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Perceived physical exertion is a good indicator of neuromuscular fatigue for the core muscles

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ABSTRACT

Although several studies have assessed core training, specific prescription recommendations remain lacking. The purpose of the present study was to determine the association between the rate of perceived exertion (RPE) and neuromuscular fatigue of the core muscles during the prone bridging endurance test. Fifteen healthy and moderately active subjects participated. Neuromuscular fatigue was assessed with surface electromyography on the rectus abdominis (RA), external oblique, internal oblique, and lumbar erector spinae. Participants rated the RPE (Borg CR 10) every 5 s. The time to failure was 123.7 ± 58.1 s. From the midpoint of the time to failure, the RPE significantly increased ($p < 0.05$). The RA muscle showed increased neuromuscular fatigue during the second half of the time to failure ($p < 0.05$). The other core muscles showed increased neuromuscular fatigue during the last 30% of the time to failure ($p < 0.05$). The RA muscle showed a strong correlation between neuromuscular fatigue and the RPE (R^2 0.85). The other core muscles showed a moderate correlation between neuromuscular fatigue and RPE (R^2 0.50–0.69). The measured RPE and neuromuscular fatigue were closely linked for the RA muscle and moderately linked for the other core muscles during the prone bridging endurance test.

1. Introduction

The core is a muscular box composed of 19 pairs of muscles surrounding the central region of the body (Akuthota et al., 2008). The stability needed for distal joints to produce force and movement is provided by the core, which additionally helps maintain spinal movement within safe limits when performing different daily activities (Kibler et al., 2006, McGill, 2010). For these reasons, core stabilization and strengthening have been used in athletic conditioning and rehabilitation programs (Searle et al., 2015, Willardson, 2007). Strength and endurance training of the core have been associated with improvements in sports performance (Tse et al., 2005) and injury prevention (McGill, 2010). This training is also considered one of the key factors in preventing and treating lower back pain (Wang et al., 2012). In the working population, for example, conditioning of the core muscles effectively lowers the intensity of back pain (Jakobsen et al., 2015). A typical outcome for comparing the effectiveness of different core stability exercise protocols, in both healthy and clinical populations, is the endurance of the core muscles (Hoppes et al., 2016, Sekendiz et al., 2010, Shamsi et al., 2016, Tse et al., 2005). A widely used method to assess core endurance is the prone bridging test, which is valid and reliable for evaluating abdominal muscle fatigue (De Blaiser et al., 2018).

Although several studies have assessed core training, specific prescription recommendations remain lacking (Hoppes et al., 2016; Mayer et al., 2015). It has been suggested that the best approach for improving core stability is to train muscle endurance through maintained and safe spine positions (McGill et al., 2003). To this end, isometric planks are the most used type of core stability exercise (Brumitt and Dale, 2009, Fredericson and Moore, 2005, Mayer et al., 2015, Prieske et al., 2016). However, the way these exercises are dosed in terms of intensity is still controversial. While surface electromyographic (sEMG) values reported in previous studies can help in initial exercise selection (Calatayud et al., 2017, Ekstrom et al., 2007), a more individualized approach is needed to prescribe intensity when applied to different populations (e.g., with different levels of pain and disability). In addition to safer

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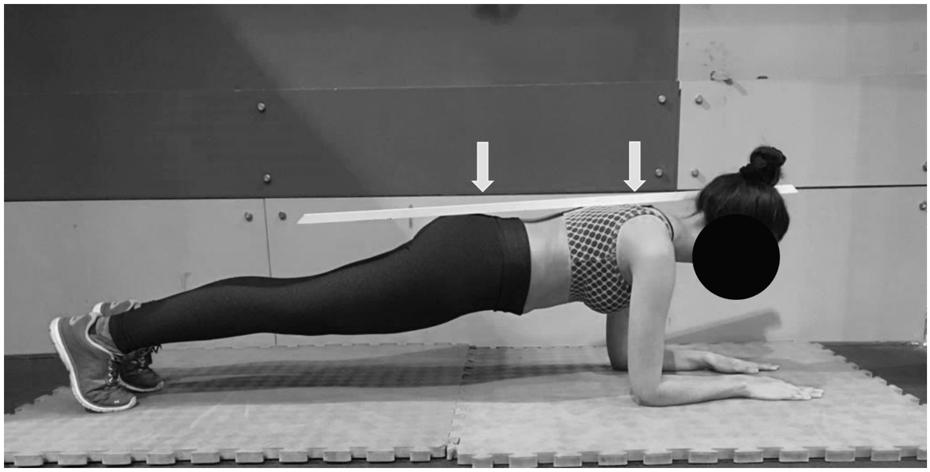

Fig. 1. Prone bridging test position. The white arrows indicate the point where the wood strip was placed (i.e., sacrum and dorsal spine) to provide feedback and ensure correct alignment of the pelvis and thoracic spine.

dosing, this would help patients more effectively exercise and achieve progressions.

