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Electrode Type and Placement Configuration for Quadriceps Activation Evaluation

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Context: The ability to accurately estimate quadriceps voluntary activation is an important tool for assessing neuromuscular function after a variety of knee injuries. Different techniques have been used to assess quadriceps volitional activation, including various stimulating electrode types and electrode configurations, yet the optimal electrode types and configurations for depolarizing motor units in the attempt to assess muscle activation are unknown.

Objective: To determine whether stimulating electrode type and configuration affect quadriceps central activation ratio (CAR) and percentage-of-activation measurements in healthy participants.

Design: Crossover study.

Setting: Research laboratory.

Patients and Other Participants: Twenty participants (13 men, 7 women; age = 26 ± 5.3 years, height = 173.85 ± 7.3 cm, mass = 77.37 ± 16 kg) volunteered.

Intervention(s): All participants performed 4 counterbalanced muscle activation tests incorporating 2 different electrode types (self-adhesive, carbon-impregnated) and 2 electrode configurations (vastus, rectus).

Main Outcome Measure(s): Quadriceps activation was calculated with the CAR and percentage-of-activation equations, which were derived from superimposed burst and resting torque measurements.

Results: No differences were found between conditions for CAR and percentage-of-activation measurements, whereas resting twitch torque was higher in the rectus configuration for both self-adhesive (216 ± 66.98 Nm) and carbon-impregnated (209.1 ± 68.22 Nm) electrodes than in the vastus configuration (209.5 ± 65.5 Nm and 204 ± 62.7 Nm, respectively) for these electrode types ($F_{1,19} = 4.87$, $P = .04$). In addition, resting twitch torque was greater for both electrode configurations with self-adhesive electrodes than with carbon-impregnated electrodes ($F_{1,19} = 9.33$, $P = .007$). Bland-Altman plots revealed acceptable mean differences for agreement between electrode type and configuration for CAR and percentage of activation, but limits of agreement were wide.

Conclusions: Although these electrode configurations and types might not necessarily be able to be used interchangeably, differences in electrode type and configuration did not seem to affect CAR and percentage-of-activation outcome measures.

Key Words: burst superimposition, interpolated twitch technique, central activation ratio, knee, motor neurons

Key Points

- The self-adhesive and carbon-impregnated electrode types and the vastus and rectus electrode configurations might not be able to be used interchangeably to assess quadriceps activation.
- Electrode type and configuration did not affect quadriceps central activation ratio and percentage-of-activation outcome measures.
- Clinicians and investigators can use the electrode type that is most accessible and cost-effective for them.

Volitional quadriceps activation has been reported to be lower in patients with anterior cruciate ligament (ACL) deficits, ACL reconstructions, and anterior knee pain than in healthy matched controls.[1] Researchers have hypothesized that this neuromuscular quadriceps dysfunction after a knee joint injury results in part from reflex inhibition of the muscle,[2] which might impair movement patterns involved in gait[3] and landing.[4] Although the full effect of quadriceps activation deficits after knee injury is not understood, convincing evidence shows that deficits in neuromuscular quadriceps function might be a risk factor for posttraumatic osteoarthritis.[5] Therefore, the ability to determine the best methods for assessing quadriceps dysfunction in this population is vital and might allow more accurate diagnosis of quadriceps activation failure and proper rehabilitation for neuromuscular impairment.[6,7]

Volitional quadriceps activation is evaluated by using an exogenous stimulus to recruit motor units that cannot be activated voluntarily. This technique requires stimulating electrodes to be positioned over the quadriceps to activate as much of the inhibited musculature as possible, which provides the most valid evaluation of muscle activation. Although varying stimulus variables might play a role in outcomes, different stimulating electrode types and electrode placement configurations also might affect the results reported by investigators. The best method for testing activation must be determined systematically so outcomes can be compared among laboratories and clinics. Both self-adhesive electrodes positioned on the skin of the anterior thigh[8–12] and carbon rubber–impregnated electrodes using conduction gel secured to the surface of the quadriceps with an elastic bandage[13–15] have been applied for this purpose. In addition, researchers commonly have reported 2 electrode placement configurations, including a rectus configuration[16–20] with electrodes positioned over the proximal and distal rectus femoris and a vastus configuration[13–15] with electrodes positioned over the proximal vastus lateralis and the distal vastus medialis. Positioning the electrodes on the vastus muscles might allow more musculature to be stimulated because the vastus lateralis is the largest quadriceps muscle. In addition, increasing the distance between the electrodes with the vastus placement might allow deeper penetration of the current and more muscle to be activated. However, no data are available to determine whether one electrode type and configuration is superior to the other. This knowledge would help to establish a methodologic framework for future studies that might lead to better comparisons of outcomes among laboratories and possibly a guideline for potential clinical assessment of quadriceps activation. Therefore, the purpose of our study was to determine whether stimulating electrode type and configuration affect quadriceps activation assessment using the central activation ratio (CAR) and percentage-of-activation equations in healthy participants. We hypothesized that the vastus electrode configuration using the carbon-impregnated electrodes would excite the greatest amount of the inhibited quadriceps musculature, thereby producing the lowest and most valid estimates of quadriceps activation.

