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Title: Reliability of telemetric electromyography and near-infrared spectroscopy during high-intensity resistance exercise

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Abstract

This study quantified the inter- and intra-test reliability of telemetric surface electromyography (EMG) and near infrared spectroscopy (NIRS) during resistance exercise. Twelve well-trained young men performed high-intensity back squat exercise (12 sets at 70-90% 1-repetition maximum) on two occasions, during which EMG and NIRS continuously monitored muscle activation and oxygenation of the thigh muscles. Intra-test reliability for EMG and NIRS variables was generally higher than inter-test reliability. EMG median frequency variables were generally more reliable than amplitude-based variables. The reliability of EMG measures was not related to the intensity or number of repetitions performed during the set. No notable differences were evident in the reliability of EMG between different agonist muscles. NIRS-derived measures of oxyhaemoglobin, deoxyhaemoglobin and tissue saturation index were generally more reliable during single-repetition sets than multiple-repetition sets at the same intensity. Tissue saturation index was the most reliable NIRS variable. Although the reliability of the EMG and NIRS measures varied across the exercise protocol, the precise causes of this variability are not yet understood. However, it is likely that biological variation during multi-joint isotonic resistance exercise may account for some of the variation in the observed results.

1. Introduction

Surface electromyography (EMG) provides a non-invasive, objective method to measure physiological processes occurring during muscular contraction. The EMG signal is influenced by a number of factors, such as motor unit discharge rates, muscle fibre membrane characteristics, and non-physiological properties including electrode size, shape and placement (Farina et al., 2004). Daily variations in EMG recording may be associated with differences in electrode re-application, including alterations in electrode position and differences in skin preparation. Although EMG has demonstrated moderate to high levels of reliability during quadriceps contractions (Larsson et al., 2003; Mathur et al., 2005), the systems typically used have required wired attachment between electrodes and an EMG amplifier. Such systems are cumbersome when performing complex movements, limiting their application during field-based testing. Furthermore, the risk of leads becoming dislodged from their electrode increases the chance for data loss.

Recent technological advances have resulted in the development of telemetric EMG systems to mitigate these limitations. These systems require only one electrode for targeted muscles, compared to wired systems requiring up to two electrodes per muscle and an additional reference electrode. However, whether this telemetric configuration results in reliable data is not well understood. While one investigation has reported the reliability for telemetric EMG during uphill running activity as 0.98 (presumably correlation coefficient) (Lowery et al., 2014), the methods and analyses employed to assess reliability were not stated.

It must also be acknowledged that research examining the reliability of EMG technologies has not typically used dynamic multi-joint exercises, or assessed whether resistance exercise intensity can affect the reproducibility of EMG variables. As such, the current body of reliability research in this field may be limited in its application to common resistance training methods. For increases in muscular size and strength, resistance training is typically performed using moderate and high loads, and with a set volume (i.e. number of repetitions in a set) that corresponds to the exercise intensity (Bird et al., 2005). However, it is not currently clear whether manipulating these training variables affects the reliability of EMG measurements.

Muscle oxygenation status has also been investigated during resistance exercise models to describe the intramuscular metabolic environment (Azuma et al., 2000; Hoffman et al., 2003). During resistance exercise, increases in intramuscular mechanical pressure lead to reduced blood flow (MacDougall et al., 1985), resulting in transient muscle hypoxia (Spiering et al., 2008), which may facilitate increased hypertrophy (Hoffman et al., 2003). Indeed, localized muscular hypoxia induced via blood flow restriction has resulted in enhanced anabolic responses to resistance exercise (Abe et al., 2005; Takarada et al., 2000). While the effects of muscle oxygenation status on resistance training adaptations are not fully understood, the use of near infrared spectroscopy (NIRS) to monitor muscle oxygenation has become popular among exercise scientists (Quaresima et al., 2003). This may be especially important for research investigating resistance training with blood flow restriction or additional systemic hypoxia, which is currently promoted as a beneficial new training stimulus (Scott et al., In Press). NIRS is non-invasive, and reflects the balance of oxygen delivery to working muscles and oxygen consumption in capillary beds.

NIRS values during isometric erector spinae activity have demonstrated a moderate to strong intraclass correlation coefficient (ICC; 0.69-0.84) (Kell et al., 2004). NIRS data during knee extension exercise has also yielded moderate to strong ICC values during both isokinetic (0.73-0.97) (Pereira et al., 2005) and isotonic (ICC

= 0.85 and coefficient of variation [CV] = 0.07%) (Tanimoto and Ishii, 2006) exercise protocols. More recently, significant ICC values (0.39-0.87) have been shown for NIRS measures in the forearm muscles during handgrip exercise at various intensities (Celie et al., 2012). While these studies have reported the reliability of NIRS during single-joint resistance exercise, no data have reported on the reliability of NIRS measures during multi-joint isotonic resistance exercise. Furthermore, these studies reporting on the reliability of NIRS have utilized static or seated exercises, and it remains unknown whether the greater postural control required during dynamic exercises might affect its reliability. It is possible that different contributions from synergistic muscles during dynamic multi-joint exercise may alter the reliability of muscle oxygenation within a single muscle.