One measurement for exercise intensity is the rate of perceived exertion (RPE) (Grant et al., 1999), which correlates well with some physiological variables (e.g., oxygen consumption, blood lactate) and is widely determined using the Borg CR10 scale (Chen et al., 2002). In relation to the core, a recent study predicted maximal core endurance by measuring performance time until reaching a RPE of 8 on the Borg CR10 scale, suggesting that this approximation could be used to evaluate initial intensity and prescribe core training exercises (George et al., 2018). However, the association between muscle activation, neuromuscular fatigue, and the RPE has only been reported for specific lumbar, shoulder, and cervical exercises, but not for a typical core stability exercise, such as the frontal plank (Kankaanpää et al., 1997; Otto et al., 2018; Troiano et al., 2008). Better understanding the RPE-neuromuscular fatigue relationship is relevant when recommending test and training protocols for the core muscles. For example, a relevant degree of muscle fatigue may be reached well before termination of the exercise (Enoka and Duchateau, 2008). Complete muscle fatigue, i.e., training to “failure,” can also be achieved when performing core stability training. Nevertheless, avoiding muscle fatigue during certain stages of rehabilitation may be preferable for some patients. Therefore, a simple and easily obtainable measure of core muscle fatigue is warranted.

Assessments of neuromuscular fatigue through sEMG are useful in explaining the physiological mechanisms affecting endurance performance (Kankaanpää et al., 1997; Otto et al., 2018) and can be used to evaluate the validity of the RPE as a measure of neuromuscular fatigue. The RPE could, therefore, be an easy-to-use alternative to sEMG in assessing muscle fatigue. This measure could result in a more specific prescription of core stability programs, with exercises graded according to muscle fatigue and intensity being dosed for each specific case. Therefore, this study determined the association between RPE and neuromuscular fatigue of the core muscles during the prone bridging endurance test.

2. Methods

2.1. Subjects

A total of 15 subjects participated in the study (9 females, 6 males). The inclusion criteria were as follows: 18–30 years old; low to moderate level of physical activity, as measured by the short version of the International Physical Activity Questionnaire (Roman-Viñas et al., 2010); and a body mass index < 25. The exclusion criteria were as follows: musculoskeletal injury in the six months prior to measurements; scoliosis; spinal surgeries; any degenerative disease affecting the elbow, shoulder, ankle, knee, or hip; and any cardiovascular or respiratory disease.

Before starting the study, the participants were informed as to the purpose and content of the investigation. Informed consent was read and accepted by each participant. This study adhered to the Declaration of Helsinki and was approved by the ethical committee of the Faculty of Medicine, University of Chile (Number 052-2017).

2.2. Procedures

Each participant completed two experimental sessions conducted one week apart and at the same time of day (between 3:00 p.m. and 6:00 p.m.). Participants were asked to refrain from consuming alcoholic or caffeinated beverages in the 48 h prior to each session and to sleep a minimum of 8 h the night before each session. All measurements were taken by the same investigators and were conducted in the same university facility.

In the first session, each participant was familiarized with and practiced the prone bridging test. This test was performed based on previous recommendations (Cortell-Tormo et al., 2017a; De Blaiser et al., 2018; Schoenfeld et al., 2014; Tong et al., 2014), with emphasis on correct posture and alignment between the trunk and pelvis. To this end, an explanatory video with the correct prone bridging technique was shown. Additionally, use of the Borg CR10 scale for measurements was explained. The RPE is defined as “the conscious sensation of how hard, heavy, and strenuous a physical task” is in a specific zone (Marcora and Goldstein, 2010; Pageaux, 2016). During the exercise, the subjects had to state their RPE in the core region every time they heard a signal, which was played every 5 s (George et al., 2018).

