Validity of using perceived exertion to assess muscle fatigue during resistance exercises

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Background. The rating of perceived exertion (RPE) is correlated with physiological variables. The purpose of this study was to assess the validity of using the Borg CR-10 scale and velocity to predict muscle fatigue assessed by surface electromyography during single joint resistance exercises.

Methods. Fifteen healthy males underwent different fatigue levels of unilateral elbow flexion (EF) and knee extension (KE), consisting of low, medium, and high volumes at 65% of their one-repetition maximum. The RPEs, spectral fatigue index (SFI), and mean velocity of the experimental exercises were assessed throughout the trials.

Results. Significant differences in overall RPE ($p < 0.001$) and average SFI ($p < 0.001$) were observed between the conditions in both exercises. Significant changes in RPE and SFI ($p < 0.001$) were observed throughout the EF, whereas a SFI increase ($p < 0.001$) was only observed at the end point of KE. Multiple regression analyses revealed two significant models ($p < 0.001$) for the prediction of muscle fatigue during EF ($R^2 = 0.552$) and KE ($R^2 = 0.377$).

Conclusions. Muscle fatigue resulted in similar increases in perceptual responses, demonstrating that RPE is useful for assessing fatigue when resistance exercise is performed. However, velocity changes may not reflect muscle fatigue correctly when exercise is no longer performed in an explosive manner. We recommend combining RPE responses with velocity changes to comprehensively assess muscle fatigue during clinical and sports situations.

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16 Abstract

17 **Background.** The rating of perceived exertion (RPE) is correlated with physiological variables.
18 The purpose of this study was to assess the validity of using the Borg CR-10 scale and velocity
19 to predict muscle fatigue assessed by surface electromyography during single joint resistance
20 exercises.
21 **Methods.** Fifteen healthy males underwent different fatigue levels of unilateral elbow flexion
22 (EF) and knee extension (KE), consisting of low, medium, and high volumes at 65% of their
23 one-repetition maximum. The RPEs, spectral fatigue index (SFI), and mean velocity of the
24 experimental exercises were assessed throughout the trials.
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26 observed between the conditions in both exercises. Significant changes in RPE and SFI ($p <$
27 0.001) were observed throughout the EF, whereas a SFI increase ($p < 0.001$) was only observed
28 at the end point of KE. Multiple regression analyses revealed two significant models ($p < 0.001$)
29 for the prediction of muscle fatigue during EF ($R^2 = 0.552$) and KE ($R^2 = 0.377$).
30 **Conclusions.** Muscle fatigue resulted in similar increases in perceptual responses, demonstrating
31 that RPE is useful for assessing fatigue when resistance exercise is performed. However, velocity
32 changes may not reflect muscle fatigue correctly when exercise is no longer performed in an
33 explosive manner. We recommend combining RPE responses with velocity changes to
34 comprehensively assess muscle fatigue during clinical and sports situations.

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36

Introduction

37

38   Fatigue appears in daily life and can be defined as a sensation of tiredness and weakness,
39 underpinned by many physiological and psychological processes (González-Izal et al., 2012;
40 Azevedo et al., 2021). In sports and rehabilitation situations, exercise-induced fatigue is an
41 inevitable factor. It is considered to be related to sports performance because of the
42 accompanying impairments in the force and/or power generating capacity (Sparto et al., 1997).
43 Muscle fatigue during exercise can also increase injury risks (Borotikar et al., 2008). Muscle
44 fatigue could be quantified by many physiologically relevant measures, such as blood lactate and
45 muscle force (Skurvydas et al., 2010; Sánchez-Medina & González-Badillo, 2011). Surface
46 electromyography (sEMG) is a method for non-invasively assessing neuromuscular fatigue
47 responses and is widely used in sports science (Hermens et al., 2000; González-Izal et al., 2012;
48 Campanini et al., 2020). Neuromuscular changes that occur due to fatigue can be measured by
49 analyzing signals collected during muscle contractions (González-Izal et al., 2010; Campanini et
50 al., 2020). sEMG signals have been shown to provide reliable information regarding the
51 mechanism of muscle fatigue (Yoshitake et al., 2001). In using sEMG for muscle fatigue
52 assessment, the manifestation of fatigue is defined as compression of the power spectrum, which
53 is induced by physiologically relevant factors (such as muscle fiber conduction velocity) (Brody
54 et al., 1991). The compression of the power spectrum causes a decrease in mean and median
55 frequencies toward lower spectral frequencies, that are generally considered fatigue indicators
56 (Campanini et al., 2020).

57   It is crucial for personal trainers, coaches, and physical therapists to grasp the fatigue
58 conditions of their subjects. However, it is not realistic for them to have their own sEMG devices
59 because these devices are very expensive. Even if sEMG assessment was available, real-time
60 feedback of fatigue is required in many exercise scenarios (such as rehabilitation), which cannot
61 be achieved by monitoring spectral changes as they occur over a much longer time scale
62 (Dimitrov et al., 2006). Moreover, sEMG signal spectral characteristics are strongly affected
63 during dynamic contractions, and the measurements of the myoelectric manifestations of muscle
64 fatigue in dynamic contractions require considerable competence and caution (Dimitrov et al.,
65 2006; Campanini et al., 2020).