It is evident that the reliability of telemetric EMG and NIRS devices during dynamic multi-joint resistance exercise at various intensities is not yet known. Understanding the reliability of these technologies during resistance exercise is important to ensure that any measured differences in muscle activation or oxygenation status are indicative of actual change, rather than error in the measurement itself. In addition, many studies investigating the reliability of EMG and NIRS variables have focused largely on ICC values to test reliability. The ICC is a relative measure of reliability, and is affected by the range of the values being assessed (Atkinson and Nevill, 1998). For a more detailed reliability analysis, further statistics such as typical error (often expressed as a percentage CV) should be included (Atkinson and Nevill, 1998; Hopkins, 2000). Therefore, the purpose of this study was to comprehensively investigate the intra- and inter-test reliability of a telemetric EMG system and NIRS device during moderate- and high-intensity dynamic multi-joint resistance exercise.

The research also aimed to determine if the intensity or number of repetitions performed within a set affected reliability.

2. Methods

2.1. Experimental Approach to the Problem

Subjects visited the laboratory on four occasions, each separated by one week. Sessions one and two involved familiarisation and 1RM testing using a modified harness back squat (HBS) exercise (Figure 1). Sessions three and four were identical, and involved experimental trials of a high-intensity resistance exercise protocol using the HBS. During experimental trials, muscle activation and oxygenation status were continuously monitored to determine the reliability of telemetric EMG and NIRS technologies.

INSERT FIGURE 1 NEAR HERE

2.2. Participants

Twelve healthy males (age: 24.8 ± 3.4 yr, height: 178.6 ± 6.0 cm, body mass: 84.8 ± 11.0 kg) volunteered to participate in this study. All participants had at least two years resistance training experience and were free of musculoskeletal disorders. Prior to commencement, participants were informed of the nature of the research, provided informed consent, and were screened for medical contraindications. They were instructed to abstain from alcohol and caffeine for 24 hours before each testing session, and to avoid any strenuous physical activity for the duration of the research. Subjects were also instructed to replicate their food and liquid intake for the 24-hour period prior to each test. The University of Newcastle Human Ethics Committee approved the study and its methods.

2.3. Familiarisation and 1-Repetition Maximum Testing

To ensure subjects were confident in performing the HBS exercise, which has been described previously (Scott et al., 2014), they were familiarized with testing procedures and equipment prior to experimental trials. This exercise was chosen as it is a dynamic multi-joint exercise, and has both clinical and athletic applications. Within one week of familiarization, subjects were tested for 1RM of the HBS exercise. For the 1RM test, subjects completed a general warm-up (five minutes on a cycle ergometer at a moderate intensity), before performing three specific warm-up sets of the HBS, comprised of 10 repetitions at 50% of predicted 1RM weight (as estimated by the subject), 5 repetitions at 70%, and 1 repetition at 90%. Following the warm-up sets, weight was increased by ~5% and subjects performed a single repetition. This process continued until subjects were unable to successfully perform a lift, with three minutes rest between attempts. Subjects' 1RM was defined as their heaviest completed repetition, and was determined within 3-6 sets.

2.4. Experimental Trials

Subjects reported to the laboratory on two further occasions to perform identical resistance exercise trials. Upon arrival, EMG and NIRS devices were affixed before subjects completed a general warm-up, followed by three specific warm-up sets (10 repetitions at 50% of measured 1RM, 5 repetitions at 65%, and 1 repetition at 80%). Following the warm-up, subjects rested for three minutes, before beginning 12 sets of a high-intensity resistance exercise protocol (Table 1), during which muscle activation and oxygenation status were monitored via EMG and NIRS, respectively. Subjects wore the same footwear for each trial.

The exercise protocol was designed to assess muscle function within both single and multiple repetition sets at various high-intensity loads, in order to provide a comprehensive examination of device reliability. Single-repetition sets were included to examine EMG and NIRS reliability during a maximal effort at a given intensity, as subjects were instructed to perform the concentric phase of the lift as quickly as possible. Multiple-repetition sets were included to quantify reliability during sets at various high-intensities when a typical set volume was employed. That is, for individuals completing strength training it is common to perform 3, 6, and 10 repetitions at intensities of 90, 80 and 70% 1RM, respectively.

INSERT TABLE 1 NEAR HERE

Subjects squatted down to an elastic stringline each repetition, which was set so that each individual's superior hamstrings came in contact with it when the top of the thighs were parallel with the ground (Cotterman et al., 2005). This was visually assessed by a researcher positioned adjacent to the participant. Subjects were also given verbal cues on when they were to halt the down phase, and begin the up phase, of the squat (Cronin and Hansen, 2005). To ensure consistent feet placement, subjects positioned the posterior edge of their shoes on a horizontal line marked on the floor beneath the Smith machine, with their feet equidistant from a centre marking on this line (Hori and Andrews, 2009). Throughout the movement, heels of the feet remained flat on the ground, the spine was maintained in a neutral position and the head was kept level.

2.5. Electromyography Monitoring

Muscle activation during each set of the HBS exercise was monitored via EMG recordings from the left gluteus maximus (GM), vastus lateralis (VL), vastus medialis (VM) and biceps femoris (BF) muscles. These muscles have previously been used to examine the myoelectric activity of hip and thigh muscles during the back squat in well trained weightlifters (Caterisano et al., 2002). Prior to electrode placement, the skin was shaved, lightly abraded and cleaned with alcohol to ensure optimal electrical conductance. Telemetric surface electrodes (Trigno™ Wireless, Delsys Inc., Boston, USA) were positioned on the belly of the muscle, and according to the recommendations of surface EMG for non-invasive assessment of muscles (SENIAM) (Hermens and Freriks, 1997). The position of electrodes is shown in Figure 2. Electrodes were affixed with double-sided adhesive, running parallel with the muscle fibres. To ensure consistent electrode placement between trials, the position of each electrode was outlined using a permanent marking pen during the first experimental trial. Subjects were provided with pens and instructed to re-outline the marker position if it faded prior to the second experimental trial (Kacin and Strazar, 2011).