METHODS

We used a crossover design in which muscle activation was measured in all participants with both electrode types (self-adhesive, carbon-impregnated) and both electrode configurations (rectus, vastus). The orders of electrode type and configuration were counterbalanced, and the investigator (B.G.P.) conducting the muscle activation measurements was blinded to the electrode type and configuration. Blinding was administered by a separate unblinded investigator (N.M.S.), who applied the electrodes while the testing investigator was secluded in a separate room for a standardized period. The main outcome measures in this study included quadriceps CAR and percentage of activation, and resting twitch torque (RT) was investigated secondarily. All outcome measures were assessed in the self-reported *dominant leg,* which was defined as the leg with which participants reported they preferred to kick a ball. The entirety of the testing for each participant was performed on the same day in approximately 1 hour and 15 minutes.

Participants

Twenty people (13 men, 7 women; age = 26 ± 5.3 years, height = 173.85 ± 7.3 cm, mass = 77.37 ± 16 kg) volunteered to participate in the study. Eighteen were right-leg dominant, and 2 were left-leg dominant. All participants were healthy, with no history of lower extremity surgery or knee injury and no history of ankle, back, or hip injury in the 6 months before the study. No participants reported a history of diagnosed neurologic, muscular, or cardiovascular disorders. All participants provided written informed consent, and the study was approved by the Institutional Review Board for Health Sciences Research at the University of Virginia (HSR-13844).

Instrumentation

Isometric force signal was recorded using a dynamometer (Biodex System 3 Pro; Biodex Medical Systems, Inc, Shirley, NY) and exported through a remote access port via a custom-built coaxial cable to a 16-bit, analog-to-digital converter (MP150; BIOPAC Systems, Inc, Goleta, CA), where it was digitized (200 Hz).[13,15,21] A dual-output, square-wave stimulator (S88; Grass Technologies, West Warwick, RI) in conjunction with a stimulation isolation unit (SIU8T; Grass Technologies) produced a 100-millisecond train of 10 stimuli at 100 pulses per second with a 0.6-millisecond pulse duration and a 0.01-millisecond pulse delay. With the low switch engaged on the stimulation isolation unit and an estimated 3000-Ω load, each participant was stimulated with approximately 125 V,[13,15,21] which was the maximum voltage output for this machine.

Highly conductive multipurpose Signa Gel (Parker Laboratories, Inc, Fairfield NJ) was used as a coupling agent and applied to 2 separate 8-×14-cm carbon-impregnated electrodes (Bloomex International, Inc, Elmwood Park, NJ), which were secured to the quadriceps with an elastic bandage (HARTMANN USA, Inc, Rock Hill, SC) to prevent movement of the electrodes during testing.[13,15,21] Alternatively, 2 7-×13-cm Dura-Stick II (Chattanooga Group, Hixson, TN) self-adhesive electrodes were used to deliver the stimulus to the quadriceps muscles for the other electrode type condition (Figure 1).

