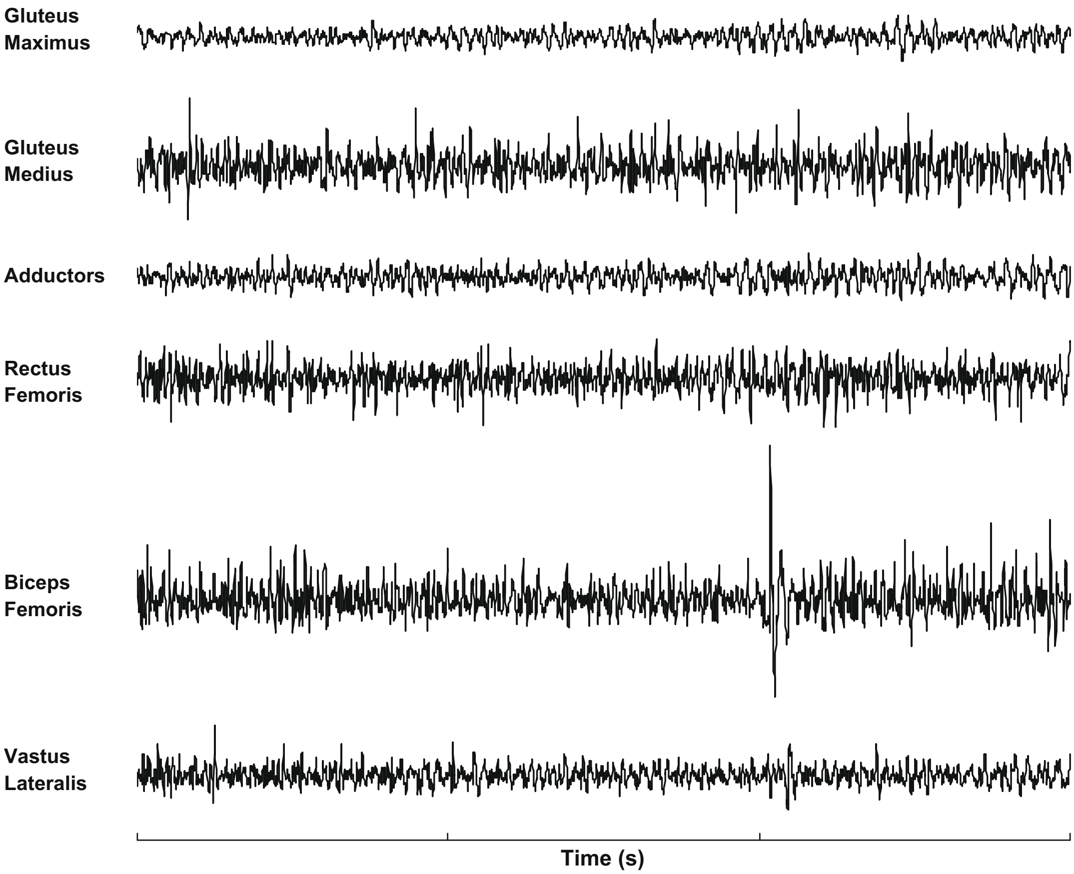

Fig. 1. Filtered EMG from the six muscles of interest during the middle 3 s of a representative trial of single leg stance (SLS) normalization.

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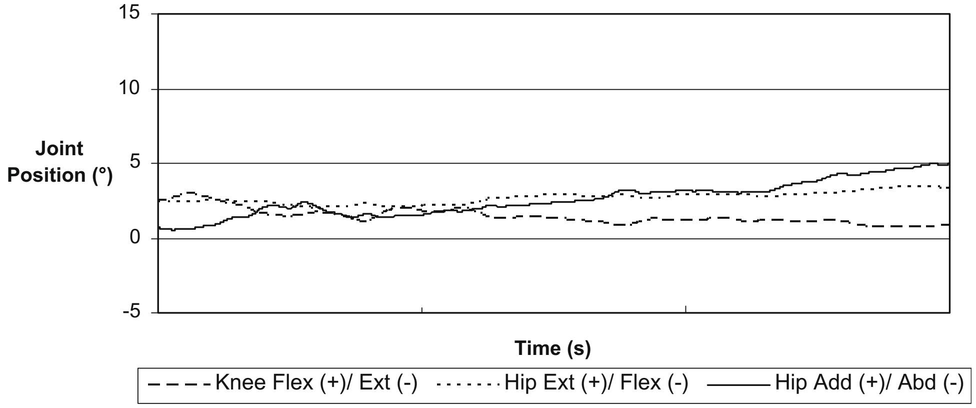

Fig. 2. Sagittal plane knee and hip, and frontal plane hip angles during the middle three seconds of a representative trial of single leg stance (SLS) normalization.

tions. The standard deviations associated with mean hip kinematics during SLS ranged from 4.1° to 6.0°, indicating that the variability observed during this task is no larger than the anecdotally observed variability in subject positioning that can be expected during assessment of MVICs. Though dissimilar joint positions between subjects are known to impact the amplitude of the EMG signal (De Luca, 1997), Worrell et al. (2001) determined that EMG amplitude only differed by 10–15% of the MVIC in the gluteus maximus and hamstrings during isometric knee flexion and hip extension at joint angles of 0° and 30°. As a result, the observed differences in EMG activity amplitude during SLS, where subject positioning varied by no more than ±6°, can be attributed to variations in subject muscle activation and are not the by-product of small differences in the length–tension relationships between subjects.