66   Recently, velocity assessment has become very common in resistance exercise situations,
67 and a wide range of tools are currently available for velocity monitoring (Evandro et al., 2019;
68 John et al., 2021). Based on the easy-to-use characteristics of velocity measures, velocity
69 changes (the transient decline in velocity due to the reduction in force generating capacity) and
70 velocity loss (the percent loss in velocity from the fastest to the slowest repetition of each set)
71 have been recommended as new fatigue indicators for resistance exercises (Sánchez-Medina &
72 González-Badillo, 2011; Mayo, Iglesias-Soler & Kingsley, 2019). Evidence has been presented
73 that these velocity-based parameters are significantly correlated with metabolic and mechanical
74 measurements of fatigue during resistance exercises (Sánchez-Medina & González-Badillo,
75 2011; Mayo, Iglesias-Soler & Kingsley, 2019). However, most sports science studies on velocity
76 changes have only examined the relationship between velocity and muscle fatigue when exercise

77   is performed in an explosive manner. Thus, velocity changes may not reflect muscle fatigue
78   correctly in non-explosive settings. For example, for hypertrophy-aimed training programs, the
79   cadence of repetitions is always controlled because the time the muscle spends under mechanical
80   tension is critically important for muscle protein synthesis (Vargas-Molina et al., 2020). Under
81   this setting, velocity changes may be inappropriate for muscle fatigue assessment. Further, for
82   beginners and athletes with injuries, it is dangerous for them to perform explosive exercises
83   because of the lack of strength, proper technique, and joint stability (Thomas & Roger, 2008).
84   Consequently, the validity of velocity changes as a muscle fatigue indicator might not be
85   justifiable or adequate when explosive performance is no longer the aim of exercise.
86   The rating of perceived exertion (RPE) scale is a perceptual-based assessment method that
87   uses a combination of numbers, verbal, and pictorial descriptors (Borg, 1998; Robertson et al.,
88   2003, 2004). The RPE has been reported to relate to physiological responses, such as muscle
89   activation and oxygen consumption during aerobic exercise (Robertson et al., 2004; Fontes et al.,
90   2010). In recent years, the RPE has been widely used in resistance exercise to quantify the
91   intensity of exercises. For example, the RPE is reported to relate to the percentage of one-
92   repetition maximum (1RM) lifts during resistance exercise (Lagally et al., 2002a; Lagally et al.,
93   2002b; Eston, James & Evans, 2009). More recently, task-specific RPE scales have also been
94   developed and can be used for prescriptions of both aerobic and resistance exercises (Robertson
95   et al., 2003, 2004). Despite the differences between these RPE scales, it is thought to be a valid
96   and easy-to-use tool for prescribing resistance exercise (Gearhart et al., 2001; Robertson et al.,
97   2003). However, the association between RPE and muscle fatigue has only been examined for
98   some isometric exercises because the sEMG signal is thought to be unstable during dynamic
99   exercise situations (Troiano et al., 2008; Otto, Emery & Côté, 2018; Cruz-Montecinos et al.,
100   2019).
101   Recently developed mathematical simulation-based methods for muscle fatigue assessment
102   using sEMG signals are now available (Dimitrov et al., 2006; González-Izal et al., 2012). Thus,
103   the relationship between RPE and muscle fatigue induced by dynamic contraction might be
104   evinced by using the new sEMG processing technique. Assessing and predicting exercise-
105   induced muscle fatigue through a simple and effective method would be beneficial, as such a
106   method would allow coaches to monitor the fatigue condition of athletes to avoid both acute and
107   chronic injury risks.
108   The interdependence between physiological and perceptual responses during exercises
109   indicate that the RPE may be a valid method of assessing muscle fatigue during resistance
110   exercises. Moreover, the correlation between muscle fatigue and RPE might be demonstrated by
111   using well-suited sEMG measurements. Accordingly, this study aimed to examine the validity of
112   using RPE to assess muscle fatigue processed by new sEMG parameters and develop a
113   prediction model for muscle fatigue during single-joint resistance exercise. We hypothesized that
114   RPE would exhibit similar responses corresponding to muscle fatigue levels. Further, muscle
115   fatigue could be predicted using the RPE score and velocity obtained during single-joint
116   resistance exercises.

117

Materials & Methods

Participants

120   The sample size was calculated with a statistical power effect size of 0.4 and alpha of 0.05;
121   power was determined to be 0.95 (Cruz-Montecinos et al., 2019). Thus, a minimum of 14
122   subjects was indicated for this study. Accordingly, 15 healthy male adults with no neuromuscular
123   disorders or skeletal muscle injuries and under no medication were recruited to participate in this
124   investigation. Participants were informed about the experimental protocols, measurement items,
125   potential risks, possible discomfort, and benefits of the study, and then provided written consent
126   to participate in this study. The study was developed in accordance with the ethical guidelines of
127   the Declaration of Helsinki, and this experiment was approved by the Waseda University Human
128   Ethics Committee (No. 2020-042).

129

Experimental procedures

131   This study used a randomized, crossover, repeated-measures design. The experiment was
132   undertaken in two separate sessions (separated by at least 24 h). During the initial session, the
133   instructions of Borg's CR-10 scale were explained to participants. We then obtained descriptive
134   information on each participant. The 1RM of the experimental exercise was measured. The
135   participants were then familiarized with the experimental protocols. During the experimental
136   session, the anchoring procedure, which determined the range of subjective feelings during
137   experimental conditions, was performed first. Three experimental conditions consisting of 30%
138   (Low, L), 60% (Medium, M), and 90% (High, H) volume were performed in random order. The
139   RPE score, sEMG signal, and velocity were recorded throughout the experimental conditions.

140

Orientation and familiarization session

142   During the orientation session, the purpose, experimental protocols, measurement items,
143   potential risks, possible discomfort, and benefits were explained to the participants. The
144   descriptive characteristics of each participant were measured using a bioelectrical impedance
145   device (InBody 720 body composition analyzer, Biospace Co. Ltd, South Korea). The length of
146   the limb was also obtained to calculate the locations of the sEMG electrodes. The unilateral
147   biceps curl and unilateral leg extension exercises were selected as the elbow flexion (EF) and
148   knee extension (KE) exercises. The 1RM of the EF and KE exercises were measured for each
149   arm and leg, and each participant completed the 1RM test of the right arm, left arm, right leg,
150   and left leg separately. The EF exercise was performed using a dumbbell (UESAKA T.E Co.,
151   LTD, Japan). The EF was performed with participants in a standing position, feet shoulder width
152   apart. The participants' backs were positioned as flat as possible against the wall, and their upper
153   arms were in contact with the wall throughout the lifting procedure. The concentric action started
154   with the elbows in full extension and the dumbbell at the closest point to the floor. When the
155   concentric phase commenced, participants were requested to flex the elbow until maximum
156   flexion occurred. This was followed by the eccentric phase, and the dumbbell was lowered back