Considering previous studies, a light wooden slat (250 g) fixed with double-sided tape on the back was used as a guide to keep the pelvis in a neutral position (Schoenfeld et al., 2014) (Fig. 1). The subject received verbal feedback from one of the researchers when needed to correct the pelvis position. Based on a recent recommendation for improving the reliability of the prone bridging endurance test, each participant was asked to perform the exercise only once until reaching complete mechanical fatigue, defined as the decay in force-production capability as expressed through the inability to maintain the prone bridging position (Tong et al., 2014).

For the second session, hair was removed from skin overlying the muscles of interest on the dominant side of the body. Each shaved area was then cleaned by rubbing with cotton wool dipped in alcohol, and bipolar surface electrodes (3.0 cm of diameter Ag–AgCl, Kendall Medi-

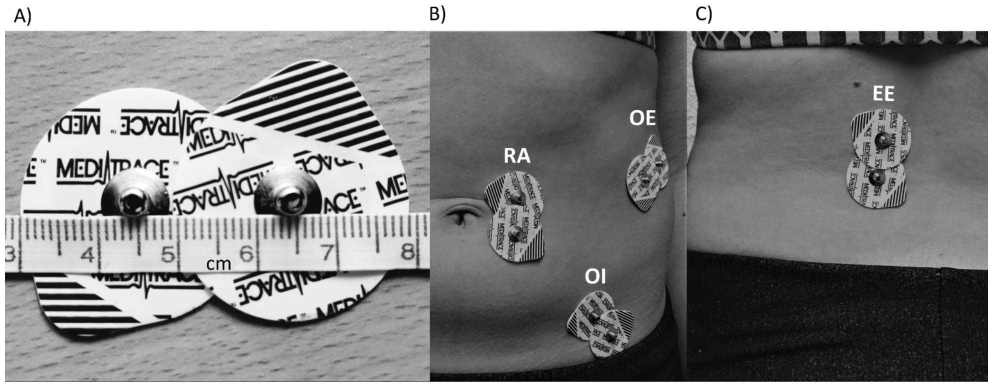

Fig. 2. (A) The bipolar surface electrodes used to record surface electromyography signals. (B) Locations of the surface electrodes on the rectus abdominis (RA), internal oblique (IO), and external oblique (EO). (C) Locations of surface electrodes on the lumbar erector spinae (EE).

Trace Mini ECG Electrodes, Neurotronics, Randwick, NSW, Australia) were then placed, with an inter-electrode spacing of 2 cm (Hermens et al., 2000) (Fig. 2). For the rectus abdominis (RA), the electrodes were placed laterally 2 cm from the umbilicus (Chanthapetch et al., 2009; De Blaiser et al., 2018) (Fig. 2). For the external oblique (EO), the electrodes were placed diagonally on the inferior edge of the line connecting the most inferior point of the costal margin with the contralateral pubic tubercle (Boccia and Rainoldi, 2014, Chanthapetch et al., 2009, De Blaiser et al., 2018) (Fig. 2). For the internal oblique (IO), the electrodes were placed 2 cm below the most prominent point of the anterior superior iliac spine, medial and superior to the inguinal ligament (Boccia and Rainoldi, 2014; Chanthapetch et al., 2009; De Blaiser et al., 2018) (Fig. 2). For the lumbar erector spinae (EE), the electrodes were placed laterally at two finger widths from the spinous process of the L1 vertebra (Hermens et al., 2000) (Fig. 2).

Neuromuscular electrical activity was recorded by sEMG (MyoSystem DTS, Noraxon USA., Inc., Scottsdale, CA, USA), with a sample rate of 1500 Hz. To normalize sEMG amplitude, the maximal voluntary isometric contraction of each muscle was manually resisted. This consisted of three contraction for 3 s, as based on previous descriptions (Dankaerts et al., 2004), with 1 min of rest between measurements. After 10 min of rest, each subject performed the prone bridging test until failure. The same technique and parameters for the plank exercise were used for both sessions, with the RPE reported every 5 s.

Considering previous evidence showing that a posterior pelvic tilt greatly influences activation of the RA and EO muscles during the plank exercise (Schoenfeld et al., 2014), two inertial sensors with a sample rate of 100 Hz (XSENS, Xsens Technologies BV, Enschede, the Netherlands) were positioned at the level of the sacrum and the lumbar spine (L1) to track pelvis angle variations.