INSERT FIGURE 2 NEAR HERE

Data were sampled at 4000 Hz, passed through a differential amplifier at a gain of 300, and band-pass filtered (fourth order Butterworth filter) at 16-500 Hz. The concentric phase was selected for EMG analysis, and was identified using data derived from a triaxial accelerometer housed within the EMG devices. The root mean square (RMS) of vertical acceleration (with reference to the orientation of the electrode when standing) at the VL electrode was used to identify the change in acceleration direction at the bottom (beginning of concentric phase) and top (end of concentric phase) of each repetition. The identification of lifting cycles from RMS acceleration data was performed offline by the same investigator and was highly reliable (CV = 2.2%, ICC = 1.00). An example trace of the accelerometer data, and corresponding EMG signal from the muscles assessed is illustrated in Figure 3.

The mean signal amplitude during the concentric phase of each repetition was calculated using a sliding RMS filter, with a window of 0.125 s and overlap window of 0.065 s. The integrated EMG (iEMG) signal across the duration of each set (from the beginning of the first repetition to the end of the last) was also calculated using the same windows. Concentric EMG median frequency (MDF) was obtained by fast Fourier transformation, using a window of 512 points with a 256-point overlap. EMG data were analysed using EMGworks software (v4.01, Boston, Delsys Inc, USA).

INSERT FIGURE 3 NEAR HERE

2.6. Near-infrared Spectroscopy (NIRS) Monitoring

Muscle oxygenation of the right VL was monitored continuously during experimental trials using a portable NIRS device (Portamon, Artinis Medical System, BV, The Netherlands). The device was positioned on the belly of the VL, following the same placement guidelines as previously described for VL EMG assessment, though on the opposite leg (Figure 2). As described for EMG electrodes, the NIRS apparatus was outlined on subjects' skin to ensure consistent placement. The device was wrapped in transparent plastic to eliminate direct contact with the skin and sweat and was affixed using dark tape to prevent contamination from ambient light.

During experimental trials, data were sampled at 20 Hz and transferred live via Bluetooth connection to a personal computer for analogue-to-digital conversion, storage, and analysis using Oxysoft software (Oxysoft, Artinis Medical Systems, BV, The Netherlands). Changes in tissue oxyhaemoglobin ([HbO_2]) and deoxyhaemoglobin ([HHb]) concentrations were measured using their chromophoric properties at 750 and 860 nm. Tissue saturation index (TSI) was also calculated automatically by Oxysoft software, to represent the relative concentration of HbO_2 in relation to the total amount of haemoglobin as an absolute parameter.

To obtain maximal HHb and minimum HbO_2 values, cuff ischemia was performed after five minutes of passive recovery following each experimental trial. This process involved placing a thigh cuff superior to the NIRS apparatus, which was rapidly inflated to 250 mmHg for eight minutes, or until a nadir in [HHb] was reached. The cuff was administered with subjects lying supine and the instrumented leg extended horizontally. Following cuff ischemia, the cuff was deflated and subjects rested passively for five minutes. NIRS data were smoothed using a 0.5 s moving average, before relative HHb and HbO_2 for each resistance exercise set were calculated (Hoffman et al., 2003). To report on changes in peripheral oxygenation state during resistance exercise, data are reported as relative minimum [HbO_2] (HbO_{2min}) and maximum [HHb] (HHb_{max}) values, as well as the absolute minimum TSI (TSI_{min}) during each set.

2.7. Statistical Analysis

Data distribution was tested for normality using the Shapiro-Wilk test. As not all data were normally distributed, data were transformed by taking the natural logarithm to allow parametric statistical comparisons that assume a normal distribution. This treatment of data and reliability analyses were performed using a custom made spreadsheet designed for this purpose (Hopkins, 2002). Intra-test reliability analyses were performed on selected EMG and NIRS variables between paired identical sets at each intensity and repetition range within the first experimental trial. Inter-test reliability analyses were performed on these same variables, between the first matching set at each intensity and repetition range, between the two experimental trials. Reliability was calculated as the typical error (expressed as a percentage CV), ICC and 95% confidence intervals (CI). The ICC was interpreted as per previous research (Dascombe et al., 2007): 0.0-0.2: very week; 0.2-0.4: weak to low; 0.4-0.7: moderate; 0.7-0.9: strong; 0.9-1.0: very strong. Paired sample *t*-tests were used to test if differences existed between the repeated tests. Criterion alpha level for significance was set at $P \leq 0.05$. Paired sample *t*-tests analyses were performed using SPSS v20.0 (IBM Corporation, Somers, USA).

3. Results

3.1. Reliability of EMG measures

Significant intra-test differences were only observed between MDF values for sets 1 and 2 of single-repetition sets at 80% 1RM for GM (P=0.035). The intra-test and inter-test reliability of the EMG system during resistance exercise is shown in Figures 4 and 5, respectively. The intra-test CV data demonstrated varied reliability for the GM (1.6-18.3%), BF (5.6-22.0%), VL (2.8-31.2%) and VM (4.2-21.2%). Further, the ICC ranged from moderate to very strong for the GM (0.77-0.99), BF (0.43-0.94), VL (0.66-1.00) and VM (0.61-0.98).