Procedures

Stimulating Electrode Setup. Before the stimulating electrodes were applied, the skin was shaved and, if necessary, debrided and cleaned. All participants were seated in the dynamometer while the investigator marked the positions for the electrodes. The exact electrode positions were marked with a felt-tip pen, allowing the investigator to replicate positioning between electrode type and electrode configuration conditions. The vastus configuration consisted of positioning the superior aspect of the proximal electrode at the height of the greater femoral trochanter, with the medial electrode border in line with the anterosuperior iliac spine. The distal electrode was po-

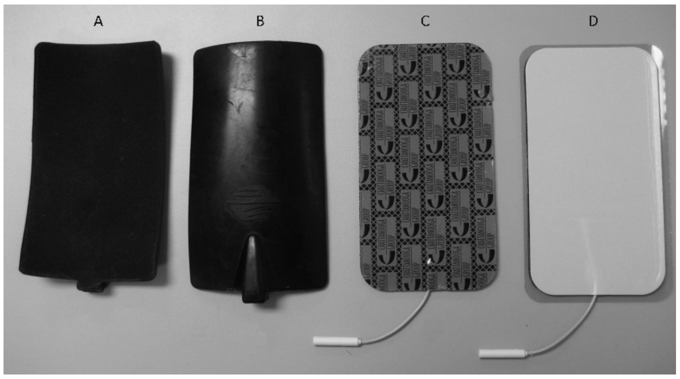

Figure 1. Electrode types. A, Carbon-impregnated electrode with the surface in contact with skin exposed. B, Carbon-impregnated electrode with the back exposed. C, Self-adhesive electrode with the surface in contact with skin exposed. D, Self-adhesive electrode with the back exposed.

sitioned with the inferior aspect of the electrode 3 cm superior to the patella and the medial border of the electrode in line with the midline of the patella. The rectus configuration consisted of positioning the superior aspect of the proximal electrode at the height of the greater femoral trochanter, with the midline of the electrode aligned with the anterosuperior iliac spine. The distal electrode was positioned with the inferior edge 3 cm superior to the patella and the midline of the electrode in line with the midline of the patella (Figure 2). New self-adhesive electrodes were simply applied to the marked areas. However, before placement, a layer of conductive gel was applied over the stimulating electrode surface of the carbon-impregnated electrodes, and after being placed on the marked points, they were applied to the leg by the same investigator and secured with an elastic bandage.[8–11,22] The cathode of the stimulating electrodes always was positioned distally, whereas the anode was positioned proximally, regardless of the electrode condition.

Quadriceps Activation Testing. Participants were secured in the chair of the dynamometer unit with hips flexed to 85° and knees flexed to 90°. All landmarks were aligned according to the specifications of the manufacturer and previously reported in the literature.[13,15]

A graded warmup was conducted using the first electrode condition assigned to the participant to ensure that participants could exert maximal effort during the test and were accustomed to the stimulus. A series of submaximal contractions at 25%, 50%, and 75% of their perceived maximal voluntary isometric contractions (MVICs) were paired with submaximal stimuli at 25%, 50%, and 75% of the maximal testing voltage of 125 V. In addition to submaximal trials, participants performed 3 to 5 practice MVICs until the investigator was confident that each participant could exert maximal effort.[21]

During testing, an exogenous stimulus was applied to the quadriceps when the test administrator observed that a maximal force plateau had been reached. All participants were given oral encouragement from the investigator and were provided visual feedback from a computer screen depicting a force tracing in real time. Participants were encouraged to generate force to reach a target that was scaled to be slightly higher than the MVICs produced during their practice trials. Two acceptable trials separated by a 60-second rest period were performed and averaged for each electrode condition. The same 125-V stimulus was applied to the resting quadriceps muscle 60 seconds after the 2 active contraction trials.[21] This series of contractions was performed 4 times to test both electrode configurations and electrode types.

Data Analysis

The CAR was calculated by dividing the force produced during the MVIC (F_{MVIC}) by the force produced by the superimposed burst plus the MVIC (F_{SIB}), multiplying the quotient by 100, and expressing the product as a percentage (Equation 1).[23] The percentage of activation was calculated by subtracting the F_{MVIC} from the F_{SIB} and then dividing the difference by the force produced by the RT. The quotient was subtracted from 1 and multiplied by 100 (Equation 2).[20]

$$\text{CAR} = (F_{MVIC}/F_{SIB}) \times 100 \qquad (1)$$

$$\text{Percentage of activation} = [1 - (F_{SIB} - F_{MVIC})/\text{RT}] \times 100 \qquad (2)$$

The F_{SIB} value and the F_{MVIC} were calculated from the mean of the 2 acceptable separate trials at each time in the series while the superimposed burst was applied. The F_{MVIC} was calculated from a 0.1-second time epoch immediately before the exogenous electric stimulus was administered. The RT was calculated from the peak RT.