157   toward full extension (180°) to complete a full repetition (Lagally et al., 2002b; Robertson et al.,
158   2003; Eston, James & Evans, 2009). The 1RM of EF was determined from the weight of the
159   dumbbell (to the nearest 1 kg). The KE was performed using a leg extension machine (Prime
160   Fitness, USA) (Robertson et al., 2003). The back and hip were positioned flat against the back
161   support and the seat, and participants were asked to grip the stabilizing handle near the seat
162   throughout the trial. The seat position and back support were adjusted for each subject to ensure
163   knees were at 90° flexion at the start of the concentric phase. Participants were instructed to
164   extend their knee as far as possible during the concentric phase and to control the descent of the
165   leg during the eccentric phase. The 1RM of KE exercise was determined from the weight stack
166   (to the nearest 5 lbs.). The processes were conducted according to guidelines set by the National
167   Strength and Conditioning Association (Thomas & Roger, 2008). This included the warm-up
168   sets, which were followed by a progressive increase in training load until participants
169   successfully completed their maximum effort of one repetition. After the basic measurement,
170   Borg's CR-10 scale was administered to each participant. Borg's CR-10 scale was used because
171   it is one of the most common RPE scales (Noble et al., 1983). This scale ranges from 0 (no
172   exertion at all) to 10 (maximal exertion) and includes standard verbal anchors of perception of
173   effort for intermediate values (Borg, 1998). The scale's instructions include the following
174   information: "In the next experimental session, you will be asked to perform a series of upper
175   and lower body resistance exercises. During the exercises, we will use this scale to assess your
176   subjective exertion during exercise. The perception of physical exertion is defined as the
177   subjective intensity of effort, strain, discomfort, and fatigue that you feel during exercise
178   (Lagally & Robertson, 2006). This scale comprises verbal anchors and numbers. Numbers from
179   0 to 10 represent the range of your subjective feelings from no exertion at all to maximal
180   exertion. The verbal descriptors next to the numbers will help you to describe the feeling. The
181   numbers should represent your feelings in the limb you have just lifted. For example, if you are
182   asked to lift with your right arm, consider only the feeling in your right arm when reporting your
183   subjective exertion. When reporting your subjective exertion value, please select the nearest
184   number that corresponds to your feeling." After this instruction, the lifting cadence and RPE
185   reporting practice were demonstrated to all the participants. During the practice, lifting cadence
186   was determined with a cadence of a 2 s eccentric phase, 1 s of concentric phase, and 2 s of pause
187   between repetitions. The cadence was controlled by a metronome, and participants were asked to
188   report their current feelings repetition-by-repetition using numbers from the CR-10 scale during
189   the pause. The scale was placed where it could be readily viewed by the participants.
190
191   ***Experimental session***
192   Prior to beginning the experimental trial, a series of warm-up exercises were demonstrated
193   to all the participants. The warm-up started with a 5 min cycle ergometer exercise at 50 W within
194   the range of 60 rpm. After the ergometer exercise, warm-up lifts were provided for both limbs.
195   For each arm, participants performed three sets of unilateral bicep curls that comprised six
196   repetitions at 50% of the 1RM. For each leg, three sets of unilateral leg extensions were

197   performed for six repetitions at 50% of the 1RM. Overall, each participant performed six sets of
198   unilateral bicep curls and six sets of unilateral leg extensions. After the warm-up procedure, the
199   experimental trial was performed in random order. The relative intensity for EF and KE exercise
200   was 65% of 1RM (Robertson et al., 2003). For both exercises, the lifting cadence was
201   determined with a cadence of a 2 s eccentric phase, 1 s of concentric phase, and 2 s of pause
202   between repetitions controlled by a metronome. As the exercises advanced, muscle fatigue
203   occurred, and the pace of repetition was difficult to maintain. Participants may unconsciously
204   shorten the pause and swing their limbs slightly to catch the cadence of the concentric phase. To
205   avoid the influences caused by these unnoticeable movements, the participants were asked to try
206   their best to follow the metronome during the eccentric phase and to pause between repetitions.
207   For both exercises, the first set was the anchoring procedure, which determines the range of
208   subjective exertion during later trials. The onset of muscular failure was reported to become the
209   main determinant of perceived exertion (Hackett et al., 2012; Mayo, Iglesias-Soler & Fernández-
210   Del-Olmo, 2014; Hiscock et al., 2016). Accordingly, the physical failure was anchored to an
211   RPE of 10 on the CR-10 scale. Participants were asked to perform a single set of unilateral EF
212   (or unilateral KE) until physical failure. The following instructions were given to the
213   participants: "You will undergo a single set of unilateral bicep curls (or unilateral leg extensions)
214   to establish the range of exertion during later trials. The perception of physical exertion is
215   defined as the subjective intensity of effort, strain, discomfort, and fatigue that you feel during
216   exercise. The perception of exertion when you are sitting down in a relaxed state before any
217   physical activity is equivalent to a score of 0, which means 'nothing at all' (Eston, James &
218   Evans, 2009). We will ask you to perform a single set of unilateral bicep curls (or unilateral leg
219   extensions) until physical failure, which means you cannot lift another repetition. When you
220   reach failure, the perceptions of exertion are equivalent to a score of 10, which represents feeling
221   'extremely strong' (Mayo, Iglesias-Soler & Kingsley, 2019). You need to remember this range of
222   feelings, and we will ask you to report your score of perceived exertion during later trials based
223   on the range. You need to maintain the cadence of 1 s of the raising phase, 2 s of the lowering
224   phase, and 2 s of pause between repetitions as closely as possible." This set was performed on
225   random arms and legs, and the volume was recorded and used to calculate the volume of the L,
226   M, and H volume conditions. After the anchoring trial, participants were allowed a 5-min rest
227   before the next trial.
228   After the anchoring trial, three experimental condition trials were conducted on the arm and
229   leg that did not perform the anchoring trial. For example, participants would perform three
230   experimental trials on the right arm if the anchoring trial were performed on the left arm. When
231   performing the experimental trials, three experimental conditions were executed randomly.
232   Participants were not informed of the required repetitions beforehand; however, they were
233   informed of the penultimate repetition and told to stop immediately after the last repetition.
234   Participants were asked to report their feelings of exertion by using a number from the CR-10
235   scale repetition-by-repetition during the 2 s pause between repetitions. As the exercises
236   advanced, muscle fatigue occurred, and the pace of repetition was difficult to maintain. Under