INSERT FIGURE 4 NEAR HERE

Significant inter-test differences were present between iEMG values from VL in the single-repetition sets at 90% and 70% 1RM (P=0.049 and 0.041, respectively), and in multiple-repetition sets at 80% and 70% 1RM (P=0.044 and 0.009, respectively). The inter-test CV data demonstrated some variability for the GM (5.2-30.0%), BF (12.4-31.6%), VL (3.8-64%) and VM (4.3-31.4%). Further, the ICC ranged from weak to very strong for the GM (0.49-0.89), BF (0.01-0.86), VL (-0.39-0.97) and VM (0.27-0.97). The frequency component of EMG signals generally displayed higher levels of reliability than amplitude components.

INSERT FIGURE 5 NEAR HERE

3.2. Reliability of NIRS measures

Significant intra-test differences were observed between HHb_{max} values for multiple-repetition sets 90%, 80% and 70% 1RM (P=0.001, 0.015 and 0.009, respectively). The intra-test and inter-test reliability of the NIRS device to monitor HbO_{2min}, HHb_{max} and TSI_{min} during the resistance exercise protocol are shown in Figures 6 and 7, respectively. The intra-test CV and ICC values for NIRS variables between the paired sets within the same testing session ranged from 1.8-25.3% and 0.75-0.98, respectively. Generally, HbO_{2max}, HHb_{max} and TSI_{min} were more reliable (i.e. smaller CV and larger ICC values) during single-repetition sets, than the multiple-repetition sets at each intensity. However, this trend was reversed for CV values from HHb_{max} data.

INSERT FIGURE 6 NEAR HERE

There were no significant inter-test differences for NIRS variables. The CV and ICC values for NIRS variables between corresponding sets within the two testing sessions ranged from 6.1-43.5% and 0.44-0.87, respectively. As with intra-test reliability of NIRS variables, HbO_{2min}, HHb_{max} and TSI_{min} were more reliable during single-repetition sets, than multiple-repetition sets, with the exception of CV values from maximum HHb_{max} data.

INSERT FIGURE 7 NEAR HERE

The magnitude of CV and ICC measures for both EMG and NIRS data demonstrated greater levels of reliability for paired sets within the same session, than for matched sets between experimental trials. There was also a trend for smaller ranges of 95% CI for intra-test reliability values than for inter-test values.

4. Discussion

The current study investigated the reliability of a telemetric EMG system and NIRS device to quantify muscle activation and oxygenation status, respectively, during dynamic resistance exercise. The major findings of this research are i) intra-test reliability was higher than inter-test reliability for EMG and NIRS variables; ii) MDF was generally more reliable than RMS and iEMG variables; iii) the reliability of NIRS variables during resistance exercise is affected by the volume of each set and; iv) NIRS-derived measures of TSI_{min} were more reliable than HbO_{2min} and HHb_{max}. The current findings have important implications for both practitioners and researchers, as this is the first study to comprehensively assess the reliability of these telemetric EMG and NIRS technologies during dynamic multi-joint resistance exercise at various intensities.

4.1. Reliability of EMG measures

The current data demonstrate that each EMG variable differed in reliability across the various intensities of resistance exercise, with RMS, MDF and iEMG values generally displaying moderate to strong levels of intra-test reliability. While these findings are similar to previous research reporting intra-test ICC values for mean RMS and frequency during single-joint isokinetic tests (Larsson et al., 1999a; Larsson et al., 1999b), these previous investigations have demonstrated a smaller range of ICC values than the current study. While this may indicate greater variability in the current study, caution should be taken when comparing ICC values between separate investigations, as this statistic is largely influenced by the range of data scores and the population studied (Atkinson and Nevill, 1998).

Past studies have been limited to isokinetic dynamometry of single-joint exercises (Larsson et al., 1999a; Larsson et al., 1999b). As such, a back squat variation was employed in the current study to analyse multi-joint isotonic resistance exercise. As the HBS exercise has more degrees of freedom than single-joint isokinetic dynamometry, there is greater potential for variability in exercise technique both within and between testing sessions. For example, it is possible that the position of the knees in reference to the toes during the HBS might have altered slightly between sets and/or testing sessions. Such changes in technique would likely influence segmental orientation, and subsequent motor recruitment patterns. However, as the current investigation did not extend to a kinematic analysis of the HBS exercise, it is unclear whether alterations in technique did in fact affect muscle activation patterns.

As expected, the reported inter-test reliability of EMG variables was lower than the intra-test reliability. Further, the CV and ICC reliability measures both varied greatly across the exercise intensities and repetition schemes assessed. Varied reliability has been previously reported by Larsson et al. (2003) for non-normalized RMS (ICC = 0.05-0.95), and median frequency (ICC = 0.48-0.88) variables, between two trials of 100 maximum concentric knee extensions at $90°\cdot s^{-1}$ separated by 7-8 days (CV values not reported). Interestingly, the current MDF data displays moderate to strong levels of reliability between sessions for the GM, VL and VM. However, the inter-test reliability of MDF from BF was poor. Although it is unclear why MDF from BF is unreliable from the current data, it is possible that these findings relate to the antagonistic role of BF during the HBS. During knee extension, the hamstrings stabilize the knee and hip joints (Schwanbeck et al., 2009). During heavy dynamic resistance exercise, the recruitment of antagonist muscles is dependant upon proprioceptive balance and stability feedback, and the higher variability in BF recruitment may reflect small adjustments made in segmental orientation in order to maintain balance and stability during exercise.