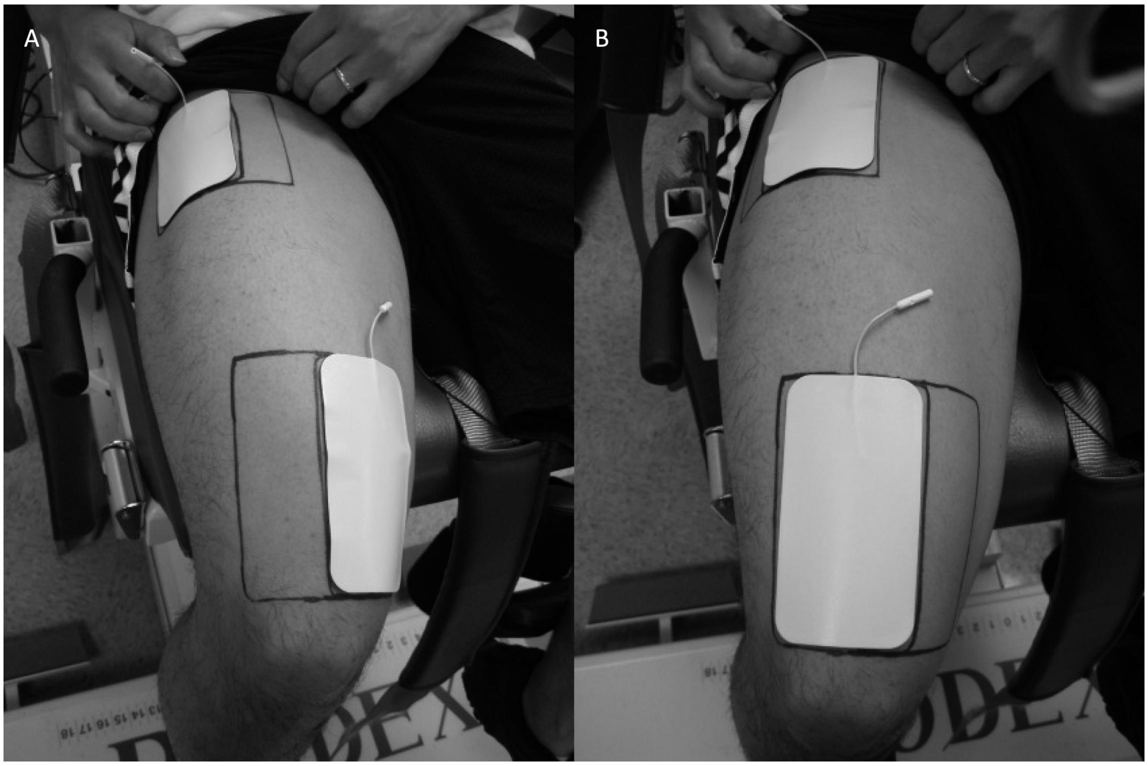

Figure 2. Electrode configuration setup. A, Positioning of electrodes for the vastus configuration. B, Positioning of electrodes for the rectus configuration. Only self-adhesive electrodes were used for this illustration.

Statistical Analysis

Means and standard deviations were calculated for the main outcomes of CAR and percentage of activation and the secondary outcome of RT. Two separate, 2×2 repeated-measures analyses of variance (ANOVAs) were used to detect differences in CAR and percentage of activation between electrode types and configurations. A separate 2×2 ANOVA was performed to determine whether peak RTs were different between electrode types and configurations. The α level was set a priori at .05 for all interferential statistics. Four Bland-Altman plots were constructed using mean difference values surrounded by limits of agreement to determine the agreement within each outcome measure when electrode types and configurations were manipulated for both CAR and percentage-of-activation outcome measurements. Mean differences were calculated by subtracting the rectus from the vastus measurements for configuration plots and the carbon-impregnated from the self-adhesive measurements for electrode type plots. Cohen effect sizes with 95% confidence intervals were calculated to determine the magnitude of difference in both CAR and percentage of activation between electrode types and configurations. Mean differences for standardized effect sizes were calculated similarly to those in Bland-Altman plots and were divided by pooled standard deviations.