237 this condition, the participants were asked to try their best to follow the metronome during the
238 eccentric phase and to pause between repetitions. After each condition, the overall RPE was also
239 obtained from participants, which represented the total perceived exertion of the latest trial. The
240 following instructions were given to participants before the trial: "You will undergo several sets
241 of unilateral bicep curls (or unilateral leg extensions) on different arms (or legs). You will not be
242 told the required repetitions before the trial until you have reached that number. We will inform
243 you at the second to last repetition. After that, you can stop the exercise after you finish the last
244 repetition. During the trial, you need to maintain a cadence of 1 s of the raising phase, 2 s of the
245 lowering phase, and 2 s of pause between repetitions as closely as possible. During the pause,
246 you need to report the exertion score of the latest repetition by using a number from the CR-10
247 scale. After the trial, we will ask you to report your overall exertion of the latest trial. This
248 exertion score should be considered based on the range of subjective feelings you establish in
249 failure situations and should be as accurate as possible. When reporting the score, make sure to
250 only consider the exercising limb." A 5-min rest interval was allowed between trials (George et
251 al., 2018). Before the beginning of the next trial, participants were asked about their RPE to
252 ensure that the subjective exertion had returned to 0. If not, the participants were allowed a
253 longer rest. Overall, all participants reported a 0 from the CR-10 scale, and a 5-min rest interval
254 was provided to all participants.
255
256 ***Surface Electromyography***
257   The sEMG signals for the biceps brachii (long head), brachioradialis, triceps brachii (lateral
258 head), vastus medialis, vastus lateralis, and biceps femoris muscles were obtained using bipolar
259 surface electrodes (ADMEDEC Co., Ltd, Japan). Two Ag/AgCl electrodes were used for each
260 muscle, and the inter-electrode distance was 1 cm. The skin was prepared for the placement of
261 the surface electrodes by shaving, abrasion with sandpaper, and then cleansing the skin using
262 alcohol swabs (Hermens et al., 1999). The location of electrodes was determined based on the
263 recommendations by Barbero et al. (Barbero, Merletti & Rainoldi, 2012) to avoid the innervation
264 zone. The signals were recorded using an active differential preamplifier configuration and then
265 transferred to a telemetry device (MARQ MQ-8, Kissei-Com Tech, Japan). The sampling
266 frequency was 1,000 Hz. The signals were processed with an analog digital converter, amplified,
267 and transferred to a computer. Further, a camera (FMVU-03MTC-CS, FLIR Systems, Inc.,
268 Canada) was connected to the computer, and the sEMG signals were synchronized with the
269 motion during exercises. The raw signal was then divided into a single repetition and exported
270 for subsequent analysis.
271   A fourth-order Butterworth band-pass filter (20–450 Hz) was designed to filter noise (Otto,
272 Emery & Côté, 2018). This filtered signal was then used to calculate muscle fatigue. sEMG
273 spectral characteristics are strongly affected during dynamic contraction, as discussed in the
274 Introduction section (Gerdle, Larsson & Karlsson, 2000; Dimitrov et al., 2006). To address this
275 problem, new, highly sensitive spectral fatigue index (SFI) was adopted to assess the muscle
276 fatigue level (Dimitrov et al., 2006) (The authors used the acronym "FI$_{nsm5}$" based on

277 mathematical reasoning. We changed the acronym "FI$_{nsm5}$" to "SFI" to enhance the readability of
278 this paper). SFI provides reliable evaluation of muscle fatigue during dynamic contractions
279 comparable with the traditional sEMG spectral characteristics. A fast Fourier transformation was
280 applied to calculate the power density spectrum. Spectral moments were used to extract the
281 characteristic features of the power spectral density function and were calculated using the
282 following formula:

283
$$M_k = \int_{f_{min}}^{f_{max}} f^k \cdot PS(f) \cdot df \quad (1)$$

284 where Mk is a spectral moment of order k, PS(f) denotes the power frequency spectrum as a
285 function of frequency f, and f$_{min}$ and f$_{max}$ delineate the bandwidth of the signal. SFI was
286 calculated as the ratio between orders -1 and 5, based on the following formular:

287
$$SFI = \frac{\int_{f_{min}}^{f_{max}} f^{-1} \cdot PS(f) \cdot df}{\int_{f_{min}}^{f_{max}} f^5 \cdot PS(f) \cdot df} \quad (2)$$

288   SFI was calculated for each repetition, and the relative changes in values for each repetition
289 were calculated against the first repetition of the corresponding set. The results of those muscles
290 were averaged to obtain a single variable, which was then used in the statistical analyses. This
291 process was performed using MATLAB R2020a (Mathworks, Natick, MA, USA).
292
293 ***Velocity measurements***
294   The velocity during exercise was recorded using a linear encoder (Fitro Dyne, FiTRONiC
295 s.r.o., Bratislava, Slovakia). This encoder was placed directly under the dumbbell/weights and
296 attached to weights through a cable. The sampling frequency was 100 Hz, and
297 upward/downward displacement changes over time during the lifting were transferred to the
298 computer and recorded with the assistance of proprietary software (Premium 3.0, FiTRONiC
299 s.r.o., Bratislava, Slovakia). The mean concentric velocity was used in subsequent analyses. As
300 different numbers of repetitions were required for each experimental condition of each
301 participant, the first, median, and last repetition of experimental conditions were used for
302 velocity analysis during three experimental conditions.
303
304 ***Statistical analyses***
305   The overall RPE and average SFI of the experimental conditions were analyzed using one-
306 way analysis of variance (ANOVA). When analyzing RPE, SFI, and the mean velocity of the
307 experimental trial, two-way (3 conditions × 3 timepoints) repeated ANOVA was used to test for
308 main and interaction effects of conditions and time. Further, the Bonferroni post-hoc test was
309 used to determine the significant effects and interactions between variables. As every participant
310 performed a different number of repetitions, the first, median, and the last repetition from
311 experimental conditions were used for 2-way ANOVA analysis.
312   Stepwise multiple regression analyses were performed with RPE, mean velocity, and SFI.
313 The predictors were the RPE score obtained during exercise and the mean velocity, while the
314 output variable was the SFI. The non-overlapping part of the three conditions was used in the