The increased inter-test variability may also be explained by small alterations in the re-application of electrodes prior to the second trial. Despite subjects being instructed to re-mark electrode locations between trials, some marks were not visible at the second trial and were subsequently re-measured. While this is likely to occur in applied exercise science and clinical settings that employ EMG assessment (Larsson et al., 2003), changes in electrode placement may explain the decreased reliability of inter-test values. Nonetheless, as the intra-test reliability of EMG values also varied, factors other than electrode placement must influence reliability. At present, it is difficult to determine the cause of the varied reliability within certain sets, as no clear relationships are evident between the level of reliability and either the number of repetitions performed in a set, nor the intensity of the set. It is possible that the small sample size employed, although similar to previous investigations that have assessed EMG reliability (Larsson et al., 1999a; Larsson et al., 1999b), may have contributed to these findings.

4.2. Reliability of NIRS measures

While previous research has established the test-retest reliability of NIRS to monitor muscle oxygenation status during various exercise protocols (Celie et al., 2012; Kell et al., 2004; Pereira et al., 2005; Tanimoto and Ishii, 2006), this research is the first to assess the reproducibility of NIRS during isotonic multi-joint resistance exercise. The current data demonstrate that at most intensities and set volumes, HbO_{2min} and HHb_{max} values display acceptable intra-test reliability. Further, TSI_{min} values were found to be highly reliable across each set. An intriguing finding was that the reliability of HbO_{2min} and HHb_{max} appeared to be affected by the volume of each set (i.e. number of repetitions) across all intensities. HbO_{2min} displayed greater reliability during single-repetition sets, whereas the reliability of HHb_{max} was increased during multiple-repetition sets. While these results might reflect increased variability in factors known to affect muscular oxygen kinetics, such as mitochondrial efficiency and total blood delivery to the working muscles, the exact reason for these findings is unclear at this time.

The current investigation suggests that the inter-test reliability of NIRS during multi-joint resistance exercise is lower than reported in previous investigations using isokinetic and isometric exercise (Celie et al., 2012; Kell et al., 2004; Pereira et al., 2005; Tanimoto and Ishii, 2006). While great attention was paid to standardize experimental conditions between exercise trials, several factors may have contributed to the day-to-day variability observed. Differences in the range of scores and the subject population are likely to have influenced the reliability statistics (Atkinson and Nevill, 1998). Small differences in ambient and muscular temperature (Ferrari et al., 2004), as well as slight changes in posture (Bringard et al., 2006), can affect NIRS-derived measurements of muscle oxygenation. It is possible that increased intramuscular temperature, as well as changes in posture across the duration of the testing protocol due to muscular fatigue, may have accounted for some of the variation between trials, as previously discussed for EMG variables. Furthermore, while care was taken to ensure consistent placement of the NIRS device between testing sessions, small differences in its positioning could have contributed to variation in measurements, similarly to EMG.

Many inter-test CV values observed in the current study are greater than the 5-10% threshold that is generally recommended to consider a measurement as reliable (Hopkins, 2000). However, this does not necessarily imply that NIRS-derived measures during resistance exercise are unusable. Indeed, moderate and strong intra-test ICC values were observed when monitoring HbO_{2min} and TSI_{min} during most single-repetition sets at each exercise intensity. The easy-to-use non-invasive nature of NIRS, and its practicality during tests in the laboratory or the field, make it an attractive method to monitor muscle oxygenation status during and following exercise (Buchheit et al., 2011). Moreover, the results of the current investigation are similar to those reported for the reliability of NIRS to quantify muscle re-oxygenation and oxygen uptake recovery kinetics following intermittent running activity (Buchheit et al., 2011).

While the sample size used in this research is similar to previous investigations that have examined the reproducibility of EMG and NIRS measures during dynamic resistance exercise (Larsson et al., 1999a; Larsson et al., 1999b; Pereira et al., 2005), it is possible that a larger sample size may have provided less variance in mean reliability results. Nonetheless, we recruited well-trained young men only in an attempt to investigate a homogenous subject group, with respect to repeated resistance exercise performance. In this way, we have attempted to account for any variation in our data resulting from differences between the genders and from inconsistent exercise performance in untrained participants. However, caution should be taken when interpreting the current results for female or untrained participants. Furthermore, it should also be acknowledged that the methods used to ensure consistent device placement (outlining the devices between trials) might be impractical in real-world contexts. For these situations, other methods to orientate the device's position during subsequent tests should be explored.

In conclusion, the current study highlights that the reliability of both EMG and NIRS variables is greater within a single session, than between sessions. Despite best efforts being made to ensure consistent electrode and device placement, the increased variability between separate testing sessions is likely to be accounted for by small changes in the location of sensors. While the reliability of EMG and NIRS variables observed in the current study is lower than in some previous investigations, these studies have generally employed single-joint, isometric or isokinetic exercises. As such, greater physiological variability would be expected in the current study, which was reflected in our data. Furthermore, differences in statistical methods may affect the comparison of reliability results between studies. Importantly, the non-invasive and user-friendly nature of telemetric EMG and NIRS devices provides important information pertaining to the function of contracting muscle during resistance exercise. To improve the reliability of these devices, consistent device placement, exercise technique and testing conditions are vital, particularly when monitoring dynamic multi-joint resistance exercises.

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Figure Captions

Figure 1. Example of a subject performing the HBS exercise, highlighting the squat position at the end of the eccentric/beginning of the concentric phase (A), and at the end of the concentric phase (B).

Figure 2. Placement positions of the NIRS device on the right vastus lateralis (1), and EMG electrodes on the left vastus lateralis (2), vastus medialis (3), gluteus maximus (4) and biceps femoris (5) from an anterior (A) and posterior (B) view.