RESULTS

No differences were detected between electrode types ($F_{1,19}=0.008$, $P=.90$ and $F_{1,19}=0.64$, $P=.43$) or electrode configurations ($F_{1,19}=0.25$, $P=.62$ and $F_{1,19}=0.02$, $P=.90$) for CAR and percentage of activation, respectively (Table 1). For RT measurements, the rectus configuration elicited greater quadriceps torque production than the vastus configuration ($F_{1,19}=4.87$, $P=.04$), and self-adhesive electrodes elicited greater torque production than carbon-impregnated electrodes ($F_{1,19}=9.33$, $P=.007$) (Table 1). Effect sizes for electrode types were weak in both rectus and vastus configurations for CAR, percentage of activation, and RT (Table 2). In addition, effect sizes between electrode configurations were weak for both self-adhesive and carbon-impregnated electrodes for all outcome measures, including CAR, percentage of activation, and RT (Table 2).

Mean difference scores were smaller for CAR than the mean differences for percentage of activation between electrode configurations for both self-adhesive (0.70% and 1.37%, respectively) and carbon-impregnated (–0.01% and 0.30%, respectively) electrode types and between electrode types under both rectus (–0.05% and –0.66%, respectively) and vastus (0.34% and 0.40%, respectively) configurations (Figures 3 and 4). The ranges for the limits of agreement were greater when the percentage-of-activation equations were used than the CAR for both electrode type and electrode configuration conditions. Limits of agreement for percentage-of-activation measurements encompassed ranges from 17.44% to 26.08%, with 1 data point falling outside the limits of agreement for each of the percentage-of-activation Bland-Altman plots (Figure 4). Limits of agreement were narrower for all CAR plots than for the percentage-of-activation plots, with ranges from 11.68% to 16.04% and 1 data point falling outside the limits of agreement for all electrode type and electrode configuration conditions (Figure 3).

DISCUSSION

Volitional quadriceps activation is an important measurement for assessing neuromuscular deficits after knee injury[8,11,24–27] and the effects of therapeutic interventions[22,28–30] in treating arthrogenic muscle inhibition. The ability to accurately assess quadriceps activation is vital for understanding the nature of neuro-

Table 1. Outcome Measures by Configuration and Electrode Type, Mean ± SD

	Vastus Configuration		Rectus Configuration	
Measure	Self-Adhesive Electrodes	Carbon-Impregnated Electrodes	Self-Adhesive Electrodes	Carbon-Impregnated Electrodes
Central activation ratio	88.08 ± 9.2	88.32 ± 9.21	88.79 ± 8.39	88.42 ± 9.24
Activation, %	80.8 ± 14.5	81.2 ± 14.99	82.18 ± 13.43	81.52 ± 14.73
Resting twitch, Nm	209.5 ± 65.5[a]	204 ± 62.7	216 ± 66.98[a,b]	209.1 ± 68.22[b]

[a] Indicates different from carbon-impregnated electrodes.
[b] Indicates different from vastus configuration.

Table 2. Effect Sizes (95% CI) Between Electrode Types and Between Electrode Configurations

	Effect Size (95% CI) Between Electrode Types[a]		Effect Size (95% CI) Between Electrode Configurations[b]	
Measure	Vastus Configuration	Rectus Configuration	Self-Adhesive Electrodes	Carbon-Impregnated Electrodes
Central activation ratio	–0.04 (–0.66, 0.58)	0.03 (–0.59, 0.65)	0.08 (–0.54, 0.70)	0.01 (–0.61, 0.63)
Activation, %	–0.05 (–0.67, 0.57)	0.03 (–0.59, 0.65)	–0.1 (–0.52, 0.72)	–0.05 (–0.57, 0.67)
Resting twitch, Nm	–0.10 (–0.72, 0.52)	–0.09 (–0.70, 0.72)	–0.1 (–0.52, 0.72)	–0.08 (–0.54, 0.70)

Abbreviation: CI, confidence interval.
[a] Calculated as (carbon-impregnated electrodes − self-adhesive electrodes)/pooled SD.
[b] Calculated as (rectus configuration − vastus configuration)/pooled SD.