315   analysis (Migliaccio et al., 2018). The determination coefficients obtained from regression
316   analyses were interpreted as trivial (<0.02), small (0.02 to <0.13), medium (0.13 to <0.25), or
317   large (>0.25) effects, according to Cohen (Cohen, 1992). The variance inflation factors were
318   used to assess multicollinearity. Overall, 163 EF and 235 KE trials were used in the multiple
319   regression analysis. Statistical significance was acceptable at $p < 0.05$ in all analyses. The
320   statistical analyses were performed using SPSS version 24.0 (SPSS Inc., USA).

321

322 Results

323   The descriptive data of participants (mean ± SD) were as follows: age (yr) 23.20 ± 3.00,
324   body mass (kg) 72.96 ± 13.09, height (cm) 171.40 ± 5.84, fat (%) 16.92 ± 6.44. The 1RM
325   strength of EF of the right side was 15.70 ± 4.46 kg, and the left side was 15.81 ± 4.23 kg; the
326   1RM of KE of the right side was 50.17 ± 14.13 kg, and the left side was 50.24 ± 13.54 kg. For
327   the EF exercise, 12.60 ± 2.90 repetitions were performed for the anchoring trial, and 3.80 ± 1.08,
328   7.67 ± 1.68, and 11.40 ± 2.59 repetitions were determined for the L, M, and H conditions. For
329   the KE exercise, 18.33 ± 10.05 repetitions were performed for the anchoring trial, and 5.60 ±
330   3.07, 10.73 ± 6.10, and 16.33 ± 9.17 repetitions were determined for the three experimental
331   conditions.
332   Significant differences in overall RPE (EF: $F (2, 42) = 20.491$, $p < 0.001$, $\eta^2 = 0.494$; KE: F
333     $(2, 42) = 21.279$, $p < 0.001$, $\eta^2 = 0.503$) were observed between the L (95%CI of EF: 2.046 to
334   4.221; 95%CI of KE: 2.702 to 4.631), M (95%CI of EF: 4.779 to 6.954; 95%CI of KE: 5.169 to
335   7.098), and H (95%CI of EF: 6.912 to 9.088; 95%CI of KE: 7.102 to 9.031) conditions (Fig. 1a
336   and 1b). Similar results were observed in the average SFI for EF ($F (2, 42) = 20.051$, $p < 0.001$,
337     $\eta^2 = 0.488$, 95%CI of L: 1.057 to 1.171; 95%CI of M: 1.189 to 1.303; 95%CI of H: 1.309 to
338   1.423) (Fig. 1c). With regards to the SFI for KE, a significant increase ($F (2, 42) = 5.228$, $p =$
339   0.010, $\eta^2 = 0.199$) was observed between H with L (95%CI of L: 0.969 to 1.061; 95%CI of M:
340   0.994 to 1.085; 95%CI of H: 1.069 to 1.160) (Fig. 1d).
341   Figure 1. Near here
342   A significant overall main effect on time was observed in the RPE ($F = 182.862$, $p < 0.001$,
343     $\eta^2 = 0.934$), SFI ($F = 53.536$, $p < 0.001$, $\eta^2 = 0.805$), and velocity ($F = 11.294$, $p < 0.001$, $\eta^2 =$
344   0.465) throughout the EF trial. Significant differences were observed in RPE and SFI between
345   conditions at the mid-point (RPE: $F = 43.619$, $p < 0.001$, $\eta^2 = 0.770$, 95%CI of L: 1.427 to
346   3.394; 95%CI of M: 2.800 to 5.093; 95%CI of H: 4.578 to 6.708; SFI: $F = 24.007$, $p < 0.001$, η^2
347     $= 0.649$, 95%CI of L: 1.073 to 1.177; 95%CI of M: 1.202 to 1.335; 95%CI of H: 1.280 to 1.486)
348   and the last repetition during EF exercise (RPE: $F = 74.911$, $p < 0.001$, $\eta^2 = 0.843$, 95%CI of L:
349   2.448 to 4.618; 95%CI of M: 5.348 to 7.852; 95%CI of H: 8.510 to 9.757; SFI: $F = 24.746$, $p <$
350   0.001, $\eta^2 = 0.639$, 95%CI of L: 1.155 to 1.303; 95%CI of M: 1.334 to 1.575; 95%CI of H: 1.512
351   to 1.979) (Fig. 2a and 2c). A significantly lower velocity ($F = 18.319$, $p < 0.001$, $\eta^2 = 0.567$,
352   95%CI of L: 0.684 to 0.838 m/s; 95%CI of M: 0.690 to 0.927 m/s; 95%CI of H: 0.451 to 0.700
353   m/s) was observed in the H compared with the L and M conditions on the last repetition (Fig.
354   2e). With regard to KE, the overall main effect on time was observed in the RPE ($F = 437.174$, p

355   < 0.001, $\eta^2 = 0.961$) and SFI ($F = 16.044$, $p < 0.001$, $\eta^2 = 0.534$). There were significant
356   differences in the RPE between the experimental conditions at the mid-point ($F = 20.977$, $p <$
357   0.001, $\eta^2 = 0.600$, 95%CI of L: 1.549 to 3.585; 95%CI of M: 3.114 to 5.019; 95%CI of H: 4.242
358   to 6.024) and the last repetition ($F = 86.838$, $p < 0.001$, $\eta^2 = 0.861$, 95%CI of L: 2.919 to 4.947;
359   95%CI of M: 6.059 to 7.808; 95%CI of H: 8.069 to 9.531) (Fig. 2b). A significantly higher SFI
360   ($F = 8.184$, $p = 0.006$, $\eta^2 = 0.369$, 95%CI of L: 0.989 to 1.111; 95%CI of M: 1.044 to 1.235;
361   95%CI of H: 1.134 to 1.403) was observed in the H compared with the L and M conditions for
362   the last repetition (Fig. 2d). Significant interactions (conditions × times: $F = 3.695$, $p = 0.009$, η^2
363   $= 0.209$) were observed in exercise velocity during KE; however, pairwise comparisons did not
364   indicate any difference between time and conditions (Fig. 2f).
365   Figure 2. Near here
366   The results of the regression analysis are shown in Table 1. The models were significant (p
367   < 0.001), and determination coefficients were large in both EF ($R^2 = 0.552$) and KE ($R^2 = 0.377$).
368   The scatter plots of the predicted SFI and the measured SFI are shown in Fig. 3.
369   Table 1. Near here
370   Figure 3. Near here
371
Discussion