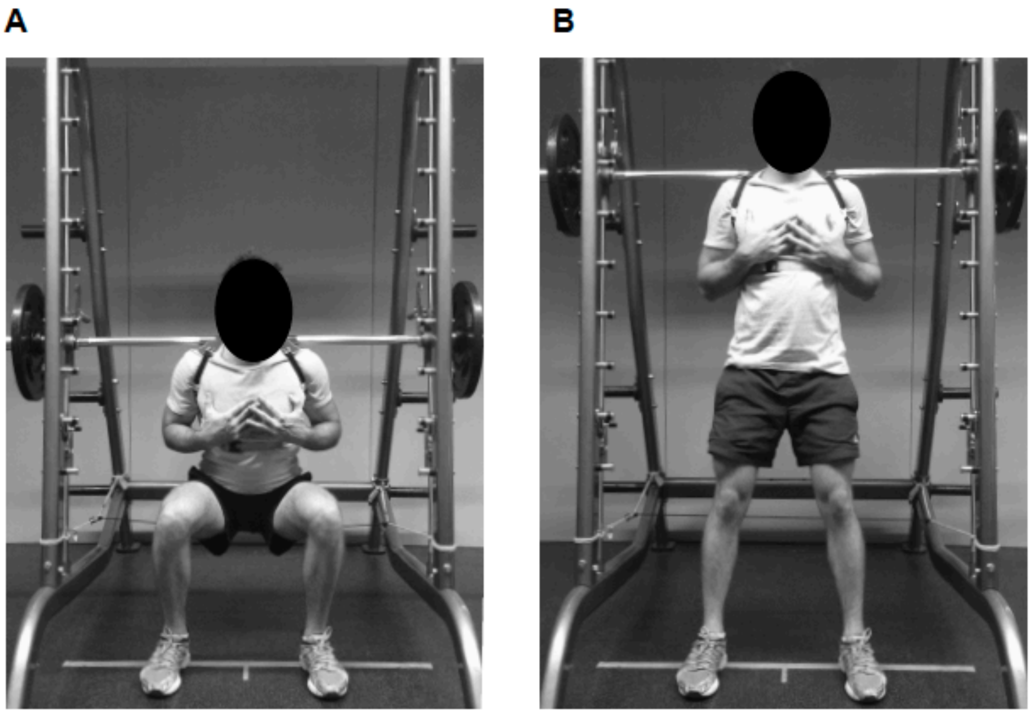
Figure 3. Example of the accelerometry trace from the VL electrode and typical raw EMG traces from the GM, BF, VL and VM muscles during three repetitions of the HBS exercise. Shaded sections represent the concentric phase of the lift.

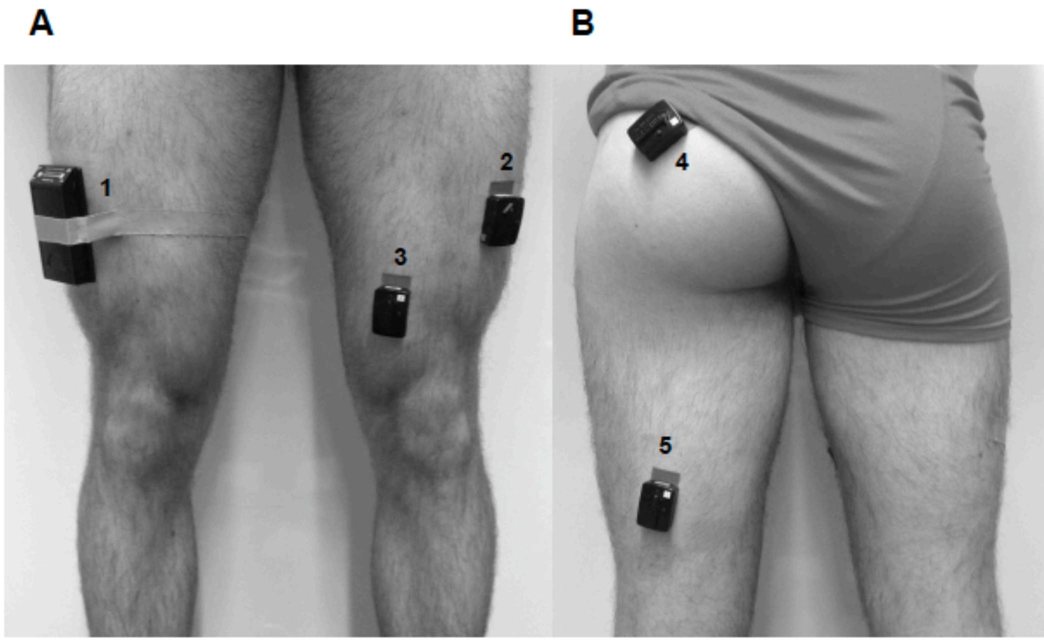
Figure 4. The ICC (± 95% CI; unfilled boxes) and CV (± 95% CI; filled circles) of RMS, MDF and iEMG data between identical repeated sets of HBS exercise within a single testing session from the (a) gluteus maximus, (b) biceps femoris, (c) vastus lateralis and (d) vastus medialis muscles.