2.3. Signal processing and data analysis

The raw signals for each subject were first visualized to guarantee the absence of artifacts and powerline interference (Fig. 3). All signals were then processed with the Matlab software (MathWorks, Inc., Natick, Massachusetts, United States). The sEMG signals were digitally filtered by a band pass filter (20–500 Hz). Determinations of sEMG amplitude with the root mean square (RMS) and median frequency (MF) were quantified by successive 250 ms timeframes. The RMS activity in each muscle was normalized to the respective maximal voluntary isometric contraction. The MF was normalized to the first 2 s of the task. Neuromuscular fatigue was determined by a significant decrease in MF and significant increase in RMS over time (Enoka and Duchateau, 2008, Kallenberg et al., 2007). Since the MF and RMS do not necessarily change simultaneously, both needed to significantly change over time to determine the occurrence of neuromuscular fatigue. The pelvis angle was processed with a low pass filter (10 Hz). Finally, each signal (i.e., RMS, MF, pelvis angle) and the RPE were normalized in 10% intervals of the time to failure.

2.4. Statistical analysis

The sample size was calculated by the G * Power v.3.1.9.2 software (http://www.gpower.hhu.de/), assuming a high correlation coefficient ($r = 0.94$) between a RPE of 8 on the Borg CR10 scale and maximal endurance time during the prone bridging test (George et al., 2018). Assuming a 20% loss of participants, 15 subjects were determined enough to have $p = 0.001$ and $\beta = 0.01$.

All statistical analyses were performed using the Statistics and Machine Learning Toolbox in the Matlab software (MathWorks, Inc., Natick, Massachusetts, United States). After evaluating data distribution with the Shapiro-Wilks test, the Friedman test was applied for all variables obtained during each 10% interval of time. If a significant result was found over time, a post hoc test with Bonferroni correction for multiple comparisons was applied. Significant changes in sEMG for the core muscles were associated with the RPE of the respective participant through the coefficient of regression analysis. P values < 0.05 were considered statistically significant. The nonparametric effect size was calculated through an r conversion of the z-score (without sign) from the Wilcoxon signed-rank test. The effect-size magnitude of r can be interpreted as follows: 0.1, small; 0.3, medium; and 0.5, large (Pautz et al., 2018).

3. Results

3.1. Demographic characteristics

The average age of the subjects was 22.1 years ± 3.1, and the average body mass index was 23.1 ± 2.0 According to the short version of the International Physical Activity Questionnaire, 14 subjects had a moderate physical activity level, while 1 subject had a low physical activity level.

3.2. Time to failure and the RPE

The mean time to failure was 123.7 ± 58.1 s. Analysis showed that the RPE significantly increased over time ($p < 0.001$). As compared to the first 10% interval, the RPE significantly increased from the 50% interval of the endurance test ($p < 0.05$) (Fig. 4, Table 1).

3.3. sEMG and pelvis angle

All muscles evidenced a significant increase in RMS amplitude over time ($p < 0.001$), as compared to the first 10% interval of the time to

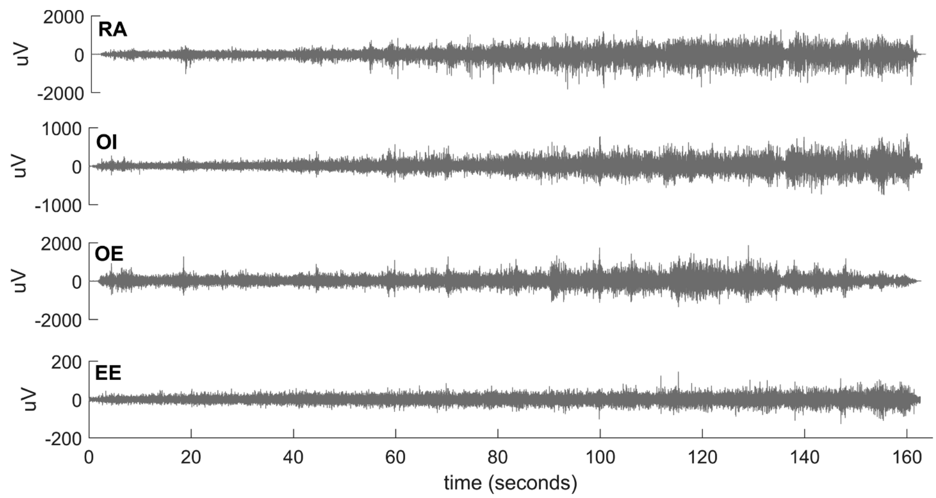

Fig. 3. Example of a raw surface electromyography signal of the core muscles during the prone bridging test for one subject. Rectus abdominis (RA), internal oblique (IO), external oblique (EO), and lumbar erector spinae (EE).

failure: RA, significant increase from the 50% interval; OI, from the 60% interval; OE from the 60% interval, although no significant increase was found at the 70% interval; and EE from the 60% interval (Fig. 5, Table 1). Similarly, all muscles presented a significant decrease in MF amplitude over time ($p < 0.001$), as compared to the first 10% interval of the time to failure: RA, significant decrease from the 50% interval; OI, only at the 90% interval; OE, from the 70% interval; and EE from the 70% interval (Fig. 6, Table 1). By contrast, pelvis angle did not significantly change in position over time ($p = 0.146$; median 30.0° [min 24.4°; max 31.3°]).