373   The purpose of this study was to investigate the validity of using RPE for assessing
374   exercise-induced muscle fatigue and to establish prediction models for fatigue in resistance
375   exercise situations. The most important contributions of this study are that it: 1) confirmed RPE
376   as an effective tool for assessing exercise-induced muscle fatigue, 2) established two prediction
377   models for assessing muscle fatigue by using the RPE score and velocity during single-joint
378   resistance exercises, and 3) suggested that velocity changes may not reflect muscle fatigue
379   correctly when exercise target is no longer explosive performance.
380   During dynamic exercises, effort sensation increases in response to both central and
381   peripheral changes, such as motor unit recruitment, firing rate, and anaerobic glycolysis (Lagally
382   et al., 2002b; Amann et al., 2011; de Morree, Klein & Marcora, 2012; Blain et al., 2016). For
383   instance, Lagally et al. revealed that sEMG and blood lactic levels changed correspondingly,
384   with results similar to RPE under different intensities (Lagally et al., 2002b). In our study, the
385   relative intensity was designed to be constant between conditions; thus, the possibility that RPE
386   was dependent on intensity could be eliminated. The cause of the difference in RPE can be
387   attributed to the difference in duration of consecutive exercises. Previous research indicated that
388   more repetitions could have an impact on glycolytic metabolism and RPE, even when the total
389   rest time remain constant (Esteban M. et al., 2012; Mayo, Iglesias-Soler & Kingsley, 2019; Zhao,
390   Yamaguchi & Okada, 2020). Consistent with these previous findings, we observed that a greater
391   number of repetitions were performed continuously with increasing volume, which might have
392   induced more severe peripheral perturbation, such as hydrogen ion concentration in skeletal
393   muscles. These contraction-induced mechanical and chemical changes can stimulate afferent
394   feedback from molecular receptors on the terminal end of myelinated (group III) and

395   unmyelinated (group IV) nerve fibers in skeletal muscle, increasing the perception of exertion
396   (Amann et al., 2011; Blain et al., 2016; Broxterman et al., 2018). As a result, RPE was higher
397   during this trial which was statistically significant. Moreover, the dramatic disruption in
398   homeostasis interfered with the conduction velocity of the muscle fiber (Brody et al., 1991),
399   indicated by the shifting of the spectral power frequency to a low frequency band and a
400   significant increase in the SFI. These corresponding changes suggest that the RPE reflects
401   fatigue responses of single-joint resistance exercises.
402   When the results of the upper and lower body were compared, fatigue in the lower body
403   was more difficult to predict. The upper body exhibited a higher level of R^2 than the lower body
404   (EF: $R^2 = 0.552$; KE: $R^2 = 0.377$). This may be attributed to the differences in muscle fiber
405   composition. Some studies have indicated that there are larger type-I fiber distributions in the
406   vastus lateralis compared to the biceps and triceps brachii (Miller et al., 1993; Mygind, 1995).
407   Moreover, these differences in fiber distribution could lead to variations in lactate kinetics in the
408   arms and legs (Van Hall et al., 2003). The values of the SFI during the H condition were
409   consistent with this inference, where arm muscles displayed unignorable fatigue faster than the
410   legs (mid-point vs. last repetition of the H condition). Thus, the different fatigue development
411   patterns in the arms and legs may be due to muscle fiber distribution differences, which might
412   have changed the accuracy of the model.
413   As for the results of velocity, a significant difference was only observed at the end point of
414   EF exercise, whereas no significant difference was observed between conditions at any time
415   point during KE exercise. It seemed that the experimental designs with non-explosive, non-
416   failure, and single-joint settings were unsuitable for using velocity changes as measures of
417   fatigue. In previous research that focused on the relationship between velocity and fatigue-
418   related measures, multi-joint exercises, explosive manner, and until-failure design were always
419   selected and performed (Sánchez-Medina & González-Badillo, 2011; Evandro et al., 2019;
420   Mayo, Iglesias-Soler & Kingsley, 2019). To assess the validity of velocity changes as a muscle
421   fatigue indicator in various resistance exercise situations, we used single-joint exercises, a non-
422   explosive manner, and a non-failure design. In these situations, the validity of velocity changes
423   seemed to have very limited precision for mechanical measurement of fatigue. Although the lack
424   of familiarity with unilateral exercises and the deviations in weight determination (nearest kg for
425   EF exercise and nearest 5 lbs. for KE exercise) may have had some influence on velocity
426   measures, the volume of the H condition observed (90% of until-failure volume) was considered
427   to be very close to the volitional failure, and we expected to observe velocity changes
428   corresponding to the experimental conditions. Although significant interaction (EF: $p < 0.001$;
429   KE: $p = 0.009$) was observed, similar significant changes in velocity corresponding to SFI failed
430   to occur during post hoc test. Similar changes in velocity are likely to be observed if a larger
431   sample size was recruited. Nevertheless, we can conclude that velocity changes are inappropriate
432   for fatigue assessment of non-explosive, non-failure, and single-joint resistance exercises.
433   When using velocity changes as a muscle fatigue indicator in sports exercise and clinical
434   situations, only explosive, until-failure, and multi-joint settings are acceptable. Some training