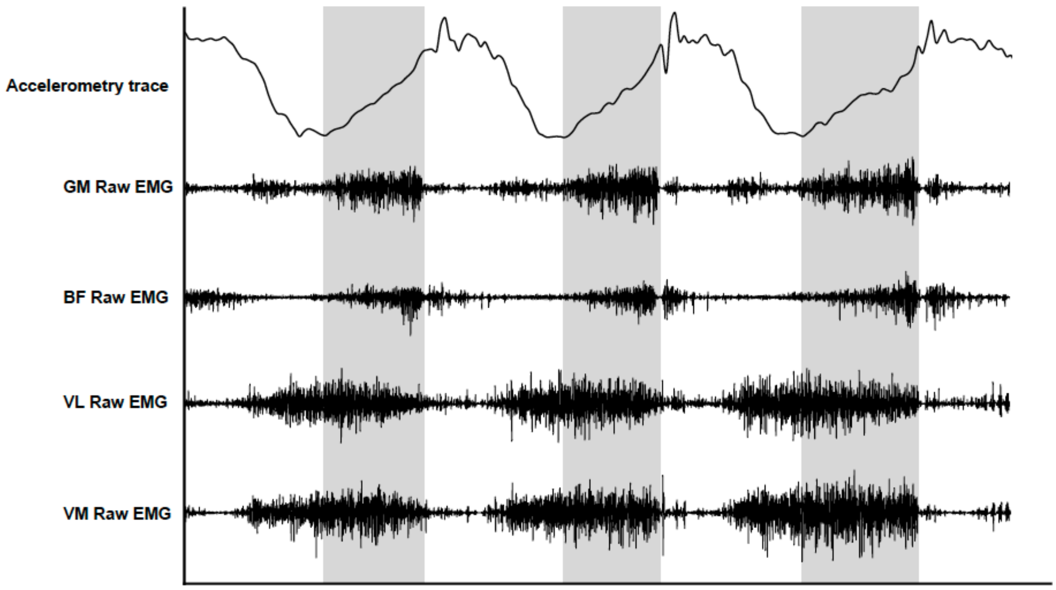
Figure 5. The ICC (± 95% CI; unfilled boxes) and CV (± 95% CI; filled circles) of RMS, MDF and iEMG data between identical matched sets of HBS exercise in separate testing sessions from the (a) gluteus maximus, (b) biceps femoris, (c) vastus lateralis and (d) vastus medialis muscles.

Figure 6. The ICC (± 95% CI; unfilled boxes) and CV (± 95% CI; filled circles) of HbO_2 (%), HHb (%) and TSI (%) data between identical repeated sets of HBS exercise within a single testing session from the vastus lateralis.

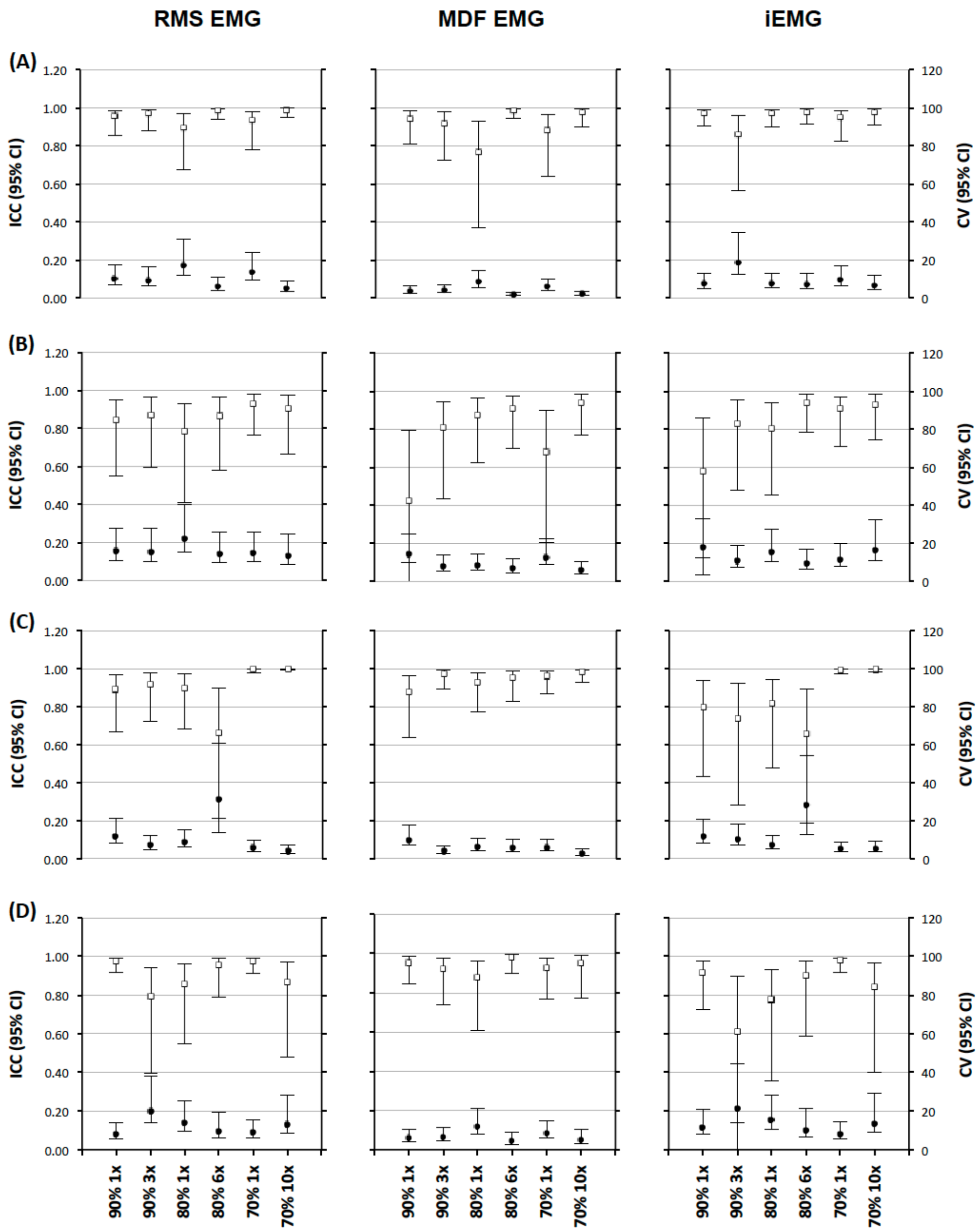
Figure 7. The ICC (± 95% CI; unfilled boxes) and CV (± 95% CI; filled circles) of HbO_2 (%), HHb (%) and TSI (%) data between identical matched sets of HBS exercise in separate testing sessions from the vastus lateralis.