3.4. Relationships between the RPE and sEMG

Linear regression analysis revealed a significant correlation between the RPE and sEMG variables in all muscles (Table 2). The highest correlation was found in the RA muscle, with the MF being significantly correlated in all subjects (mean $r = 0.85$).

4. Discussion

The main findings of the present study were as follows: i) the RPE, as evaluated with the Borg CR10 scale, was closely correlated with neuromuscular fatigue of the RA muscle during the prone bridging endurance test; and ii) the RPE increased from the 50% interval of time to failure as compared to the first 10% interval. Both results support our hypothesis that the RPE would be closely linked with neuromuscular fatigue during core stability exercises. This is the first study to demonstrate a high association between the Borg CR10 scale and neuromuscular fatigue during a typical core-stabilization exercise. This novel evidence may have prescription implications for healthy individuals and may serve as a first step towards studying such associations in patients. Therefore, the RPE represents an easy-to-use tool for assessing core muscle fatigue, e.g., in clinical practice, at workplaces, and in sports.

The obtained results make sense since the RA muscle is the main muscle activated during the prone bridging test (De Blaiser et al., 2018). In line with this, the RA muscle seems to be the main muscle responsible for limiting endurance performance during the prone bridging test (De Blaiser et al., 2018). This prior observation is consistent with the present results, where the RA muscle showed increased neuromuscular fatigue during the last half of the time to failure, with a large effect size (Figs. 5 and 6, Table 1) and a high correlation with the RPE in all subjects (Table 2). Neuromuscular fatigue of the other core muscles was also correlated with the RPE and influenced endurance performance (Table 2), albeit to lesser extents. More specifically, the IO, EO, and EE presented increased neuromuscular fatigue from the 70–90% intervals of the time to failure, with moderate to large effect sizes (Figs. 5 and 6, Table 1). Another explanation for the high

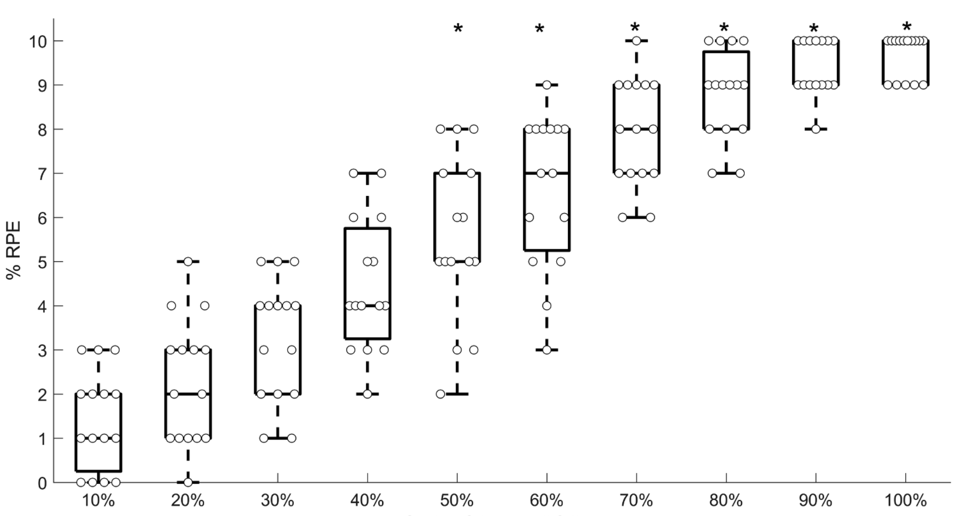

Fig. 4. The rate of perceived exertion (RPE) during the prone bridging test during each 10% interval for the time to failure. * denotes significant differences ($p < 0.05$) as compared to the first 10% interval of the test. Data are expressed as the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. Circles indicate individual datum (n = 15).