Table 1
Mean ± standard deviation (SD) of sagittal and frontal plane hip angles and sagittal plane knee angle during the single leg stance (SLS) normalization procedure in degrees.

Joint position	Mean (°)	SD (°)
Hip extension	7.4	6.0
Hip abduction	0.7	4.1
Knee flexion	1.3	6.0

4.2. Measurement reliability during SLS and MVIC

The EMG activity across trials in all muscles during both SLS and MVIC methods demonstrated good-to-excellent reliability with ICCs >0.80 (Table 2). However, due to a limited number of studies reporting ICCs during MVIC or dynamic tasks in these muscles, a comparison to previous work for all muscles is not possible. None-

Table 2
Intraclass correlation coefficients (ICC) (2, 1) and standard errors of the mean (SEM) in millivolts (mV) of mean EMG amplitude by muscle during single leg stance (SLS) and maximal voluntary isometric contraction (MVIC).

		Gluteus maximus	Gluteus medius	Rectus femoris	Vastus lateralis	Adductor group	Biceps femoris
SLS	ICC (2, 1)	0.85	0.93	0.94	0.90	0.94	0.80
	SEM (mV)	8.5	19.5	18.6	27.3	6.1	11.2
MVIC	ICC (2, 1)	0.95	0.98	0.95	0.98	0.84	0.99
	SEM (mV)	49.4	50.4	120.8	84.0	201.0	30.7

Table 3
Intersubject (Inter CV) and intrasubject (Intra CV) coefficients of variation of EMG amplitude by muscle during single leg stance (SLS) and maximal voluntary isometric contraction (MVIC).

		Gluteus maximus	Gluteus medius	Rectus femoris	Vastus lateralis	Adductor group	Biceps femoris
SLS	Inter CV (%)	58.6	77.0	136.9	165.5	104.6	135.1
	Intra CV (%)	22.7	20.2	34.4	54.6	27.0	59.4
MVIC	Inter CV (%)	60.8	84.5	90.0	92.1	90.0	118.0
	Intra CV (%)	13.6	12.8	20.3	14.5	35.8	9.0

Table 4
Pearson product moment correlations (*r*) and associated *p*-values of EMG amplitude during the first trial of single leg stance (SLS) and maximal voluntary isometric contraction (MVIC) by muscle (correlation is significant when $p < 0.05$).

	Gluteus maximus	Gluteus medius	Rectus femoris	Vastus lateralis	Adductor group	Biceps femoris
r	0.250	0.905	0.862	0.743	0.604	0.673
p	0.288	<0.001	<0.001	<0.001	0.005	0.001

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theless, the ICC for GMed across MVIC trials (0.98) is in agreement with previous work by Bolgla and Uhl (2007) who reported an ICC of 0.92 when MVICs were measured before and after a single exercise session. The VL ICC of 0.98 during MVIC is similar to that reported by Earl et al. (2001), 0.99, when MVIC was used as the normalization method during mini-squat exercises. Knutson et al. (1994) calculated ICCs of gastrocnemius EMG activity across trials using MVIC, peak dynamic, and mean dynamic measures during single leg stance on a balance board and found the ICC using MVIC, 0.80, to be greater than the ICCs using mean dynamic (0.66) and peak dynamic (0.54) methods. Our findings, that both SLS and MVIC methods of EMG normalization demonstrate good-to-excellent reliability, indicate a consistent measure of EMG amplitude activity across trials.

4.3. Measurement precision during SLS and MVIC

As important as reliability in evaluating EMG amplitude normalization methods is the notion of precision, or accuracy, of the measure which can be assessed using SEMs and the intrasubject CVs. In this study, SEMs expressed in millivolts, are not useful as a measure of precision due to the extreme differences in the EMG amplitude scales resulting from MVIC and the much less demanding SLS, as well as the potential influences of a variety of experimental factors on the raw amplitudes (e.g. subcutaneous tissue thickness, electrode-fiber orientation, etc.). As a result, intrasubject CVs, the values of which are very similar to the SEMs expressed as a function of mean EMG activity during the task, were evaluated as a more appropriate measure of precision. Generally, intrasubject CVs were lower for the MVIC method compared to SLS except in the ADD muscle group (Table 3). The greatest discrepancies in intrasubject CVs between procedures occurred with the RF (MVIC = 20.3%, SLS = 34.4%), VL (MVIC = 14.5%, SLS = 54.6%), and BF (MVIC = 9.0%, SLS = 59.4%). We propose that a combination of anatomical factors and the relatively limited demands placed on these muscles during SLS contributed to these high intrasubject CVs. Both the RF and BF are biarticular muscles that act in concert with uniarticular muscles at the hip and the knee to meet moment requirements about both joints. As such, the relative contributions of muscles responsible for meeting the knee and hip extension moment requirements during SLS are likely more variable during this functional task than during an isolated MVIC. This notion is supported by the lower reliability in the biarticular gastrocnemius with a dynamic normalization method observed by Knutson et al. (1994), and the greater intersubject variability in the EMG signal of biarticular muscles compared to single joint muscles during gait reported by Winter and Yack (1987). These findings are consistent with the high intersubject CVs displayed in the RF and BF during both MVIC and SLS in the present study. In addition, the relatively low demand on the RF, VL, and BF during SLS results in lesser mean EMG amplitudes compared with the amplitudes measured during MVICs. These smaller mean amplitudes make these measures of precision more susceptible to very small fluctuations in the EMG signal, inflating the SLS intrasubject CVs to a much greater extent than with MVIC.