435   programs should be avoided, such as open kinetic chain and muscular hypertrophy-aimed
436   exercises. For instance, it is possible that muscle fatigue appeared while velocity changes failed
437   to occur. For lower-body exercises, more caution should be observed when using only velocity
438   changes as an assessing tool in the fatigue prediction process. This is consistent with the
439   rationale offered earlier concerning muscle fiber distribution. It is desirable to assess muscle
440   fatigue by combining the RPE score with velocity changes during resistance exercise situations.
441   If Borg's CR-10 scale is the only available tool in the fatigue assessment process, muscle fatigue
442   in the arm would appear around an exertion level ranging from "Moderate" to "Somewhat
443   strong". For the leg, significant muscle fatigue would appear around the "Very strong" level.
444   The current study has several limitations. First, the metabolic and endocrine variables were
445   not assessed in this study. Some studies have noted that training volume might translate into
446   different neuroendocrine system perturbations and/or neuromuscular function changes,
447   potentially affecting perceived exertion (Hiscock et al., 2018). Second, the present study only
448   assessed single-joint exercises. Different results might be observed when performing multi-joint
449   exercises because more muscle groups will be recruited. Further, the findings may not offer
450   insights on contribution of gender as a factor, as all participants were male. Otto et al. (Otto,
451   Emery & Côté, 2018) revealed that sex differences affect fatigue adaption strategies in certain
452   muscles. Accordingly, future studies should focus on the metabolic and endocrine measures,
453   multi-joint exercises, and sex-specific effects of RPE and muscle fatigue.
454

Conclusions

456   The current study demonstrated that the SFI and RPE changed correspondingly, which
457   revealed a link between perceptual responses and muscle fatigue. We concluded that muscle
458   fatigue exhibits similar increases in perceptual responses when resistance exercise is performed.
459   These results demonstrate that RPE is a useful tool for assessing fatigue during single-joint
460   resistance exercises. Furthermore, we offer two significant models for predicting muscle fatigue
461   by using RPE score and velocity in clinical and sports situations. However, velocity changes
462   have only limited precision on fatigue assessment when the exercise target is no longer explosive
463   performance, and more caution should be used when predicting muscle fatigue in the legs. It is
464   recommended to combine RPE responses with velocity changes and assess muscle fatigue
465   comprehensively during clinical and sports situations.
466

Acknowledgements

468   The authors declare that they have no conflicts of interest and competing interests.
469

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626

Output of multiple regression analyses.

SFI, spectral fatigue index; EF, elbow flexion; KE, knee extension; RPE, ratings of perceived exertion; SEE, standard error estimators; β, coefficients.

1   Table 1:

2   Output of multiple regression analyses.

Output-variable	Predictors	R^2	Adj. R^2	SEE	Constant (Sig.)	β_{RPE} (Sig.)	$\beta_{Velocity}$ (Sig.)	F	Model sig.
SFI of EF	RPE, Velocity	0.552	0.546	0.198	1.551 ($p < 0.001$)	0.053 ($p < 0.001$)	-0.600 ($p < 0.001$)	98.555	$p < 0.001$
SFI of KE	RPE, Velocity	0.377	0.371	0.122	1.077 ($p < 0.001$)	0.030 ($p < 0.001$)	-0.223 ($p < 0.001$)	70.101	$p < 0.001$

SFI, spectral fatigue index; EF, elbow flexion; KE, knee extension; RPE, ratings of perceived exertion; SEE, standard error estimators; β, coefficients.

Figure 1

Overall ratings of perceived exertion (RPE) and average spectral fatigue index (SFI) of elbow flexion (EF) and knee extension (KE) exercises.

The *p* value represents the differences and significance levels between experimental conditions.
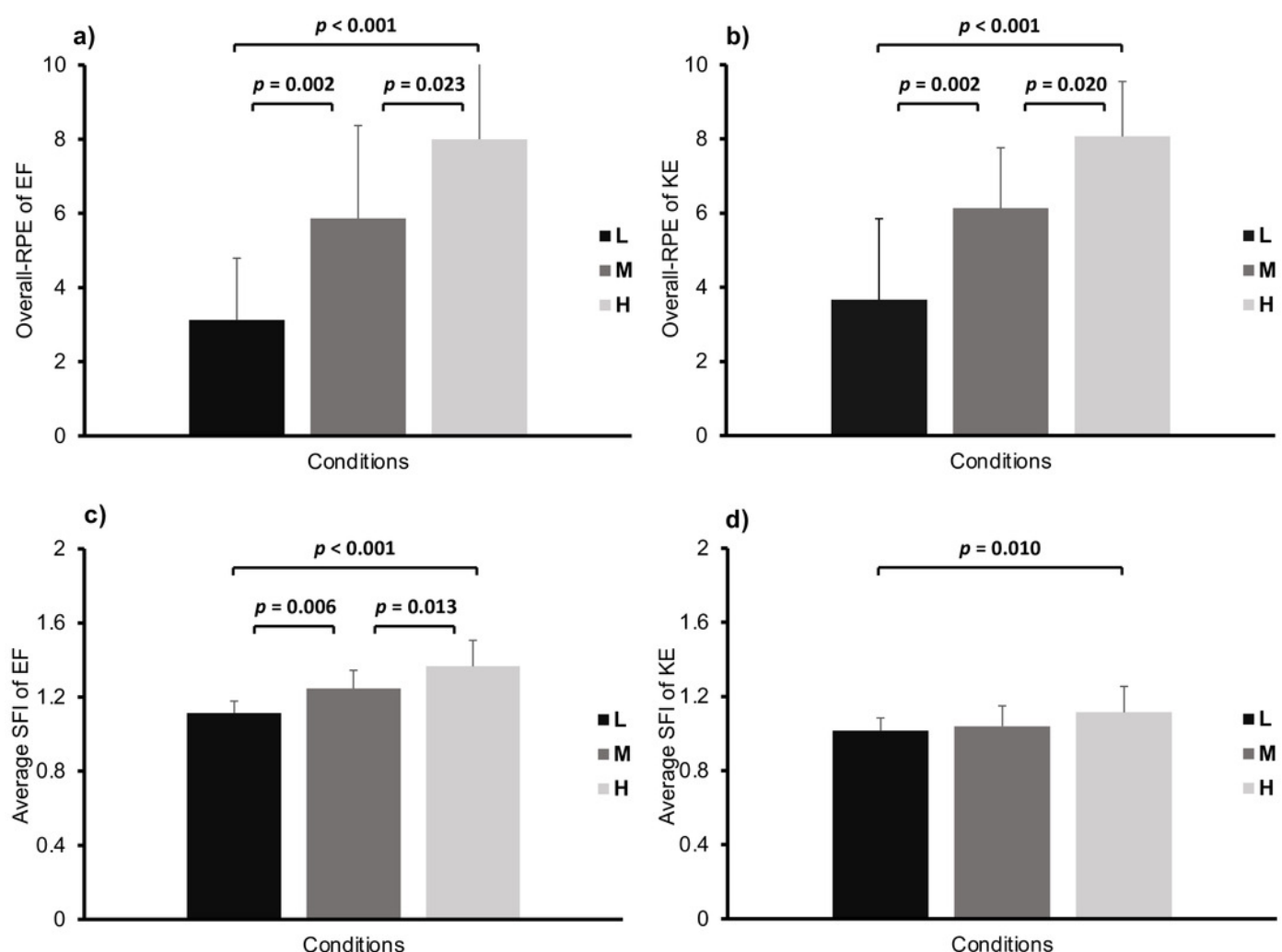
Figure 2