Table 1
P-values and the effect size (ES) of r for comparisons between the first 10% interval and subsequent intervals of the time to failure during the prone bridging endurance test. Abbreviations: EE, lumbar erector spinae; EO, external oblique; IO, internal oblique; MF, median frequency; RA, rectus abdominis; RMS, root mean square; RPE, rate of perceived exertion; sEMG, surface electromyography. Significant differences (p-value < 0.05) and large ES are bolded.

Variables		Time to failure	20%	30%	40%	50%	60%	70%	80%	90%	100%
RPE		p-value	1.000	1.0000	0.327	**0.020**	< **0.001**	< **0.001**	< **0.001**	< **0.001**	< **0.001**
		ES	0.418	**0.827**	**1.110**	**1.125**	**1.194**	**1.209**	**1.211**	**1.219**	**1.230**
sEMG	Muscle										
RMS	RA	p-value	1.000	1.00	0.141	< **0.001**	< **0.001**	< **0.001**	< **0.001**	< **0.001**	< **0.001**
		ES	0.086	0.036	0.461	**0.546**	**0.696**	**0.653**	**0.857**	**0.825**	**0.846**
	OI	p-value	1.000	1.000	1.000	0.210	**0.011**	**0.002**	< **0.001**	< **0.001**	< **0.001**
		ES	0.170	0.225	0.311	0.364	0.450	0.439	**0.557**	**0.621**	**0.760**
	OE	p-value	1.000	1.000	1.000	0.430	**0.033**	0.148	**0.017**	**0.002**	**0.0170**
		ES	0.032	0.064	0.203	0.268	0.311	0.386	0.461	**0.503**	0.461
	EE	p-value	1.000	1.000	1.000	1.000	**0.007**	**0.021**	< **0.001**	< **0.001**	< **0.001**
		ES	0.064	0.139	0.139	0.278	0.332	0.353	0.428	0.418	**0.503**
MF	RA	p-value	1.000	1.000	0.604	**0.033**	< **0.001**	< **0.001**	< **0.001**	< **0.001**	< **0.001**
		ES	0.311	**0.750**	**1.208**	**1.146**	**1.119**	**1.167**	**1.167**	**1.199**	**1.199**
	OI	p-value	1.000	1.000	1.000	0.510	0.171	0.141	0.141	**0.017**	0.604
		ES	0.418	0.353	**0.632**	**0.707**	**0.707**	**0.610**	0.375	**0.593**	0.257
	OE	p-value	1.000	1.000	0.604	0.358	0.094	**0.008**	**0.002**	< **0.001**	< **0.001**
		ES	0.086	0.225	**0.589**	**0.632**	**0.760**	**0.793**	**0.900**	**0.857**	**1.082**
	EE	p-value	1.000	1.000	0.501	0.051	0.062	**0.001**	< **0.001**	< **0.001**	< **0.001**
		ES	0.311	0.364	**0.578**	**0.750**	**0.707**	**0.750**	**0.739**	**0.750**	**0.750**