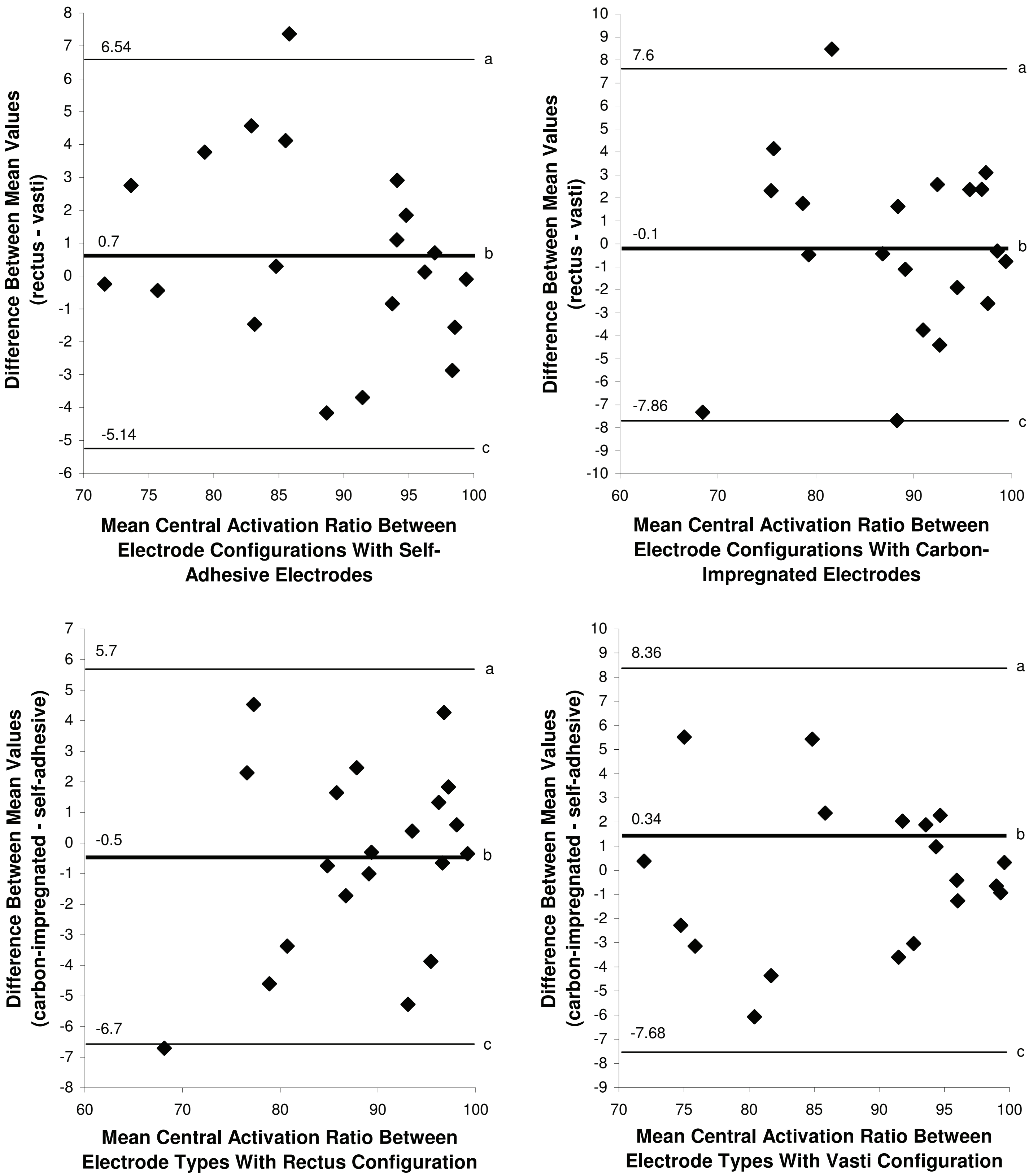

Figure 3. Bland-Altman plots for agreement between electrode type and configuration using the central activation ratio. [a] Indicates upper limit of agreement. [b] Indicates the mean difference score. [c] Indicates lower limit of agreement.