4.4. Association between SLS and MVIC

The relationships between EMG amplitudes during SLS and MVIC vary considerably as a function of the muscle of interest (Table 4). The strongest correlation was noted for GMed with approximately 82% of the variance in the SLS EMG amplitude explained by that of the MVIC. RF, VL, ADD, and BF were also significantly associated, though only 74%, 55%, 36%, and 45% of the variability in the EMG amplitude during SLS was explained by the EMG amplitude during MVIC, respectively. GMax EMG amplitudes during SLS and MVIC were not significantly correlated, as only 6% of the variability in one measure was explained by variability in the other. The observed associations between the two measures for RF, BF, ADD, and VL can be classified as moderate–moderately high (Hinkle et al., 1998), and are most likely due to subject differences in coordination of muscle activation to meet the joint moment requirements during SLS. For example, subjects are able to generate hip extension moment required to maintain SLS using the GMax and/or BF, and the relative contributions of these two muscles to meet this demand may vary considerably between subjects. As a result, relatively weak associations would be observed when measures with a lot of variability in the EMG amplitudes between subjects (SLS) due to differences in muscle coordination strategies are correlated with measures that have less variation between subjects (MVIC). Due to the fact that MVICs are generally obtained in positions that are non-functional, normalization of EMG amplitude using the SLS procedure may be more representative of strategies employed during functional tasks and agrees with the recommendations of previous researchers that EMG normalization should be performed relative to a meaningful reference procedure using a similar neuromuscular pattern to the one employed during the activity under investigation (Fernández-Peña et al., 2009; Rouffet and Hautier, 2008).

4.5. Limitations

This study has several limitations that should be addressed. First, during the MVIC trials, subjects were given verbal encouragement and placed in standardized testing positions as described in the literature to facilitate maximal effort. However, without the use of methods such as the superimposed burst technique, an inherent limitation to the MVIC procedure is that there is no way to accurately determine whether a subject has provided a maximal effort (Kent-Braun and Le Blanc, 1996). Similarly, it is not possible to precisely quantify what level of sub-maximal activation was utilized by subjects to meet the demand of the SLS task. Additionally, the SLS method is limited to subjects that can maintain the required testing position in much the same way that the MVIC method is limited to healthy/uninjured subjects who are capable of providing maximal effort.

Another limitation to the current investigation is the lack of a randomized testing order. Due to the need to confirm subject positioning during SLS, kinematic analysis requiring the use of a marker set was performed. Subjects could not be placed in several of the standardized MVIC testing positions while wearing this marker set. As a consequence, and due to the time required to place these markers on the subject, we felt it most prudent to standardize the testing order. This avoided giving subjects rest periods of different durations between test conditions as would have occurred with a randomized testing order when the marker set would have had to be placed during the middle of the testing protocol.

Finally, there is always the potential for cross-talk to occur between muscles as well as other extrinsic threats to the integrity of the EMG signal. To limit potential influences, subject skin preparation and electrode location was standardized, and EMG activity was visually confirmed for each muscle using an oscilloscope. Furthermore, the same researcher positioned the EMG electrodes on all subjects.

5. Conclusion

This study was the first to examine the relationship between EMG amplitude during SLS and MVIC methods of EMG normalization and concomitantly evaluate the reliability of these measures. Based upon our results, we do not recommend that the SLS normalization procedure utilized in this study be used for the RF, VL, or BF. Even with the high reported ICC values indicating good reliability, the lack of precision of the EMG activity amplitude as illustrated by

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high intrasubject CVs suggest that these values demonstrate too much variability to be considered as stable reference values. Conversely, we do feel that it is appropriate to utilize the SLS normalization procedure for the GMax, GMed, and ADD due to the high ICCs and relatively low intrasubject CVs suggesting the combination of both reliability and precision of the EMG amplitude in these muscles. Furthermore, we suggest that the SLS EMG amplitude normalization procedure should be used for tasks during which EMG is being sampled from these muscles as this method (1) minimizes subject effort by requiring subjects to perform a single reference procedure for multiple muscles simultaneously, (2) requires substantially less effort than MVIC, thus reducing the likelihood of fatigue and potential complications in injured populations, and (3) provides a normalization criterion that more closely resembles the coordinated function of the lower extremity musculature during closed kinetic chain tasks.

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