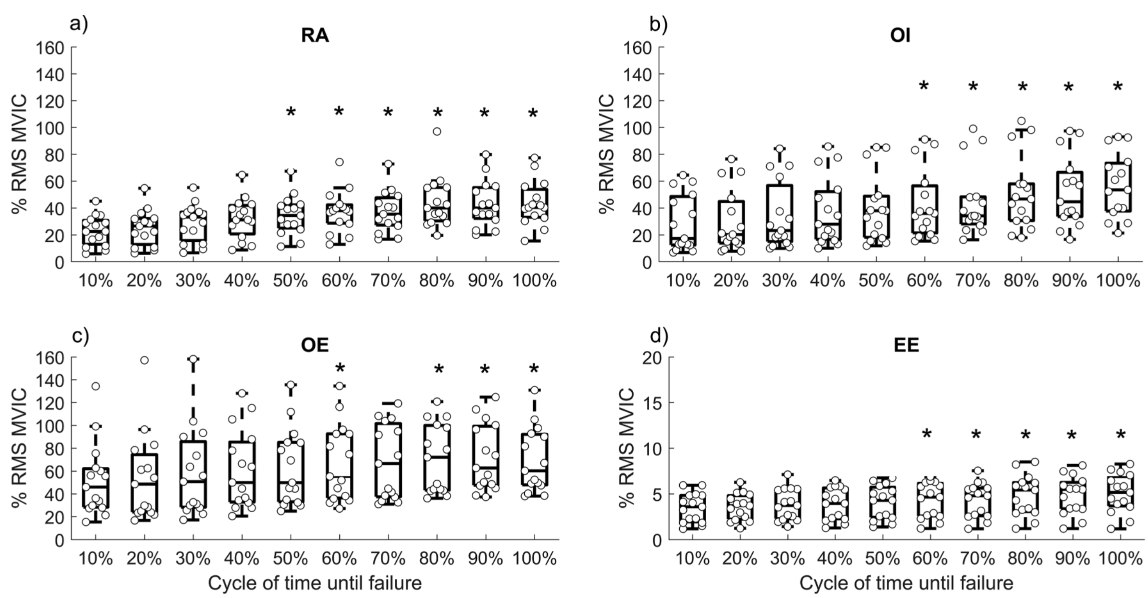

Fig. 5. Variations in surface electromyography amplitude, normalized to the maximal voluntary contraction during each 10% interval of the time to failure. * denotes significant differences (p < 0.05) as compared to the first 10% interval of the test. Data are expressed as the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. Root mean square (RMS), rectus abdominis (RA), internal oblique (IO), external oblique (EO), and lumbar erector spinae (EE). Circles indicate individual datum (n = 15).

relevance of the RA muscle during the test might be the trunk flexor function of this muscle and the role thereof in limiting pelvic anteversion during the prone bridging test (Schoenfeld et al., 2014). However, the present study found no variation in pelvic angle, indicating that this was not the main contributor to increased neuromuscular fatigue. This result also indicates that the verbal feedback, as guided by one wooden slat over the pelvis and trunk, was sufficient to guarantee correct execution of the prone bridging test.

Previous studies report that the RPE has a close association with paraspinal muscle fatigue and endurance time in healthy subjects during the modified Biering-Sørensen test (Dedering et al., 1999). The authors proposed that the RPE could be useful for clinical testing, where the time of performance until a RPE of 5 would be related to a significant reduction of MF in the EE muscle (Dedering et al., 1999). The current study found that the occurrence of neuromuscular fatigue in the RA muscle at 50% of the time to failure coincided with a significant increase in the RPE (i.e., Borg CR10 of 5 at 50% of the time to failure). At this time point, no other muscles presented increased neuromuscular fatigue. This finding could be associated with a greater stimulation of high-threshold motor units and could have relevant practical applications in training regimes. In fact, a recent *meta*-analysis found that longer isometric contractions induced greater hypertrophy than did shorter contractions (Oranchuk et al., 2018). Therefore, sustaining the isometric front plank until reaching a RPE of 5 would be needed to provide substantial neuromuscular fatigue of the RA muscle. Additionally, keeping a RPE below 5 could serve to avoid excessive stress in individuals without training experience or that are more prone to experiencing discomfort, such as with injured patients.

A recent study reported that a RPE of 8 on the Borg CR10 scale predicted maximal core endurance time during the prone bridging test, suggesting that this could be used to evaluate initial intensity and prescribe core training (George et al., 2018). In the present study, the