Rating of perceived exertion (RPE), spectral fatigue index (SFI), and mean velocity during low (L, circle with solid lines), medium (M, square with dashed lines), and high (H, triangle with dotted lines) volume conditions of elbow flexion (EF) and knee ex

* represents a significant difference in comparing L with other conditions, $p < 0.05$; ** $p < 0.01$; # represents a significant difference in comparing M with other conditions, $p < 0.05$; ## $p < 0.01$; § represents a significant difference in comparing H with other conditions, $p < 0.05$; §§ $p < 0.01$; The p value indicates the overall main effects and significant level for time.
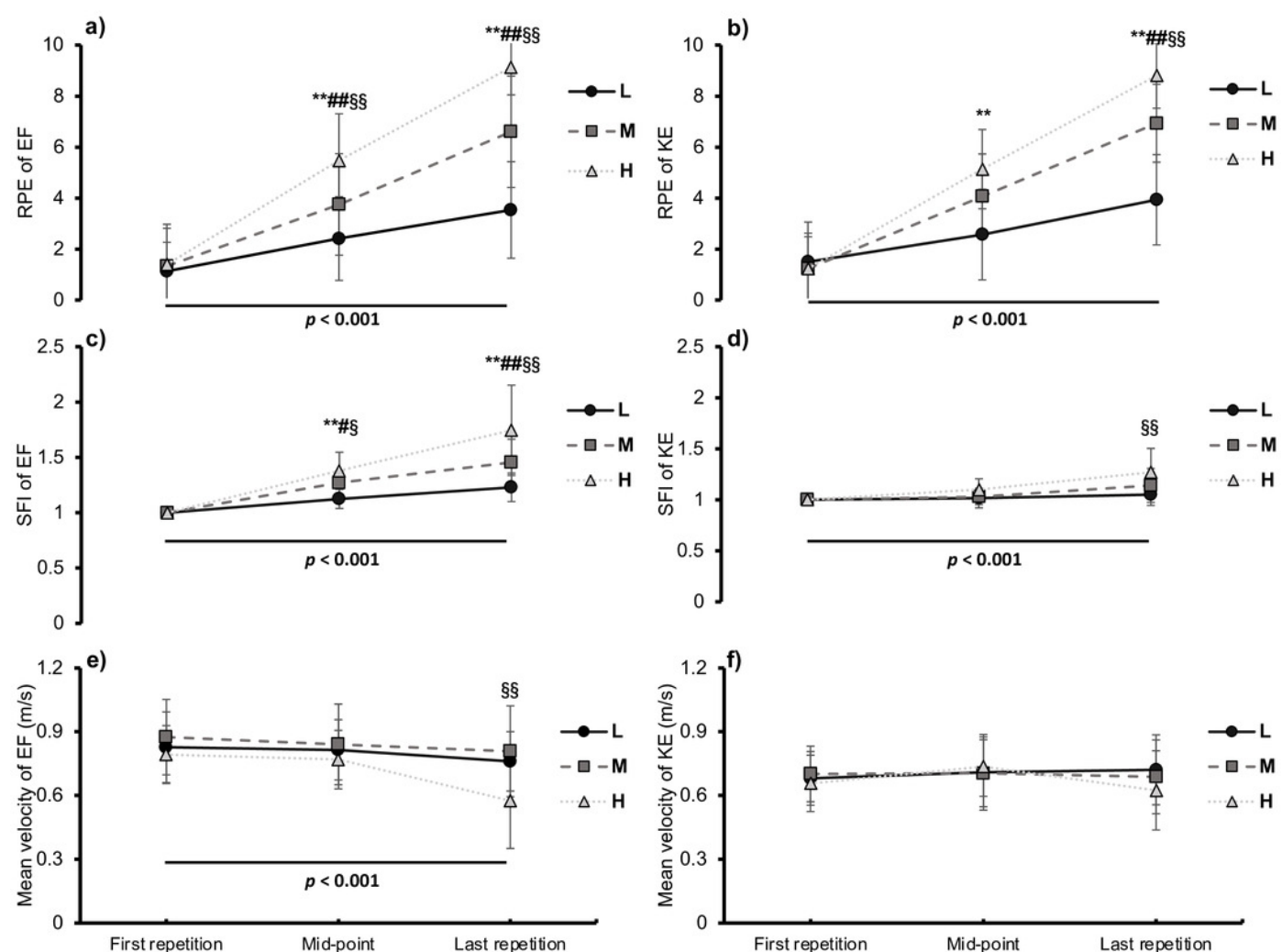
Figure 3

Measured versus predicted spectral fatigue index (SFI) of elbow flexion (EF) and knee extension (KE) exercises.

The *p* value represents the significant level of linear regression models.