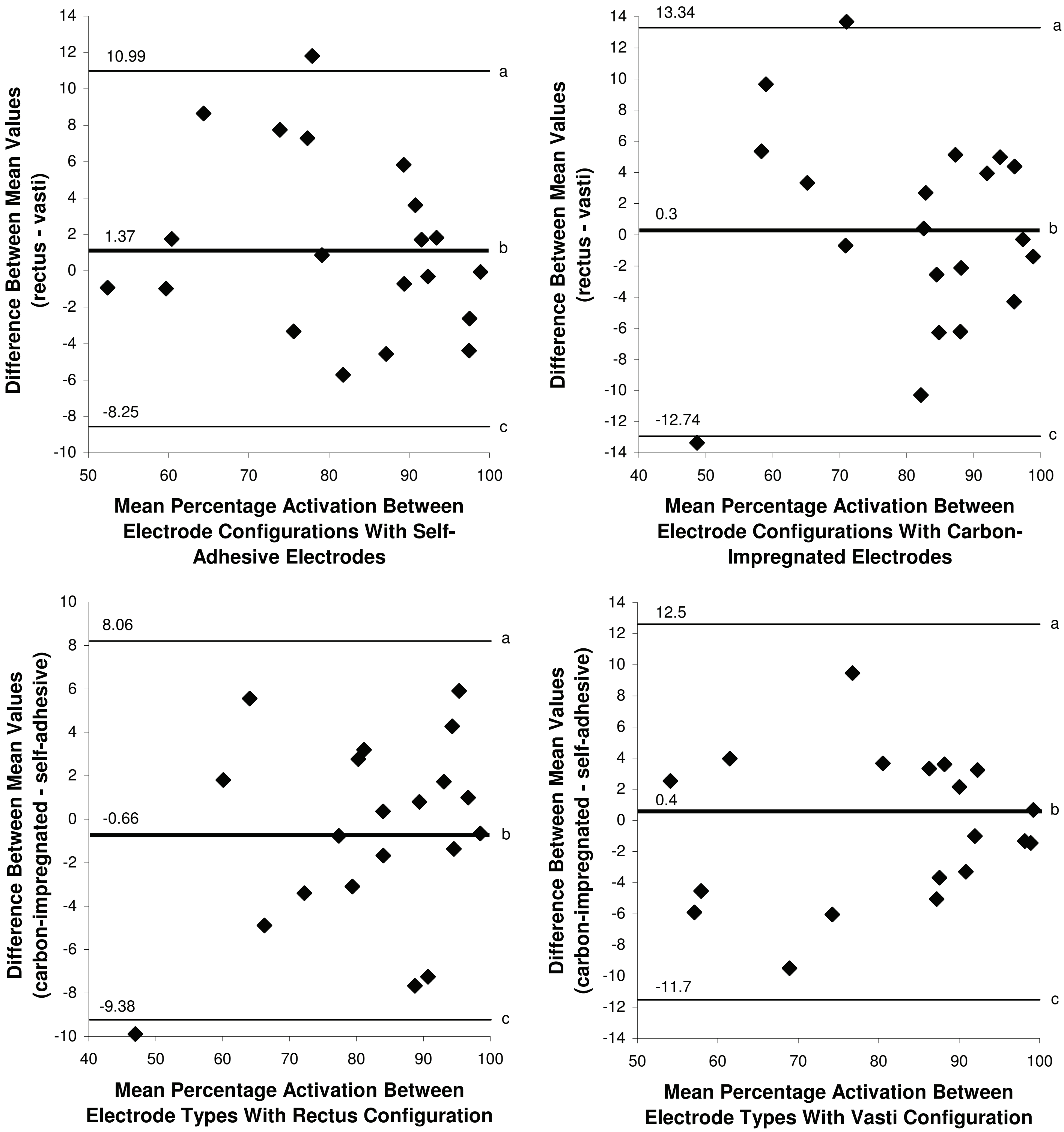

Figure 4. Bland-Altman plots for agreement between electrode type and configuration using the percentage-of-activation equation. [a] Indicates upper limit of agreement. [b] Indicates the mean difference score. [c] Indicates lower limit of agreement.

muscular impairments after joint injury, which might put people at risk for further joint injury.[4] Honing the vast array of current methods in volitional muscle assessment would allow greater confidence in the data interpreted and provide a standard practice for various researchers, which we hope would transition into data that could be compared better among laboratories.

We found that the use of self-adhesive electrodes and carbon-impregnated electrodes did not affect quadriceps activation measurements calculated with either the CAR or percentage-of-activation equations. Similarly, vastus and rectus electrode configurations did not seem to change traditional quadriceps activation measurements. Weak effect sizes with confidence intervals that crossed 0 were found between different electrode types and configurations, providing further evidence to support the finding that these characteristics do not seem to relevantly affect muscle activation measurements.