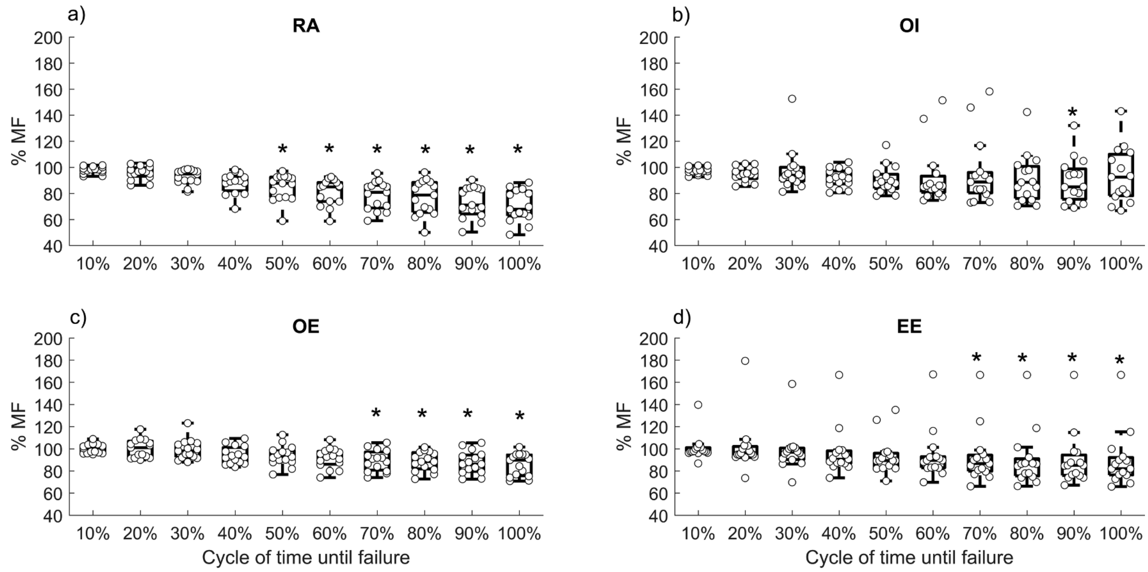

Fig. 6. Variations in the median frequency (MF) of surface electromyography during each 10% interval of the time to failure. * denotes significant differences ($p < 0.05$) as compared to the first 10% interval of the test. Data are expressed as the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. Rectus abdominis (RA), external oblique (EO), internal oblique (IO), and lumbar erector spinae (EE). Circles indicate individual datum (n = 15).

Table 2
Linear regression analysis showed a significant correlation between the rate of perceived exertion and surface electromyography variables. Data are expressed as the mean, and the 95% confidence intervals (CI) are given. Abbreviations: EE, lumbar erector spinae; EO, external obique; IO, internal oblique; MF, median frequency; RA, rectus abdominis; RMS, root mean square.

Variable	Muscle	R^2	95% CI	# Subjects $p < 0.05$
RMS	RA	0.67	0.53–0.83	13/15
	OI	0.66	0.49–0.81	13/15
	OE	0.50	0.31–0.68	9/15
	EE	0.65	0.51–0.80	12/15
MF	RA	0.85	0.77–0.93	15/15
	OI	0.51	0.28–0.75	10/15
	OE	0.50	0.31–0.68	9/15
	EE	0.69	0.55–0.84	14/15

RPE significantly increased at 50% of the time to failure, as compared to the first 10% of the test, evidencing a large effect size (Fig. 4, Table 1). Our results provide novel evidence for a RPE greater than 5 being highly related to neuromuscular fatigue of the RA muscle and moderately related to neuromuscular fatigue of the other core muscles. Considering the results together, we propose that the Borg CR10 scale could be useful in prescribing the intensity of core stability exercises.

The present study has several limitations. The interpretation of neuromuscular fatigue (i.e., amplitude and/or spectral features) is affected by electrode size and inter-electrode distances (Afsharipour et al., 2019). Therefore, the results would not be replicable with a different electrode configuration. Additionally, crosstalk between the abdominal muscles cannot be discarded. However, crosstalk is inherent to every sEMG measurement, and previously recommended methodologies were applied to reduce this phenomenon (Calatayud et al., 2017, De Blaiser et al., 2018, Hermens et al., 2000). Moreover, traditional recommendations were followed in shaving and alcohol-cleaning the skin (Hermens et al., 2000). However, current recommendations of massaging with abrasive paste and cleaning with water might have helped to decrease skin impedance (Piervirgili et al., 2014). Another limitation was that all participants were active and healthy; consequently, caution should be taken in extrapolating results to clinical populations (e.g., patients with lower back pain), specifically since the relationship between the RPE and neuromuscular fatigue may change. Additionally, while there is evidence for scapular positioning influencing core-muscle sEMGs during the prone bridging test (Cortell-Tormo et al., 2017b), the present study did not measure upper-limb sEMG. Although this measurement could have provided interesting information, our investigative focus was on evaluating the main contributors relevant to explaining performance during the prone bridging test. Future studies are, therefore, needed to determine the contributions of scapular and upper-limb muscles to the time to failure for the prone bridging test. Finally, despite the validity and reliability of the prone bridging test in evaluating abdominal muscle fatigue, the trial-to-trial and intraday reliability of the Borg CR10 scale and neuromuscular fatigue during core exercises need to be assessed in future research.

In conclusion, use of the Borg CR10 scale to measure the RPE during the prone bridging endurance test revealed a close link with neuromuscular fatigue of the RA muscle and moderate link with neuromuscular fatigue of the other assessed core muscles. These results confirm that the Borg CR10 scale can be used as a tool to assess abdominal muscle fatigue during the front plank exercise, which would help to determine thresholds for maximum activity. Our results may facilitate prescribing more specific and individualized exercise doses.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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