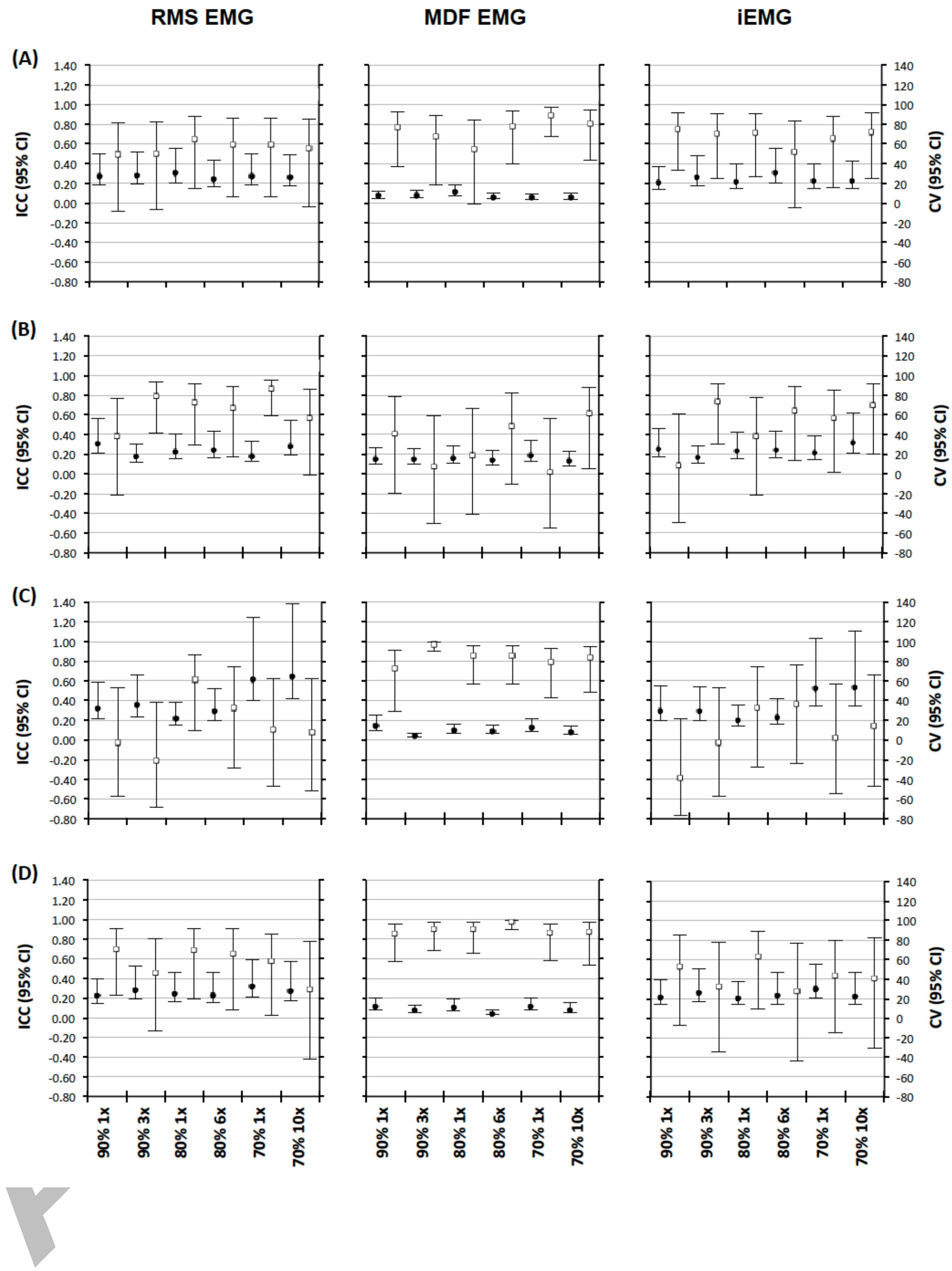




Accelerometry trace
GM Raw EMG
BF Raw EMG
VL Raw EMG
VM Raw EMG



RMS EMG
MDF EMG
iEMG
(A)
(B)
(C)
(D)
ICC (95% CI)
CV (95% CI)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
120
100
80
60
40
20
0
90% 1x
90% 3x
80% 1x
80% 6x
70% 1x
70% 10x



RMS EMG
MDF EMG
iEMG
(A)
(B)
(C)
(D)
ICC (95% CI)
CV (95% CI)
90% 1x
90% 3x
80% 1x
80% 6x
70% 1x
70% 10x