Examination of the Bland-Altman plots revealed small mean differences for CAR (Figure 3) and percentage-of-activation (Figure 4) scores. The mean difference scores for CAR between electrode configurations were 0.7 and –0.01 for self-adhesive and carbon-impregnated electrodes, respectively. The electrode configuration limits of agreement for both the self-adhesive (±5.84) and carbon-impregnated electrodes (±7.73) had ranges well within the standard deviation of the CAR measurement (Table 1). The difference scores for percentage of activation for electrode configurations were slightly larger than CAR values for self-adhesive electrodes (1.37) and for carbon-impregnated electrodes (0.3), with limits of agreement of ±9.62 and ±13.04, respectively, that also fell within standard deviations of the measurement. The limits of agreement for CAR for electrode type were ±6.2 for rectus and ±8.02 for vastus configurations, whereas percentage-of-activation values were ±8.72 for rectus and ±12.1 for vastus configurations. Again, these limits of agreement fell within the standard deviations of the respective measurements in this population (Table 1).

Interestingly, RT measurements were greater with the rectus configuration using the self-adhesive electrodes. Although the exact mechanisms behind this finding are unclear, we speculate that greater RTs with the rectus configuration might result from greater amounts of adipose tissue in the areas where the vastus electrodes are positioned than where the rectus electrodes are positioned. Biologic composition might affect the transmission of the electric current, allowing more muscle to be activated by the stimulus with a rectus configuration. The magnitudes of these differences were weak, and wide confidence intervals rendered these results inconclusive. However, the findings might provide evidence that self-adhesive electrodes placed within the rectus configuration can produce a larger amount of torque and depolarize the greatest number of motor units. Although the RT is input directly only in the percentage-of-activation equation, it provides an estimate of the ability of the stimulating electrodes to maximally activate the quadriceps,[31] which is a critical variable needed in both the CAR and percentage-of-activation equations.[32] Whereas the rectus configuration and self-adhesive electrodes might be slightly beneficial in stimulating resting muscle tissue, the weak effect seems to be irrelevant when CAR and percentage-of-activation outcome measures are computed, suggesting that these small differences found in resting torques do not affect the CAR and percentage-of-activation outcome measures.

These electrode type and electrode configuration variables did not seem to affect volitional activation outcome measures, but many other variables still can be assessed and standardized to provide the most valid and generalizable volitional activation measurements. Although some researchers already have suggested reasonable electric stimulation guidelines for assessing quadriceps volitional activation,[33,34] optimal guidelines have not been determined. In addition, computerized methods for standardizing stimulation delivery have been published recently and might provide more accurate data.[35] We focused on 2 major electrode configurations, but electrodes could take on numerous orientations, including position and angling of the electrodes, which might produce slightly different outcomes than we presented. Individual participant cohorts also might introduce unique variables independent of neural function, which might change activation measurements. For example, a more obese population exhibiting muscle volitional activation percentages similar to those of a less obese population might display artificially high activation levels because excess adipose tissue inhibits penetration by electric stimulation, thus not allowing standard excitation of the quadriceps muscle.[36] Therefore, such variables should be studied, and accurate correction factors should be used to adjust data accordingly. In addition, we also should note that our CAR means were lower than 95%, which has been reported as normal by others.[37] Activation levels of less than 95% have been reported in healthy participants.[13,15,23]

CONCLUSIONS

Our evidence suggests that although these electrode configurations and types might not necessarily be able to be used interchangeably, it seems unlikely that these variables would be an important factor determining outcome measures. Future investigators and clinicians who are interested in assessing volitional quadriceps activation could use either of these electrode types and configurations and find similar results. Our data provide evidence that clinicians and investigators can use the electrode type that is most accessible and cost-effective for them. In addition, these data suggest that small variations in electrode configuration do not change CAR outcomes, which might provide more confidence to those interested in using this measurement in a clinic with multiple practitioners conducting the measurement.

The rectus configuration with self-adhesive electrodes provided the greatest RT, but the effect sizes between corresponding vastus and carbon-impregnated methods were small. However, CAR and percentage-of-activation estimates derived from either of the other electrode type and configuration conditions that we studied should not be considered inferior. When all variables are input into the CAR and percentage-of-activation equations, none of the aforementioned electrode conditions changed traditional interpretations of these main outcome measures.

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